Geothermal Energy Resources for Developing Countries

D. Chandrasekharam & J. Bundschuh - editors

GEOTHERMAL ENERGY RESOURCES FOR DEVELOPING COUNTRIES

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Foreword by Töpfer

Most governments today recognize that renewable energy technologies have important roles to play in their energy sectors. Renewables can help a country diversify its energy resources, satisfy unmet rural energy demand, reduce fuel imports, hard currency expenditures, and both local and/or global environmental impacts of energy use.

Governments also recognize that the life-cycle costs of some of today's renewable energy systems exceed those of conventional alternatives. As a result, governments are increasingly providing financial incentives to help overcome cost differentials and level the playing field in ways that counter-balance those provided to conventional alternatives and which account for environmental costs and benefits not considered in conventional economic comparisons and pricing methodologies.

The objective of the Framework Convention on Climate Change is to stabilize greenhouse gas emissions in the atmosphere in order to mitigate climate change. Implementing the Climate Change Convention is a major challenge to the international community because of its broad scope, the international negotiation process and political will it entails, the need to present scientific evidence, and the ability of industry and population groups to adapt to new energy sources.

Since most of the greenhouse gases generated from anthropogenic activities come from the use of fossil fuels, finding ways to promote sustainable development that do not require use of fossil fuels is one of the key steps in meeting the objective of the Climate Convention. To industrialized countries, it implies major shifts in the present energy matrix towards renewable sources and measures to improve energy efficiency. To developing countries, it implies satisfying their increasing energy needs through the use of renewable energy technologies at high efficiency levels in order to provide energy services in rural areas, promote private energy sector investment and curtail increases in greenhouse gas emissions.

Many advancements have been made in the use of conventional energy technologies during the last decade and promoting their widespread commercial use could improve the efficiency of use of petroleum-based fuels beyond present levels. Also, the adoption of modern renewable energy and energy-efficient technologies in various industrial sectors and implementation of demand-side-management programs can together have a significant impact on reducing greenhouse gas emissions.

Since most of the increase in energy demand will occur in developing countries, these countries must be afforded access to the modern technologies in the shortest time possible. This implies technological, institutional and political leap-frogging in order to guarantee both the commercialization of modern energy and energy-saving industrial technologies and the introduction of demand-side-management and new forms of energy planning. Developing countries must participate in this technological revolution from the start, not only as receivers of modern technology but also as participants in their development, commercial production and use. The traditional process of waiting for technologies to become commercially viable before they are promoted in developing countries is not satisfactory for the purpose of abating greenhouse gas emissions nor for the development of the private sector in emerging market countries.

Policy instruments have to be created in order to make non-renewable energy costs account for environmental damage and improve the competitiveness of clean technologies. With major improvements in energy efficiency and conservation, approximately 40 to 50 percent of the world energy demand may be delivered from renewable sources by the end of the present century as opposed to about 12 percent in 1990 (large-scale hydro-power excluded). Interests within the fossil fuel sector may resist the development of markets for clean technologies. These interests refer not only to oil producers but also to investors and related industries in the sector.

For a private sector perspective, establishing a renewable energy-based project in a developing country entails significant upfront costs and risks for the developer and his financial backers. The capital-intensive front-end nature of most renewable investments, the requirements of government and lenders for data and other information, and the need to establish a sustained professional work force are part of the assumed costs of a project regardless of its size. The larger the project, the more power production there will be to spread out these costs. For these reasons, many private developers see small projects as simply uneconomical or, if they express interest, the potential power prices will be higher than those from competing traditional sources.

As the financial mechanism to the UN Framework Convention on Climate Change (UNFCCC), the UNEP is a catalyst for innovative projects and institutional linkages that can provide sustainable development and environmental benefits would be otherwise difficult to achieve through traditional financing channels.

Roles that UNEP can play include monitoring projects and trends in emerging clean power markets, and the roles of public and private sector; collecting and distilling experiential information and successful strategies, providing support for human resource development, acting as advisors, impartial brokers and catalysts for promising projects, and identifying sources of loan, investment and grant funding for selected high impact projects.

A role that UNEP can play through its Technology Transfer Networks is to facilitate public-private partnerships for viable, market driven initiatives that use clean technology approaches, such as geothermal, and help bring them to the point where they are suitable for commercial investment. This means providing pre-investment support for feasibility work, due-diligence and negotiations that will result in the signature of power purchase, and other agreements that may be necessary to create a clear path for the active participation of developers and investors.

Although the Technology Transfer Network program is still in its startup phase, strong collaborative interest has been expressed by a number of multi and bilateral agencies, national laboratories, export credit agencies, NGOs and private investment funds. This strong display of interest in partnership-based relations confirms a consensus that like-minded programs linked together can accomplish much more than stand-alone programs working in isolation from each other. In this regard, the program is well on its way to becoming a pioneer in the development field.

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Foreword by Obasi

Access to adequate energy resources and their use are vital for socio-economic development. In the past two centuries, the demand for energy has grown at the rate of 2 per cent per year. Rapid socio-economic development and the mounting expectations of a growing world population are placing an ever-increasing demand on access to affordable energy. Yet, today nearly two billion people do not have access to electricity in the developing world, and only about 30 per cent of the population has grid-based electric supply.

The fast depletion of conventional sources of energy, mainly fossil fuels such as coal, oil and gas, has been associated with increase in atmospheric greenhouse gases (GHGs) with implications for potential changes in the Earth's climate and in turn for sustainable development. The need for the development of renewable energy sources such as hydro, wind, solar, bio-mass, tidal and geothermal has become most pressing since their potential is also highly promising in the developing countries. Furthermore, renewable energy systems are part of the Clean Development Mechanism, as required by the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC).

Over the years, considerable efforts have been made in the development, generation and utilization of hydropower, wind and solar energy. On the other hand, limited efforts have been made in geothermal energy, especially in the developing countries. For this reason, the editors and the authors of the publication "Geothermal Energy Resources for Developing Countries" should be congratulated for focussing attention on this topic. The publication gives a valuable and comprehensive treatment of geothermal energy, covering issues related to the sources, technologies, cost and value, and worldwide status of installed and projected systems. The barriers and risks that are limiting the promotion of geothermal energy have been well identified and ways that include proposals for policy reform to overcome them have been shown.

It is vital to move towards a comprehensive global strategy for energy, specifically addressing the needs of rural and remotely-located populations of the developing world. In this way, the publication, written in mostly non-technical language, would be useful to a wide range of users including students, teachers, funding institutions as well as scientists and policy makers.

I am sure that the reader will recognize the value and the potential for geothermal energy generation and use in their own national and local contexts. Within its mandate, the World Meteorological Organization (WMO) as part of the UN system will continue to support national efforts geared towards increased development and use of new and renewable environment-friendly energy resources, and towards the minimization of environmental pollution and the conservation of the Earth's natural resources for future generations.

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Preface

Renewable energy can be particularly appropriate for developing countries. In rural areas, where half of the world's rural population lives, have no access to modern forms of energy. In such areas transmission and distribution of energy generated from fossil fuels can be difficult and expensive. Producing renewable energy locally can offer a viable alternative. Interest in renewable energies has increased recently due to environmental problems associated with conventional energy sources. It is generally accepted that the emission of greenhouse gases from fossil fuels causes global warming and declining air quality. Renewable energies generally do not cause pollution or cause greenhouse gas emissions. In addition to this, a decline in the cost of renewable energy technologies and improved efficiency and reliability of such technologies added further interest.

A meeting of the Framework Convention on Climate Change in 1997 established the Kyoto Protocol, which set firm targets for greenhouse gas emissions for developed countries. Also agreed at Kyoto was the Clean Development Mechanism (CDM), which allows developed countries to meet targets for reducing emissions by gaining certified credits from projects undertaken in developing countries.

Cost has been a major inhibitor to the widespread adoption of renewable energy in the past in the developing countries. Further, slow technical progress over the past decades has been a major constraint to the mainstream adoption of renewable energy. But now we are looking at a different situation. Coupled with changes in market forces and improvements in technology have created new opportunities for renewable energy.

The Clean Development Mechanism (CDM) could be an important impetus to adoption of renewable energy in developing countries. However, to meet CDM criteria, a project has to satisfy a number of requirements environmental, technological, and economic and others – creating a substantial increase in administration. The issue of how carbon credits would be shared between the donor country and the recipient also has to be resolved. The increased administrative load and the complications of carbon credit allocation may act as barriers to the implementation of renewable energy projects. A successful project is one which links energy and socio-economic aspect, meets needs, uses appropriate technology, reliable and sustainable and economically viable.

Access to renewable energy will not alleviate poverty unless it is seen as an economic development issue rather than an energy issue. To achieve economic development, renewable energy should be linked or be part of another project that improves development with a strong involvement of local communities and uses site specific technology. Entrepreneurial skills by the communities are very essential to gain economic benefits from renewable energy projects.

In developing countries, local communities will show interest in renewable energy project only when such projects meet their economic and cultural needs. This aspect should be considered while implementing renewable energy projects in developing countries.

About 70% of the total available geothermal sources are located in developing countries in Asia, Latin American and African countries. In fact, electric power plants driven by geothermal energy provide over 44,000 million kilowatt hours of electricity worldwide per year, and world capacity is growing at greater than 9% per year. Out of this growth, the demand for energy in developing countries constitutes more than half of this percent. With advancement of binary technology and with vast low temperature resources available in the developing countries, geothermal will become the most suitable, cost effective and sustainable energy source in the present decade in such countries. Industrialized countries support is very essential in this respect. These industrialized countries should take the responsibility of providing the improved technology and machinery as well as to provide capacity building to meet the energy demands of developing countries. This will make developing countries to implement CDM at an early date and control the global climate change.

To improve the standard of living, a country needs collective effort of the academic and administrative machinery. Academic machinery will provide solutions and administrative machinery will implement the solutions. Keeping this in mind the book "Geothermal Energy Resources for Developing Countries" is designed specially for developing countries involving both scientific and administrative inputs.

This book, demonstrates how geothermal energy can be a driving force for an economically sound and sustainable development of developing countries. It looks at the provision of geothermal energy within the framework of sustainable energy development in the developing countries for power generation, rural electrification and direct use to support small-scale industries, like food processing, greenhouse cultivation, aquaculture etc., and balneology and tourism. The book gives an overview of the world geothermal resources, their possible uses as function of temperature and economical availability, suitable geothermal exploration techniques, and optimal geothermal exploitation methods. Country updates on geothermal energy resources in certain developing countries are also included.

Environmental aspects; benefits of geothermal energy utilization in controlling the greenhouse and other gases within the framework of local environmental protection; as a cost effective mechanism in controlling global climate changes within the framework of international climate change policies; and as a clean energy development mechanism opportunity for non-Annex I countries of FCCC are discussed. Institutional, policy regulations and financial obstacles. which hinder the growth of geothermal energy, and ways to overcome such problems, are discussed. The book also contains issues, which need legal, institutional and political framework and which calls for international support for capacity building and popularizing geothermal energy utilization.

In particular, the need for private sector participation, possible tools to attract and facilitate private sector investment, mechanism to overcome financial obstacles and opportunities for investments are also discussed. Certain policy reforms, which this energy sector needs, are also proposed.

The book is addressed to 1) leading decision and policy makers and administrators in the Government; 2) business houses in energy sector, engineers and scientists, independent power producers, hydrogeologists related to non-conventional energy projects; 3) International bodies, like International Development Banks, Financial institutions, donors etc., associated with technical and economic cooperation in developing countries; 4) teaching, research institutions and R and D establishments involved in non-conventional energy related projects.

Success of a book depends on the support the editors derive from funding organizations and institutions and scientists recognized in promoting clean energy mechanism. We are extremely fortunate to have the financial support from the World Meteorological Organization, International Geothermal Association, Instituto Costarricense de Electricidad ICE, Costa Rica and Indian Institute of Technology, Bombay. Scientists from leading Energy institutions and UN organizations extended their full support and made excellent contributions. Without their help the book would not have taken the present shape. All the chapters in the book in one way or the other address the technical and scientific problems related to energy use and demand and provide solutions to adopt clean energy mechanism thereby improving the living standards of the developing countries. We are grateful to the above organizations and all the authors who rendered support in bringing out this book.

Editors

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Sustainability assessment of energy systems: An overview of current status

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ABSTRACT: This review is aimed to introduce historical background for the sustainability concept development. In the assessment of global energy resources attention is focussed in on the resource consumption and its relevancy to the future demand. In the review of the sustainability concept development special emphasize is devoted to the definition of sustainability and its relevancy to the historical background of the sustainability idea. In order to introduce measuring of sustainability the attention is devoted to the definition of respective criteria. There has been a number of attempts to define the criterions for the assessment of the sustainability of the market products. Having those criterions as bases, it was introduced a specific application in the energy system design. Special attention in this review is devoted to the potential energy sustainable development options.

1 INTRODUCTION

Our civilization through the history has been under constrains with economic, social and ecological perspectives in its development. Since the beginning of industrial revolution need for harmonized development of different commodities leading to the better life has been recognized. In this respect, economic and social developments have been based on the natural capital available at the respective level of technology development.

Through the history of human society there have been different patterns of social structure, each of the successive social structure has been different with the complexity of its internal organization. The industrial revolution has triggered a new pattern of complexity determined by the need to generate more and more power to be used in everyday life. New scientific achievements and technological progress have opened a new venture in the development of our society. In this respect, it is our need to look ahead in order to see if we can forecast our future in the near term and long-term scale. This is a reason that a number of scholars have devoted substantial attention to the future of our society. It is obvious that there is need to dwell into the complexity of this issue in order to be able to understand the processes, which are going to affect our future.

In particular the attention was focused to the indicators related to the material resources and environment. The first and second energy crises have shown the vulnerability of the present state of our society. Recent claims that the concentration of CO_2 is reaching limit, which may trigger irreversible changes in the environment with catastrophic consequences for the life on our planet.

Special attention is devoted to the most recent development of the concept off sustainability science. A new field of sustainability science is emerging that seeks to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes with the ecology and so characteristics of particular places and sectors. With a view toward promoting research necessary to achieve such advances, it was proposed an initial set of core questions for sustainability science.

This review is aimed to introduce historical background for the sustainability concept development. Special reference is given to the energy resource depletion and its forecast. Since, this chapter is part of the book Geothermal Energy for Developing Countries special emphasize will be given to the need of less developed countries. In the assessment of global energy resources attention is focused on resource consumption and its relevancy to the future demand. In the review of the sustainability concept development special emphasize is devoted to the definition of sustainability and its relevancy to the historical background of the sustainability idea. The recent assessment of sustainability is reflecting the normative and strategic dimension of sustainability.

Numbers of scientific meetings have been devoted to the different aspects of the resources limits. It has been unambiguously proved that there are limits. The accuracy of the assessment method may only affect the time scale of our prediction. This fact has become a driving force for the promotion of the programs to mobilize human, economic and technological entities to take actions needed to prevent the adverse effect to our environment and civilization.

2 ENERGY RESOURCE LIMITS

Energy, water and environment are essential commodities needed for the human life and in the development of our civilization these three commodities have served as the fundamental resources for the economic, social and cultural development. In early days of human history it was believed that there are abundant resources of these commodities. With industrial revolution, use of the resources has become the essential driving force for the economic and social development. With the increase of population and respective increase of the standard of living, the natural resources have become scarce in some specific regions. With the further increase in their demand, it has become evident that the scarcity of the natural resources may attain global dimension and affect human life. Energy crises in 1972 and 1978 have focused attention of our community in large to investigate the limits in energy resources. This was a moment when our society through the different institutions has launched programs aimed to investigate global scarcity of natural resources on our planet. It has become obvious that modern society has to adapt a new philosophy in its development, which has to be based on the limited natural resources.

2.1 *Energy resources*

Energy resources have always played an important role in the development of the human society (Marchetti 1995) and since the industrial revolution the energy has been a driving force for the development of modern civilization. Technological development and consumption of energy, along with the increase in the world population, are interdependent. The industrial revolution, especially to the momentum created by the change from reciprocal engines to the great horsepower of steam engines in the late nineteenth century, which brought about a revolution in dynamics – began a drastic increase both in consumption and population of the world (Marchetti 1994).

The history of life on the Earth is based on the history of photosynthesis and energy availability (Ohta 1994). The history of such a planet lies on the capture of the solar energy and its conversion by photosynthesis in plants and phytoplankton as organic molecules of high energy content. The plants convert this energy into other organic compounds and work by biochemical processes. Photosynthesis counteracts entropy increase and degradation since it tends to put disordered material in order. By capturing the solar energy and decreasing the planetary entropy, photosynthesis paves the way for biological evolution.

Boltzman, one of the fathers of modern physical chemistry, wrote in 1886: "the struggle for life is not a struggle for basic elements or energy, but a struggle for the availability of negative entropy in energy transfer from the hot Sun to the cold Earth". In fact, life on the Earth requires a continuous flux of negative entropy as the result of the solar energy captured by photosynthesis. The Sun is an enormous machine that produces energy by nuclear fusion and offers planet Earth the possibility of receiving large quantities of negative entropy. Every year the Sun sends 5.6×10^{24} joules of energy to the Earth and produces 2×10^{11} tons of organic material by photosynthesis. This is equivalent to 3×10^{21} joules/year. Through the billions of years since the creation of the planet Earth this process has led to the accumulation of an enormous energy in form of different hydrocarbons. Most of the fossil fuels belong to the type of material where molecular binding is due to Van der Waals potential between every two molecules of the same material. Mankind's energy resources rely heavily on the chemical energy stored in the fossil fuel. Table 1 shows assessed energy resources (Master 1987).

Energy and matter constitute the earth's natural capital that is essential for human activities such as industry, amenities and services in our natural capital as the inhabitants of the planet earth may be classified as:

- Solar capital (provides 99% of the energy used on the Earth);
- Earth capital (life support resources and processes including human resources).

These, and other, natural resources and processes comprise what has become known as "natural capital" and it is this natural capital that many suggest is being rapidly degraded at this time.

All natural resources are, in theory, renewable but over widely different time scales. If the time period for renewal is small, they are said to be renewable. If the renewal takes place over a somewhat longer period of time that falls within the time frame of our lives, they are said to be potentially renewable. Since renewal of certain natural resources is only possible due to geological processes, which take place on such a long time scale that for all our practical purposes, we should regard them as non-renewable. Our use of natural material resources is associated with no loss of matter as such. Basically all earth matter remains with the earth but in a form in which it cannot be used easily. The quality or useful part of a given amount of energy is degraded invariably due to use and we say that entropy is increased.

Table 1. Resource indicators.

	Name	Definition	Unit
RI_{fuel}	Fuel Resource Indicator	The amount of fuel consumed in tonnes divided by energy produced in life-time	kg/kWh
RI_{CS}	Carbon Steel Resource Indicator	The amount of carbon steel in tonnes, used in the construction of the plant divided by energy produced in life-time	kg/kWh
RI_k	Copper Resource Indicator	The amount of copper in tonnes, used in the construction of the plant divided by energy produced in life-time	kg/kWh
RI_{Al}	Aluminium Resource Indicator	The amount of aluminium in tonnes, used in the construction of the plant divided by energy produced in life-time	kg/kWh

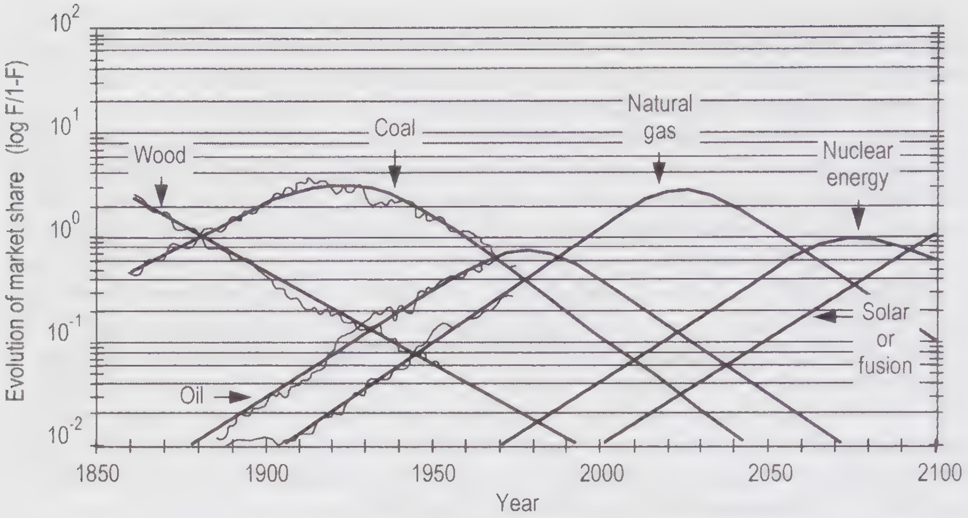

Figure 1. World wide use of primary energy source.

2.2 *Energy consumption*

The abundant energy resources at the early days of the industrial development of the modern society have imposed the development strategy of our civilization to be based on the anticipated thinking that energy resources are unlimited and there are no other limitations, which might affect human welfare development. It has been recognized that the pattern of the energy resource use has been strongly dependent on the technology development. In this respect it is instructive to observe (Marchetti 1980, 1991) the change in the consumption of different resources through the history of energy consumption. Worldwide use of primary energy sources since 1850 is shown in Figure 1.

In Figure 1, F is the fraction of the market taken by each primary-energy source at a given time. It could be noticed that two factors are affecting the energy pattern in the history. The first is related to the technology development and, the second, to the availability of the respective energy resources. Obviously, this pattern of energy source use is developed under constraint immanent to the total level of energy resources consumption and reflects the existing social structure both in numbers and diversity (Arnold et al. 1995, Farinelli 1994, Marzzuraachio et al. 1996, Noel 1995). The world energy consumption is shown in Figure 2.

Looking at the present energy sources consumption pattern, it can be noticed that oil is a major contender, supplying about 34% of energy followed by coal supply, which is around 24.0%, natural gas 19.5% and nuclear energy 5.6%. This means that current fossil fuel supply is 77% of the present energy use. In this respect it is of common interest to learn how long fossil fuel resources will be available, as they are the main source of energy for our civilization. The amount of fuel available is dependent on the cost involved. For oil it was estimated that proved amount of reserves has, over past twenty years, levelled off at 2.2 trillion of barrels produced under $20 per barrel. Over the last 150 years we have already used up one-third of that amount, or about 700 billion of barrels, which leaves only a remaining of 1.5 trillion of barrels. If compared with the present consumption, it means that oil is available only for the next 40 years.

2.3 *Energy consumption forecast*

It is known that the energy consumption is dependent on the amount of energy consumed per capita and the growth of population. It has been proved that there is a strong correlation between

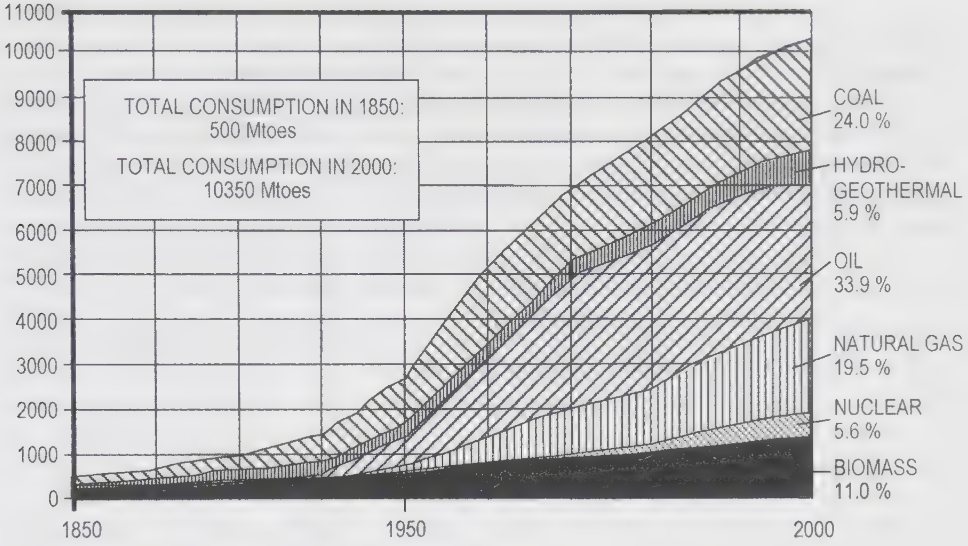

Figure 2. World energy consumption by source.

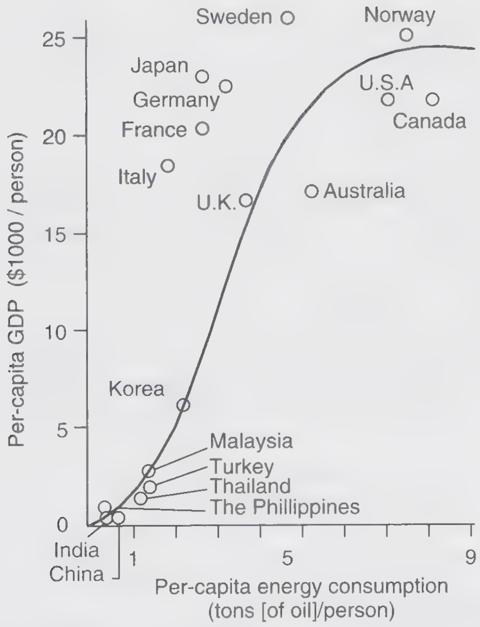

Figure 3. Economic growth and energy consumption for selected countries in 1990.

the Gross Domestic Product and Energy consumption per capita. Figure 3 shows the economic growth and energy consumption for a number of countries in 1990 (Medows et al. 1972).

There is a number of scenarios, which are used for the forecast of the world economic development. With this assumption that the recent trend in the economic development will be conserved in the next 50 years, considering the demographic forecast in the increase of human population, as shown in Figure 4 (Keatany 1993), the future energy consumption could be calculated, as shown in Figure 5 (WEC Message for 1997).

Compared with the available resources, the depletion of the energy resources is an immanent process, which our civilization will face in the near future. Nevertheless, whatever is the accuracy of our prediction methods and models, it is obvious that any inaccuracy in our calculation may affect only the time scale but not the essential understanding that the energy resources depletion process has begun and requires the human action before adverse effects may irreversibly enforce.

Natural resources scarcity and economic growth are in fundamental opposition to each other. The study of the contemporary and historical beliefs showed (Barnett & Morse 1963), that:

- natural resources are economically scarce, and become increasingly so with the passage of time;
- the scarcity of resources opposes economic growth.

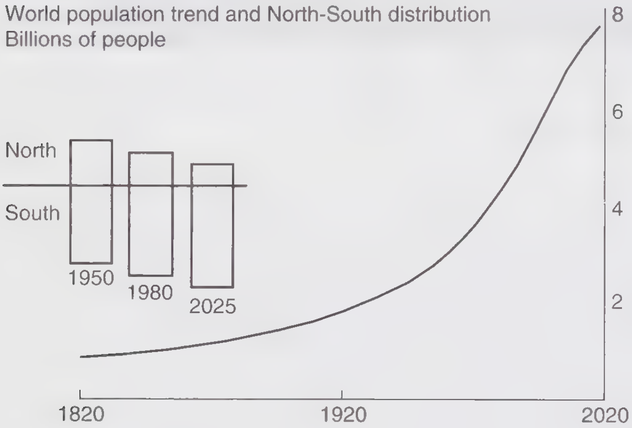

Figure 4. World population growth.

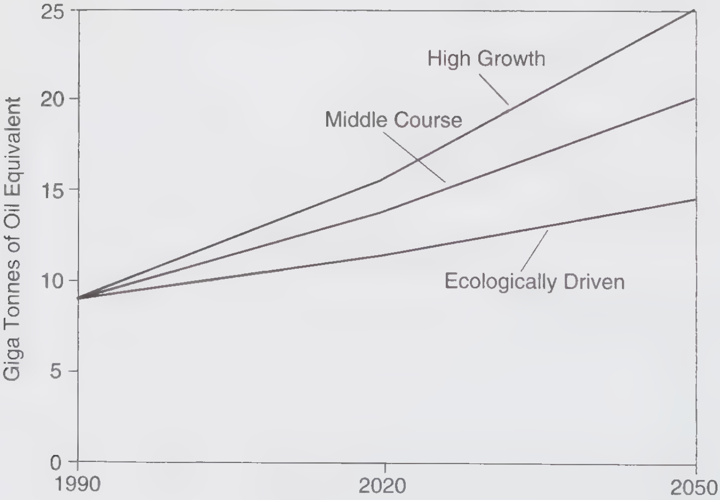

Figure 5. Future energy consumption for different assumptions.

There are two basic versions of this doctrine. The first, the Malthusian, rests on the assumption that there are absolutely limits; once these limits are reached, the continuing population growth requires an increasing intensity of cultivation and, consequently, brings about diminishing returns per capita. The second, or the Ricardian version, viewed the diminishing returns as current phenomena reflecting the decline in the quality of resources brought within the margin of a profitable cultivation. Besides these two models, there is also the so called "Utopian case" where there is no resources scarcity. There have been several attempts to apply these models to the energy resources in order to define the correlation between specific energy resources and economic growth.

2.4 *Environment degradation*

Primary energy resources use is a major source of emissions (Mackey & Probert 1995, Price et al. 1995). Since fossil fuels have demonstrated their economic superiority, more than 88% of primary energy in the world in recent years has been generated from fossil fuels. However, the exhaust gases from combusted fuels have accumulated to an extent where a serious damage is being done to the world global environment. The accumulated amount of CO_2 in atmosphere is estimated at about 2.75×10^{12} t. The global warming trend from 1900–1990 is shown in Figure 6 (Hought & Woodwell 1989).

The future trend of the carbon dioxide concentration in the atmosphere can be seen from the Figure 7 (Wu & Li 1984).

It is rather obvious that the further increase of the CO_2 will lead to disastrous effects to the environment. Also, the emission of SO_2, NO_2 and suspended particulate matters will substantially contribute to exasperate the effect on the environment.

In a world scale, coal will continue to be a major source of fuel for electric power generation. Many developing countries, such as China and India, will continue to use inexpensive, abundant, indigenous coal to meet growing domestic needs (Sustainable Energy Strategy 1995, Report of the United Nation Conference on Environment and Development, 1992, Agenda 21 1992). This trend greatly increases the use of coal worldwide as economy in the other developing countries continues to expand. In this respect, the major long-term environmental concern about coal use has changed from acid rain to greenhouse gas emissions – primarily carbon dioxide from combustion. It is expected that coal will continue to dominate China's energy picture in the future. The share of coal, in primary energy consumption is forecast to be not less than 70% during the period 1995–2010. In 1993 China has produced a total of 1.1×10^{12} tons of coal, in 2000 was 1.5×10^{12} tons, and in 2010 it will be 2.0×10^{12} tons. Since China is the third largest

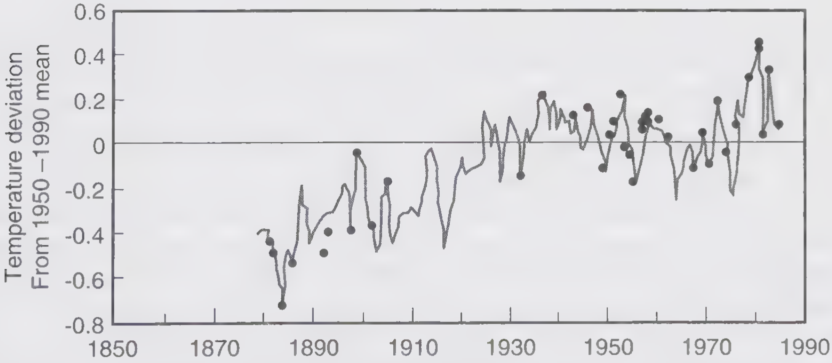

Figure 6. Global warming since 1880.

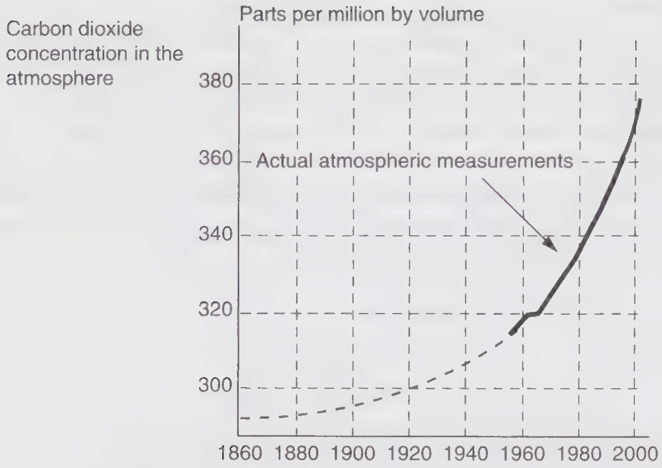

Figure 7. Increase of carbon dioxide concentration in the atmosphere since 1860.

energy producer in world, after USA and Russia, its contribution to the global accumulation of the CO_2 will be substantial if the respective mitigation strategies will not be adopted.

3 SUSTAINABILITY CONCEPT DEVELOPMENT

3.1 *Sustainability definition*

The definition of sustainability concept involves an important transformation and extension of the ecologically based concept of physical sustainability to the social and economic context of development. Thus, terms of sustainability cannot exclusively be defined from an environmental point of view or basis of attitudes. Rather, the challenge is to define operational and consistent terms of sustainability from an integrated social, ecological, and economic system perspective. In this respect the weak and strong sustainability concept are discussed.

Lately, in a number of years "sustainability" has become a popular buzzword in the discussion of the resources use and environment policy. Before any further discussion of the subject, it is necessary to define and properly assess the term we are going to use. So, what is sustainability? Among the terms most often adapted are the following:

(a) for the World Commission on Environment and Development (Brundtland Commission) "development that meets the needs of the present without compromising the ability of future generation to meet their own needs",

(b) for the Agenda 21, Chapter 35 "development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available",

(c) for the Council of Academies of Engineering and Technological Sciences (Declaration of the Council Engineering and Technological Sciences 1995) "it means the balancing of economic, social, environmental and technological consideration, as well as the incorporation of a set of ethic values",

(d) for the Earth Chapter (The Earth Chapter 1995) "the protection of the environment is essential for human well-being and the enjoyment of fundamental rights, and as such requires the exercise of corresponding fundamental duties", and

(e) Thomas Jefferson, Sept. 6 1889 (Jenkinson 1987) "then I say the earth belongs to each generation during its course, fully and in its right no generation can contract debts greater than may be paid during the course of its existence".

All five definitions stand for the emphasis of specific aspect of sustainability. Definition (a) and (e) implies that each generation must bequeath enough natural capital to permit future generations to satisfy their needs. Even if there is some ambiguity in this definition, it is meant that we should leave our descendants the ability to survive and meet their own needs. Also, there is no specification in what form resources are to be left and how much is needed for the future generation, because it is difficult to anticipate the future scenarios.

Definitions (b) and (c) are more politic ply for the actions to be taken at global, regional and local levels in order to stimulate United Nation, Government and Local Authorities to plan development programs in accordance with the scientific and technological knowledge. In particular it should be noticed in definition (c) the ethic aspect of the future development actions to be taken to meet sustainable development.

Definition (d) is based on the religious believes playing the responsibility and duties toward the nature and Earth. In this respect, it is of interest to enlighten that the Old Testimony in which the story of creation is told is a fundamental basis for Hebrew and Christian doctrine of the environment. In the world of Islam, nature is the basis for human consciousness. According to the Koran, while humankind is God's vice-regent on Earth, God is the Creator and Owner of nature. But human beings are his trusted administrators, they ought to follow God instructions, that is, acquiesce to authority of Prophet and to the Koran regarding nature and natural resources.

3.2 *Normative and strategic dimension of sustainability*

The normative dimension of sustainability implies the acknowledgement of a hierarchy in dependence of economy, society and environment: market economy depends on society and environment (Annan 2000): While societies are possible without a market economy, neither can exist without natural environment. Thus, economic processes are subordinated to social and ecological constrains. In this context, sustainability refers to claims and commitments to:

- Compatibility between social, economic and environmental goals at all levels;
- Social equity and social justice as an overriding goal;
- Recognition of cultural diversity and multiculturalism;
- Support and maintenance of biodiversity.

Strategically, sustainability implies a system of governance at all levels – local to global – that appropriately implements policies that move toward sustainability, especially with respect to social equity and social justice, the compatibility between social, economic and environmental goals, and the participation of local actors.

The main target of strategies towards sustainability should be the identification and transformation of existing mechanisms of non-sustainability.

3.3 *Sustainability science*

Meeting fundamental human need while preserving the life-support systems of planet Earth is the essence of sustainable development, an idea that emerged in the early 1980s from scientific perspectives on the relation between nature and society (Kates et al. 2001). During the late '80s and '90s, however, much of the science and technology community became increasingly estranged from the preponderantly societal a political processes that were shaping the sustainable development agenda. This is now changing as efforts to promote a sustainability transition emerge from international scientific programs, the world's scientific academies, and indepen-dent networks of scientists.

3.3.1 *Core questions*

A new field of sustainability science emerging that seeks to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes. The regional character of much what sustainability science is trying to explain means that relevant research will have to integrate the effects of key processes across the full range of scales from local to global. It will also require fundamental advances in our ability to address such issues as the behaviour of complex self-organizing systems as well as the responses, some irreversible, of the nature-society system to multiple interacting stresses. Combining different ways of knowing learning will permit different social actors to work in concert, even with much uncertainty and limited information.

With a view toward promoting research necessary to achieve such advances, we propose an initial set of core questions for sustainability science. These are meant to focus research attention on both the fundamental character of interactions between nature and society and on society's capacity to guide those interactions along more sustainable trajectories.

3.3.2 *Research strategies*

The sustainability science that is necessary to address these questions differs to a considerable degree in structure, methods, and content from science. In particular, sustainability science will need to do the following:

- span the range of spatial scales between such diverse phenomena as economic globalisation and local farming practices,
- account for both the temporal inertia and urgency of processes like ozone depletion,
- deal with functional complexity such as is evident in recent analyses of environmental degradation resulting from multiple stresses,
- recognise the wide range of outlooks regarding what makes knowledge usable within both science and society,
- define the criteria and indicators for the sustainability assessment of energy, water and environment systems that are to provide guidance for the efforts directed to a transition toward sustainability,
- recognise the limits for the energy, water and environment that are marking irreversible changes on our planet,
- make sustainability become operational in everyday life with paradigm manifesting the interdisciplinary and multidisciplinary.

Pertinent actions are not ordered linearly in the familiar sequence of scientific inquiry where action lies outside the research domain (National Research Council 1999). In areas like climate change, scientific exploration, and practical application, which are interdependent on each other (Watson 1998), must occur simultaneously.

In each phase of sustainability science research, novel schemes and techniques have to be used, extended, or invented. These include observational methods that blend remote sensing with fieldwork in; conceptually rigorous ways, integrated place-based models that are based on semi qualitative representations of entire classes of dynamic behaviour, and inverse approaches that start from outcomes to be avoided and work backwards to identify relatively safe corridors for a sustainability transition. New methodological approaches for decisions under a wide range of uncertainties in natural and socio-economic systems are becoming available and need to be more widely exploited, as does the systematic use of networks for the utilization of expertise and the promotion of social learning.

3.3.3 *Institutions and infrastructure*

Progress in sustainability science will require fostering problem-driven, interdisciplinary research; building capacity for this research; creating coherent systems of research planning, operational monitoring, assessment, and application; and providing reliable, long-term financial support. Institutions for sustainability science must foster the development of capacities ranging from rapid appraisal of knowledge and experience needs in specific fields situations, rough global operational observation and reporting systems, to long-term integrated research on nature-society interactions in key places and regions of the world.

Generating adequate scientific capacity and institutional support in developing countries is particularly urgent as they are most vulnerable to the multiple stresses that arise from rapid changes in social and environmental systems. The difficulties of the situation are aggravated by resource and knowledge differences and a deepening digital divide. However, the opportunity to bridge this information gap rapidly and to share knowledge and new technologies with even the most remote and disadvantaged communities may be realised in the next few decades.

Some of the new infrastructure needs can be met with Internet-oriented systems that link interdisciplinary research teams across regions and users of scientific information with the scientists who provide it. However, comprehensive approach to capacity building will have to nurture these global institutions in tandem with locally focused, trusted, and stable institutions that can integrate work situated in particular places grounded in particular cultural tradition with the global knowledge system. Examples of such arrangements are few, but our experience includes such diverse examples as global ENSO (El Niño-Southern Oscillation) forecasting decision support systems in Africa, scientific support for the Convention and Long-Range Trans-boundary Air pollution in Europe, the Yaqui Valley study of land-use change in Mexico, the Sustainable Cities Ph.D. program with its focus on Los Angeles, and mountain development in Himalayas. In the Himalayan study, for example, local institutional teams including natural and social scientists from five countries (China, India, Nepal, Pakistan, and Bangladesh) plus the International Centre for Integrated Mountain Development (ICIMOD) focus on the effect. In particular, they have been identifying the coping strategies to meet the challenges and harness the opportunities offered by the globalisation process (van den Kroonenberg 1994).

3.4 *Sustainability concept definition*

In correspondence with the World Commission on Environment and Development definition, sustainable development is generally defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainable development is more precisely defined as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all harmony and enhance both current and future potential to meet human needs and aspiration (Hammond 1994, 2000, Veziroglu 2002).

The terms of sustainability cannot exclusively be defined from an environmental point of view or basis of attitudes. Rather, the challenge is to define operational and consistent terms of sustainability from an integrated social, ecological, and economic system perspective. This gives rise to two fundamental issues that need to be clearly distinguished before integrating normative and positive issues in an overall framework.

The first issue is concerned with the objectives of sustainable development; that is, what should be sustained and what kind of development do we prefer. These value judgments are usefully expressed in terms of a social welfare function, which allows an evaluation of trade-offs among the different system goals.

The second issue deals with the positive aspect of sustainable development. This can be represented in a dynamic model by a set of differential equations and additional constraints. The entire set of feasible combinations of social, economic and ecological states describes the intertemporal transformation space of the economy in the broadest sense (Binswangen 2001, Neance 2001, Pemberton 2001).

Various definitions and stationary-state criteria of sustainability have been proposed. But, the social dimension did not receive the same attention, and has not adequately been integrated into formal analysis. Moreover, positive aspects of feasibility and the normative content of sustainable development have not been clearly distinguished.

3.5 *Strong versus weak sustainability*

The meaning of sustainability is the subject of intense debate among environmental and resource economists (Ayres et al. 1999). Perhaps no other issue separates the traditional economic view of the natural world from the views of most natural scientists. The debate currently focuses on the substitutability between the product so of the market economy and the environment – manufactured capital and natural capital a debate captured in the terms weak vs. strong sustainability. It is increasingly clear that the criteria for weak sustainability, based on the requirements for maintaining economic output, are inconsistent with the conditions necessary to sustain the ecosystem services of the natural world.

3.5.1 *Weak sustainability*

The concept of weak sustainability has come to dominate discussions of natural resources and of environmental policy. A development is said to be weakly sustainable if the development is non-diminishing from generation to generation. This is by now the dominant interpretation of sustainability.

An instructive example of extreme implications of weak sustainability in practice is small Pacific island nation of Nauru. In 1900 one of the worlds richest phosphate deposits was discovered on Nauru and today, as a result of over ninety years of phosphate mining, about eighty percent of the island is totally devastated. At the same time, the people of Nauru have had, over the past several decades, a high per capita income. Income from phosphate mining enabled the Nauruans to establish a trust fund estimated to be as large as $1 billion. Unfortunately, the Asian financial crisis, among other factors, has wiped out most of the trust fund. The people of Nauru now face a bleak future. Their island is biologically impoverished and the money Nauruans traded for their island home has vanished. The "development" of Nauru followed the logic of weak sustainability.

3.5.2 *Strong sustainability*

The alternative to weak sustainability is strong sustainability, which means sustainability as "non-diminishing life opportunities". This should be achieved by conserving the stock of human capital, technological capability, natural resources and environmental quality.

Under the strong sustainability criteria, minimum amounts of different types of capital (economic, ecological, social) should be independently maintained in physical/biological terms. The major motivation for this insistence is derived from the recognition that natural resources are essential inputs in economic production, consumption, or welfare that cannot be quasi-moral, namely, acknowledgment of environmental integrity and "right of nature".

Both "weak" and "strong" criteria, involve an implicit assumption that may be challenged. They both imply a centralized decision-making process and decision maker who decides on behalf of society among alternative programmes and plans. In reality, virtually all economic decisions are decentralised among, individuals, family groups and communities of people with common interest or firms. If firms were to sell "service" than "product" and all material goods were regarded by product "capital" as "capital" rather than "throughput", the incentives facing decentralisation managers would be much more consistent with planetary sustainability.

4 ENERGY SUSTAINABILITY CRITERIA

There have been a number of attempts to define the criterions for the assessment of the sustainability of the market products (UNEP Working Group 1997), which can be applicable to specific system design. Energy system design is defined as:

1. Strategic Design: The strategic design will require holistic planning that meets and considers all interrelated impacts e.g. logistic, space planning and resource planning. As regard the energy system, it may be interpreted as: mixed energy concept with optimisation of local resources, urban and industrial planning with transport optimisation, use of renewable energy sources.
2. Optimised Design: The design optimisation of the energy system means the selection of the structure and design parameters of a system to minimize the energy cost under conditions associated with available materials, financial resources, protection of the environment and government regulations, together with safety, reliability, availability and maintainability of the system.
3. Design of Dematerialization: This will imply that the energy system, plant and equipment are designed with optimal use of information technology in order to prevent duplications, prevent operational malfunction, and assure rational maintenance scheduling. Dematerialization in the design may be seen as the introduction of knowledge-based systems, use of virtual library, digitised video, use of on-line diagnostic systems, development of new sensor elements and development of new combustion technologies.
4. Design of Longevity: A complex energy system is commonly composed of different subsystems and individual equipment elements. It has been recognized that the life tie of the elements and subsystems is not equal. In this respect, optimal selection of the life cycle for elements and subsystems may lead to the retrofitting procedure, which will reflect need for the sustainable criterion application. Examples for this criterion can be seen as: modular design of subsystems, standardization of elements, lifetime monitoring and assessment, co-ordination of suppliers and buyers.
5. Life Cycle Design: This will mean that the energy system and its subsystems have to be designed to meet sustainability through every stage of the life cycle. It is known that the energy system is designed to work under different conditions in order to meet load changes, environment change, social changes, etc. It is obvious that there will be different cycles for each of the mentioned time scale processes. In this respect the system has to fulfil its function without failing to meet sustainability requirements. As an example, we can see: water cooling temperature change, social change may lead to the requirement to decrease the load to meet sustainability criterions, building pumping power station for energy saving at night, period of thermal power plant technical minimum, etc.

5 ENERGY SYSTEM INDICATORS

There have been a number of attempts to define the criterions for the assessment of the sustainability of the market products. Having those criterions as bases, it was introduced a specific application in the energy system design. Measuring sustainability is a major issue as well as a driving force of the discussion on sustainability development. Developing tools that reliable measure sustainability is a prerequisite for identifying non-sustainable processes informing design-makers of the quality of products and monitoring impacts to the social environment. The multiplicity of indicators and measuring tools being developed in this fast growing field shows the importance of the conceptual and methodological work in this area (Indicator of Sustainable Engineering 1996, Dángelo et al. 1996, Caffier 1995, Afgan & Carvalho 2000).

In order to cope the complexity of sustainability related issues for different systems the indicators have to reflect the wholeness of the system as well as the interaction of its subsystems. Consequently, indicators have to measure intensity of interactions among elements of the system and its environment. This will imply that complexity indicators will be defined reflecting links among internal parameters and external parameters of the system. This may be interpreted in the thermodynamic vocabulary as the intensive and extensive parameters of the system.

The effective indicator has to meet characteristics reflecting a problem and criteria to be considered. Its purpose is to show how well system is working. Indicators are strongly dependent on the type of the system they monitor.

It is known that any numerical number, semantic expression or mathematical sign is information. Also, positive or negative sign of the variable are also information.

Collecting information and its processing will convert them in data. So, data represent agglomerated information, which are partially or finally processed.

In order to use the data for the assessment of the respective system, it is necessary to convert them into the indicator. So, the indicator represents measuring parameter for the comparison between different states or structure of the system. Also, we can evaluate different structure of the systems by the indicator. In this direction is the assessment of intelligence use in the improvement of the system compatibility with its surrounding measured by the respective indicators.

To quantify criterions for the sustainability assessment of any design of energy system the indicators are defined to meet this requirement. In this respect, the efficiency of resources use and the technology development are of the fundamental importance. The efficiency of energy resource use is a short-term approach, which may give return benefit in the near future. As regard the technology development, the long-term research and development is needed. In some cases it will require respective social adjustment in order to meet requirements of the new energy sources.

5.1 *Indicators definition*

For the sustainability assessment of energy system the following indicators are used (Afgan et al. 1998, 2000):

1. Resource Indicator – RI
2. Environment Indicator – EI
3. Social Indicator – SI
4. Efficiency Indicator – FI

5.1.1 *Resource indicators*

The resource indicators for the energy system comprise four resource indicators such as fuel, stainless steel, copper, and aluminium. This means that the following elements compose the resource indicator.

The fuel indicator comprise the total organic fuel needed for the annual energy production including fuel consumption for energy production and energy needed for the respective materials production. In this respect, the definition of resource indicators is shown in Table 1.

5.1.2 *Environment indicators*

The environment indicators are composed of three elements, namely, CO_2, NO_2, SO_2. Following the same procedure used in the definition of resource indicators, we can adapt that the environment indicators are given in Table 2.

5.1.3 *Social indicators*

The social indicator elements include job, standard indicator and community. The job indicator element represents the number of new jobs to be opened corresponding to the respective option.

The standard indicator element reflects the potential increase of the standard of living in the community. The community indicator element takes into a consideration the community benefits due to individual option. The social indicator are defined and shown in Table 3.

5.1.4 *Economic indicators*

Economic indicators include effectiveness, investment and energy unit cost. The effectiveness indicator element is defined as the thermodynamic efficiency of the system. It will include the energy efficiency conversion from the energy resources to the final energy. The investment cost indicator is aimed to obtain valorisation of the investment per unit power. The energy unit cost indicator comprise the cost of the energy per unit kW production. Following adapted procedure the economic indicators is presented in Table 4.

Table 2. Environment indicators.

	Name	Definition	Unit
EI_{CO2}	Carbon dioxide Environment Indicator	The amount of carbon dioxide in tonnes produced by the plant divided by energy produced in life-time	kg/kWh
EI_{NOx}	Nitrogen oxide Environment Indicator	The amount of nitrogen oxide in tonnes produced by the plant divided by energy produced in life-time	kg/kWh
EI_{SO2}	Sulphur dioxide Environment Indicator	The amount of sulphur dioxide in tonnes produced by the plant divided by energy produced in life-time	kg/kWh
EI_{waste}	Waste Environment Indicator	The amount of waste in tonnes produced by the plant divided by energy produced in life-time	kg/kWh

Table 3. Social indicators.

	Name	Definition	Unit
SI_{job}	New Job Indicator	Number of paid hours per kWh produced in life-time	hours/kWh
SI_{Inv}	Capital Indicator	The amount of capital per kWh produced in life-time	USD/kWh
SI_{Div}	Diversity and Vitality Indicator	Number of respective entity per kWh produced in life-time	Number/kWh

Table 4. Economic indicators.

	Name	Definition	Unit
EcI_{Effic}	Efficiency Economic Indicator	The efficiency of the system divided by the energy production	1/kWh
EcI_{inv}	Capital Investment Indicator	Amount of USD invested in the respective option divided by the energy production in life-time	USD/kWh
EcI_{com}	Community Economic Indicator	Gain of GNP for the community per unit kWh	USD/kWh

System analysis is both, a philosophical approach and a collection of techniques, including simulations developed explicitly to address problems dealing with complex systems. System analysis emphasizes a holistic approach to problem solving and use of mathematical models to identify and solving important characteristic of complex systems (Calen 1962).

An energy system is a complex system with a respective structure and can be defined by different boundaries depending on the problem. Since every energy system has a social function in our life, a link may also be established between the energy system and surrounding, taking into consideration social interaction between the system and environment. In this respect, the Onsager relation gives good example of the possible relation among the fluxes of interaction between the system and its environment (Prigogine 1966).

Each of the interaction fluxes is a result of the very complex interaction between the elements of the energy system within the system and with surroundings. In our analysis we will use synthesized parameters of the system in form defined in classical analyses of energy systems. In this analysis, the indicators for resources utilization are resource indicators and for the heat conversion process effect on the environment is the CO_2 concentration in exhaust gas. The electric energy cost will be used to measure economic benefits of energy system and NO_2 release of the energy system will be used as its social indicator.

In this analysis, indicators represent the measure of different interactions between the energy system and its surrounding. All indicators are in deterministic or stochastic relation with respective parameters of the system. Their interpretation and collection require respective organization and systematisation of the parameter of the system and the environment. The process of collection and interpretation of different parameters, which are synthesized in the respective indicators, can be represented graphically, as shown in Figure 8 (O'Farrel 1999).

It can be noted that data collection for the earth's resources, environmental pollution parameters, economic system parameters, social structure and quality is the first step in generating the indicators. The second step is the definition of the energy system concept, including the definition

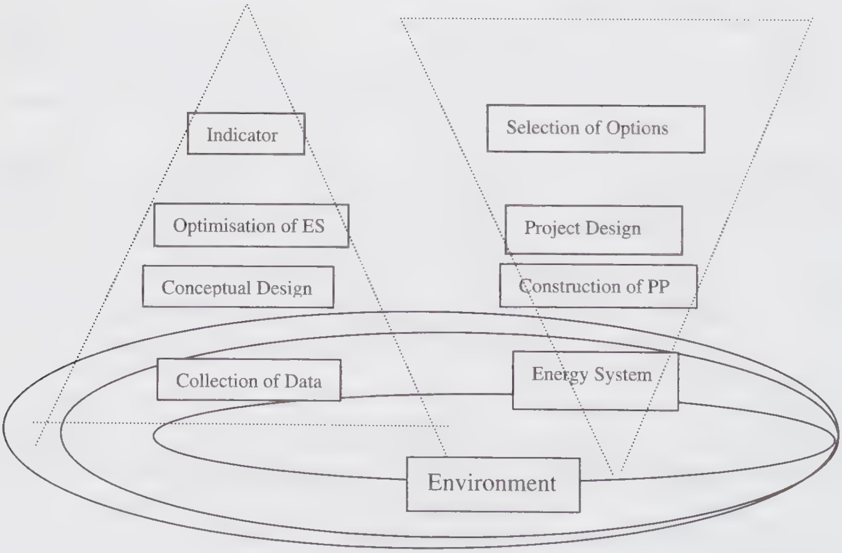

Figure 8. Process of collection and interpretation of different system parameters, synthesised in respective indicators.

of the structure and interaction between the elements and processes. This implies the selection of energy conversion process and its interaction with inlet parameters.

According to the life cycle analysis of the selected energy system, the interpretation of interaction of the system, with its economic, environmental and social surroundings can be defined. Since each of the selected indicators represents collective interpretation of different interactions of the system and its surrounding, their mutual relation is interpreted as the independent parameter of the system.

Multi-criteria assessment of the energy system is the method to establish a measuring parameter, which is comprised of different interactions of the system and its surrounding (Climaco 1997, Fishburn 1970, Gal & Hanne 1999). This may lead to the development of the method, which will help us to understand in deep specific role of energy system selection and quality of our life.

The multi-criteria assessment is based on the decision making procedure reflecting combined effect of all criteria under consideration and is expressed in the form of General Index of Sustainability (Hovanov et al. 1996, 1997, 1999). A selected number of indicators are taken as measure of the criteria comprising specific information of the options under consideration. The procedure is aimed to express options property by the respective set of indicators.

6.1 *Sustainability index definition*

The decision-making procedure comprises several steps in order to obtain mathematical tool for the assessment of the rating among the options under consideration. The next step in the preparation of data for the multicriteria sustainability assessment is arithmetization of the data.

This step consists in the formation of particular membership functions $q_1(x_1), \dots, q_m(x_m)$. For every Indicator x_i we have: (1) to fix two values $MIN(i)$, $MAX(i)$; (2) to indicate is the function $q_i(x_i)$ decreasing or increasing with argument x_i increasing; (3) to choice the exponent's value λ in the formula

$$q_i(x_i) = \begin{cases} 0, & \text{if } x_i \le MIN(i), \\ \left(\dfrac{x_i - MIN(i)}{MAX(i) - MIN(i)} \right)^{\lambda}, & \text{if } MIN(i) < x_i \le MAX(i), \\ 1, & \text{if } x_i > MAX(i) \end{cases} \tag{1}$$

for the increasing function $q_i(x_i)$.

The functions $q_1(x_1), \dots, q_m(x_m)$ formation process being finished with a matrix$(q_i^{(j)})$, $i = 1, \dots, m, j = 1, \dots, k$, where an element $q_i^{(j)}$ is a value of i-th particular criterion for j-th option. In this analysis it is assumed that the linear functions $q_1(x_1), \dots, q_m(x_m)$ are used. For q_1, q_2 and q_4 membership function the decreasing function are adapted.

General indices method comprise formation of an aggregative function with the weighted arithmetic mean as the synthesizing function defined as

$$Q(q;w) = \sum_{i=1}^{m} w_i q_i \quad \text{x} \tag{2}$$

where w_i – weight-coefficients elements of vector **w**, and q_i – indicators of specific criteria.

In order to define weight-coefficient vector the randomisation of uncertainty is introduced. Randomisation produces stochastic with realizations from corresponding sets of functions and a random weight-vector. It is assumed that the measurement of the weight coefficients is accurate to within a steps h = 1/n, with n a positive integer. In this case the infinite set of all possible vectors may be approximated by the finite set W(m,n) of all possible weight vectors with discrete components.

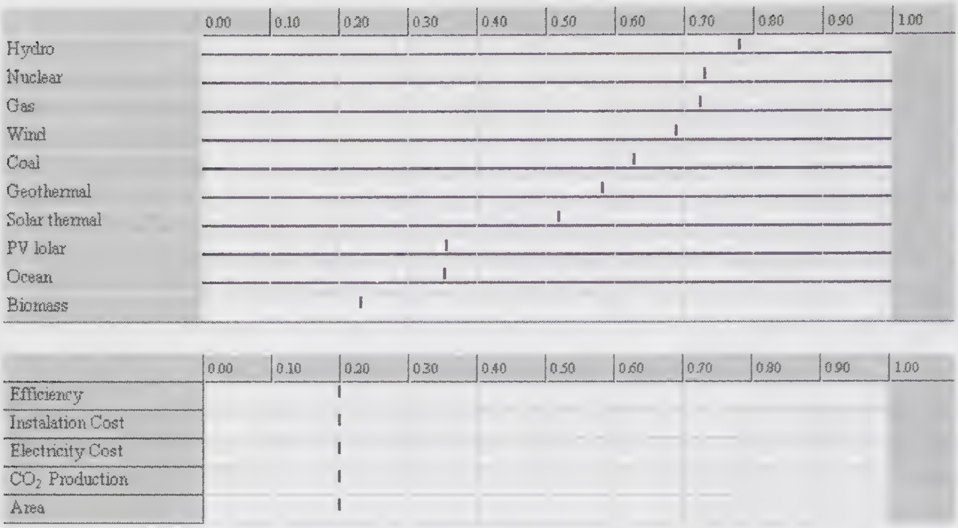

Figure 9. General index of sustainability and weighting coefficients for case 1. Upper diagram: General index of sustainability, lower diagram: weighting coefficients rating.

For nonnumeric, inexact and incomplete information I = OI U II used for the reduction of the set W (m,n) of all possible vectors **w** to obtain the discrete components set W (I;n,m) is defined a number of constrain reflecting nonnumeric information about mutual relation among the criteria under consideration.

6.2 *Multi-criteria assessment of energy systems*

As the non-numerical information we will impose condition, which will define mutual relation of the individual criteria (Afgan & Carvalho 2002, Afgan et al. 2002). This will give us possibility to introduce a qualitative measure between the criteria.

The group of cases are designed to give priority to the single indicator with other indicators having the same values. Each case will represent a different option in the priority of criteria as they are used in the definition General Index of Sustainability. Among the cases which are designed with the preference of single options.

6.2.1 *Case 1*

Even this case with equal weighting coefficients (Fig. 9) is not very realistic from the assessment point of view it gives possibility to evaluate the importance of this case as a neutral logic occasion. The high rating of hydro, nuclear, gas and wind options is expected and due to the relation of indicators for the individual criteria.

6.2.2 *Case 2*

This case reflects the priority given to the energy system efficiency criteria (Fig. 10). As has been shown, the efficiency of systems with the different basic principles is not very realistic indicator to be used for the comparison of the system. This suggests that in evaluation of the efficiency criteria it would be better to use the relative value of the efficiency for each system. For example, for the heat conversion system the Carnot efficiency should be used as the absolute efficiency.

As the result of this constrain we have obtained again a highly exaggerated priority of hydropower plant while other options are divided in two groups with similar value of General Index of

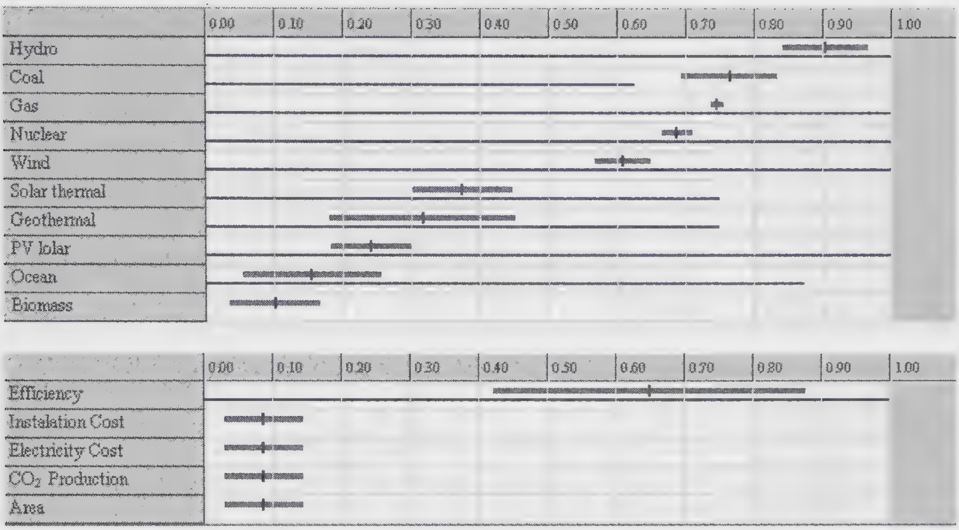

Figure 10. General index of sustainability and weighting coefficients for case 2. Upper diagram: General index of sustainability, lower diagram: weighting coefficients rating.

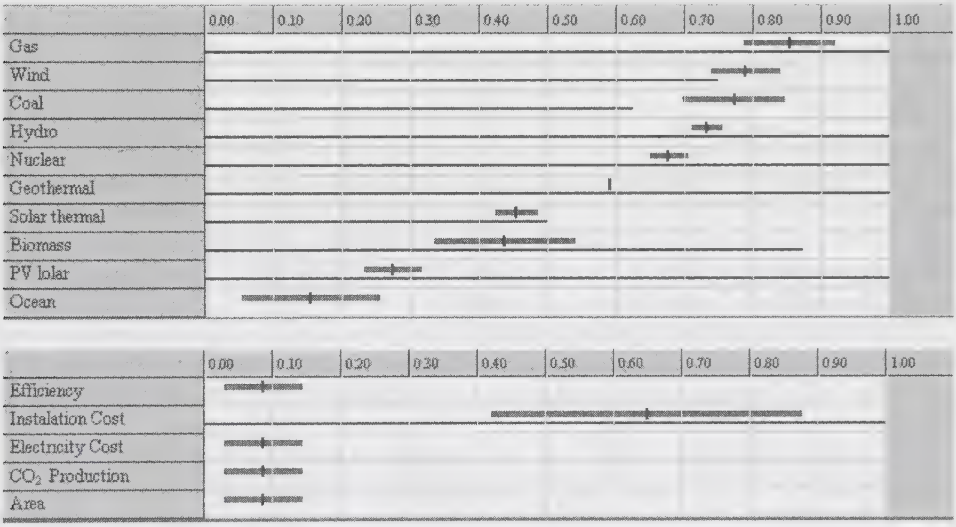

Figure 11. General index of sustainability and weighting coefficients for case 3. Upper diagram: General index of sustainability, lower diagram: weighting coefficients rating.

Sustainability. With the high value of the probability of dominance in this case it can be concluded that the priority list give high confidence in obtained results.

6.2.3 *Case 3*

The change in priority from the efficiency criteria to installation cost criteria has led to the drastic change in the priority list (Fig. 11). Hydro, nuclear, wind and geothermal energy systems form a single group with the General Index of Sustainability being marginally different among themselves. It is of interest to notice that the effect of single criteria can be so strong to bring into

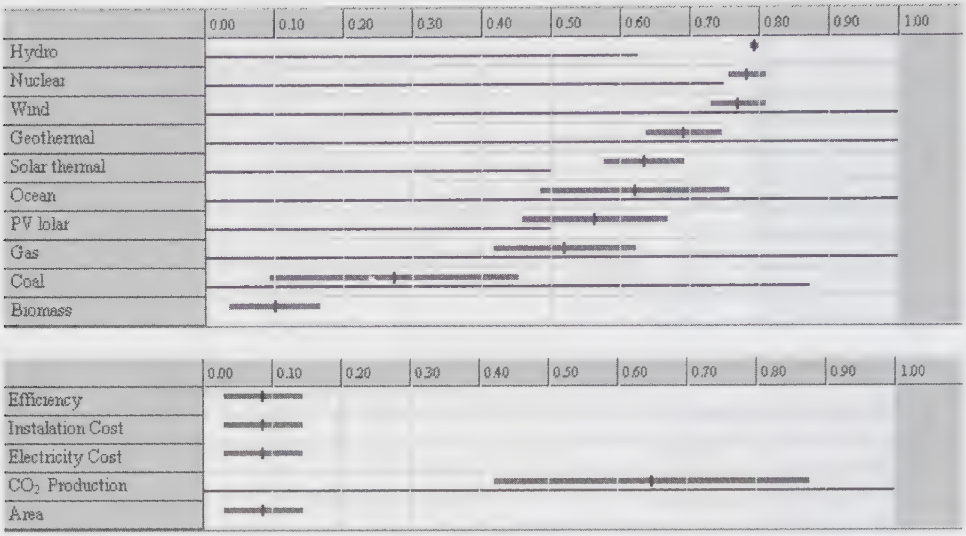

Figure 12. General index of sustainability and weighting coefficients for case 4. Upper diagram: General index of sustainability, lower diagram: weighting coefficients rating.

the picture different priority list. From the values for probability of dominance in this case it is visible that this case do not have highly certain option.

6.2.4 *Case 4*

This case represents the situation when the priority is given to the environmental criteria (Fig. 12). This implies that the CO_2 production indicator is having dominancy to the other indicators, while they are considered to have equal values. It can be noticed that under these conditions all options with the low production of CO_2 have gained higher priority in comparison with those with the high CO_2 production. In this case, we can see that the single indicator might substantially affect the rating of options.

The evaluation made here is aimed to obtain the option rating based on the multi-criteria decision making procedure. The primary goal of this analysis is to use the method based on the non-numerical information as the criteria for the design of cases, which are resulting in the respective rating among the options.

The selection of the group of cases is aimed to perform an evaluation of the options with constrains giving possibility to have predetermined relation between indicators.

Even this analysis is based on limited number of cases taken into consideration, it can be noticed that the priority on rating list is result of the respective relation among the criteria under consideration. In the group, it can be noticed that the option, which is the first on the rating list, is closely related to the respective indicator priority and its value. In the group of cases it can be noticed that if the priority is given to the single criteria with the other criteria having respective value of indicators for individual option, it may affect the rating list of the options. In this respect the hydropower plant options is the first on the rating list if the weighting coefficients of all indicators is the same. If the efficiency criterion has been given priority there are substantial changes in the rating list. The same can be noticed if priority is given to the other indicators. For the case the Installation Cost Indicator has priority, the gas power plant is the first on the rating list of the option under consideration. Also, if CO_2 Production Indicator and Area Indicator, the hydro and nuclear power plants are rated on the first place in the rating list of the options. Beside the changes on the first place on the rating list, it can be noticed that there are changes in the rating among the other options. Options with renewable energy power plants have gained higher place on the rating list in comparison with the case with equal weighting factor for all indicators.

It should be mentioned that it would be possible to obtain required relation among the indicator for the specific rating list among the options if this combination exists within the set of the combination generated in this analysis.

7 ENERGY SUSTAINABLE DEVELOPMENT

In order to reach the goals indicated by the sustainable energy development the energy conversion use has to meet several criterions. The potential for the efficiency improvement is generally underestimated. Most of the energy conversion systems consider the efficiency improvement as a separate process and their analysis reflects only the potential improvement of the process but not the potential for the efficiency improvement obtained by an energy analysis of the energy system. Fossil fuel energy resources use is mostly conversion to heat by the combustion processes. Since the combustion process is taking place at temperatures between 900–1300°C and over 40% of heat is used a low temperature, it is indispensable to take into consideration the thermodynamic assessment of the efficiency in order to bring in line energy conversion processes and energy demand to obtain the optimum fuel utilization.

In the definition of sustainability it is of substantial importance to envisage its broad aspect, which composes versatility of the components to be taken in consideration. In this respect, wholeness of sustainability has to include definitions of those components, which are linked to specific parameters to be taken into consideration of the assessment of sustainability of specific situations in global, regional and local environments. There are a number of characteristic entities, which will be used to define the wholeness of the sustainability: life diversity, natural resources, environment capacity, population increase, social disturbances and ethic changes.

Each of these entities has to be defined with specific parameters, which can be used to determine characteristic indicators for global assessment. The possible use of indicators is characterizing the changes, which are determined by the maximum values technically feasible. It is reflecting the difference between the state of the entity with the maximum availability and respective current state of the entity. If applied to the individual energy resources there is a difference between known maximum exploitable resources with known technologies and current resources to be obtained with present technological capacity. Possible changes are functions of the technological development in the resource discovery.

7.1 *Prevention of the energy resources depletion with scarcity index control*

Whichever scarcity model is used, the energy resource scarcity is in direct relation to the social production output. In this respect, the efficiency of resources use and technology development is of fundamental importance. It is obvious that the efficiency of the energy resource use is a short-term approach, which may give a return benefit in the near future (Mitro et al. 1998, Hein 1995).

The availability of energy resources is limited by two factors: capital to be invested in prospecting of new resources and prospecting technologies for energy resources.

From recent experiences it was learned that there is a direct correlation between capital invested in prospecting and the amount of the available reserves. It was proved that a fixed amount of 18 $/t is needed for new energy reserves. In many developing countries this is a limiting factor for the availability of energy resources.

The prospecting technology for new energy resources is composed of three phases. The geological subway based on the real prospecting and respective diagnostic techniques for electromagnetic waves detection. The resolution of the instrument employed is one of the limitations, and it is under consideration for further development. The second phase of prospecting technology is related to software for the design of the resource body based on the ultrasonic scattering or earthquakes generated by local explosions. The main limitation in the development of new software is the speed and memory size of computers. It can be expected that with the further development of computer technology this problem will be overcome.

7.2 *Efficiency assessment*

The potential improvement of the energy conversion process is a driving force for its development (El-Said & Evans 1970, Sama 1994). In the assessment of the conversion process a promising tool is the exergy analysis of the energy system. By definition, the exergy is a parameter for the validation of the efficiency of the energy conversion process and system. Taking into account the law of thermodynamics, the technology improvement appears as a significant factor responsible for an entropy change in the energy system. The application of the principle of Carnot therefore allows determining an absolute limit to any transformation of the deposit of free energy.

Following the first energy crisis (1972), many countries have organized an energy efficiency assessment campaign with the aim to improve the efficiency and gain saving, which has contracted the increase of energy price. It was proved that this approach has resulted in the increase of efficiency of energy use between 10–20% in a number of European countries. The main emphasis has been given to the evaluation efficiency of different technologies and utilizations of energy.

It is of great importance the effort directed to the evaluation of the technological processes for energy saving (White 1995, Furfare 1995). A favourable example for this achievement is the development of a new lighting system with fluorescent lamps and which, in comparison with traditional bulbs, have a saving of about 40%. Cogeneration of heat and electricity is one of the potential means to improve the efficiency of the energy resource utilization (Darwish 1995).

7.3 *Clean air technology development*

The combustion process is an irreversible thermodynamic process with a high degree of availability losses in the energy conversion cycle. In this respect there is a potential opportunity to increase the energy conversion efficiency by improving the combustion process. There are a number of potential combustion technologies, which might lead to an efficiency increase of the combustion process.

7.3.1 *Catalytic combustion*

The low temperature catalytic combustion of lean natural gas mixtures represents an effective method for heat generation (Klvana et al. 1995). Zeolite is a catalyst widely used in chemical industry. The catalysis mechanism at the interface between electrode and electrolyte ensures the electron transfer from the input hydrogen molecule to the electron metal. The search for low cost alternatives has not been very successful but lately the good performance of some of active composition of La, Ni, Co, O (LSNC powder) leads to promising expectation.

7.3.2 *Fluidised bed combustion*

A recent progress in the fluidised bed combustion has led to substantial developments of this new energy system (van Swaaj & Afgan 1985). In first alternate of the combustion in fluidised beds, the coal is depressed in a mass of its ashes and absorbent lime and the process is developed at a temperature of 850°C. The second alternative of the fluidised bed combustion power plant is the circulating fluid design, offering a high degree of operating flexibility in coal quality use. The efficiency of the existing circulating fluidised bed plants is about 30%.

7.3.3 *Low NOx burners*

The present, advanced energy technology is focused to reach further improvements in the emission control (Duaro et al. 1992, Weinberg 1995). In order to minimise SOx, NOx, and particulates emissions a new burner design is envisaged to meet the requirements for minimization of initial NOx formation. Numerical modelling of the processes in combustion chambers has become important in design and analysis of tools (Carvalho et al. 1988, Carvalho & Coelho 1989) for improving air distribution in power plant burners.

7.3.4 *New boiler designs*

A new generation of pulverized coal-fired boiler technologies is currently under development, which will permit a generating efficiency in excess of 42%. The improvement in heat and mass transfer research has substantially contributed to new boiler designs and will lead to the increase of availability of modern power plant systems (Afgan 1995, De Jong 1995).

7.4 *Development of intelligent energy systems*

The recent development of artificial intelligence has opened the possibility to utilize those achievements in the energy sustainable development. There are three major paths, which are described below.

7.4.1 *Expert system in energy engineering*

The expert system development in energy engineering is focused in two directions: expert system for energy system design and knowledge-based for on-line diagnostic (Afgan et al. 1991, 1996, 1999, Afgan & Carvalho 1996). It has been shown that the expert systems for energy system design can be an efficient tool in selection, optimisation and assessment of power plant design. The knowledge-based system for the fault diagnostic in energy systems has proved to be a powerful tool for the evaluation of system parameters in order to forecast a potential malfunction of system elements.

7.4.2 *Fuzzy logic control*

The new fuzzy logic control system is demonstrated to be a qualitatively efficient system for the on-line control of energy systems (Jamshidi 1999). While similar model-based control systems designs are trial and error, the knowledge-based controller is "ad hoc" at present time. A common definition of fuzzy control system is that it emulates a human expert. Under this situation, the knowledge of human operator would put in form of a set of fuzzy linguistic rules.

7.4.3 *Intelligent energy systems*

In order to provide the design criterions reflecting complex requirements imposed by the intelligent energy system design, it is necessary to define the respective indicators to be used in the evaluation of the specific design of thermal equipment (Leicester City Council 1994, Fritz 2000). These indicators should be based on the optimisation of the efficiency of respective thermal equipment, resource use assessment and validation, environment capacity use and degradation, modular structure with multipurpose elements, end of life assessment and economic justification of specific designs.

7.5 *New and renewable energy sources (NRES)*

Renewable energy sources by definition, meet the requirements of sustainability. It is therefore expected that the long-term energy strategy will rely on renewable energy resources. The total availability of the renewable energy resources is very large. This picture reflects the presently available technologies in the field of renewable energy resource use and exploitation (Bekovski 1989, Afgan 1989). Very promising alternatives are envisaged with the promotion of new technologies under development.

7.5.1 *Solar energy resources*

Solar energy can be exploited in three main modes:

- by enhanced absorption of solar energy in collectors, which provide low-grade heat,
- by using reflecting devices to concentrate the solar energy in a heat carrier, which is then used to generate electricity, and
- by converting sunlight directly into electricity.

Solar energy resources do not have clear limits. The annual influx on the Earth's surface is 10,000 times as large as the current human energy consumption; the fraction reaching the land surface is 3000 times as large and even 35% of this would make 1000 times more energy than we demand today. As we can notice the resource of solar energy is huge but diluted. In the literature it is assessed that feasible tool use of solar energy from the technical standpoint is about (Winter et al. 1991, Zafran 1993):

Thermal solar for	170 Mtoe/year
Decentralized electric solar for	450 TWh/year
Network electric solar for	230 TWh/year

In the local resources evaluation for these three solar systems one could take into consideration its minimum and maximum capacity to be installed. From the present status of the development the following capacity can be taken into consideration

	Minimum	Maximum
Thermal solar	150 kW	80 MW
Decentralized electric solar	30 kW	5700 kW

If the mean insulation for the specific location is taken into consideration then the respective values for the land to be used will be obtained. For this purposes, it will be used $q_R = 5.4\,\text{kWh/m}^2/\text{day}$ so that the following extension of land is required for the specific use of the solar energy:

	Minimum land [m^2/kW_e]
Thermal solar	20–35
Decentralized electric solar	36–80

It should be mentioned that for insulation lower than $q_R = 4\,\text{kWh/m}^2/\text{day}$, it might be difficult to adopt the same method of validation.

Solar energy use is presently demonstrated in three options: solar thermal, solar photovoltaic and solar power plant. Solar thermal energy production plant has reached an industrial level and is available on the market in many countries. There is a number of designs differentiated with respective efficiency and sophistication of the material used. Solar thermal option is mostly available for the hot water production units. It is also demonstrated for air heater and climatization units. Since it has reached maturity, it is not expected major breakthrough in this field, which might affect its potential use. Water heater units are available in the market with the following ranges:

	Temperature range [°C]
Unglazed flat plate collectors	<40
Glazed flat plate collectors	40–100
Vacuum tube collectors	150–200

The solar thermal is anticipated to cost 8 -9 UScents/GJ in the medium term. In the long-term this could come to 4–6 UScent/GJ. The solar photovoltaic system is also in its demonstration stage, with a number of various applications. It has been demonstrated in three levels, namely:

	Power
Ubiquitous solar cell	not fixed
Solar unit for electronic application	50 W–1 kW
Solar units for irrigation	5–60 kW

The first level is not an energy intensive application and has no significance for its consideration for the energy source strategy point of view. The second option is being used as the only energy source in the remote areas and has been demonstrated as a reliable energy source. It ranges in power production from 50 W to 1 kW and is commercially available at competitive prices. Figure 13 shows schematic representation of solar power plant.

For the third option there have been a number of demonstration projects, which have proved its feasibility for rural areas. Even, the energy available from the grid for many countries is lower than the energy produced by a photovoltaic unit, and the difference in energy may be compensated by the additional capital investment needed for a new grid construction for remote areas.

Solar power plants are in the stage of development. They are available as photovoltaic cell modular units and can be installed when the power demand requires a system augmentation. As demonstrated, the modular power ranges between 50 kW and 1 MW. Solar power plants with concentrators are still in the development stage and will not be considered in the technical assessment of the solar energy utilization (Best & Kwshlik 1993, Gigopoulos 1993, Morse & Kazmerski 1997).

Present estimate of photovoltaic solar plant electricity ranges from a cost of 23 to 33 UScent/kWh. It is expected that in the medium term this cost will be as low as 2.2 -2.4 UScents/kWh.

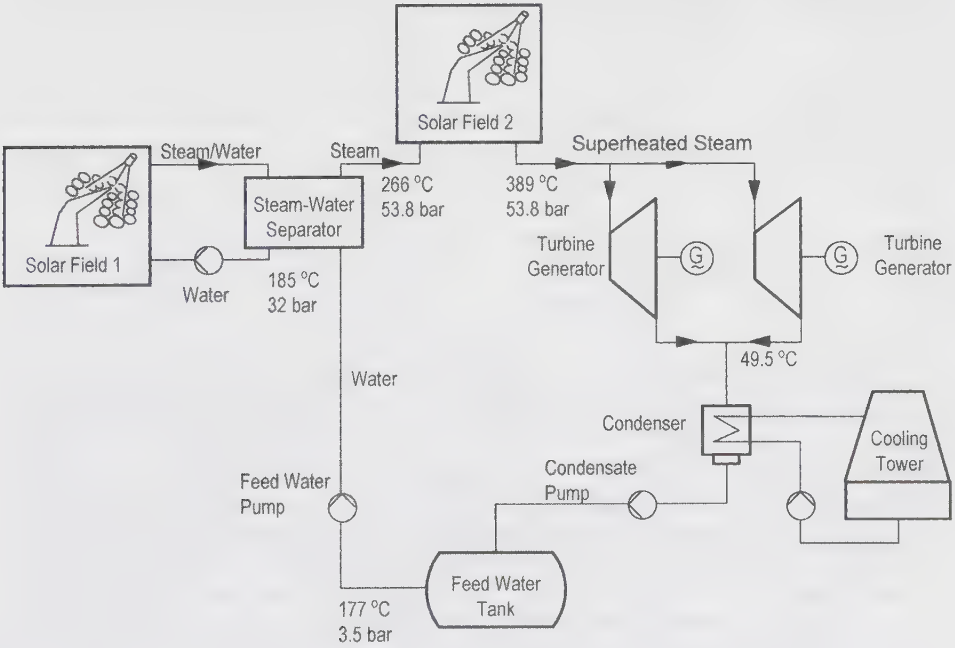

Figure 13. Schematic design of a solar power plant.

7.5.2 *Geothermal energy resources*

Resources exploitable at current energy prices correspond to aquifers in narrowly localized volcanic zones (Fridleifson & Freston 1993, Dikson & Fanelli 1995). Presently installed and in construction plants reach a total electrical capacity of 7100 MW (high enthalpy energy). Low enthalpy hot water to be used directly for heating is estimated to about 13 Mtoe/year. These two groups of geothermal energy systems are specified by the temperature and flow capacity of the individual well. From the experience, the following limits are adopted:

	Min. temperature[°C]	Min. capacity [m^3/h]
High enthalpy geothermal	90	2900
Low enthalpy geothermal	35	1000

Geothermal utilization is commonly divided into two categories: electric production and direct application.

Conventional electric power production is limited to fluid temperatures above 140°C, but a considerable lower temperature may be used with the application of binary fluids. Geothermal electric energy plants have reached their maturity and have proved to be very reliable sources of energy. They are used in 21 countries, with a total world installed capacity of 6017 MW distributed over 330 individual turbine generator units. The geothermal power plants are built in four versions, namely: direct steam plants, flash steam plants, binary plants and hybrid plants.

Direct steam plants are used with vapour-dominated resources. Steam from production wells is gathered and transmitted via pipelines directly to a steam turbine. In most direct steam plants the capacity of the turbine is greater than 5 MW. Typical schematic representation of direct steam plant is shown in Figure 14.

Flash steam production is used when the fluid, in the geothermal reservoir is pressurized hot water or a mixture of liquid and vapour at the wellhead. It is designed in two modifications, namely, with single flash steam unit and dual flash units. Single flash plant is a simple flash unit. The flashing process takes place between the reservoir condition and the power plant. The flash usually occurs in the well at the point where the geofluid pressure falls to the saturation pressure corresponding to the temperature and composition of the geofluid. A significant improvement

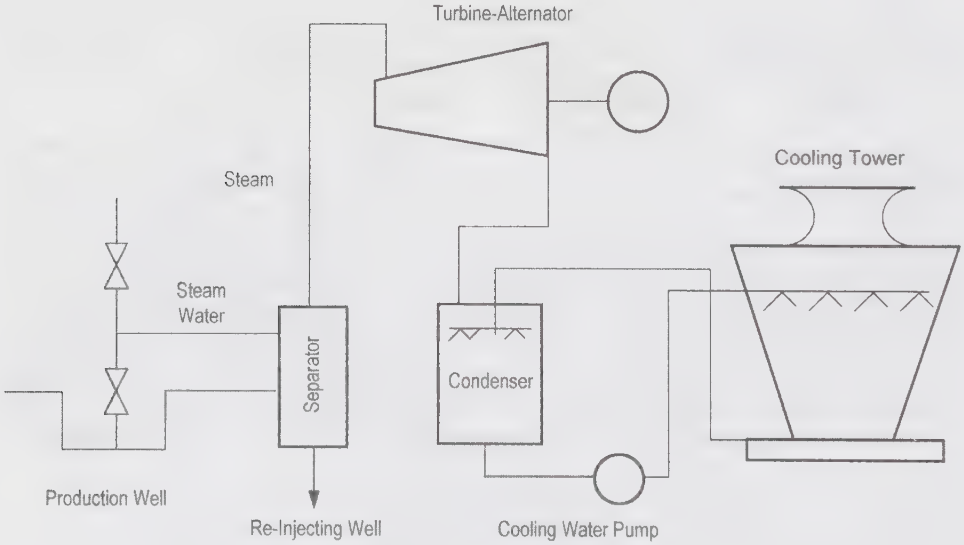

Figure 14. Schematic representation of direct steam geothermal plant.

in resource utilization can be achieved by adding a secondary flash process. Instead of being discharged, the liquid that is removed from the separator is subjected to another pressure drop in which releases additional steam. The lower pressure steam is admitted to the turbine at an appropriate stage and generates additional power.

Hybrid plants can be used to achieve higher efficiency or to overcome the potential problems related to geofluid characteristics.

The ideal inlet temperature for house heating is about 80°C, but with the application of large radiators with heat pumps or auxiliary boiler, the thermal water with a temperature of only few degrees, above the ambient temperature, can be beneficially used.

It uses mostly known technology and straightforward engineering. It is estimated that the installed thermal power that uses geothermal fluids for direct non-electric application is over 11,385 MW, with a total energy production of 31×10^{12} kJ. This was achieved with a flow rate of about 84,000 kg/s at an average load factor of 36%.

Electricity production from geothermal sources cost is around 4 UScent/kWh and for the heat generation the cost is around 2 UScents/kWh.

7.5.3 *Biomass energy resources*

Biomass provide about 14% of the world energy or about 25 millions barrels of oil equivalent per day (Mboe/day) (Werroko-Brobi & Hagen 1995, Hall 1991, Hall et al. 1992, Walker & Jenkins 1995). It is the most important source of energy in developing countries. In general, it is rather difficult to estimate biomass resources because they are strongly dependent on natural vegetation. Detailed analysis shows that if it is assumed 35 GJ/capita the consumption for developing countries, the land required per capita with biomass yield 2, 5 and 10 t/ha/year, will be 1.0 and 0.2 ha/capita, respectively. It is estimated that for biomass use for energy production it would be needed a minimum of 5 t/ha/year yield and it could be used in an area where local energy consumption is substantially below the average for developing countries.

Biomass energy production can be obtained through different routes for biomass conversion processes. Biomass derived liquids are mainly ethanol and methanol. Gases are mainly biogases from anaerobic digesters, gasifiers producing gases, which can be used for electricity generation and, possibly, coupled to efficient gas turbines.

There are two main branches of biomass conversion, namely: bioconversion process and thermal process. The bioconversion processes are alcoholic fermentation and anaerobic fermentation In this respect, bioconversion technology for the ethanol production falls into a category of technologies, which are presently commercially available. For the ethanol production there are three options:

	Capacity [l/day]
Micro system	<200
Mini system	200–20,000
Macro system	>20,000

Among these options, the mini system is ideal from the technical, economical, social and environmental standpoint. It appears to be a highly viable solution to the liquid fuel energy problem, especially for developing countries.

There are a vast number of technical systems used for biogas production. Pyrolisis and combustion processes are based on high temperature conversion processes with partial or full combustion of biomass fuel. They are used for charcoal or heat production, depending on the process of biomass conversion. The charcoal production plant has not proved its maturity and is yet not available as commercial technology.

The combustion process of biomass is not substantially different from the combustion of any solid fuel. In particular there is a great interest for the waste incineration boiler as energy source. Figure 15 shows schematic representation of typical biomass power plant.

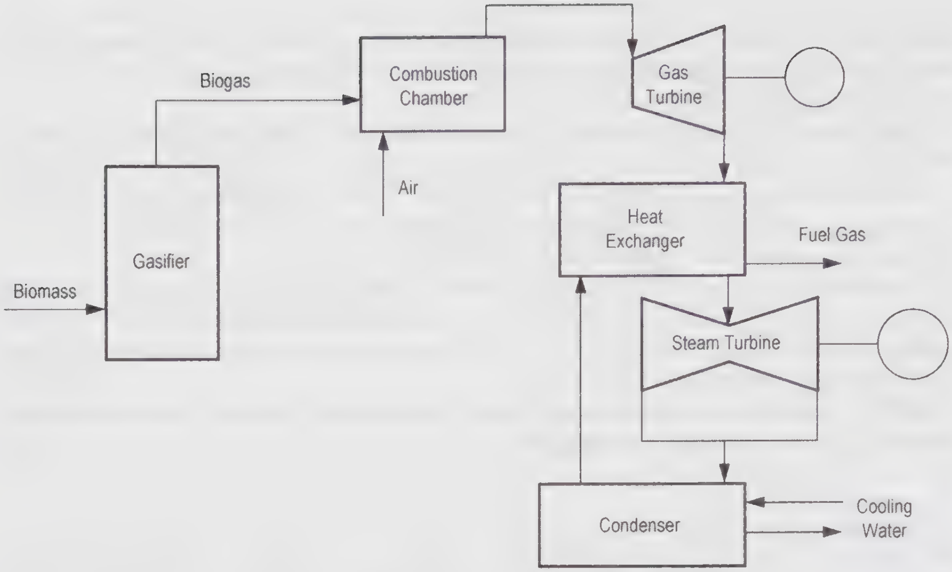

Figure 15. Design of a typical biomass power plant.

It is expected in the medium term, that at a biomass cost of 2 UScents/GJ the electricity produced will reach 10–15 UScents/kWh.

7.5.4 *Wind energy resources*

The world technically exploitable resources are estimated about 300 TWh/year (Walker & Jenkins 1995, Sesto et al. 1993). It was recognized that the most economical turbines are those with a rating between 1 kW and 350 kW. It is estimated that 4–8 MW could be installed on 1 km^2. In defining the resource conditions for the wind energy utilization the following parameters are needed:

1. average wind velocity at the specific location,
2. probability distribution of wind velocity.

7.5.5 *Hydro energy resources*

It is estimated that the gross theoretical productivity of hydro energy is about 30 millions GWh/year with an exploitable production of about 13 millions GWh/year (Jiandong et al. 1995, Casenave et al. 1993). The present production of the existing plants is of the order of 2.2 millions GWh/year. The average percentage of hydroelectric energy production is for developed countries 7% and for developing countries 54%.

In many countries emphasis is given to the utilization of the small-scale hydropower potential. The total capacity of the mini/micro power plant is about 1.5% of the total installed hydropower potential. An equal amount of small-scale plant capacity is currently in the planning stage.

The water flow rate is a very sensitive parameter for small hydropower plants. It varies seasonally and sometime daily. Small hydroelectric plants can be grouped in three classes:

	Flow rate [m^3/h]	Height [m]
Small hydropower plant	5–1000	10–300
Mini hydropower plant	0.5–50	2–100
Micro hydropower plant	0.2–3	2–50

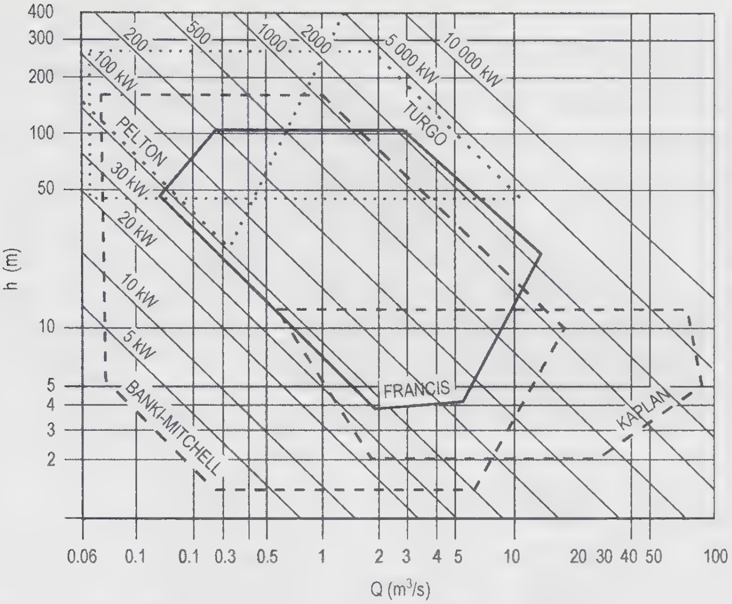

Figure 16. Diagram for selection of hydro turbine type.

According to UNIPEDE classification there are three types of hydropower plants, namely:

	Power [kW]
Small power plants	<10,000
Mini power plants	<2000
Micro power plants	<500

Technically, there are three main types of hydro turbines, depending on the water flow rate and available height:

	Height [m]
Kaplan turbines	2–20
Francis turbines	5–200
Pelton turbines	50–1000

In Kaplan turbines a mechanical momentum is produced by helical blades formed to develop a pressure difference at the front and rear surface of the blades.

The Francis turbine is designed to uptake the water radial flow through fixed blades into rotating blades on the turbine rotor. The Pelton turbine is designed in the form of one-row double spoon blades exposed to the injected water stream. The diagram shown in Figure 16 gives the possibility to select the respective hydro turbine type in accordance with the available flow rate and potential height. It also shows the power of the respective turbine to be obtained for the specific parameters of the respective location.

7.6 *Environment capacity for the combustion products*

It has been shown that the natural processes in the biosphere possess the maximum rate of change. This rate of change exceeds by orders of magnitude the contemporary rates of the parameters defining the anthropogenic impact to the environment and by four orders of magnitude, the mean rate of change of the parameters defining the geophysical processes (Marchuk & Kondrotev 1992).

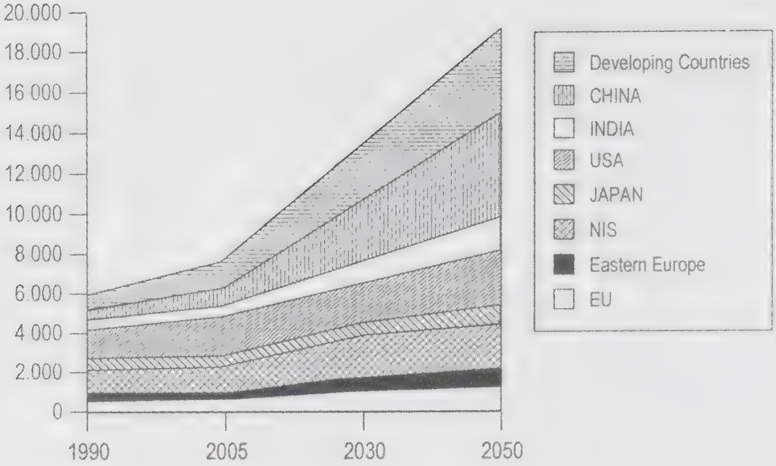

Figure 17. Forecast of carbon dioxide emissions.

The fluxes of the organic material produced by the synthesis and decomposition processes in the biosphere are within the accuracy of one hundredth percent of the anthropogenic fluctuation resulting in the environment in the geological time scale. This slow change in the environment in the geological time scale can be compensated by biological processes leading to the biosphere control of the chemical composition of the environment.

The adverse effects of the emission gases are recognized by two processes: the greenhouse effect leading to global warming and depletion of the ozone layer in the stratosphere. The global warming is observed by the increase of the mean earth temperature. It can be noticed that recent changes in concentration of CO_2 in the atmosphere are correlated with the changes in the global temperature. This has led a number of specialists in the field to conclude that the damage is irreversible. Figure 17 shows estimated trend of CO_2 production.

7.7 *Mitigation of nuclear power threat to the environment*

The nuclear power plants are very beneficial in light of greenhouse effects because they have no exhaust gases. But, it is known that present nuclear power reactor have the potential possibility to be enormous sources of radioactivity emissions. Opponents to nuclear energy outline two points that are crucial for them: the possibility of major radiological releases following to accidents and the heavy inherit age of long lasting radioactive wastes for future generations. Major accidents may be generated by a reactivity excess (Chernobyl) (Nenat et al. 1996), or by a loss of coolant (Three Miles Island) or by a loss of flow rate or by anticipated transients without the interruption of the nuclear chain. Against these possible accidental chains a "defence in dept" strategy has been developed with three main lines: a "preventive line", a "protective" line, and an "imitative" line. This strategy worked at Three Mile Island accident with external releases of few curies of radioactivity but did not work at Chernobyl due its absence of external containment and many other design deficiencies.

Present reactor designs for the second line of defence have a majority of "active" safety systems and a minority of "passive" ones. An "active" system needs an external energy supply for intervention and a "passive" one is based on physical laws like natural convection, thermal dilatation, stress-strain relations, etc. to operate (Cumo 1995). The present trend of designers is to increase the percentage of passive safety systems to counteract the possible accidental chains, proposing the so-called "advanced passive" reactors for a transition period from the first to the second generation of nuclear reactors. This trend is also associated with a preference of a deterministic approach instead of the more scientific probabilistic one, for better gaining the acceptability of common people who often remember the old saying "if it can happen, it will happen".

This reactor has been conceived for small electric networks and for co-generation purposes, to increase the overall efficiency and multiply the possibilities of utilization. It is modular and assembled in small parts that are totally built and controlled, with quality assurance produced in factories.

The problem related to the disposal of waste is still opened to interesting solutions. The radio nuclides with long lasting lifetime can be converted into short life isotopes by their mutation through nuclear reactions in high flux nuclear reactors or in a coupled device of subcritical nuclear reactor in which a beam of high energy particles are injected by means of a powerful accelerator.

A device to covert long lasting isotopes has been recently proposed by Rubbia et al. (1995), with a subcritical fast reactor cooled by lead in natural convection, fed by spallation neutrons generated by a beam of protons accelerated till 1 GeV. Figure 18 shows a schematic representation of the conceptual design of this fast neutron operated high power energy amplifier.

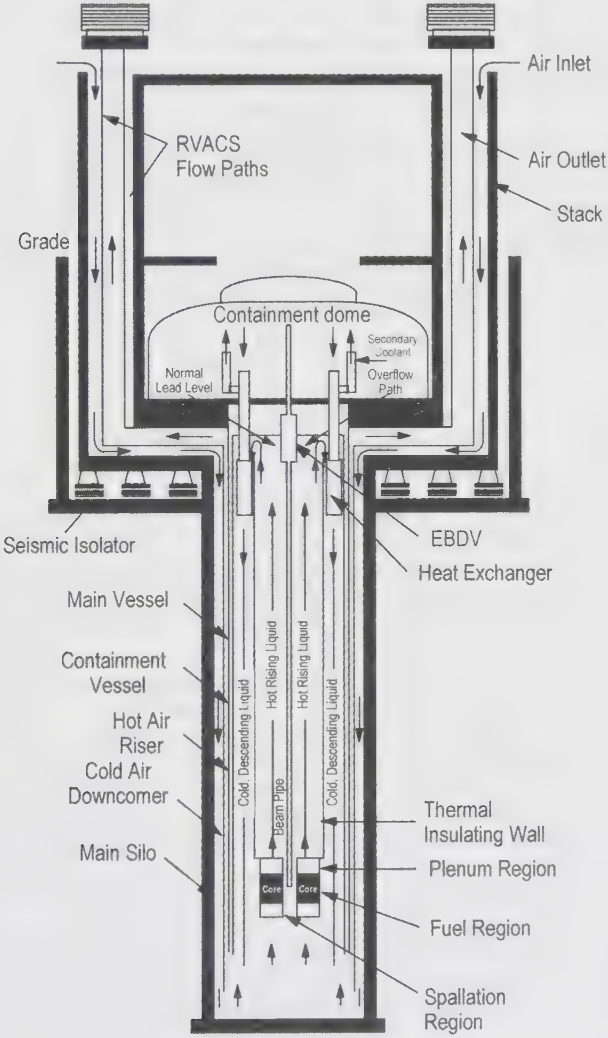

Figure 18. Conceptual design of a fast neutron operated high power energy amplifier.

8 CONCLUSIONS

It is shown that present energy strategy requires adaptation of new criterions to be followed in the future energy system development. Together with social aspect of the future economic development, it is of paramount interest for the modern society to implement the world leaders adapted resolutions before it will be too late.

The sustainability concept based on the evaluation of economic, social and environmental aspect of energy system has become a leading path for the development of future strategy of energy system development. Modern engineering science has to be oriented to those areas, which may directly assist in our future energy planning. Modern technologies will help to adopt essential principles of the sustainable energy development.

In order to promote the sustainability assessment method, the multi-criteria decision making procedure is demonstrated.

1. The presented method is of interest to be used in the evaluation of the different option of power plants.
2. Non-numerical information expressed in the form of mutual relation between criteria has proved to be useful tool in the evaluation procedure.
3. The decision-making method presented in this experiment, is only a tool to be used in the generation of priority list reflecting individual cases.

It is of particular importance to emphasise that multi-criteria assessment method leads to the introduction of new approach in the design of the future energy strategy which is suppose to be based on the larger share of new and renewable energy sources. Within this scope it is of paramount importance to focus attention to the potential use of geothermal energy sources. In this respect the quantification of sustainability indicators for the geothermal energy sources utilization will be of substantial importance in the decision-making procedure.

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Geothermal Energy Resources for Developing Countries, Chandrasekharam & Bundschuh (eds)
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The value of geothermal energy for developing countries

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ABSTRACT: We discuss social costs and benefits of geothermal energy production, and examine some factors that explain why the private sector may avoid investments in geothermal energy production although the investments are beneficial in a social perspective. It is found that the main obstacle is probably related to the various uncertainties, either directly connected to the development of geothermal plants or to the alternatives, such as fossil fuels. In order to make investors take the social advantages of geothermal energy into account, governments need to be strong and conscious about the energy policy. A broader international cooperation in developing clean energy world wide, for example through the CDM mechanism of the Kyoto Protocol, may also be helpful in this respect.

1 INTRODUCTION

The economic growth in developing countries, especially on the Asian and Latin-American continents, is expected to lead to a strong increase in energy demand over next decades. In the reference case projections from Energy Information Administration (2002), world energy consumption is forecasted to increase by 60% from 1999 to 2020, from 1.11 million TWh to 1.78 million TWh. The world energy market is known to be strongly influenced by political events, such as the terrorist attacks in the US on September 11, 2001, and its aftermath in Afghanistan. Such events may strongly affect economic growth, and thus energy demand, in developing countries. As shown in Figure 1, a large part of the growth in worldwide energy use is nevertheless expected to take place in the developing world. In particular, energy demand in the developing Asia and Central and South America is projected to more than double between 1999 and 2020. The corresponding annual growth rate is about 4% throughout the period. This accounts for about half of the total projected increment in world energy consumption and 83% of the increment for the developing world alone.

The combination of a rapidly increasing energy demand and vulnerability to fluctuations in the world energy markets in developing countries calls for a development of energy supply systems preferably based on domestic resources. To alleviate power blackouts and rationing of electricity, which are both very common in many developing countries, the development of reliable electricity systems is also vital. The implication of this, at least in the long term, is that it is important to encourage the development of renewable domestic energy resources in order to mitigate the vulnerability to fluctuations in world energy markets. As it stands today, however, many developing counties rely on imported fossil fuels to cover increasing energy demand.

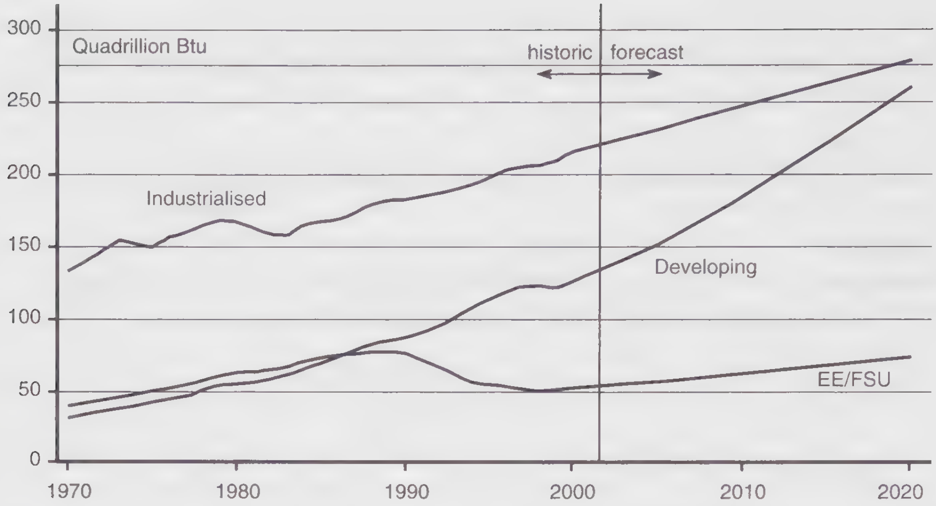

Figure 1. World energy consumption between 1970 and 2020 by region (after: Energy Information Agency 2001 and 2002).

Geothermal resources represent an alternative source of energy to many countries, and provide at the same time many advantages compared to increasing imports of fossil fuels in developing countries. With few exceptions, however, the potential for development of geothermal energy seems to be largely unexploited. In this chapter, we discuss to what extent economic arguments can explain why.

From an economic point of view, the attractiveness of geothermal energy production depends on the expected costs and benefits. The usual response from economists to people who claim that the potential of a project is positive, despite the fact that it is not implemented is "If you're that smart, why aren't you rich?" thus indicating that there is probably something wrong with the assessment. In this chapter, we ask why seemingly beneficiary geothermal projects may not be implemented, and discuss whether developing countries might take advantage of such developments even though few, if any, investors are willing to take part in it. We also examine the possibilities of lowering the barriers for potential investors in order to get socially beneficial projects carried out.

2 INTEGRATING ASPECTS OF DEVELOPMENT IN THE VALUE OF GEOTHERMAL ENERGY

The prospects for the future in developing countries are inevitably linked to the possibilities of economic growth. These possibilities critically depend on the availability of energy. Experience tells us, however, that abundant energy resources do not guarantee welfare for ordinary people. People in many countries suffer from poverty and severe pollution, despite a national level of energy use similar to that of the rich part of the world. Thus, energy has to be managed as a scarce resource, not only because many countries have a short supply, but also because a waste of energy may cause severe, but avoidable problems.

Increasing energy demand may always be covered by importing fossil fuels, but it makes countries vulnerable to shifts in world energy markets, which have oscillated vigorously over the past 25 years. Developing countries seldom possess the stable economic foundation that is required if the dependency of energy imports increases. The challenge is to find sources that can be provided domestically without large environmental impacts. Within a process of development, the alternative energy sources cannot be evaluated only with reference to expected monetary costs and benefits. One must also take into account that a stable supply of energy is a key factor in the transition from a risky low-income country to a developed economy better integrated in the world economy, but probably more challenged with respect to environmental issues.

Without integration of these factors, alternatives to increased imports of fossil fuels will usually be based on pure economic comparisons, that is, the costs of developing alternative energy systems and an evaluation of risk. In this respect, the combination of high capital costs and uncertain energy prices often disfavour domestically produced clean energy resources, such as renewable or geothermal energy. Being an alternative to fossil fuels, the value of the clean energy resources will be subject to the uncertainties in the world market for fossil fuels. In addition, there are usually uncertainties related to relatively new technologies that investors tend to emphasise. As long as the revenues from these investments in most cases will be spread over a long period, the uncertainties imply a substantial amendment to the expected cost to the investor.

Although we would like to draw attention to the importance of integrating a wider scope of social impacts when evaluating alternative energy sources, the importance of monetary costs and benefits of investments in developing countries should not be underemphasized. Developing countries are often faced with financial restraints, uncommon to developed countries. It may thus not be sufficient to point out social benefits of clean energy sources, even when tangible, such as in the case of reduced dependency of energy imports if these benefits do not enter into the accounting of the fundraiser.

Among the social benefits of alternative domestic energy resources, the implied enhanced security of the energy supply and avoided environmental impacts may be pointed out as particularly important. In a purely economic sense, the risk of increased dependency on energy imports may be translated to uncertainty in the price of fossil fuels. In a national context, the consequences of a sudden shortage of energy supply that leads to a rapid increase in prices may, in addition, have serious indirect impacts on the whole economy, especially if subject to financial restraints.

This became particularly clear in the wake of the oil price hikes in the 1970s, when most countries ran into a trade deficit. The poorest suffered the most, however, because these economies were less able to apply alternative energy or adjust their activities to a less energy intensive mode. At the same time, the loss of export income as a result of the general slow-down of the economic growth worldwide reinforced the initial problems originating from more expensive energy. The social dynamics of these problems thus made it very difficult for developing countries to recover. The drop in energy prices ten years later did not have the reverse effect, however, neither on the world economy nor as an impulse to growth in developing countries.

Thus the difference between the perspectives of private investors and public authorities is striking. To a private investor, the uncertainties in the fossil fuel markets mean uncertain cost in the imports alternative, but at the same time a corresponding uncertainty in the value of the domestic alternative. If fossil fuels are expensive, the value of the domestic alternative is high. But if the world market price of fossils is low, the domestic alternative also has a low value. Therefore, the fluctuations in world markets for fossil fuels do not necessarily affect the relative values between fossil fuels and other energy sources because they are all affected by the same uncertainty. But other factors, which are important to the investors, may turn out to be disadvantageous to the domestic alternatives. These factors include high capital intensity of alternative energy production, which involves a considerable risk to the investor, and uncertainties about the performance of the technology

To the national authorities, on the other hand, imports of fossil fuels involve disadvantages that private investors may disregard. In a national context, high prices of fossil fuels in the world markets are in most cases considered disadvantageous to the national economy. High prices may lead to long-term recession, which is reinforced if the economy is dependent on energy imports. Thus, domestic energy resources may contribute to stabilising the domestic energy market.

At the same time, it is harder to believe that low prices in the world market spur development impulses, because all countries are subject to low prices, and the countries depending on energy imports do not gain from low energy prices relative to other countries. Hence, the interpretation of "good news" and "bad news" are likely to be opposite for a private investor and an agent that makes decision on behalf of a nation. This also explains why energy supply securing may be considered a separate issue on the national level.

In addition, national authorities have to consider the externalities of fossil fuel consumption. The quality of the environment, air quality in particular, is closely related to the use of fossil fuels. A poor environmental standard does not necessarily affect the economic performance of industries directly, but may impose substantial costs to the society in terms of poor health standards, and damages to vegetation and buildings. The usual proposal to make private agents act in an environmentally acceptable manner is to impose restrictions on the sources of pollution, for example through charges. However, such restrictions are quite uncommon in developing countries. This is easy to understand because the major polluters are often the large industries, which represent the main potential for future economic growth. To charge these industries for the pollution they cause is thus considered a threat to growth. By turning to cleaner energy, one may avoid the political impossibility of putting restrictions on the use of fossil fuels, and at the same time improve the quality of the environment. To assess the potential of such an option, all the effects all through the society need to be integrated.

Geothermal resources can provide a stable supply of energy, in contrast to many alternative domestic renewable energy resources, such as hydropower. Although the importance of a stable energy supply is considered to be limited in developed countries with a highly coordinated transmission system, it may be vital to developing countries. In comparison to thermoelectric plants geothermal power plants, also require less maintenance and hence less interruption of the production resulting in plant capacity factors.

Over the past decade the attention to global environmental issues, notably climate change, has been rapidly increasing particularly in the rich part of the world. Developing countries are clearly more concerned about their current problems. Most of them are reluctant to take an active part in the mitigation of climate change because they regard it as a problem that has been created mainly by developed countries. On the other hand, it is recognized that global warming cannot be mitigated unless developing countries take an active part, not least because of the substantial contribution to the future growth in emissions of greenhouse gases from these countries.

The Clean Development Mechanism (CDM) in the Kyoto Protocol of the UN Framework Convention on Climate Change may, however, spur involvement by developing countries on a voluntary basis. The CDM gives an opportunity to countries with commitments, so-called Annex 1 countries, to relax their domestic emission targets, provided that they contribute to cutting greenhouse gas emissions in the same order in some developing country. The aim of the mechanism is twofold: partly to provide developed countries with low-cost opportunities for reducing emissions of greenhouse gases, and partly to encourage sustainable development in developing countries.

There are a lot of practical problems related to the initiation of the CDM. It is, for example, difficult to determine the emission cuts of a particular project, because it requires a counterfactual assessment of future emissions. Moreover, the design and thereby the cost of projects are clearly subject to conflicts of interest between the investing country and the host country. Investing countries are concerned about emissions, while host counties are concerned about the aspects of development. This also points at an inherent contradiction in the whole mechanism, because, if successful, it may contribute to growth, which encourages demand for energy, including fossil fuels. This generates emissions, while the initial aim was to reduce emissions. This is, however, a contradiction that the Parties of the Convention are fully aware of, recognizing that development in a large part of the world is necessary if the climate change is to be mitigated in an effective way.

It is hard to say how large the potential for CDM will be. In essence, it nevertheless creates a value for producing energy without greenhouse gas emissions, and thereby contributes to enhancing the value of non-carbon energy. Equally promising is that some of the abovementioned obstacles for investments in domestic energy production in developing countries are reduced as a consequence of potential contributions from foreign interests. Thus, financial constraints may become less limiting, since the investing country is to pay the full additional cost of the "clean" alternative. Moreover, the uncertainties related to the technical performance of new technologies may be reduced, partly because investing countries in some cases may be familiar with it, and partly because the responsibility for operation and maintenance can be shared between the two countries. Thus, the development of "clean" energy seems to fit particularly well with both aims of the CDM by reducing emissions of greenhouse gases and, as a consequence, reducing important hinders for development in developing countries.

3 THE ECONOMY OF GEOTHERMAL ENERGY PRODUCTION

In section 2, we discussed the issues that we believe are the most important to consider when comparing the social costs and benefits of providing energy supply in developing countries with the costs and benefits of private investors. In this section, we discuss how geothermal energy production as an alternative to domestic extraction and imports of fossil fuels could be evaluated with reference to these issues.

Although geothermal energy is based on the extraction of a natural resource, it is not easily classified along the lines that are usually applied when analysing economic management of natural resources. In some sense, it may be regarded renewable, as there are no limits for the duration of the resource. But unlike other renewable resources, there are no limits to the rate of extraction either, such as a maximum sustainable yield from the resource. In this sense, it resembles a non-renewable resource that needs to be explored before extraction can take place. However, the resource base is practically speaking infinite, and there are no reasons to manage geothermal heat today with respect to the future loss of wealth. In this respect, geothermal energy is not non-renewable in an economic sense. Hence, the issue of economic management of geothermal energy as a natural resource becomes irrelevant.

3.1 *The potential*

What geothermal has in common with other natural resources is that location is relevant to the economic potential. Although heat from the earth is, in principle, available everywhere, the possibilities to extract it differ considerably around the world. The largest potentials of high-temperature resources as required for power generation – are found along the tectonic plate boundaries (see Bundschuh et al., this book). They are predominantly found in developing countries predominantly in Latin America, Africa and the Pacific region. In contrast, low-temperature geothermal resources are more equally and widely distributed, bur more intensively used in industrialised countries than in developing countries.

The current frequency of geothermal energy plants is, thus, clearly correlated with the income level of a country. This can be explained by the general level of energy demand, particularly when compared with domestic supply of energy. Except for coal, Europe is relatively short on energy resources, which probably is why geothermal energy is of interest. One may expect this shortage to be reflected in energy prices, but it is difficult to find complete statistics of energy prices across countries. On the other hand, the price of fragile energy, such as oil, is likely not to differ much. To the extent that differences in the energy market are reflected in prices, it is probably better to look at the electricity markets.

Figure 2 shows domestic electricity prices for the EU and Japan, other OECD countries, excluding the new members, Mexico and Korea, and a selection of other countries. These are not only

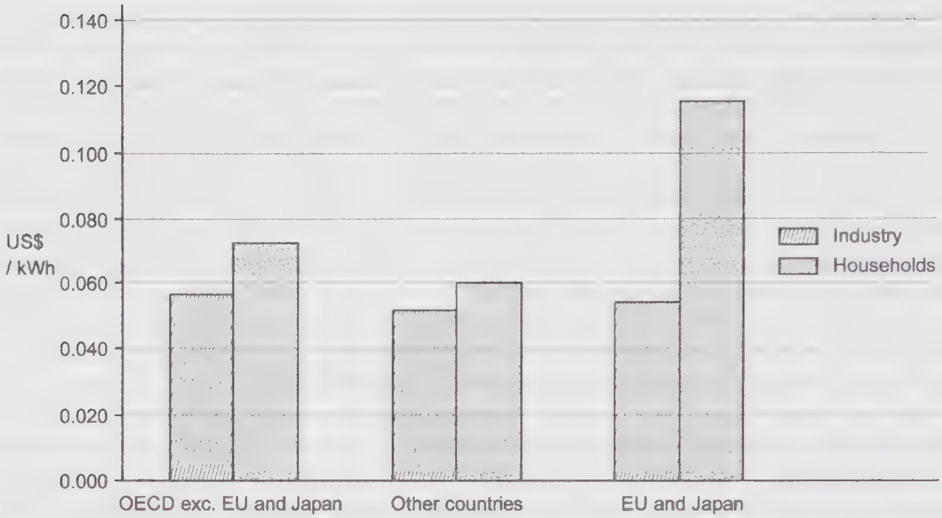

Figure 2. Electricity prices in industries and households groups of selected countries, 4th quarter, 2000 (after: International Energy Agency 2002).

developing countries, but include formerly centrally planned economies in Europe ("Other countries" include Chinese Taipei, the Czech Republic, Hungary, India, Korea, Mexico, Poland, the Slovak Republic, South Africa, and Turkey).

While the electricity prices for industry are very similar in all countries, household prices differ significantly, and households in EU and Japan, in particular, face much higher electricity prices than the other countries. The pattern of industry prices can be explained by competition in the product markets, which forces the electricity price down to the world market level, while the household prices better reflect domestic conditions. For an evaluation of the potential for geothermal energy, household prices are probably also relevant, because a large part of this energy, such as district heating, will supply households and small economic units.

By comparing the household price in EU/Japan and the other countries, one may thus indicate an interval for electricity prices within which development of geothermal energy could change from being a relatively undeveloped resource to a relatively frequent source of energy supply. The household price in "EU and Japan" shows at which level even geothermal heat far from the tectonic boundaries is economically feasible. In countries where these boundaries cross, one should expect geothermal energy to be utilized at a much earlier stage.

However, the figures also show that the relationship between electricity prices and development of geothermal energy should not be oversimplified. Although geothermal energy is widespread in USA and Canada, the west coast of North America, in particular, has a larger potential for power generation. One explanation may be that electricity prices are only slightly higher here than in the group of other countries, despite a high energy demand, thus making geothermal energy less interesting for investors. This is, however, not the case in Japan, where the price of electricity in households is 0.23 US$/kWh. Geothermal energy is, on the other hand, scarce when compared with the geothermal potential.

3.2 *The costs*

Production of geothermal energy is very capital intensive, even when compared with other renewable energy sources. Table 1 shows intervals for installation costs, plant factor, and energy costs

Table 1. Comparison of costs of electricity generation from renewable resources under expected technological development from 2000 to 2010. Source: Energy Information Administration (2000).

Source/technology	Installation costs (1998 US$/kW)	Plant factor (%)	Energy costs (1998 US cent/kWh)
Solar thermal	3043–2748	42–56	0.135–0.092
Solar photovoltaic	4318–1813	28–29	0.288–0.117
Wind	979–941	30–34	0.057–0.049
Hydropower	1800–1800	55–55	0.051–0.051
Geothermal	1811–1054	87–87	0.037–0.021

for some renewable alternatives. The plant factor is the possible percent time running at full capacity during a year. The figures are based on scenarios for technological development over the next ten years, and provide figures expected to prevail from 2000–2010. They must be regarded only indicative, and it should be noted that the figure for hydropower applies for Costa Rica.

Still the figures indicate that although the capital costs, or installation costs, for geothermal energy are high, the cost of energy is relatively moderate. This is partly because the operating costs are low, but mainly because geothermal energy provides a stable energy source that may produce at high capacity all year round. For most other renewable energy sources, daily and/or seasonal variations in inflow require that the capacity cannot be fully utilized all the time. The importance of this property depends, however, on the fluctuations in demand.

To further evaluate the costs of geothermal energy, we need to make a distinction between direct use for heat purposes and generation of electricity. Low thermal resources apply mainly for direct use. If heat pumps are being used, the thermal limit downwards is not far above 0°C. The two main factors for the cost of heat are the temperature in the well and the distance between the well and the user.

Direct use requires an infrastructure to distribute the heat. The distribution systems are usually very costly to establish, but expansion of the system's capacity or linking new users to an existing system may be undertaken at low cost. Hence, the marginal cost of direct heat may be low while the average cost is high. In order to establish a new system, the investors therefore need to make sure that sufficiently many users will connect to it. Once built, the owners of the distribution system may, however, turn into a natural monopoly, unless they are subject to some regulation. These factors, plus the fact that establishment of geothermal energy plants requires extensive exploration, explains why it is difficult to be specific about the potential for geothermal energy in a country with reference to a general description of the geological conditions.

The World Bank has indicated the costs of geothermal heat to be in the range from 3 to 6 US$/ton of steam and 10 to 40 cents/ton of hot water, provided that the point of delivery is less than one kilometre from the well. The costs depend mainly on the temperature of the delivery, but other factors, such as the geological conditions, may also be critical. If we assume that it takes 40 kWh to boil a ton of hot water, this indicates a cost of boiled water at approximately 5 to 10 cents/kWh. Lower temperatures can sometimes be accepted, and the cost is thereby reduced. For the comparison between steam and hot water, the World Bank suggests 3.0–4.5 US$/ton steam and 20–40 cents/ton hot water, both with temperatures above 100°C. One has to take into consideration, however, that steam has a broader range of applications. The willingness to pay for steam may, therefore, be higher than for hot water.

Electricity may be produced from wells with temperatures above 180°C. The cost of development depends on the quality of the resource and on the capacity of the plants. Moreover, power production generates wastewater that may be utilised directly in district heating systems if it is located close enough to the users. This may help to reduce the cost of power production. The World Bank's estimates of the costs for geothermal electricity plants are shown in

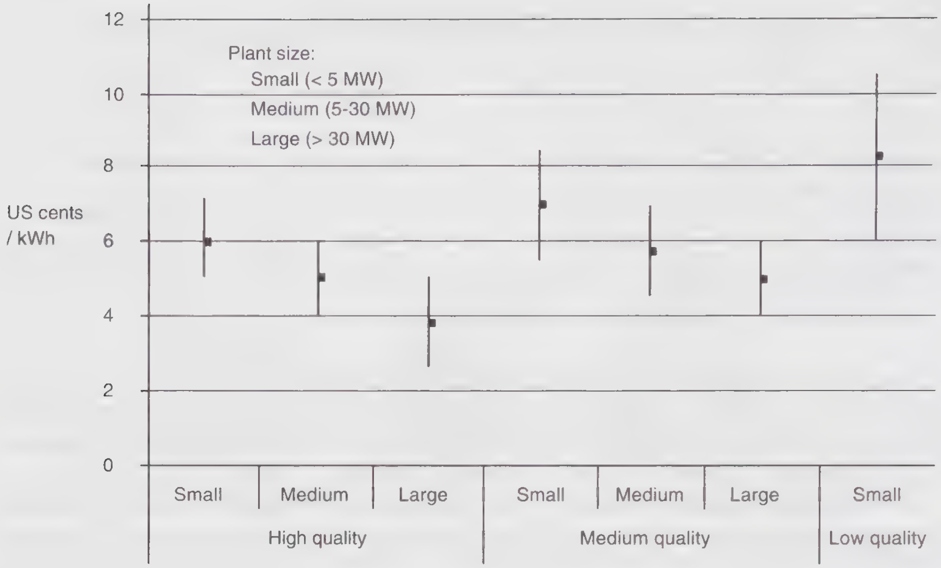

Figure 3. Estimated ranges of unit costs of geothermal electricity plants in developing countries. US cents/kWh. Source: World Bank (2002).

Table 2. Economic benefits of improved air quality from reductions of 1 TWh from coal fired power plants in Hungary calculated from three alternative approaches. Source: Aaheim et al. (2000).

Approach	Average benefit (Million US$/TWh)	Marginal benefit (US cents/kWh)
Reduction in economic damages	8.0	0.8
Willingness to pay for improved air quality	36.4	3.6
Macroeconomic assessment	2.5	2.6

Figure 3. The cost figures refer to developing countries, where indirect costs, such as training and transaction costs, are expected to be relatively high.

As one might expect, the unit costs of electricity plants clearly exhibit economies of scale and the quality of the resources constitute an important cost factor. One might assume, also, that the variability of costs increases as the quality of the resource declines. This pattern can be observed for small plants, but does not seem to matter for larger plants. Medium and large plants usually require medium or high quality resources.

The costs range from 2.5 cents/kWh for large plants with high quality resources to 11 cents/kWh in small plants with low quality. As one might expect, this corresponds to the equilibrium prices for energy delivered to households, and indicates that the costs expressed in Figure 3 refer to the costs of installed capacity. When considering the potential for geothermal energy, the figures in Table 2 should not, therefore, be interpreted as cost functions, which show marginal costs independent of market conditions.

As mentioned above, the costs of geothermal energy plants consist mainly of capital costs, which often constitute more than 90%. The capital costs can be divided into costs of exploration, development of the steam field and construction of the plant. Figure 4 shows an approximate distribution of the various capital cost for power plants. To the costs of deliveries, one has to add transmission costs and distribution to consumers, which are also predominantly capital costs.

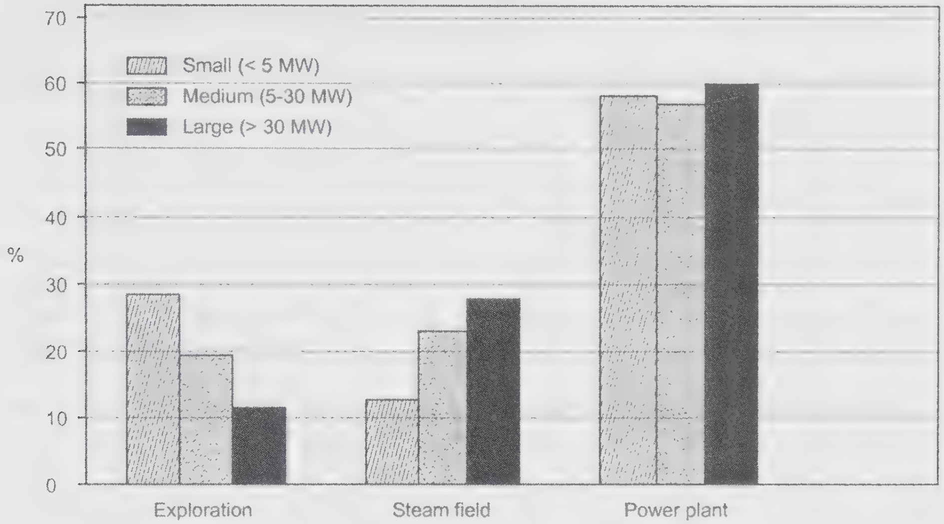

Figure 4. Distribution of capital unit costs of geothermal power plants (after: World Bank 2002).

While the costs of the power plant constitute around 60% of total capital costs independent of the size of the plants, the relative costs of exploration and of the steam fields vary considerably. This is mainly because total exploration costs are relatively independent on the size of the plant, while the total cost of the steam field increases according to the scale.

3.3 *Investments from the perspective of private agents*

The advantage with capital-intensive production is that future costs may be regarded as relatively certain, and that the plant may be operated at low costs once it is financed. Compared with fossil fuel power plants, for example, this implies a relative gain in times when the price of fossil fuels is high. Also an absolute gain may arise when the fossil prices are high because the price of energy follows the price of fossil fuels to a certain extent. Similarly, a relative loss may occur if the price of fossils drops. One might therefore expect that an investor who is to choose between a fossil and a non-fossil fuel plant with equal expected unit costs is indifferent between the two as long as the price of fossil fuels may equally well increase as decrease.

However, the different composites of capital and operating costs make a difference between alternative investments. Large capital costs mean that one cannot reduce costs much by reducing production in times with low energy prices. Rather, production has to be maintained in order to cover parts of the capital costs, but may be with substantial financial deficits. Consequently, the owners take a much higher risk if investing in a capital-intensive geothermal plant.

A simple example may illustrate how important the opportunity to be flexible with respect to costs may be. Compare a geothermal power plant with a fossil fuel plant. In order to stylise the example, assume the costs in the fossil plant entail only operating costs, such as purchase of fuel, and that the costs of the geothermal plant are due to investments only. At full operation over two periods, both plants can produce at a unit cost of 5 cents/kWh in the first period, but because the price of fossil fuel is uncertain, there is also uncertainty about costs of the fossil plant in the second period. For simplicity, assume that the unit costs in the fossil fuel plant will be either 5.3 or 4.7 cents/kWh in the second period. The price of energy is 5.1 cents/kWh in both periods. Thus, both alternatives are expected to be equally profitable, and the geothermal plant is profitable in both periods, since there is no uncertainty attached either to the price or to the costs.

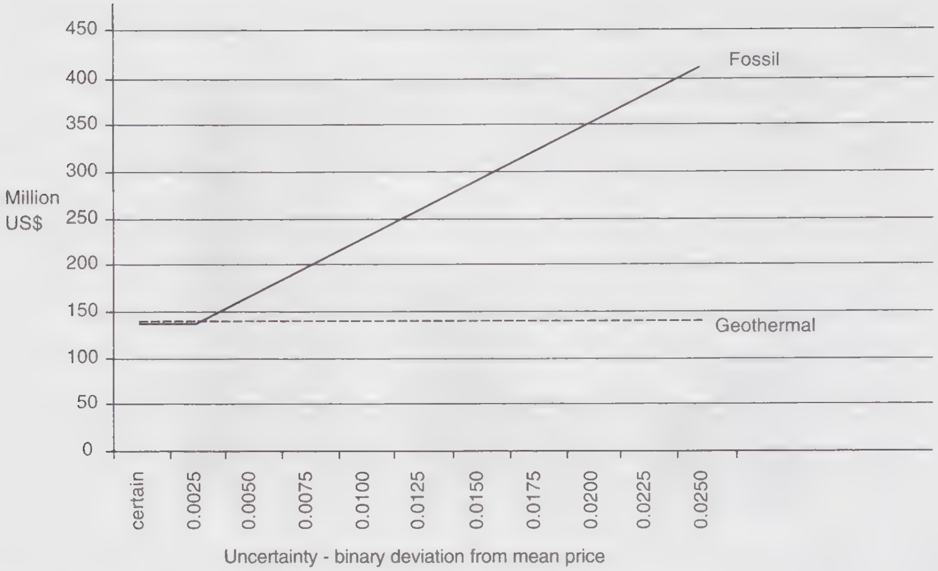

Figure 5. Value of alternative power plants with uncertain price of fossil fuels.

The fossil plant may, on the other hand run into deficit in the second period. However, if the price of fossil turns out high, it is better to close the whole plant down, in which case the owner earns nothing. But he will not lose either, because all the costs become zero once the plant shuts down. The expected gain in the second period is therefore the average between the earnings at low fossil fuel prices and nothing.

Figure 5 displays how the expected value of the two alternatives in this example changes with increasing uncertainty about fossil fuel prices in the second period. Each plant is assumed to produce 25 GWh/year under full operation. Uncertainty is represented with a binary distribution of costs with the same mean. The example uses extreme cases described above (operating costs only versus investment costs), and the importance of uncertainty is therefore exaggerated. It nevertheless demonstrates how sensitive technologies that involve large investments, such as geothermal energy, may be to uncertainty when compared with more flexible alternatives.

If the uncertainty is small, there is no difference between the two alternatives, because the fossil fuel plant will still operate with a profit if the price is high in the second period. But very soon, the uncertainty starts to matter. Even with moderate uncertainty, for example expected price ± 1 cent in the second period, the value of the flexible fossil plant, defined as the net profit above a normal rate of return, is nearly doubled. This corresponds to a required reduction of the geothermal plant at approximately 0.2 cents/kWh in order to be equivalent. The same argument applies of course if the price of energy is uncertain, but with the difference that the geothermal then may end up with a deficit.

3.4 *Investments in a socio-economic perspective*

Private investors are known to choose the alternative that gives the highest expected profits. This may be a relevant description for decision making also at the national level in many countries, but it does not necessarily lead to the best social decision. Below, we take a closer look at some factors that explain why decisions at a social, or national, level may deviate from the decisions that private agents make.

3.4.1 *Risk and financial constraints*

One reason is that the uncertainty that faces private agents is of a very different kind than the uncertainty that faces the society. In a social context, uncertain costs in fossil fuel plants constitute just one element of the uncertainty in the whole portfolio of social and economic activities. Low energy prices are clearly unattractive to the owners of the geothermal plant, and they may therefore prefer a fossil plant to reduce the risk. In a social context, however, low energy prices means that most other economic activities can be produced at lower costs, and the potential losses in geothermal plants are easier to bear than in times when the prospects for most other economic activities are gloomy. If an economic slow-down is due to high energy prices, the geothermal plant may actually represent a light in the dark. In this sense, they may very well contribute to "stabilising" the economy. Hence, a drawback from the point of view of the owners may be turned into a social advantage (Wilson 1982).

This aspect of uncertain energy prices may explain why many countries consider self-supply of energy to be important, even though it is difficult to get domestically provided supply financed. How important this is depends on such factors as the dependency of energy imports and how well diversified the national economy is with respect to uncertainty. The ideal would be to neutralise uncertainty completely by diversification of assets. This is, however, not the case in most countries, and it becomes less realistic the smaller the economy is. Thus, developing countries are likely to be far from the ideal, and thereby very vulnerable to uncertain fossil prices. In these countries, domestic energy plants based on alternatives to fossil fuels are most likely to be negatively correlated with the fluctuations in the rest of the economy.

Financial constraints in many developing countries, together with the evaluation of risk by private investors, may represent significant barriers to investments in capital-intensive activities, including geothermal energy production. The high share of capital costs constitutes a separate cost component, which implies that the countries may not be able to afford to choose the best alternative. One way to overcome the barriers is that the country itself takes the social aspect of risk into consideration, and supports investments. In addition, one may try to attract foreign investors by compensating for social benefits beyond those arising from the production of energy. One cannot expect private companies to take the social attitude to uncertainty, although multinational companies may be better diversified than small developing countries. Moreover, the financial constraints may be considered a result of foreign investor's reluctance to invest in developing countries, and indicates that they will require something more in return.

3.4.2 *Local environmental impacts*

Apart from the economic aspects, geothermal energy has also environmental impacts that differ considerably from those of its most frequent alternative, fossil fuels. Being a clean energy resource geothermal energy can contribute to reducing air pollution and thereby improve the local air quality as well as reduce transboundary environmental problems. The concern for environmental impacts has increased considerably over the past years all over the world, and it is becoming a routine in most countries to assess the environmental consequences of larger investments.

As an example, a conversion from oil based electricity power plants to geothermal energy reduces emissions by nearly 1000%. Oil based power plants emit approximately 723 kg CO_2/MWh (diesel fuel emission factor; UNFCCC 1997), and coal based plants emit even more. In comparison, CO_2 emissions from geothermal plants amount to 0.892 kg/MWh (UNFCCC 1997). The average SO_x emissions of geothermal plants are 0.16 kg SO_x/MWh, whereas the emission from an oil-based power plant is 4.99 kg SO_x/MWh (UNFCCC 1997). Also other emissions, such as NO_x are reduced considerably when power plants based on fossil fuels are replaced by geothermal energy.

The socio-economic impacts of reduced air pollution depend on a variety of factors, and cannot be assessed on a general basis. Important factors include the composition of pollutants and the density of exposed recipients. Hence, pollution may affect the health standards; it may cause material damage and lead to crops losses. Case studies indicate that the socio-economic value of savings related to improved air quality may be substantial, especially in countries with a combination of relatively high energy intensity and low income per capita. These countries are often characterised by high background level of air pollution, which makes people as well as materials sensitive to changes in the air quality. Most of the concern for air pollution has been concentrated on problems in the cities with high emissions. In recent years, however, increasing attention has been paid to secondary effects of air pollution, such as tropospheric ozone and secondary particles, which spread out over much larger areas. It is thus recognised that the effects of emissions beyond areas close to the sources may be larger than previously expected. For example, the impacts on crops may be substantial.

The economic value of improved air quality is, for various reasons, highly uncertain. In a case study of Hungary, Aaheim et al. (2000) found that energy savings, or correspondingly, replacing fossil fuel electricity plants with clean energy might reduce material losses by 5.5 million US$/TWh per year. The increase in crops may amount to 0.1 million US$/TWh per year. This does not reflect the total benefits for crops, however, because the calculations refer to Hungary, only, whereas lower pollution in Hungary may affect the background level in surrounding countries as well.

The most uncertain, but also the most substantial, part of the benefits from better air quality comes from an improvement in health standards. Variations in air quality affect the risk of death, as well as the risk of developing cancer. In addition, various respiratory problems are closely related to air quality. The extent to which reduced emissions may improve health standards depends on a variety of factors that are partly locally dependent, such as population, population density, weather conditions, and so on. Some general remarks on the basis of previous studies may, however, be given.

One is that even though deaths and cancer are usually far more dramatic than respiratory diseases, the social burden of respiratory diseases is likely to be heavier because it affects far more people. In the case study of Hungary, which houses 10 million people, it was found that less than eight more people would survive or avoid cancer for each TWh reduced, or replaced with clean energy. About 2% of the population would avoid acute respiratory symptoms for every TWh reduced or replaced, and the frequency of asthma would be reduced by more than 10%. The social gain, for example in terms of increased labour supply, was estimated at less than 8 man years per TWh for deaths and cancer and more than 350 for respiratory diseases, including a reduction of the personnel in the health sector.

The second remark is that the economic benefit of these savings is very difficult to assess, and the estimate may vary considerably depending on the approach. Aaheim et al. (2000) compared three approaches. One was based on the "hard" economic benefits only. Thus benefits to materials and crops were calculated by the reduction in maintenance cost and increased market value, respectively. Health benefits were calculated as a combination of increased labour productivity from affected people and reduced labour costs in the health sector.

This "hard" estimate assumes that the only benefit from improved health is that society can get more production out of each person, and the costs for medicines and care can be reduced. Few would claim that such an estimate reflects a realistic assessment of the value of being healthy. To include a broader aspect, it is often suggested to base valuation on the willingness to pay. In principle, this is the correct approach, but it faces severe difficulties. These are partly due to the fact that the preferences are not revealed from real market behaviour. Moreover, observations of the willingness to pay can provide only a point estimate at the current level of pollution, but does not take into account that the willingness to pay will be reduced if the air quality improves.

To account for the latter problem, the value of improved health standard was also implemented in an economic model, where estimates for the willingness to pay were used to parameterise demand functions for health. The estimates of the three approaches are displayed in Table 2.

The figures show that the benefits of clean electricity production may be large if it replaces fossil fuels, but it is difficult to say how large, even with fairly detailed information about the case. The marginal benefit ranges from 0.8 cents to 3.6 cents per KWh, whereas the model based estimate is 2.6 cents. Notice also that the average benefit for the model-based assessment is substantially lower than the two other estimates, because the estimates of economic damages and the willingness-to-pay are only partial assessments, for which all benefits are calculated in terms of costs and benefits. In this sense the partial estimates are more comprehensive than the model-based estimate, but they are also less informative. To evaluate the model-based result, one has to take into account that the resources in the entire economy is being utilised more effectively. Hence, the GDP is increased by approximately 380 million US$ in the model approach, which amounts to 6 times the cost of the energy-saving efforts in the Hungarian study.

When comparing fossil fuel electricity plants with geothermal plants, it must be added that also geothermal energy utilization may have negative environmental impacts. Development of geothermal resources affects land use, for example through vegetation loss and soil erosion, and may have considerable impacts on water resources. Also in this case, the extent of the impacts depends largely on the local conditions. Compared with the extensive environmental problems related to the use of fossil fuels, the negative impacts of geothermal energy must, however, be regarded as small.

Despite the uncertainties about the costs and benefits of environmental impacts, the social gains of geothermal energy may be substantial. The Hungarian case study shows that the marginal benefits of clean energy production may be as large as the total developing cost for a large, high quality geothermal power plant, according to Figure 3. However, to take into account the environmental improvements in decision-making, the national authorities in developing countries will have to introduce incentives for private investors. Instead, many countries subsidise fossil fuel, and coal in particular, for various reasons, including to assure some supply of domestic energy. But these subsidies also represent a barrier to the introduction of domestically based clean energy production. The inefficiencies that follow in terms of more expensive energy systems and a poorer environment may turn out to be large.

3.4.3 *Climate change*

Climate change has received more attention by policy makers than any other environmental problem in many countries. So far, only developed countries are subject to proposed emission targets, but the Kyoto Protocol opens for participation by developing countries through the so-called Clean Development Mechanism (CDM). The idea is that developed countries can pay developing countries to reduce emissions, and thereby obtain a "credit" on their own emission targets. The motivation for the developing county to become involved lies in the fact that their emissions of greenhouse gases have suddenly been given a value, and may be traded. Moreover, the emission cuts paid for by the developed country will most likely comprise technology transfers to developing countries. Hence, the CDM both provides foreign investors with their need for additional motivations, and relaxes the financial restraints that seem to hamper the development of geothermal energy in many developing countries.

However, it is difficult to predict how important the CDM will be, at least over the next 10–15 years. Countries subject to emission targets may also trade quotas. After USA withdrew from the Kyoto Protocol, the price of emission quotas in the international marked is not expected to exceed 5 US$/ton CO_2. According to ExternE (1995), a standard European coal fired plant causes 925 kg/MWh emissions of CO_2, if emissions from the mining are included. With a quota price at 5 US$/ton CO_2, this is approximately 0.45 cents/kWh. Hence, the CDM may at least reduce investors' barriers to investing in capital-intensive geothermal plants. One of the uncertainties for investors is that it is not entirely clear how many credits they can achieve by investing in CDM projects. Ideally, CDM projects ought to replace existing sources of emissions, but it is always difficult to say to which extent a new plant adds to or replaces previous capacity.

Hence, the investors may not get a full emissions credit. This may partly depend on how important the Conference of the Parties of the UN Framework Convention on Climate Change will consider the development aspect of the CDM mechanism to be compared with the aspect of greenhouse gas emissions.

Despite its clear advantages, geothermal energy has not attracted much attention as an opportunity for CDM projects so far. Other renewable options, such as hydropower and wind energy, seem to be considered more attractive. The only concrete proposal was the El Hoyo geothermal field in Nicaragua. The field would produce 520 GWh per year, and contribute a total reduction of 14 million tons in CO_2 emissions over 38 years. It has been approved as a CDM project, but was cancelled due to a lack of interest among investors.

The reasons why investors do not show enough interest may partly be that the development cost of the field is too high. As pointed out earlier, however, there may be additional reasons that could be overcome with a better management of energy resources, not only from the national governments' side, but also in the context of managing CDM projects in the international arena. In its present premature stage, the CDM is predominantly a matter of bilateral cooperation between the investor and the host country. The international involvement applies mainly to the verification and control of projects. Thus, the full risk of each project is imposed on the investor and the host country. This puts a particular burden on unconventional options, such as geothermal energy. Because the CDM is an international mechanism, this obstacle could be reduced considerably if all CDM projects were managed in a kind of clearing house, with the aim of spreading the risk.

Over time, the importance of international mechanisms similar to the CDM is likely to improve, also as an incentive for the development of clean energy resources. Despite current uncertainties about the willingness to take part in the Kyoto Protocol in many countries, one must expect that targets will be tightened and more countries will be subject to emission targets in the future. The price of quotas, and thereby the value of CDM projects, may increase as a result. Moreover, a better system for managing bilateral agreements may emerge, and thereby reduce obstacles for implementing geothermal energy.

4 CONCLUSIONS

Privatisation of or private sector participation in the energy sector is becoming more and more dominant also in developing countries. Alternative energy sources vary widely in terms of cost structures, economies of scale, the production properties, and the externalities of production. These properties are likely to be regarded differently depending on whether a private investor or a public authority makes the decision. In order to make private investors act in accordance with social interests, it is important, and may become even more important in the future, to find appropriate incentives for private investors.

A review of the economic properties of geothermal energy production indicates that private investors may be reluctant about development, especially in developing countries. This can to some extent be confirmed from observations. High capital costs make the economy of geothermal energy plants more vulnerable to uncertainties in the energy market and to the performance of the technology than alternative plants. Whereas the uncertainties in the energy markets affect all alternatives, the uncertainty about the technology, or performance of the plant, is probably considered larger for geothermal plants than for more traditional alternatives, such as energy production based on fossil fuels. It is well known also from other sectors that this uncertainty matters a lot for the choice of technology.

Compared with the alternatives, geothermal energy has, on the other hand, substantial advantages in a social context. The most important are, first, that it may provide a stable, domestic supply of energy in developing countries, and second, that it is a "clean" source of energy. Although it is difficult to say exactly how these advantages compare with the obstacles that private investors attach to the uncertainties, studies strongly indicate that there is a room for more extensive development.

In order to exploit the potential gains of geothermal energy, the national authorities will have to be confident in their use of available instruments. Two domestic targets may be pointed out in this respect. One is to prepare for an extensive coordination of the electricity markets. This limits the negative impacts of uncertainties both with respect to the markets and to the technological performance. The second is to internalise the social costs of the so-called negative externalities of energy production. One way to do this is to charge activities that contribute to air pollution. The social advantage of "clean energy" thus becomes visible. As a start, one should at least abolish subsidies of fossil energy production.

Finally, one may also point at the CDM as one instrument that might encourage further development of geothermal energy. The CDM accounts at least for some of the positive environmental properties of geothermal energy. Moreover, it represents one possible way out of the constraints connected to the financial requirements. However, also to the investors in CDM projects, the uncertainties seem to represent an obstacle for active involvement. These uncertainties might be reduced if the technology becomes better known, but may also diminish if the management and co-ordination of CDM projects are lifted up to the international level.

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The geothermal potential of the developing world

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ABSTRACT: In many developing countries the exponentially growing energy demand can be covered by using locally available sustainable geothermal energy resources, which can make many countries more independent from oil imports or from the over-dependence of hydropower. The potential of the actually known high-enthalpy geothermal resources, as required for electricity generation amounts to about 1100 TWh/year. Most of them are in developing countries. Till now this huge energy source has not been exploited to the extent it should have been in many developing countries. Opportunities for future use of geothermal energy in developing countries must be seen under different aspects such as: (1) Costs for electricity generation from geothermal resources will increase in future compared to conventional energy, (2) technological development in binary fluid method, and (3) the exploitation of hot dry rock (HDR) resources.

1 INTRODUCTION

In many developing countries energy demand will be growing exponentially during the next decades. The demand-supply ratio in these countries depends greatly on the availability, cost and uncertainties related to petroleum products. Developing countries with great oil potential can still be benefited to a large extent by using available geothermal energy sources compared to highly industrialized countries. Till now this source has not been exploited to the extent it should be in many developing countries.

Geothermal systems derive its heat either from the high heat fluxes from the crustal rocks due to conduction or due to magmatic bodies at deeper levels due to convection. The former systems occur mainly in continental rift zones with high heat flow and high geothermal gradient and the later occur in active volcanic region. In places where geothermal gradients are higher than the normal average value of 30°C/km, meteoric waters circulating deep in the earth crust in such areas get heated and give rise to geothermal waters. The geothermal systems associated with continental rift are "conductive" systems while those associated with active volcanism are "convective" systems. The convective systems get additional heat to drive the convective process through magma bodies. Almost all the countries in the world do have either of the above or both the system in operation. Such geothermal systems provide natural energy source for many developmental activities. Many developed countries have gone ahead in effectively utilizing these sources both for power generation as well as for direct applications while in many developing countries this energy resource has not been utilized to the extent it should have been due to several problems.

Table 1. Actually known regional geothermal energy potentials (based on advanced technology potential data from Gawell et al. 1999).

	Known geothermal potential TWh/year	Percentage of world geothermal potential %	Current total electricity use TWh/year	Geothermal potential of current electricity use %
North America	200	18.4	4333	4.6
Central and South America	224	20.6	623	36.0
Central, South America including Caribbean	354	32.5	669	52.9
Europe	97	8.9	4155	2.3
Asia and Pacific	337	30.9	3304	10.0
Africa	101	9.3	357	28.0
World	1089	100.0	13142	8.3

Geothermal resources can be divided in two groups: (1) high-temperature resources with temperature greater than 150°C, which are suitable for electricity production using conventional techniques, and (2) low-temperature resources with temperature less than 100°C, which can be used for direct applications or if their temperature is over 100°C for electricity generation using the binary fluid technique. Most of the high-temperature geothermal resources are related to young volcanic regions, whereas low-temperature geothermal resources are widely distributed.

The potential of geothermal energy resources is vast. Its use for various purposes depends on several factor such as the geological setting, location of the province, resources temperature, etc. In most countries, the geothermal potential is not well known, and only estimations are available. Different estimations were made in different countries. Since they are based on different criteria e.g. in respect to use of different applied technologies and hence required temperatures, they cannot be compared and hence calls for a future standardization of estimating criteria. A worldwide country-by-country study of geothermal potentials was published in 1999 by the Geothermal Energy Association (GEA) in Washington D.C. (Gawell et al. 1999). The data are the resource, as they are known today. Data for the different world regions are given in Table 1.

Another approach to determine the useful regional accessible geothermal potentials was made by Bijörnsson et al. (1998). Using the distribution of active volcanoes, they proposed for the high temperature resources a potential of 12,000 TWh/year. The low temperature geothermal resources were determined using a modified approach based on the studies of EPRI (1978), resulting in 176,000 TWh for direct use.

A new study of Stefansson (1998) estimated both, identified and not yet identified geothermal resources (Table 2). The use of binary fluid technology lowers the minimum resource temperatures suitable for electricity generation from about 150°C to about 100°C. This will double the energy available for electricity generation as seen in Table 2. This study is based on the distribution of active volcanoes to determine the high temperature resources. It uses an empirical relation between the frequency of high- to low temperature resources to determine the low temperature resources. This author calculated that the ratio between "total" and "identified" resources is about 5 to 10. This signifies that the Geothermal Energy Association (GEA) values are a lower estimation and that in reality the geothermal reserves are – depending on the region – in average 5 to 10 times higher than given by GEA. Since these estimations are based on statistical considerations, they cannot be used for an individual country, but only for regions.

The studies of Gawell and Stefanson agree in general in respect to the regional distribution of the geothermal resources for electricity production. Most of the resources are found in Asia and Pacific (Gawell 31%, Stefanson 36%) and in Latin America (Gawell 33%, Stefanson 25%). Africa counts of about 10% of the world geothermal resources and values for Europe vary from

Table 2. Estimation of total geothermal resources by region (based on data from Stefanson 1998).

Region	High-temperature resources suitable for electricity production				Low-temperature resources suitable for direct use TWh/year[1]
	Conventional generation technology		Conventional and binary generation technology		
	TWh/year	%[1]	TWh/year	%[1]	
North America	1330	11.9	2700	12.1	>33
Latin America	2800	25.0	5600	25.0	>67
Europe	1830	16.3	3700	16.5	>103
Asia and Pacific	4020	35.9	8000	35.7	>119
Africa	1220	10.9	2400	10.7	>67
World	11,200	100.0	22,400	100.0	>389

[1] For purpose of comparison, values are given in TWh/year instead of EJ/year (1 TWh = 3.6 EJ; E = Exa).

Table 3. Comparison of regional geothermal potentials estimated by different authors.

Estimation	Electricity generation TWh/year	Direct use TWh/year
Björnsen et al. 1998	12,000	167,000
Stefanson 1998	11,200 ± 1300	389–1500
Gawell et al. 1999	1089	–

Table 4. Use of geothermal energy by region in 2000.

Region	Electricity generation				Direct-use			
	Installed capacity		Total production		Installed capacity		Total production	
	MW	%	GWh/year	%	MW	%	GWh	%
Africa	53.5	0.7	396.5	0.8	121	0.7	491.7	1.0
Americas	3389.9	42.5	23341	47.4	5954.5	34.7	7265.9	14.1
Central	406.9		2190.9		4.2			
North[1]	2983.0		21151.0		5907.8			
South	0		0			42.5		
Asia and Pacific	3542.4	44.3	19779.4	40.1	5468.8	31.8	24580.7	47.8
Europe	998.2	12.5	5744.6	11.7	5630.4	32.8	19089.5	37.1
World	7974.1	100.0	49261.4	100.0	17174.7	100.0	51427.8	100.0

Source: Lund (2000); [1] includes Mexico.

9% (Gawell) to 16% (Stefanson). North America, which includes Mexico, accounts for 12 (Stefanson) to 18% (Gawell). In Table 3, estimates of the different authors of the regional available geothermal potentials suitable for electricity generation and for direct use are compared.

Because in the next decades in many developing countries, which actually depend on the availability and the costs and uncertainties of fossil fuels, and because the energy demand will grow exponentially, alternative and more sustainable energy resources must be considered. One alternative is the use of high-enthalpy geothermal resources, which are mostly located in young volcanic regions, which are found in many developing countries. Up till now, only very few of these resources are exploited (Table 4) or considered to be exploited in the next decades.

2 ACTUAL AND POTENTIAL USE FOR ELECTRICITY PRODUCTION

The potential use of geothermal energy for power production shall be considered under two different aspects: (1) its importance for countries which currently use predominantly fossil fuels for electricity generation: the possibility to replace environment contaminating fossil fuels, which are in the best case available locally or in the worst case must be completely imported by the respective country, (2) its importance for countries, which use actually predominantly hydroelectric power: the possibility to change the energy mix towards more geothermal energy and hence to decrease their over-dependence on hydropower, whose availability is strongly influenced by climate events and which is correspondingly related to power shortages and blackouts.

The Figures 1 to 3 show the developing countries of the world, their percentage of power generation by source, and the percentage of total national electricity production, which could theoretically geothermally generated. The actual percentage of geothermally produced power is also projected. These figures show, that world-wide 39 countries, mostly from Latin America, the Caribbean, Eastern Africa and the Pacific region can be theoretically exclusively geothermally powered, from the countries which are actually predominantly fossil fuel powered, for numerous small islands, which must mostly import completely the fossil fuels, the geothermal energy option is especially attractive. Thus, in the Pacific the Comoros Islands, Tonga, Vanuatu and in the Caribbean, the islands Nevis, St. Kitts, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent can be completely geothermally powered. From these islands, only Guadeloupe actually uses geothermally generated electricity, which amounts 2% of its total electricity production.

Within Latin America, high-temperature fields are related to the volcanism of the Andean chain in South America, their prolongation in Central America, and on several islands of the Caribbean Sea (Fig. 1). Even though high-temperature geothermal resources are equally available in South America (advanced technology potential: 14,660 MW, Gawell et al. 1999) and in Central America (advanced technology potential: 19,720 MW, Gawell et al. 1999), they are unused in South America, where the installed capacity is 0 MW whereas in 2002, the installed capacity in Central America and in Mexico amount 423 and 853 MW respectively. Since in most South American countries, no future use of geothermal energy in national energy planning is included, the future outlook seems to aggravate this relation. Looking at the current energy mix being used in South American countries and their respective available geothermal potentials, it can be recognised that Colombia, Ecuador, Peru, and Bolivia, can substitute completely their fossil fuels, whereas Chile can reduce its fossil fuel share from 60% to 15% and Argentina actually from about 60% to 40%.

Compared to Latin America (including the Caribbean and Mexico), and the Pacific region, Africa is the region with the lowest geothermal potential. Since Africa is also the region with the lowest power generation and future demand growth, this disadvantage is not only compensated, but even over-compensated. The high-temperature geothermal resources of Africa are restricted to the East-African volcanic belt and rift valleys. It comprises the countries Sudan, Ethiopia, Djibouti, Somalia, Kenya, Uganda, Rwanda, Burundi, Democratic Republic of Congo, Tanzania, Malawi, Mozambique and Madagascar and Yemen from the Arabian half island. All these countries could be completely geothermally powered. Zambia, which at present practically depends completely on hydropower, could decrease this over reliance on this source by at least 20%, whereas Zimbabwe could decrease its fossil fuel share by at least 10%. In Africa, Kenya is the only country, which generates electricity from geothermal energy, amounting to 8.7% of its national electricity generation.

In Asia and in the Pacific islands, the largest geothermal high-temperature geothermal resources are found. Indonesia (resources: 15,630 MW, Gawell et al. 1999) and the Philippines (resources: 8620 MW, Gawell et al. 1999) are the two countries which implemented the promotion of geothermal energy in national energy policies, resulting in an actual share of 5.1 and

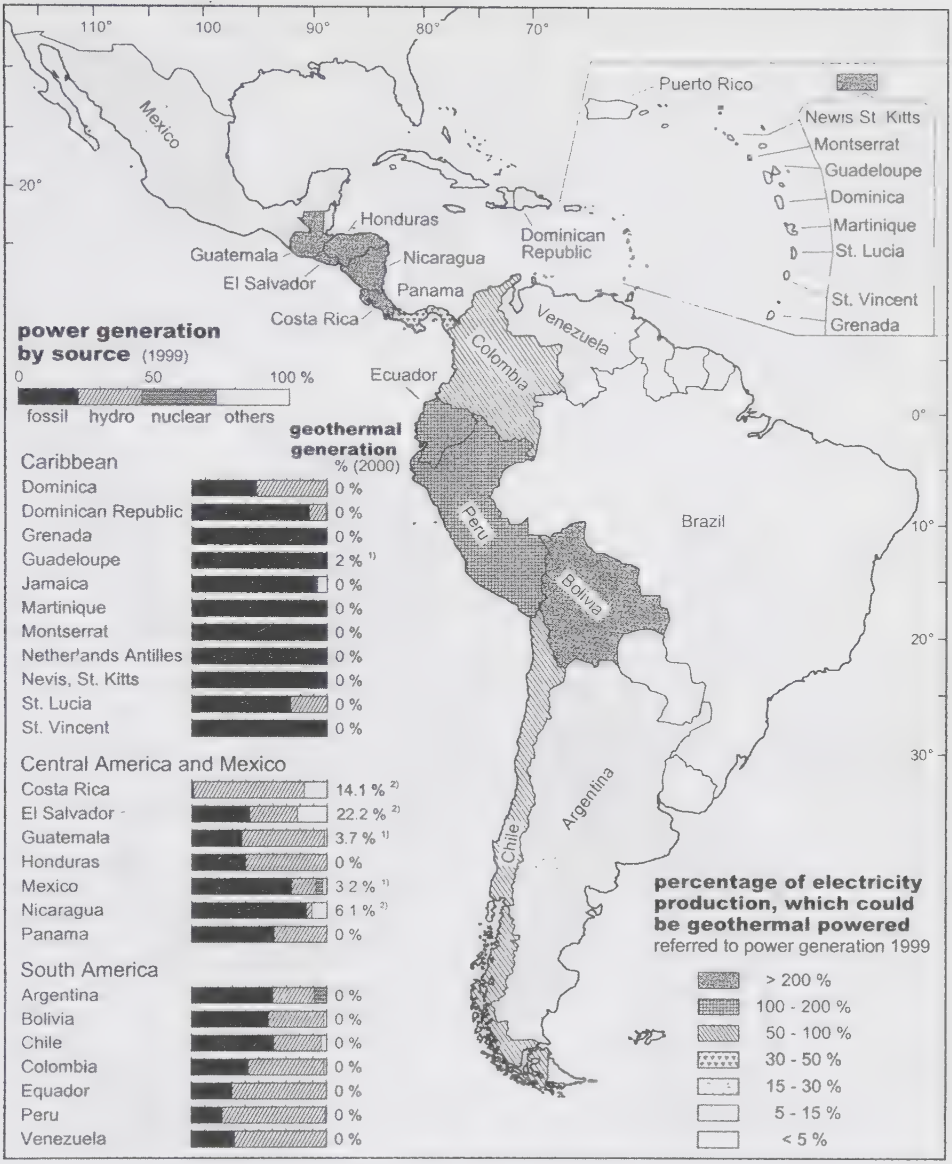

Figure 1. Potentials of geothermal energy in the developing countries of the American region. Power generation by source from Central Intelligence Agency (2001); geothermal potentials from Gawell et al. (1999); [1] Huttrer (2000); [2] data from Bundschuh et al. (2002).

21.5% respectively of geothermal produced power referred to total national power generation. Both countries could be completely geothermal powered and meet their future demand as well. Papua New Guinea could be completely geothermal powered, and could improve its actual mix of 55% fossil fuels and 45% hydropower by eliminating the fossil fuel. In countries like India though the estimated potential is very high (~10,000 MW; Chandrasekharam, 2000b), this source is yet to be utilized. Even that the potential of low temperature geothermal resources is higher compared to the high-temperature resources, the direct use is much less than for electricity production.

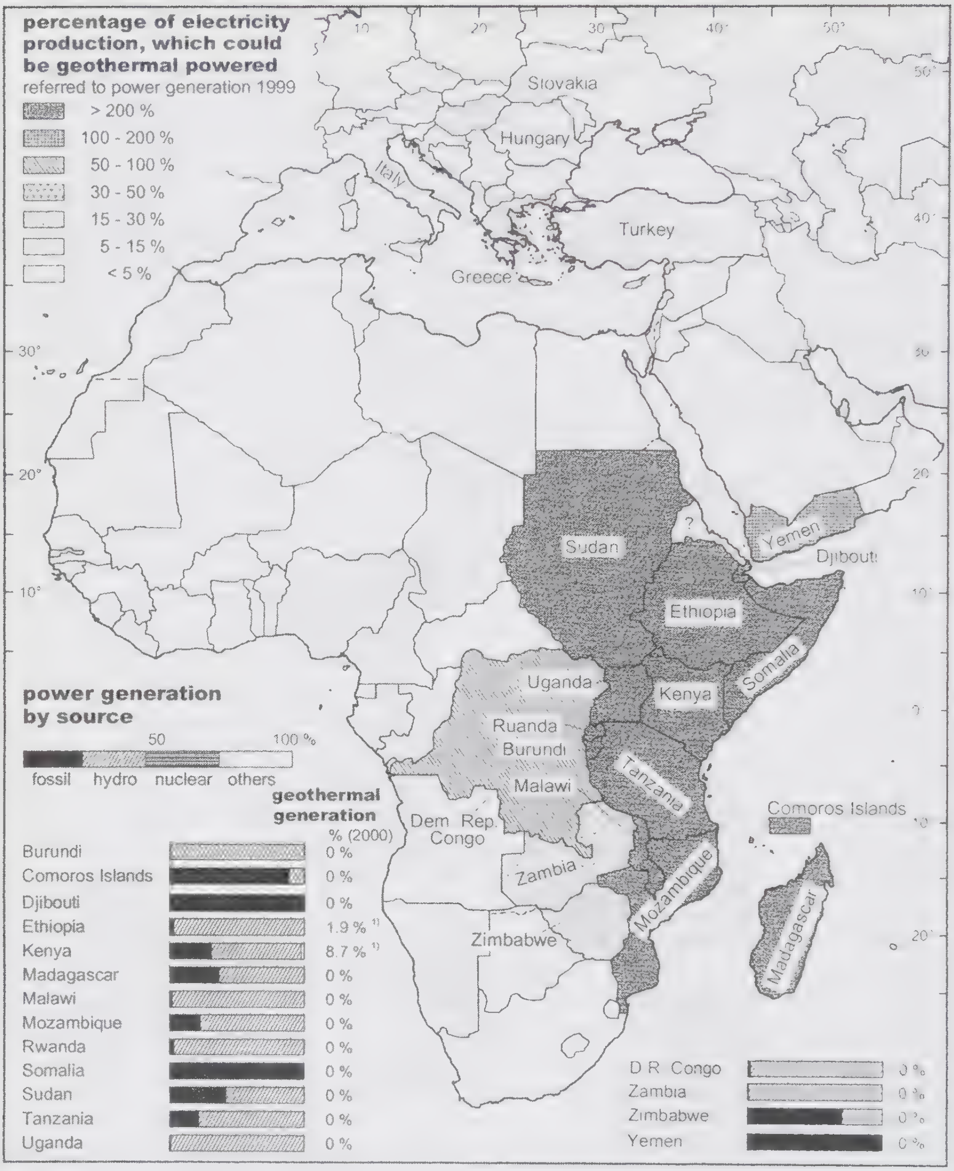

Figure 2. Potentials of geothermal energy in the developing countries of the African region. Power generation by source from Central Intelligence Agency (2001); geothermal potentials from Gawell et al. (1999); [1] Huttrer (2000).

In the case of countries like India, the problems related to the development of geothermal energy resources are of different kind. As mentioned above the country has geothermal energy resources potential of about 10,000 MW, which is yet to be put to use. The problems in this Asian country are of different kind. The estimated power shortage in India in the next decade will be well above 43,000 MW (Chandrasekharam, 2000a). Though India boasts of generating eco-friendly energy sources during the present millennium, the present power generated through non-conventional sources is far less than the installed capacity of the power plants. Thus the total installed capacity from renewable stands at 1313 MW, which is 2.6% of the total potential.

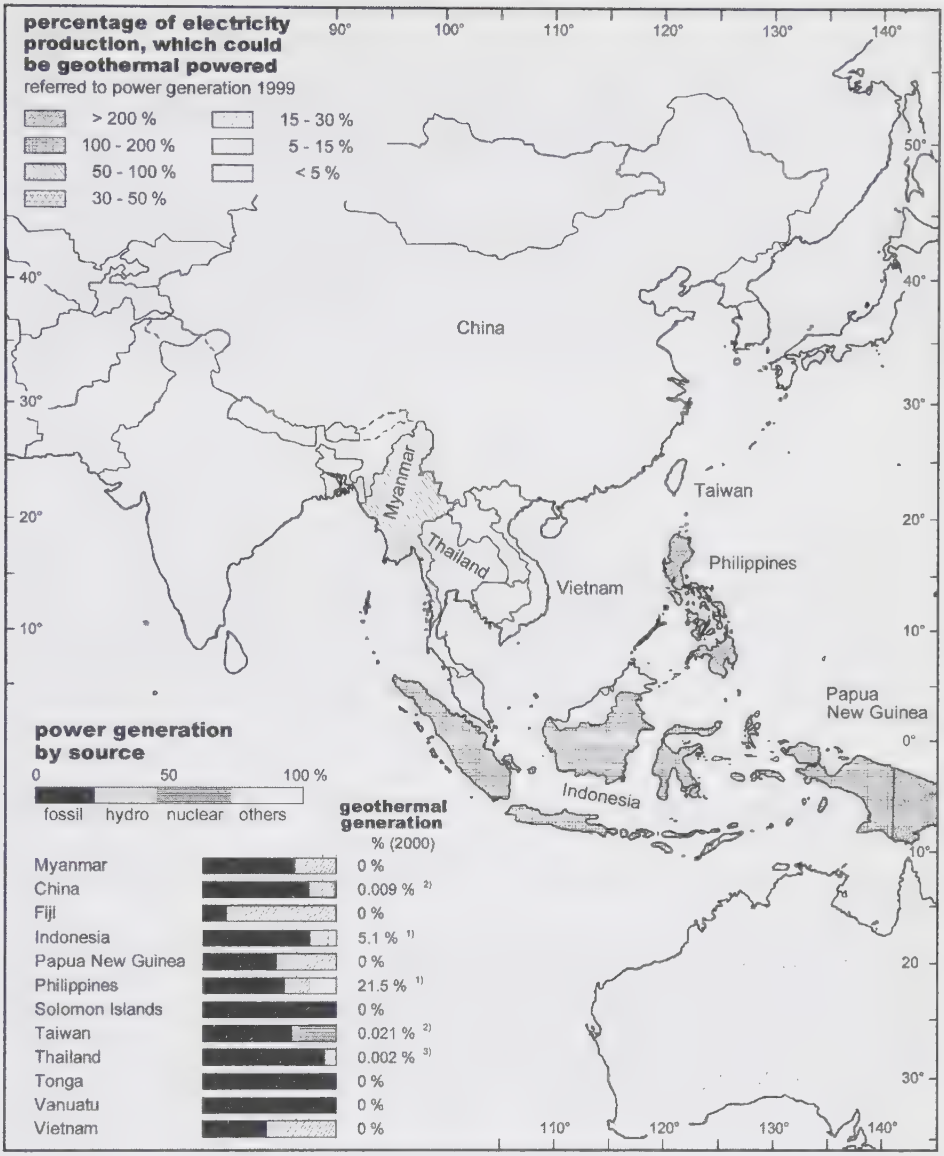

Figure 3. Potential of geothermal energy in the developing countries of the Asian and Pacific region. Power generation by source data is from Central Intelligence Agency (2001). With exception of China and Taiwan, the potential geothermal use is based on data from Gawell et al. (1999); potential of China and Taiwan from Battocletti & Li Zheng (2000). Actual geothermal use based on, [1] data from Huttrer (2000), [2] values calculated from geothermal power generation data after Battocletti (2000) and the total power generation data from Central Intelligence Agency (2001), [3] calculated from the geothermal generation data of Huttrer (2000) and the total power production from Central Intelligence Agency (2001).

Though capital subsidy and financial incentives are given by the government of India, non-conventional energy sources are not able to bridge the gap between demand and supply of power. Neither the government bodies nor the independent power producers (IPPs) are aware of the vast available geothermal energy resource in the country. If such is the geothermal energy potential, then why Indian is not keen in developing this source in bridging supply-demand power gap?

The answer lies in the 192 billion tonnes of recoverable coal reserves, which is encouraging coal based power projects and hampering the healthy growth of non-conventional energy programs. At present nearly 70% of India's power production is coal. In this decade emission of CO_2, SO_2 and NO_2 by India will exceed 1500 million tonnes, 1900 kilo tones and 1200 kilo tonnes respectively. This means that CO_2 emissions will be 775 million metric tones per year as compared to 1000 million metric tones per year produced in the entire European Union (World Bank Report 1999)! In India the present day cost of one unit (kWh) of power is less than ~US$ 0.02 in the case of coal based power while liquid fuel based power costs ~US$ 0.04 and hydropower costs ~US$ 0.03 (Chandrasekharam, 2001). But the expenditure spent to meet the consequences (like disposal of fly ash; treating the coal with high ash content etc) is high which automatically increases 0.02 US$ a unit several cents. Now a time has come to re-look into those alternate energy sources, which were not viable a decade ago due to, non-availabilities of advanced technical know how.

3 GEOTHERMAL POTENTIAL FOR DIRECT USE

Since low-temperature geothermal resources which are suitable for direct use purposes cover much more widespread areas which are not restricted as most of the high-temperature resources to active volcanic zones, their potential is much higher than those of high-temperature resources. Also the development time of direct use projects is much shorter and requires less capital than electricity projects. In contrast to these advantages of direct use opportunities, in the developing countries these are hardly found to be implemented with exception for bathing and tourist purposes.

4 FUTURE POSSIBILITIES AND NEEDS

The possibility for future use of geothermal energy in developing countries must be seen under different aspects:

- Costs for electricity generation from geothermal resources will become cheaper.
- In the next decades improved binary fluid technology will be available to tap low temperature resources (~100°C), which will double the previously determined geothermal resources for electricity generation. The low temperature resources will also be available for direct use.
- The exploitation of hot dry rock (HDR) resources will become commercial and cheaper.

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Barriers, risks and new regulatory schemes for the development of geothermal resources

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ABSTRACT: The development of geothermal resources has to come up against a variety of different barriers; these are basically regulatory, economic and financial. The true potential geothermal energy can be successfully harnessed to satisfy the growing world energy demand only if Governments undertake the preparation of institutional and regulatory frameworks necessary for attracting large inflows of private financing. Public intervention is also necessary in the form of economic incentives to private investors; such incentives need not be any more or less favourable than those granted for the development of oil or mineral resources. In order to overcome existing financial barriers and promote in a concrete way the development of a country's geothermal industry, the focus must be on seeking a balance in the distribution of those risks between the Government and private investors; the style of development of geothermal energy in some Asian countries, can be considered as an interesting example.

1 THE BARRIERS

The development of geothermal resources has to come up – everywhere in the world – against a variety of different barriers; these are basically economic, regulatory and financial.

1.1 *Economic barriers*

Renewable energy projects are usually less cost-efficient than major fossil fuel-based energy projects, particularly when the latter are protected – as is often the case – by "hidden subsidies" in the shape of non-internalisation of environmental costs.

Normally, capital costs for renewable energy projects vary between US$900 and US$2000 per kilowatt installed (even higher for unintegrated photovoltaic projects, such as domestic solar energy systems). On the other hand, capital costs for conventional projects range between US$ 300 and US$900 per kW installed, depending on the technology applied and installed capacity.

For renewable energy projects, the average rate per kWh delivered ranges from 4 to 14 US$ cents (reaching 28 US$ cents for photovoltaic projects), while for conventional projects it is lower, varying between 2 and 7 US$ cents (depending on the type of technology and power level). Nevertheless, it has to be kept in mind that the price for renewables in the future (5 to 10 years) will show a solid, decreasing trend.

The cost of generating electricity from geothermal sources varies significantly (from US$30 to US$90 mills/kWh); in some cases, it is fairly competitive in relation to conventional sources; the variability (peculiarity of this source) is related to the productivity and useful life of the wells, which constitutes the fundamental parameter for assessing the relative profitability of the operation.

While the economic viability of geothermal energy has been established internationally – witness the 160% increase in global private investment in this sector in the 1980s compared with the previous decade – it is a fact that this form of energy is economic and competitive when used close, or relatively close, to the generating plant (geographic dependency).

On the other hand, the relative prices of the other generating sources have also affected the development of geothermal energy, the most important being the reduction in oil prices. If these prices continue to decline and even if they are maintained at their current levels, the feasibility of geothermal projects will be seriously jeopardized.

However, it is important to point out that most conventional sources are subject to potential price instability, since thermoelectric plant concessions – awarded on the basis of generating rates often contain readjustment clauses, based on fluctuations in fuel prices. In 2001, oil prices hit a record 25-year low (US$12 per barrel) and most analysts agree that the medium and long-term trend will undoubtedly be for an increase in prices especially with the increasing instability in the Middle East.

In any case, with oil prices at the current (low) level, under a reductionist market model and in absence of any form of incentives, it is evident that thermal energy generation will be biased in favour of oil, despite its detrimental effect on the environment.

Public intervention is therefore necessary at some level, whether it be direct participation in the exploration, or more indirect intervention in the form of incentives to private investors. Such incentives need not be any more or less favourable than those granted for the development of oil or mineral resources.

Consideration should be given to the use of fiscal instruments for promoting sustainable development of geothermal resources. Such instruments may include exemption from and/or refund of taxes on exploration and development, which could be a type of "drawback" justifiable for environmental reasons.

The idea is to "reward" the least polluting sources, in the same way as one promotes investment in other activities; in this regard, Germany has had highly positive results with wind energy. Another alternative, although a more disputable one owing to its impact on costs would be to "penalize" the forms of energy that produce the most noxious effects (carbon dioxide or other emissions), as has been applied on a trial basis in New Zealand and Norway.

The issue is of course a debatable one. Nevertheless, the fact remains that geothermal energy is one of the cleanest sources of energy available on the planet. It is not a question of taxing conventional sources more heavily but rather of offering tax relief for new and renewable sources.

1.2 *Regulatory barriers*

Another significant obstacle to the development of geothermal resources is the absence of a legal framework – in many cases – it has actually been demonstrated that a clear and modern regulatory framework is indispensable for the development of such resources.

Despite the vast high- and low-enthalpy geothermal resources, in Latin America – for example – there is no efficient legislation that promotes in a positive and visible way the development of geothermal energy: some States adopt a dog-in-the-manger attitude or lack a proper regulatory framework. The National Congresses in Peru and Chile, for example, have recently passed legislation on geothermal energy, but do not offer the kind of incentives that private operators need in order to invest. In Argentina, a preliminary bill has been drafted and is awaiting a ruling by the competent parliamentary committees.

Parliamentarians and regulators alike are now focusing on two central issues: (a) on what basis should concessions be granted for use of resources and (b) what type of incentives should be offered to private investors. A wider analysis of the "regulatory issue" is presented in chapter 2.

1.3 *Financial obstacles*

1.3.1 *Types of risks*

Financiers, whether investors or lenders, are usually concerned about the risks involved in a project. There are two types of risks:

1. Project risks (including sponsor, contractual and fuel supply risks), and
2. Market-related risks (including political risk, macroeconomic risk).

Both investors and lenders evaluate the structure of a project and its implications for the project's long-term security and feasibility, although each party interprets and assesses risk and the outcomes in a different way. Projects and markets vary so widely that it is impossible to establish definitive guidelines relating to the financing of renewable energy projects. Nevertheless, there is now sufficient experience in this field and companies implementing projects can refer to, and emulate, case studies on satisfactory projects.

These studies have made it possible to establish a fundamental distinction between the projects, which fail to secure financing owing to structural deficiencies and those that have been affected by a significant market failure. If a project is structurally deficient, it will not succeed, however favourable the financial terms awarded. On the other hand, if the project is foundering because of market failures, financial support, as well as other facilities and policies, can be provided to help reverse the situation.

There are a series of proven market failures, which pose serious problems for financing renewable energy projects. Nevertheless, the operating companies, power consumers and the financial community are finding solutions to many of these problems, so that prospects for financing renewable energy projects are improving.

The basic concepts of risks and limited recourse financing have been elucidated on many occasions. The leverage ratio for renewable energy projects financed with the most success is between 55% and 70%, with proportionate requirements in terms of equity.

Generally speaking, the leverage ratio is not as high as in conventional energy projects, but this ratio has been rising and lenders are increasingly willing to consider such projects, providing that they are properly structured. In the Río Volcán hydroelectric project in Costa Rica, for example, the leverage ratio was approximately 70%. In general, the lower the leverage ratio, the lower the risk perception.

Investors also have to measure political, financial, market, project and legal risks. Political risks may include political instability such as nationalizations, revolutions or wars, changes in currency convertibility and non-fulfilment of contracts signed with the State.

In many developing countries, financial risks associated with the availability of foreign currency have practically disappeared, since most currencies are convertible and foreign exchange can be purchased readily.

Market risks include changes in legislation governing foreign investments, changes in pricing policies and ownership issues.

The main project risks have to do with the solvency of the primary client, which is usually a State-owned enterprise, timeliness of payments and other credit issues, which may affect the sponsor. Other project risks include non-fulfilment of contracts, fuel supply problems, agreements with the primary purchaser and competition in the areas of management, operation and maintenance.

Legal risks relate to the legislative and regulatory frameworks, procedures for the settlement of disputes and accountability for environmental damage.

In addition to the more general risk criteria described above, firms undertaking projects must also take into account various financial issues inherent in renewable energy sources and which can affect their ability to raise financing through long-term debt or equity investments. Certainly, the surest way of securing the necessary financing is to structure the project in accordance with certain generally accepted guidelines, but this is not always possible.

The loans granted to Governments in recent decades by multilateral development banks (World Bank, Inter-American Development Bank, among others) for large-scale conventional energy projects have been long-term, 20 to 25 year concessionary loans with repayment schedules and with four to six years of grace, depending on the type and scope of the project. In the 1990s, these terms were changed and repayment schedules for private conventional energy projects reduced to 12 to 15 years. Although this type of financing has been applied to independent conventional energy projects, renewable energy projects, barring a few exceptions, have not received this type of treatment.

The following are some of the arguments usually put forward to justify this state of affairs: (1) The significant capital costs inherent in renewable energy projects; (2) the scope of projects in relation to their transaction costs; (3) the course of development and experience of the firms developing the projects; (4) the lack of long-term contracts; (5) the lack of guarantees and (6) the lack of long-term loans in local currency. In short, the fundamental obstacle to the development of renewable projects (and especially geothermal projects) is the perception of the risks associated with this type of undertaking.

1.3.2 *Risks associated with geothermal projects*

The two most important risks associated with private investment in geothermal projects are, on the one hand, political risks and, on the other, those relating to exploration and field development activities. Other risks – financial, construction and operational – are usual in any capital investment project and will not be dealt with in this case.

The main political risks associated with geothermal projects, are as follows:

- specific regulatory aspects for the sector: concession regime, power purchase contracts, rates, permits and licences, among others;
- general legal framework: conflict resolution mechanisms, business practices, expropriation, civil conflicts, among others;
- economic regulations: exchange-rate regime, convertibility and repatriation of profits, tax regulations, and so forth.

The risks associated with geothermal field exploration and development is determined by the degree of reliability required for establishing field characteristics with a view to evaluating the financial feasibility of investments. The evaluation of the geothermal characteristics of a field is conducted in a series of successive stages, which implies costs associated with exploration and quantification of the resource.

The final objective is to obtain appropriate and sufficient information to make it possible to define the design characteristics for a power-generating plant: useful life, generating capacity, level of reliability of the availability of the resource (in the short and medium term), sustainability of operational performance.

1.3.3 *Possible policies for risk distribution*

In practice, there are three policy alternatives for overcoming the basic obstacle of risk perception and, consequently, for attracting private-sector investors to the development of geothermal projects, depending on the phase of the lead-time of the project when they start to participate.

These phases range from identification of a field, exploration and quantification of the resource to development of a field and construction and operation of a power-generating plant. The policies are defined by the risk distribution between the public sector and private investors and by the relatively long periods involved (six to eight years from the initial exploration to the commissioning of a generating plant).

A first policy alternative arises when an investor discovers or takes an interest in a geothermal field and presents an offer to the competent authorities for the execution of all the phases: exploration, quantification of the resource, field development and design, construction and operation of a power-generating plant. In this case, the Government has two options: (a) it may accept the offer and sign a direct agreement in principle for the sale of any electricity produced; or (b) it may consider the offer only after inviting other tenders so as to have a basis for comparison in order to stimulate competitiveness and, at the same time, to ensure that the concession award process is conducted in a transparent manner.

It should be noted that with this alternative, the investor assumes all the technical risks associated with field exploration and development, investing risk capital until the commercial feasibility of the field for electricity generation has been established. The investor hopes, thereby, to obtain a relatively high rate of return, since he assumes all the technical risks associated with exploration, sustainability of the field throughout the economic life of the plant and extracting sufficient steam for power generation. Clearly, this alternative implies a higher rate per kWh, owing to the high level of investor risks.

Under the second alternative, the Government identifies a field and undertakes exploration work, including drilling of wells. The objective is to obtain sufficient reliable information for determining the extent and quality of the resource and whether it can be developed on a commercial basis. Once this information has been obtained, the Government is a better position to attract private investors and secure more attractive rates.

Under this arrangement, the Government assumes the risk inherent in the exploration of subsoil natural resources and defrays all exploration costs. Once this information is available, the preferred approach is to launch an international invitation to tender for field development and construction of an electricity generating plant. Once reliable information is available on the exploration, private investors are in a position to reduce their risks, limiting them to the typical risks relating to the development of the field, the quality and sustainability of steam extraction and all those inherent in the financing and operation of a generating plant.

More moderate rates of return and, therefore, lower prices per kWh can thus be expected than under the previous alternative. On the other hand, the Government has the option of inserting, in the conditions for the bidding, a formula for recouping (either in cash or in kind) all or part of the expenses incurred in the exploration phase.

It should be noted that in the two earlier cases, the private investor makes the commitment to guarantee (in the energy purchasing contract) the availability of a certain generating capacity and a minimum level of energy supply. Thus, the investor assumes the full risk relating to the availability of a volume of steam of suitable quality. Usually, the power purchase contracts establish penalties for non-compliance with commitments in terms of levels of capacity and power generated.

With respect to the third policy alternative, the field operation (steam production) and the generation of electricity are assumed by different entities or companies. The Government carries out the exploration and assumes financial responsibility for the development and field operation. Separate and apart from this, the Government launches an international invitation to tender for the construction and operation of the power generating plant by private operators. In this case, the Government assumes all the risks for exploration, development and field operation, while the private investor assumes the risks of constructing and operating the generating plant, which are not very different from those of a fossil-fired power plant. This arrangement has been used in Costa Rica and the Philippines.

Governments may also hand over operation of the field to a private operator, under some concession arrangement. In any event, the steam supply to the generating plant is the subject of a separate contract between the two operators. Under such an arrangement, the operator of the generating plant is usually exempted by the power purchase contract from the obligation to satisfy capacity and generating levels if there is any problem with steam supply. Under this alternative – in view of the reduced risk for investors – the price per kWh should be lower than for the previous alternatives.

In conclusion, in order to overcome existing barriers and promote in a concrete way the development of a country's geothermal industry, the focus must be on seeking a balance in the distribution of risks between the Government and private investors. Clearly, this depends on the availability of financial resources for undertaking investments and the levels of electricity rates, which are desirable or compatible with development of the sector. In this case, the second alternative presented above would seem to be the most suitable for achieving this objective.

2 THE NEED FOR REGULATORY FRAMEWORKS

The true potential of renewable forms of energy (particularly the geothermal) can be successfully harnessed to satisfy an increasing percentage of growing world energy demand only if Governments undertake the preparation of institutional and regulatory frameworks necessary for attracting large inflows of private financing.

Existing institutional frameworks and financial mechanisms are still insufficient – in terms of scale and characteristics – for the development of a high-potential private industry such as the renewable resources industry. The volume of business is still insufficient – notwithstanding the various build-operate-transfer (BOT) and build-own-operate (BOO) projects, the joint ventures established and soft loans provided – to warrant a reduction in the price of such technologies.

2.1 *Basic requirements for geothermal development*

It has been proven worldwide that one of the basic requirements for stimulating, strengthening and regulating development of a country's natural resources is a firm political will on the part of national decision-makers.

This axiom is perfectly valid in the case of geothermal resources; in countries where the development of geothermal resources has been viewed as a political commitment, the results have been positive. This was the case in Italy and the United States in the 1970s and – more recently – in the Philippines and Indonesia, which have had successful experiences in this regard. In all these countries, a clear long-term vision has been the basis for a rapid and – in most cases, sustainable – development of national geothermal resources.

A typical example of this political will is the application of an incentive-based approach and a series of strong, specific measures for the promotion of a certain national productive sector. Typically, these measures refer to institution building - creating the competent authorities necessary for structuring regulatory frameworks, promulgating legislation and regulations – and establishing fiscal measures for the sector, which will create the appropriate incentives for development of the resource.

2.1.1 *National authority*

International experience has demonstrated that the existence of a national geothermal authority is indispensable for regulating the exploration and use of the resource. Only a handful of countries in the world (and hardly any in Latin America) have a properly established authority for granting geothermal concessions and promoting development of this resource: and it is no chance occurrence that geothermal energy has been developed satisfactorily in those countries where such clarity in the structure of authority and regulation does exist.

A geothermal authority should be made up of trained staff in the different areas relating to the geothermal problem (legal, technical and administrative) and should fulfil the following basic functions:

- exercise sovereignty over geothermal resources;
- administer the official register of national resources;
- promote prospecting and research;
- organize and execute processes for the award of concessions, invite tenders;
- assess concession-holders and grant titles/concessions/licences;
- supervise and control geothermal activities;
- settle conflicts.

It is fundamental to ensure that there is a single, national geothermal body ("one-stop-shop") for ensuring a more transparent and smoother handling of matters relating to the promotion and control of the sector.

The "Tufinõ – Chiles – Cerro Negro" binational project (Ecuador, Colombia) is a case study on the key-role of National Authority for the development of a geothermal project. The geothermal area of Tufino-Chiles-Cerro Negro is located just along the border between Ecuador and Colombia, near the cities of Tulcan and Ipiales. Feasibility studies carried out in late '80, confirmed the presence of a very promising geothermal field, which would most probably allow the installations of – at least – a 30 MW condensation plant. Considering its very peculiar geographical location (50% in Colombia and 50% in Ecuador), in 1993 the two governments subscribed and "agreement for geothermal-based electric generation" in the binational area. The agreement was a very general and political document, lacking of relevant technical and economical commitment from both side and without a clear definition of "who was in charge of developing the business" (i.e. a project-specific geothermal authority). After 6 years of negotiations, in October 1999 the governments signed a new agreement (Convenio) for the development of the field, mostly reflecting diplomatic preoccupations and once again in absence of project commitments and one, single project authority. The lack of clear rules of the game and of a specific institution in charge of regulating and promoting the project ("one-stop-shop" concept) have been keeping away – until now – any solid involvement of geothermal private developers or financing institutions.

2.1.2 *Regulatory framework*

A well-defined and modern regulatory framework is a prerequisite for the development of geothermal resources. In Latin America, for example, one of the most serious obstacles to the development of geothermal resources is the absence of appropriate legal frameworks, since no ad-hoc laws exist that are currently operative and directed specifically to development of geothermal energy. The only geothermal resource organization acts are those of Peru and Chile, but they are scarcely operative owing to the absence of a technical regulation, which marks a difference with respect to tangible incentives for private investment.

Generally speaking, the development of geothermal resources should be governed by a framework law which caters for all possible uses (high and low enthalpy) and, in line with national developments, the specific rules necessary for each particular use should be left to the regulatory framework. This should also be the approach for environmental impact problems.

Geothermal energy should be declared by law as being in the public interest; this means that exploration and development take precedence over other activities in the areas that are granted for these purposes, with due compensation for any rights infringed.

The regulatory frameworks for the development of geothermal energy should encompass all uses, with the exception of thermal spas for tourism or curative purposes. Geothermal resources (high and low enthalpy) offer a wide diversity of uses so that it would not be appropriate to create regulatory rigidities. It is preferable to have general mechanisms and to rely on regulations to govern the details of specific uses.

Thus, exploration and development of geothermal resources (from 20°C) should be regulated for activities such as:

- Production of electrical power
- Heating of buildings, soil and greenhouses
- Fish farming
- Agro-industry
- Refrigeration
- Drying of organic and inorganic material
- Evaporation and distillation
- Industrial production of chemical compounds
- Fermentation
- Other industrial, commercial or residential applications.

The "Termas de Chillan" project (Chile) is a case study on the key-role of regulatory frameworks for the development of geothermal projects. The geothermal area of Termas de Chillan is located in the central-southern part of Chile, in the country's 7th Region. Feasibility studies carried out during the 90's, suggest the existence of a very promising geothermal field; the sole exploratory well drilled in the area, confirms this assessment (wet steam at 200°C has been encountered at a depth of only 188 m). In addition to that, the "market" for both electricity and direct uses would be already guaranteed to the potential project, since in the same location is active a nation-famous ski and spa resort, which would be able to buy the kWh produced by the wells and use hot water for district heating and spa operation. Despite this very promising conditions, the project has still enormous problems in getting started, mostly because regulatory issues. As a matter fact, both ENAP (National Petroleum Company, public entity) and Somontur (the local resort operator, private entity) presented a petition for being granted a "geothermal exploration concession" in January 2001; due to the absence of a clear technical regulatory framework, to the existence of doubts regarding the interpretations of the Law and to the lack of well-prepared governmental personnel in charge of duly managing the process, the concession has not been granted yet, nor it seem it will be done in the near future. In addition to the visible damage done to the incipient and promising Chillan project, the delays and the inefficiencies of the geothermal regulatory framework in Chile is also harming the possibility of attracting private developers, thus inhibiting the creating a "national geothermal industry" and the preparation of technical and scientific personnel in the specific field.

2.1.3 *Sectoral incentives*

A central issue in development of geothermal resources is the creation of incentives to "reward" them for causing less pollution. The idea would be to establish mechanisms similar to those adopted by some countries for promoting investment in other renewable, low-environmental-impact sources. For example, the experience of Germany provides highly positive results with the promotion of wind energy.

Another alternative - although one that is more debatable, owing to its cost-impact – would be to "penalize" sources that have more damaging effects on the environment (carbon dioxide or other emissions), as recently applied on a trial basis in New Zealand and Norway. This type of measure is controversial because it impairs the situation of generating companies on competitive markets.

Nevertheless, it should be recalled that geothermal energy is one of the cleanest forms of energy on the planet. Far from seeking to tax conventional sources more heavily, the idea is to offer tax breaks to new and renewable sources.

In order to promote investment, the following incentives should be taken into consideration:

- Deduction as an expense, during the commercial operation, of all duly authorized items, which cannot be recovered: the right to recover all exploration costs – whether successful or not – and compensation among geothermal activities of carry-over losses.

- Deduction of income tax on services provided to the concession-holder duly evaluated by the competent authority by legal entities not domiciled in the country.
- Free importation and exemption from tariffs and non-tariff duties and from any other tax on the import of capital goods, equipment and inputs, duly evaluated by the competent authority during the term of the authorization.
- The right to re-export capital goods and equipment free of any tax.
- The royalties will always be a percentage of the income tax paid by geothermal operators. No taxation will be authorized apart from the economic performance results.
- Deduction of royalties, if any, from the income tax.
- Environmental drawback, since it is a new and renewable source of energy: deduction of all internal taxes – such as taxes on sales and on value added – paid during the activities of exploration and exploitation.
- Undistributed profits will be liable to taxation only when they apply to exploration and/or expansion of the development activities.
- Investments in public utility infrastructure (taxes on wealth, assets, etc.) will not be included in the tax base.
- Investments in public utility infrastructure can be offset against taxable income.
- Exemption from tax on repatriation of profits for foreign investors during the first five years of the commercial operation.

The "Sulphur Springs" project (Saint Lucia, Caribbean) is a case study on the key-role of sectoral incentives for the development of geothermal projects. The geothermal area of Sulphur Springs is located in the southern part of Saint Lucia's island. Feasibility studies carried out during 2 decades (1974–1994), confirmed the presence of a very promising geothermal field, which could probably allow the installations of – at least – a 15 MW condensation plant. The Ministry of Sustainable Development Science and Technology of Saint Lucia has been very active during the last years in the promotion of renewable, endogenous energies; efforts were mainly oriented at photovoltaic and wind applications, which got advantage of specific financial support (multilateral grants and loans form multilateral entities and governmental incentives). This has not been the case of the geothermal resources, which still have to compete – at the same level of the playing field – against conventional generation (mainly diesel and bunker). This, resulted in the lack of interest from private companies in developing the island's strategic resources: as a matter of fact, geothermal energy form Sulphur Spring could represent the 20% of the installed capacity of the country.

2.2 *A framework for stimulating the private sector*

Today, most Governments of countries with geothermal resources agree on the application of policies for promoting private-sector investment in the development of alternative sources of energy. It should be noted, however, that the risks absorbed by the private sector are usually properly reflected in rate levels so that the higher the risk in private investments, the higher the expectation of financial returns through higher rate levels.

For the reasons outlined above, policies on the development of geothermal resources should incorporate factors that mitigate all types of risk as perceived by the private sector. One such factor is the availability of regulatory frameworks that provide for the specific characteristics of geothermal development and which, in turn, may be perceived by the private sector as reliable and stable. Another problem faced by Governments is that of setting an appropriate level of investment in geothermal prospecting, which is sufficient for attracting private investment through competitive bidding.

On the other hand, Governments perceive the participation of multilateral agencies as yet another key-factor for placing greater trust in private investors.

Another risk-reducing option is the creation of a Guarantee Fund (or "Insurance"), which covers exploration risks: this scheme has been successfully applied in France for low-enthalpy projects. The purpose of this insurance mechanism is to help to lower the pre-investment risk in these projects with special reference to the coverage of exploration drilling, which is, as mentioned before, the activity of a geothermal project that entails the highest technical and financial risks.

A fund of this type applied to electricity generation projects could use instruments already applied by multilateral development banks and private investment finance institutions and would help to mitigate the risks associated with the subsequent phases of development of the resource; moreover, it would allow for a clearer definition and negotiation of the "real" cost per kWh (which would probably tend to decline).

2.3 *Environmental regulation: an opportunity for the future*

It is universally accepted that geothermal energy, if properly harnessed, can prove to be environmentally friendly and sustainable. The parameters for harmful emissions from the geothermal source compare very favourably with those for oil leaving a clear comparative advantage for this source in environmental terms. Indeed, a conventional combined cycle plant produces 12 times as much carbon dioxide and 1000 times as much nitrogen monoxide (NOx) as a geothermal plant.

On the other hand, geothermal energy should be considered among the most interesting sources for reducing the problem of global warming. In December 1997, 160 countries meeting in Kyoto reached an international agreement (Kyoto Protocol to the United Nations Framework Convention on Climate Change), the purpose of which was to limit gas emissions responsible for the "greenhouse effect" produced mainly by conventional energy sources (oil, carbon, etc.). Among the measures recommended in the protocol was the adoption of a system of environmental bonds whereby countries that reduce the level of emissions can compensate for other countries, which are above the proposed goals.

Another important mechanism proposed by the protocol is the Clean Development Mechanism (CDM), which enables industrialized countries to obtain loans through projects conducted in developing countries, which produce reductions in emissions of pollutants, which would not have occurred otherwise. Since the year 2000, the industrialized countries can receive loans for such projects in the form of certified emission reductions (CER).

Most of the developing countries are of the view that the clean development mechanism could create new financial conditions and establish important capital flows to them, with special reference to sustainable energy projects, such as geothermal projects.

For this reason, it is important to approach the problem of price and regulation of geothermal energy from an environmental point of view as well. The establishment of some of the above-mentioned mechanisms could become a decisive factor for attracting private investors and improving the competitive position of geothermal projects compared with other conventional sources. In particular, the recent fall in oil prices has meant that concessions for combined cycle projects have been granted on the basis of much lower rates than long-term marginal energy costs. Nevertheless, such rates do not include cost elements that impose penalties for emission levels and their effect on global warming.

3 EXPERIENCES FROM GEOTHERMAL OPERATION CONTRACTS IN ASIA

Electricity generation in South-East Asia has been growing at an annual rate of between 10% and 15%. Hence the need to develop capital-intensive generating facilities and the resulting expansion of transmission and distribution, all of which poses important financing problems to Governments. Consequently, there is a tendency to open up the generating sector to private productive development through the Build-Own-Operate (BOO) and Build-Operate and Transfer (BOT) schemes; under each of these, the national entity or local electricity corporation signs a contract with an Independent Power Producer (IPP) for the purchase of electricity at an agreed price and for a pre-established cooperation period.

Private geothermal projects have been gaining in importance in many areas of Asia. In particular, in the Philippines and Indonesia, two countries with a very high geothermal potential (4000 and 15,000 MW, respectively) an aggressive programme for the development of resources of this type, of comparable size and processes, was carried out in the 1990s, although using a different approach.

The Philippine model provides for conservation by the State of the field development (BOT system), while the Indonesian model allows the private developer to assume control and ownership of the field as well as of the plant (BOO system).

3.1 *Typology of private projects*

A private project is defined as an activity in which engineering, procurement and construction (EPC) as well as financing is left to a private developer. Project income must be sufficient to cover the interest and principal payments, as well as to guarantee investors a reasonable return on their investment.

As already stated, there are different approaches in relation to the private generation and the most common are the BOO and BOT systems. Under the BOO system, the plant is constructed, operated for the life span of the reservoir and then decommissioned. Under the BOT system, after construction and operation for a limited period of time by a private entity, the plant and field are transferred free of charge to the electricity authority or to a field operator.

3.1.1 *Invitations to tender*

The national electricity authority can either: (1) launch a formal invitation for international competitive bidding; or (2) hold direct negotiations with a private operator. There is a long history of competitive bidding in the United States and it has evolved to such a degree that operators now face severe competitive pressure.

In the Philippines, both schemes have been applied, although the tendency – supported by the World Bank and the Asian Development Bank – is towards competitive bidding because of the transparency it guarantees. Nevertheless, the procedures of bidding, evaluation, negotiation of conversion rates or terms of sales contracts are now being changed.

3.1.2 *Development models*

A crucially important question in the geothermal projects is whether the project includes the development of the field and the plant or only the plant. Under the first approach, the operator assumes the risk for exploration and field development and the rate is based on the full energy cost. In the second case, the operator is supplied with steam free of charge and the electricity rate is simply based on the conversion of steam into electricity.

For operators, the risk is different in the two cases, in particular because banks generally prefer not to get involved in financing the exploration, leaving it to the operator to cover exploration costs from his own funds.

The expansion of geothermal energy in the Philippines is due basically to the Government's decisive initiative, particularly at the disposal of the Philippines National Oil Company (PNOC) to absorb the risks of geothermal exploration. The approach consists in ensuring the long-term, sustainable development of the resource, optimising management of the reservoir and maintaining control, by contracting only the development of the plants. This is done on the basis of competitive bidding for a 10-year BOT-type contract.

In Indonesia, all risks for exploration and development are assumed by the private operator. The agreement with PERTAMINA (the national oil authority) is a Joint Operation Contract (JOC) and requires exploration and development, both of the field and of the plant; the electricity generated is sold to PLN (the national electricity corporation). From the government perspective, the JOC approach permits the simultaneous exploration of numerous geothermal fields in the country, using the experience and financing of private companies. In the case of the Philippines, operations are limited by the organizational capacity of PNOC.

3.2 *Recent BOT and BOO experiences in South-East Asia*

3.2.1 *Development in the Philippines*

The Philippines is the world's second largest producer of geothermally generated electricity. Today, total installed capacity exceeds 1900 MWe. Geothermal energy from six fields, in which there are 11 areas in production, accounts for more than 20% of the nation's energy supply.

Philippine authorities are committed to the development of the geothermal potential; new policies are being structured and steps taken to attract companies, which are in a position to develop the country's 4000 MW potential.

To date, geothermal electricity activity in the Philippines has been conducted basically by United States firms.

At Tongonan, the largest known Philippine field (more than 700 MWe installed), BOT legislation has encouraged a very significant expansion during the past five years. The company, Magma Power, is developing part of this important field through a 10-year, 231 MW, BOT project; it consists of three 22 MW turbines being operated in the Malitbog sector.

Under this project, PNOC finances and implements exploration, assumes all risks associated with development of the resource and makes the steam available to Magma Power, which finances, constructs and operates the plant. PNOC purchases the electricity on a "take-or pay" basis and sells it, in turn, to the national electricity corporation, NAPCOR. As an incentive, the Government has reduced the taxes for the first five years of the plant's operation by Magma Power, which receives payment on the basis of its generating capacity (capacity payment) and not on the energy actually produced (energy payment).

The payment which is effected in foreign currency (United States dollars) is based on a 10-year cooperation period and covers operating and maintenance costs, debt servicing and a return on investment. At the end of the period, ownership of the plant reverts without charge to PNOC.

California Energy has launched two other geothermal projects also at Tongonan. To finance the equity capital for the initiative, and in order to a have an available working capital, the firm sold $529 million worth of 10-year maturity, senior discount notes (rate: 10.3%). The notes were quoted at 75% and after a 2% discount raised US$390 million.

Of this amount, US$56 million was used to finance the in the company's equity participation in another development also in the Tongonan field (Mahiao project, 131 MWe); this is a 10-year, US$218 million BOT project. PNOC will hand over the land for the plant and steam cost-free, and California Energy will convert the steam into electricity.

An interesting aspect of this project is the participation of the Overseas Private Investment Corporation (OPIC) in underwriting the political risk for California Energy's equity capital during the construction phase of the project and the contribution by the Export Import Bank of the United States (EXIMBANK), of US$162 million in debt coverage for the ten years of the project.

3.2.2 *Development in Indonesia*

In 1995, Indonesia had 305 MWe of installed capacity. By the end of 2000, its capacity had expanded to 530 MWe, distributed over six fields, corresponding to more than 3% of total national capacity and 5% of the nation's energy.

The national oil company, PERTAMINA of Indonesia, has handed over to California Energy the right to develop two geothermal areas. In the first area, California Energy and the Indonesian company PT-HEA signed a joint agreement for development of the project; by a consortium under the name of DIENG Joint Venture. This consortium has plans to build, own and operate the project, which consists of four units of a total capacity of 240 MW, for a total budget of US$ 450 million. Dieng JV and PERTAMINA have negotiated with the electricity authority PLN a take-or pay contract for the sale of electricity. The first phase of the project provided for the installation of a 60 MWe plant.

A similar consortium has been formed by California Energy and the Indonesian company PT-ESA for a future project in the Patuha field, which is expected to have the same capacity (240 MW) and a similar budget (US$450 million).

However, the development of Indonesia's very considerable geothermal resources was brought to a sudden halt by the serious economic downturn in the late 1990s and the political upheaval that ensued. The power sales from geothermal plants and the feasibility of future projects have been adversely affected by this situation.

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Geothermal energy: Capacity building and technology dissemination

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ABSTRACT: The development of geothermal energy, which may provide a clean and long-term sustainable energy solution for many developing countries (and promote their social and economic development), is marginalized compared to other renewable and conventional energy resources. This could be due to a lack of awareness and local capacity in developing countries, as well as within many international aid and technical cooperation agencies. Capacity building, awareness formation and educational needs and tools are discussed in order to stimulate in-depth thinking and problem-solving actions for the promotion of the use of geothermal energy. Special focus is drawn on closing the gaps between the groups involved with geothermal energy, and the use of internet-based technologies as low-cost communication tools. This will mean improved use of local sustainable geothermal energy resources within an integral sustainable approach for direct use and power generation.

1 INTRODUCTION

The use of geothermal energy resources, which may provide a clean and long-term sustainable energy solution and promote the social and economic development in many developing countries, is marginalized compared to other renewable and conventional energy resources. Insufficient access to financing, a lack of awareness, and a lack of experts and local capacity in developing countries are some of the reasons for this marginalisation, and the promotion of geothermal energy is also being hindered by institutional and regulatory barriers.

The classical argument of developing countries is that they are contributing only little to global GHG (Green House Gas) emission. Though this is actually true, it must be countered by convincing them that their energy demand is increasing exponentially (faster than in industrialised countries), and hence their GHG emissions will also increase. This will make developing countries the principal contributors to global gas emissions within the next few decades. Additionally, they must both see, and use the potential opportunities of, the Clean Development Mechanism (CDM) to increase both their national sustainable development and to assist the Annex I parties (industrialised countries) of the Kyoto convention in their GHG emission reduction. This will both improve socio-economic development of the developing countries and reduce global climate change.

Energy (as a central part of sustainable development) is strongly related to numerous social-economic, financial, environmental, scientific-technical and political-institutional aspects, which are complexly interconnected. These interconnections become increasingly strong as energy demands and competition for energy increase. Energy resource management can no longer be viewed as purely technical, and classical project-by-project planning becomes increasingly inadequate. The use of different energy resources must be integrated among different competitive users, and special attention must be paid to those users involving a large number of people with different interests. All energy resources must be considered as an issue in which different groups of people are involved on different levels and scales and in different ways. This requires a comprehensive multi-dimensional, interdisciplinary and inter-institutional approach of the whole system, where experts of all fields must collaborate at all levels and with the general public to consider all aspects in a well-balanced way.

The prerequisites for such an approach are firstly, awareness of the sustainable energy issues, and secondly, that all professionals have high standards of fundamental and applied knowledge. Only then can natural and social scientists, economists, engineers, technicians and society in general give educated advice to decision makers so that they can formulate action and policy plans. This claim is generally far from reality in developing countries and hence corresponding awareness formation, education and capacity building are required to improve the use of geothermal energy resources and improve sustainable development. Only a learned society, aware of geothermal energy opportunities, can understand and use geothermal energy resources within the framework of sustainable development. In particular, those active in the energy and environmental fields are required to have the knowledge and skill to be able to implement energy planning within the modern concept of sustainability.

Education, capacity building and information are required in the scientific, public and private sectors for commercialisation of geothermal energy. Thorough training on the technological and economic integration of geothermal energy into the national or regional electricity systems of developing countries needs to be given. This will foster the development of knowledge and skills and their dissemination among an interdisciplinary target group comprising of leading energy decision makers, energy sector representatives and administrators, governmental policy makers, energy engineers/scientists, academics and power producers from different parts of the world as well as hydrogeologists, water resources managers and engineers, land planners, and agronomists who are concerned about energy related problems (Fig. 1).

This requires long- and short-term programmes for developing countries to build awareness about information dissemination, capacity building, education, technology transfer, identification of Clean Development Mechanism (CDM) projects, and ancillary benefits of geothermal energy and to include all these ideas in national economic planning. Education and training becomes necessary at all levels, and with international co-operation, they become of key importance for solving energy related problems, by establishing and executing necessary action plans. Only then can people and organisations working for the development of their country achieve their own economic and social development objectives in a sustainable way. Globalisation can

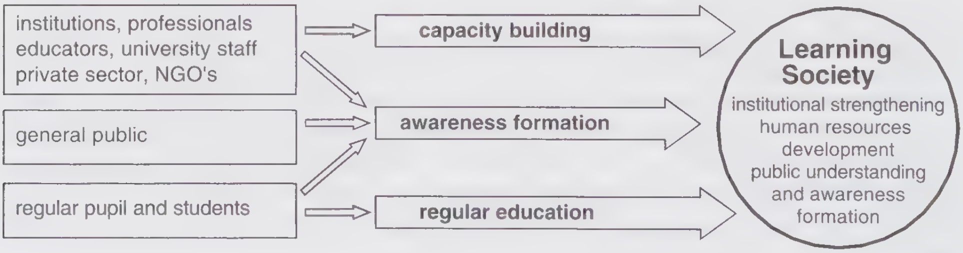

Figure 1. Target groups requiring assistance for capacity building, education and awareness formation in geothermal energy resources on national, regional and international level.

open opportunities for international policy coordination and cooperation by involving public and private sectors of different nations.

While developing corresponding strategies and tools, it must be born in mind that educational systems and methods are changing and that the economic value of knowledge and skills is becoming increasingly important. New learning techniques have been introduced and, especially with the introduction and rapid expansion of the internet, these allow the combination of classic learning strategies with modern communication technology. Classical face-to-face learning is then substituted by virtual communication which can reach the more people at a much lower cost than was ever possible before.

There are several strategies to promote the use of geothermal energy such as education, capacity building and public awareness, and these should be implemented concurrently to achieve the best results. These strategies are independent and country-specific.

The main aim of this chapter is to stimulate in-depth thinking and problem-solving actions which will help a developing society achieve the best learning processes related to geothermal energy resources within the framework of sustainable development. The best ways of capacity building, the formation of public awareness, and education will be addressed, as well as using these instruments for closing the gaps between all groups involved in geothermal energy issues. This is a prerequisite for any integral sustainable energy approach, where the best ecological and economical solutions, and social and environmental values of sustainable energy are focused. Additionally the use of internet-based technologies as low-cost tools for improving capacity building, public awareness and education will be addressed.

2 EDUCATION AND THE FORMATION OF PUBLIC AWARENESS

Many of the barriers for promoting geothermal energy also apply to other renewable energy sources. So it is astonishing that when renewable energy sources are considered, geothermal energy is often considered only marginally or not at all. As a consequence, many governmental, regional and international sustainable energy programmes underestimate, or do not even include, geothermal energy. The question that then arises is why is geothermal energy so marginalized compared to other renewables, even though geothermal energy has, in many cases, significant economic, social and environmental benefits. The real reason for its marginalisation is a lack of information and awareness about geothermal energy and opportunities, and under-representation of the geothermal community in national and international sustainable energy planning and also when developing CDM strategies during international climate negotiations.

The behaviour of non-governmental institutions (NGOs) related to global climate change and environment also contributes to the marginalisation of geothermal energy. Starting in industrialised countries in the 1970's, first the non-governmental institutions and later the green political parties promoted renewable energy resources. They particularly promoted solar, wind and biomass energy as the most appropriate energy sources and neglected geothermal energy. Over 30 years a considerable awareness of the first three renewable sources has been raised, and geothermal energy has been sidelined. Consequently, little awareness exists about geothermal energy, and this leads to underrepresentation by politicians, energy decision makers, the past and the present NGOs and the general public.

This deficit of awareness calls for an urgent popularisation of geothermal energy combined with general environmental awareness at all levels of society. This requires the strong development of educational and public awareness programmes, and the incorporation of geothermal energy into the framework of climate change and sustainable development. Since environmental problems appear, develop and expand at such a high velocity, it is not enough to offer education to only a limited part of the world or population. The thrust of education must be adapted to with exponentially increasing velocity. Each individual of society must take on environmental responsibility, including the support of sustainable energy. A general public consensus should be arrived at to decide the most suitable eco-friendly energy source and such decisions should form a political agenda during political election. Only then can pressure be brought on governmental authorities to introduce laws and regulations protecting natural resources against pollution and to provide incentives to develop markets for green products and services. The general public must decide what they are willing to pay for different levels of service. This means that the general public must be offered choices, and they must be educated so that they understand what the corresponding choices signify for them and future generations. It is now observable that in many developing countries, companies are confronting growing customer and investor sensitivity to environmental issues (as already existing since several decades in most industrialised countries). This shows that energy procurement decisions will become part of a company's public image subject to the scrutiny of customers, shareholders and stakeholders.

Hence there is an urgent need for public institutions, universities, NGOs, etc. at all levels to offer a service to popularise geothermal energy by including geothermal energy in programmes of environmental education and information to the general public in cooperation with institutions, organisations and mass media. Possibilities include courses for adults (adapted to their level of knowledge), public speeches or discourses (e.g. in cultural centres, parish halls, etc.), articles and advertisements in newspapers and journals, flyers, exhibitions, programmes in television/ radio, special channels in the television especially designed for education purposes, the internet, publication of education and information materials, etc. The dissemination of information to the public must be in the local language. International institutions as UN agencies should provide easy-to-understand, informative documents translated into the local language to improve information transfer across language barriers.

Additionally, geothermal energy courses must be included in primary, secondary and university education. The education system plays a key role in the development of an informed public and also in the distribution of information.

In both formal and informal education, the cooperation of international associations, organisations and other national or regional institutions within the developing countries is required to develop geothermal energy information, education and public awareness material for educators, pupil, students and the public. An example is the International Geothermal Association (IGA), which offers, among others, educational material and information for educators and for self learning, including discussion forums, a photo gallery, interactive world map with updated geothermal energy resources, information on per country indirect and direct use, a newsletter, general information, and a list of websites of geothermal interest. Another important source for educational material and information is the Geothermal Education Office (GEO) in Washington. The GEO is funded by the U.S. Department of Energy and by the geothermal industry. They participate in joint education and public information projects, offering geothermal facts, slide shows, class-room and public information materials, world-wide data and maps, a discussion forum and a list of links to other geothermal sites. This information is unfortunately only available in English. The purpose of the GEO is to promote public understanding about geothermal resources and its importance in providing clean sustainable energy and protecting our environment. It produces and distributes educational materials about geothermal energy to schools, energy/environmental educators, libraries, industry, and the public. A third institution, the World Renewable Energy Network (WREN) should also be mentioned. The WREN was established in 1992 and today is one of the most effective organisations supporting and enhancing the utilization and implementation of renewable energy sources that are both environmentally safe and economically sustainable. The WREN achieves this through a worldwide network of agencies, institutions, companies and individuals and represents most countries in the world, which work together towards international diffusion of renewable energy technologies and applications. The organisation is affiliated to UNESCO and maintains close links with many United Nations, governmental and non-governmental organisations. Representing most countries in the world, it aims to promote the communication and technical education of scientists, engineers, technicians and managers in this field and to address itself to the energy needs of both developing and developed countries.

3 CAPACITY BUILDING

3.1 *Capacity building needs*

The development of efficient and effective sustainable energy sectors, focusing on environmentally sound development and progress of the country or region, requires strong national institutions in the developing countries. Such institutions do not normally exist and can only be developed by their personnel receiving enough training and access to information. The development of new capacity and the building on existing capacity is required (Fig. 2). Additionally capacity building is required for NGOs and private sector leaders.

In many developing countries, governmental energy institutions are weak, capacity is insufficient and they are not brought up to international standards of decision-making. In many public energy institutions long-term thinking, planning and investment do not exist. In most cases, there is less inter-institutional co-operation than is required for implementing sustainable energy policies. National energy institutions face the problem of overcoming political and legal barriers before they can mobilise and unlock the potential of the energy sector and offer sustainable energy policies. Energy institutions usually consider environmental and social aspects for sustainable development insufficiently, or not at all. Tasks are often executed as purely technical and classical project-by-project planning.

Different options are possible for changing the situation of weak public energy services:

- Radical restructuring and reinforcement of governmental public services including a long-term investment programme, requiring obtaining loans from national and international banks. Public services should have the same access to these loans as private companies. Carried out in an appropriate manner, such public services operate cheaper than private companies. A lack of local experts and guidance on institutional restructuring makes this option unsuitable for developing countries without being assisted through capacity building and assistance programmes.
- Public-public partnerships, where assistance of various kinds is given to the public service providers to improve their services in the form of consultancy, capacity building and assistance to get finance for the required investments. This assistance can be provided by other foreign

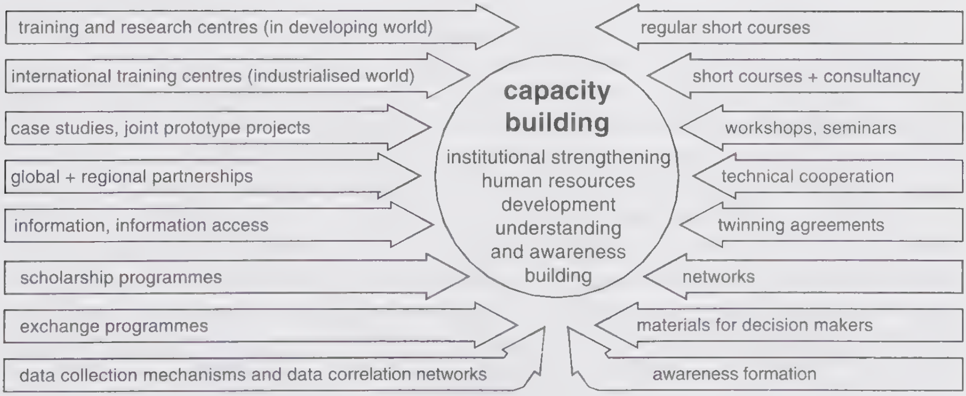

Figure 2. Tools and assistance need for capacity building on national, regional and international level.

or national public sector organisations including international agencies of technical co-operation and universities.
- Privatisation of the public services, either in the form of short-term service contracts or long-term concessions, where the provider is also responsible for investments in the form of build-operate-transfer (BOT), build-transfer-operate (BTO) or build-own-operate (BOO) contractual arrangements for private power projects. These different forms of private sector participation guarantee the input of capital, international experts and knowledge of the highest international standard as well as promote additional local capacity building.

Strong international assistance is required for all these points, and especially for national capacity building. The privatisation option requires a well-informed society to prepare for the privatisation process or for sustainable private sector participation. Only with such an informed and environmentally aware society can it be made sure that private participants do not follow market benefit rules strictly. These rules may have the highest direct benefits for them, but they do not support sustainable development, and many examples of the privatisation of public services in developing countries unfortunately show this.

To overcome the market, policy, technical and financial barriers which hinder the promotion of geothermal energy, industrialised countries must implement projects with the aim of enhancing local institutional, scientific and technical capacity building in the energy sector and the development of rapid renewable energy commercialisation in developing countries. The aim is to improve the understanding of energy problems and renewable energy planning and policies of developing countries, including mitigation analysis and climate policy, and to define areas for required actions, including the implementation of technical improvements. Institutional strengthening and human resources formation is required in the areas listed in Table 1. The preferences may vary depending on the special situation and needs of a country or a region. Capacity building is essential for including geothermal energy resources in CDM projects.

Increased capacity will lead to improved management of nationally or regionally available geothermal energy resources for direct use or power generation and also protection of the environment through the collaboration of geothermal energy professionals from universities, public institutions, non-governmental organisations, public/private sector professionals, international funding agencies and other relevant institutions.

Continuous professional training is required for all workers within the geothermal industry, whether from public or private institutions. Capacity building can be performed through training courses, bilateral and partnership programmes, technical cooperation, information etc. Joint pilot projects, feasibility studies and other direct co-operation plans are needed to provide national policy-makers and businessmen with first-hand knowledge of market-based instruments and institutions and demonstrate the potential of market-oriented approaches to develop geothermal energy technologies and other clean energy projects in developing countries. Co-operation between international experts and local people can enhance capacity building skills and confidence. With co-operation of industrial partners, these studies must be performed to analyse the technical, socio-economic and financial feasibility of clean energy projects in developing countries. Global-, multi- or bilateral partnership programmes or twinning arrangements including public, private and non-governmental partners must be implemented. Often there is little detailed information available about the pres-ence of geothermal energy resources, the cost of energy in different markets and emission rates. In cases where such information exists, it is often restricted to the national energy monopolies and not universally accessible to private national or international companies. Small private companies are especially handicapped with identifying and developing economically and environmentally sound projects. Sources of, and access to, information must be correspondingly improved by developing information networks. Networks between academic institutions, communities, the private sector and the politicians are also required. Improved capacity is also required for NGOs and university staff and academics, which have positions with highest multiplicatory effects.

Table 1. Areas in which capacity building is required to overcome obstacles limiting the promotion of geothermal energy resources.

Overcoming institutional, policy and regulatory barriers	Overcoming financial barriers
• Policy and regulatory changes to increase geothermal energy diffusion (local, national levels). • To overcome the poor linkages from research and development to geothermal energy commercialisation. • To overcome the lack of consumer confidence in geothermal energy. • To develop market-based instruments and market-based institutions. • To develop and introduce alternative financing mechanisms to overcome high front-end costs. • Geothermal resources assessment. • To show opportunities being offered by the technology. • Strengthening of capacity to implement sound geothermal energy policies. • Provision of information for targeted audiences to build a geothermal energy market. • Increasing coordination among organizations concerned with geothermal energy. • Assistance to market penetration of geothermal energy by providing incentives for market strategies. • To provide first-hand knowledge of a particular instrument or institution and demonstrate its validity to increase market penetration of geothermal energy technologies. • To shift from supply-oriented technology deployment to demand-driven, investor- and consumer-friendly approaches. • To introduce market-based instruments as concessionary financing arrangements, targeted credit lines, tax relief to investors, power purchase agreements. • To increase the financial attractiveness geothermal energy potential investors and consumers over the short-term and expand the geothermal energy market.	• Increased financial commitment of public and private sector. • Mobilization of business ventures on geothermal energy. • Training members of the financial community of developing country. • To overcome barrier with business community. • To increase the awareness of geothermal energy investment opportunities. • To bring together projects and investors. • Introduce innovative financing mechanisms. • To attract larger players and substantially increase private investments in the geothermal energy industry. • To develop market-based institutions and instruments to attract new players in the geothermal energy industry and increase investments in geothermal energy. • Market assessments and identification for clean energy programmes, e.g. how market penetration of renewable energy technology in the developing country or the region can be further stimulated. • To develop frameworks to implement commercial geothermal energy power projects. • To develop data collection mechanisms including the establishment of new or the extension of existing data correlation networks. • To develop geothermal energy standards, standard guidelines and laws.

3.2 *Training courses and centres*

Development agencies with their declining budgets are limiting their support to help to build capacity in energy and other sectors. Due to their limited finances and increasing number of requests for support, they generally offer short low-cost solutions like short-term consultancy and regular or sporadic short courses for capacity building. This support for regional and national energy and other public institutions will be necessary for short and middle term assistance, but cannot solve more major problems, and longer-term opportunities for capacity building are required. Instability and unreliability of policy and institutional guidance in many developing countries makes long-term capacity building of public institutions impossible. This problem can be overcome by supporting the installation of independent national or regional training and research centres for energy analysis and capacity building, which act as support for national

Table 2. Possibilities for tasks to be developed for training centres in developing countries.

- To develop and to offer practically oriented postgraduate courses, continued education and continuation training in geothermal energy and related fields including Masters and PhD programs, professional short courses, distance courses and training seminars, workshops, technical meetings addressed to professionals from the private and public sector as well as academics and students of a developing country or the region; their contents are related especially to problems and the requirements of the country or the region.
- To create national, regional and international networks for training and information exchange, which will involve the sharing of resources and exchange information among institutions of the developing country (or region) and the industrialised countries as well as other partners from the public/private sector, non-governmental organisations and other international initiatives.
- To promote and expand the bilateral exchange of students, postgraduates, faculty and professionals with other universities and institutions (at national, regional or international level).
- The mutual exchange of scholarly publications, manuals and scientific information.
- To introduce new communication technologies like the Internet.
- To advise about possibilities of international technical and scientific contacts, exchange programmes and sources of international information.
- Institutional strengthening, which will be accomplished through institutional appraisal, curriculum design, faculty upgrading, and procurement of equipment.
- Strengthening regional academic co-operation since in geothermally attractive areas the neighbour countries have similar problems, climatic and geological conditions.
- Developing and strengthening partnerships with public sector institutions, municipalities, non-governmental organisations and the private sector related to the energy resources and the environment to exchange actions, experiences and to develop together tasks.
- Developing and strengthening research projects that directly involve and benefit local communities (direct use of geothermal energy).
- Strengthening the programme in the area of community-based research and the social, legal and economic aspects of energy resources management.
- The enhancement of inter- and multidisciplinary work in teaching, research, and social action regarding intra- and extra-university problems.
- The establishment of projects with international organisations which allow the centre to be in the vanguard of knowledge and social action.
- To develop scholarships for participants from the country and the region in training courses.
- To carry out joint scientific and technical programmes and actions between industrialised and developing countries.

governmental institutions (Table 2). Such support is of relatively low cost and has a high multiplicatory factor. Additionally, development agencies must strengthen national and regional educational and training institutions in the issues of sustainable energy in order to popularise geothermal energy and other renewables. International support for the installation, and long-term support for the running, of training and research centres in developing countries and regions is a relatively low-cost possibility. Because of their pre-existing local staff and infrastructure, universities, with their academic freedom and their relative independence from political instability, are optimal sites which can be assisted to install and run adequate national or regional training programmes, as well as offering general information to the public. Thereby, numerous existing academic and technical bilateral and multi-lateral co-operation programmes between developing and donor countries must be used as a base where possible.

Intermediate possibilities for capacity building in developing countries include long-term training courses (one or two years) which are offered by industrialised (geothermally developed) countries. Various institutions exist in industrialised countries which offer international training courses in the area of geothermal energy resources. Such institutions also face problems. Firstly, financial constraints only allow the participation of a few persons. On the other hand it should be evaluated how far virtual training could replace the period of presence and hence decreasing the costs for provider, participant or sponsoring institution. Secondly, these courses are highly technical and scientific, so they are especially attended by persons from of countries where already geothermal activities exist. For example the Geothermal Institute at the University of Auckland, New Zealand, is an international training and research centre for professional engineers and earth scientists in geothermal energy technology. Since its foundation in 1979 this institute has trained over 500 students from Asia, Latin America, Africa and Europe. Another example is the Geothermal Training Programme of the United Nations University (UNU), which has operated in Iceland since 1979 with courses for professionals from developing countries. The aim of this institute is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. Priority is given to candidates from institutions where geothermal work is already under way. From 1979 to 2001, 261 scientists and engineers from 38 countries have completed the 6-month courses, and over 70 have received shorter training.

4 ASSISTANCE FOR THE "CLEAN DEVELOPMENT MECHANISM"

According to the Kyoto Protocol, the Clean Development Mechanism (CDM) encourages the sustainable development of Annex-I countries through capacity building and technology transfers to developing countries. The CDM should enable Annex I countries to meet part of their Kyoto commitments cost-effectively through abatement projects in Non-Annex I countries.

Geothermal projects are generally not considered as CDM opportunities by developing countries nor by the developed world. Corresponding awareness must therefore be raised through political leaders, governmental decision makers, NGOs and private sector leaders to improve the understanding of CDM with respect to geothermal energy resources.

Many of the existing CDM capacity-building programmes do not include geothermal energy issues and hence underestimate its value as a CDM opportunity. These programmes focus predominantly on biodiversity and forest conservation and on renewable energy resources such as hydroelectric, solar and biomass. The same trend can be found at the national UNFCCC focal points and national CDM and AIJ (Activities Implemented Jointly) offices, which either insufficiently, or do not, consider geothermal energy as CDM and AIJ opportunities. Even many CDM and AIJ offices do not count on energy specialists. In the list of 144 AIJ/CDM projects, only one is a geothermal energy project (El Hoyo, Nicaragua), and this was initially approved but later cancelled.

This deficit requires special tasks for strengthening UNFCC focal points and national CDM/AIJ offices in developing countries by capacity building in geothermal energy applications. Once strengthened, they are then able to sort out which geothermal projects may be economically and socially sound for CDM accreditation and how they can fit into national sustainable development priorities such as poverty alleviation, job creation, food security, tourism, etc. There is a need for capacity building to define baselines, to develop sustainability index (SID) indicators and to package the CDM information into a format that is appealing to private industry for potential investment. Developing countries must be assisted to take advantage of CDM trading through prototype projects, capacity building and awareness formation in geothermal energy uses. Capacity-building is required to help the developing countries analyse the GHG abatement options and their related costs in the energy sector in non-Annex I countries, and thus analyse the potential market for CDM.

5 CLOSING THE GAPS BETWEEN GROUPS INVOLVED

Long-term sustainable energy sector implementation requires an integrated interdisciplinary, inter-institutional, multi-level approach, where all types of available energy resources and all

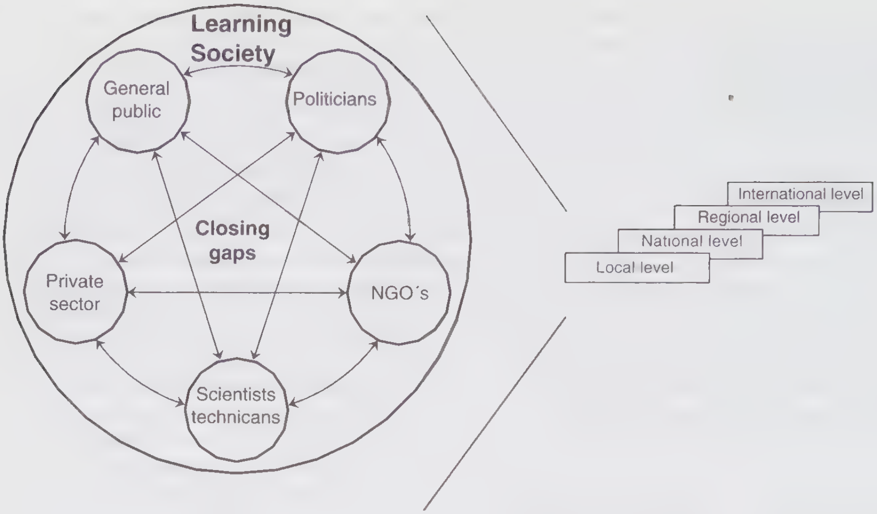

Figure 3. Closing the gaps between the groups involved in the energy issue.

energy-related socio-economic, financial, political-institutional, environmental and scientific-technical aspects must be considered.

A huge obstacle for geothermal energy in particular, and sustainable energy in general, is the long tradition of separation between scientists, politicians, the private sector and the general public. To remove this obstacle, actions and strategies must be developed and applied to close the gaps between these groups and to allow all groups to be involved in energy decisions. It is a prerequisite for any integrated energy resource management that it operates as an integrated system using a multidimensional approach and recognises geothermal energy as a tool for the sustainable development of a country or region (Fig. 3).

The five groups which are competitively involved in energy issues, (the general public, politicians, the private sector, scientists and NGOs), have different knowledge, interests and priorities. There are some possible strategies and actions which can reduce the gaps between these groups by improving information and communication.

5.1 *The gap between scientists and politicians*

Scientists, in general, have less capacity to explain facts, situations and needs. Hence they must learn to speak in a language which the politicians understand, especially in terms of money, risks or benefits.

Politicians must be convinced that an increase in the use of geothermal energy will lead to an improvement in social conditions and economic development of their region and hence be of wide-ranging benefit.

It is up to the scientists to educate and train the politicians, for example by offering them workshops, training courses, materials for making decisions, and guidelines which describe why and how to include geothermal energy resources in an integrated national sustainable energy plan. Politicians need to be presented with case studies to show that these suggestions really work and that they lead to benefits. They must be made to understand that air contamination and climate change have no political frontiers, and that environmental degradation, loss of forests and biodiversity affects industries like tourism and agriculture hence decreasing the economic and social conditions of their countries. They must also understand that different countries must cooperate with each other and that international agencies must manage and operate energy resources in sustainable and effective ways. The scientists must work together, using NGOs as catalysts if necessary, to influence the politicians.

5.2 *The gap between scientists and general public*

The scientists must help society understand their local energy situation. This means that in their own area, they should understand what contamination is, how it affects their health and economic welfare, and how it can decrease their and their children's quality of life. They should be shown how geothermal energy may be a sustainable economically sound substitution for their present energy supply, including its suitability for small scale application and its direct uses. It is important that the general public see and understand what the scientists are trying to do. They must understand that the work of the scientists is for the benefit of the society, and, correspondingly, scientists must try to find community-based solutions. Existing participatory development strategies may be used or new ones may be developed.

Scientists must cooperate with governments, the mass media, and with NGOs to offer public awareness programmes for the whole society.

5.3 *The gap between politicians and the private sector*

Many industries have a very strong lobby, as they have a strong influence on the economic development of the region. Changes in the energy sector are not of interest and industries do not generally allow political intervention. Here only international organisations can lead to change. Politicians must develop and offer the private sector economic incentives to promote the use of geothermal and other clean energy sources. Additional penalty mechanisms must be developed which consider the total value of the corresponding environmental impact through the use of a certain energy source.

5.4 *The gap between politicians and society*

Politicians must consider the culture and traditions of regional energy use in their suggestions and decisions. The real needs of people in different regions must be considered. Corresponding tools must be developed to work in the different levels of municipality, province and nation. Up- and downward mobility must be considered to guarantee that local interests are really included in national decisions and actions.

5.5 *The gap between scientists and the private sector*

Scientists must offer solutions for low cost measures to reduce contamination and environmental impacts. Clean energy technologies must be improved and implemented. In real terms this means that developments in the private sector and developments in universities should not be executed in isolation, but in close co-operation. Scientists should provide training for the private sector. Knowledge transfer from industrialised to developing countries could be improved and adaptation to local situations, needs and possibilities should be carefully considered.

5.6 *The role of non-governmental organisations*

NGOs play an important role in closing gaps between the groups by acting as transmitters and catalysts. NGO participation should be strengthened, especially where energy is being discussed.

They can help to reduce barriers for geothermal energy financing by acting as a catalyst between governments, which often desire to fund geothermal market development, but want assurance that there will be private sector continuation after the government funds are spent, and private sector investors, who want to invest in the geothermal markets, but need assurance that the government will allow them to recover their capital plus a return. Non-profit foundations can therefore act as catalysts during the formation of sustainable markets for renewable energy, and help to increase market penetration of geothermal energy.

6 INTERNET-BASED TECHNOLOGIES

6.1 *Demand and opportunities*

Facilities for training, education and information are no longer local or static. Modern communication technologies allow high-velocity data transfer to any part of the world. The implementation of virtual technologies as part of academic education and training of professionals is indispensable and must be used in the best possible way (Fig. 4).

Experiences from different developing countries show that access to training by most interested professionals is inhibited firstly by the limited economic resources of the interested participants or their institutions, and secondly by the lack of disposable time, particularly affecting professionals working in public institutions or private companies.

The high demand for training and information calls for the introduction of new ways overcoming these restrictions. The building of a virtual Internet-based "global knowledge community" is required to protect and sustain the world's environment by promoting the use of geothermal and other clean and sustainable energy resources. Participants would then be free to attend classes while at work and progress at their own pace.

These virtual methods would provide education, training and information for professionals who do not have time or economic resources to attend regular training programmes, and can

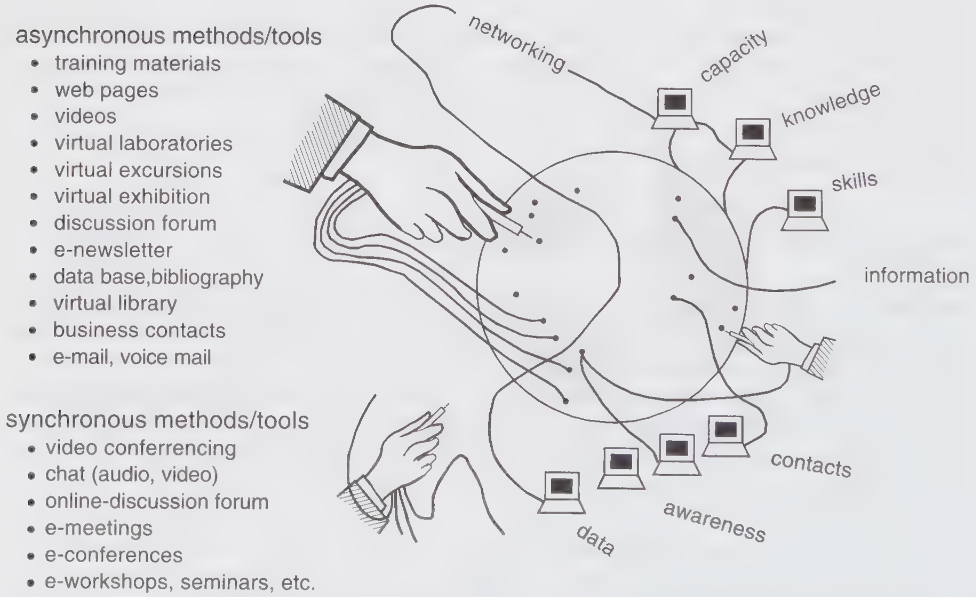

Figure 4. The Internet-based global knowledge community – everywhere at any time.

increase participation numbers. This makes internet-based training and information exchange an important tool.

Let us examine strategies, and advantages and disadvantages of such virtual training and information exchange (Tab. 3) in the light of the existing demands and needs of the developing world.

In order to determine optimal methods and materials for virtual training, the demand and equipment available for receiving virtual training was analysed by interviewing 300 professionals from Latin America. The results indicate that 95% of the people who are interested in receiving virtual training prefer to receive the training through internet. Regarding the question whether they prefer the courses in synchronous form (real time) or in asynchronous form, the results indicated that asynchronous form is preferred. This would allow attendance during spare time.

6.2 *Synchronous and asynchronous virtual training methods*

Virtual training programmes must provide an environment in which the participants do not remain passive, but play active roles, interacting directly with their instructors who are specialists in their respective topics.

The use of real-time training methods (e.g. video conferences, chat, on-line discussion sessions) has the advantage that the participants can directly interact with the instructor. This facilitates dialogue and is closer to the reality of a real classroom. Such on-line methods have the disadvantage that the participant must be at his place of training during certain fixed times, and for many professionals, this very inconvenient.

For these reasons, asynchronous teaching methods are recommended. Course material may be posted on the web at fixed time intervals. Participants may attend their class at any time they want and must submit homework before a fixed date. A discussion forum, which is accessible the whole time, should also be installed. Through that forum the participants can ask questions and discuss topical issues. Additionally the course instructor should be available through e-mail or other means.

Table 3. Advantages of Internet-based virtual training methods.

Advantages for the institutions, which provide the training	Advantages for the participants in virtual training
• To be able to offer developing countries a first-class training of first-world standard, which grants multiple benefits to students and professionals of the public and private sector. • To be able to offer the participants activities which are realized at any place of the world, which is an invaluable benefit to improve the level of education and training. • Reduction of costs for organizing courses, workshops, etc. due to decreasing costs for travel and accommodation for external instructors. • Participating institutions receive knowledge from world-class professionals.	• To attend courses, workshops, conferences, etc. without leaving his usual place of work or his classroom (reduction of costs for travel and accommodation) allowing a significant increase of the number of participants. • To receive training on the highest level (world-class eminent professionals as instructors) with training possibilities only available at first-class institutions (improved service quality). • Increased number of courses, workshops, and conferences offered by the own institution or the participating national or international institutions. • The possibility to interact directly with the instructor, asking questions, etc., so that the participants remain not passive (compared to the classical distance learning methods).

Real-time interaction can be limited to certain activities, e.g. lab-time, field excursions etc. In order not to exclude people who do not have access to the equipment necessary for real-time interactions, these activities could be made optional. Additionally, it could also possible to record these real-time activities on video and distribute them to those participants who could not participate.

Different options must be considered for undergraduate or postgraduate courses. Since students generally have less time constraints, and may need to interact more often with the course instructor, synchronous methods are recommended. These on-line courses formerly required expensive equipment, special studios, and a considerable number of personnel. These problems hindered its development since the majority of people interested in such a course did not, and still don't have the equipment for receiving such videoconferences. Using the internet as tool of communication is much cheaper. Access is through a personal computer using a modem, ISDN lines or the ever-increasing broadband access, allowing high-speed internet communication with transfer rates over 1.5 Mb/s. Videoconferencing through the internet is still in its infancy, and a dramatic increase can be expected within a few years.

Asynchronous and synchronous internet-based methods should both be considered and carefully combined when organizing courses, seminars, and conferences. Additional workshops and congresses may be prepared for the scientific community for data and information exchange. Easy accessibility and an economic operation are fundamental targets for both provider and consumer.

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Geothermal energy development – Possible market facilitation roles of UNEP and the GEF

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ABSTRACT: The conditions necessary for successful private power projects, in general, and geothermal projects, in particular, include government policies and regulation, contract enforcement procedures, existence of host country infrastructure and trained personnel, political and economic stability, accurate costing of present power sources, perceptions and responsibility for risk, project scale, long and short-term commercial interests of private developers, lenders and equity investors, and information availability and dissemination to/from developers, investors and host country governments. A strong government commitment is a critical element in determining the success or failure of private geothermal power projects. Private investment in power projects is growing rapidly. In geothermal energy projects private investment is increasing at a more modest rate. UNEP and the GEF can play pivotal roles in promoting the development of private geothermal power generation projects by taking actions that address obstacles to increased industry involvement and encourage the participation of other bi and multilateral agencies, host country governments, investment funds, equipment suppliers and private geothermal developers.

1 OVERVIEW

To meet socio-economic development goals, people and countries must have adequate energy services to provide for the household needs of their population as well as for the industrial and service sectors. The production and consumption of energy is linked to other major development issues including poverty alleviation, environmental degradation, and security concerns. Our present dependence on fossil fuels for power generation creates widespread sources of harmful emissions. A well-balanced fuel mix, in which energy resources are appropriately utilized, is essential for sustainable development. In this context, geothermal and other renewable energy technologies can have a significant impact on the energy scenarios in developing and emerging market countries.

2 THE MISSIONS OF UNEP AND GEF

The UNEP (United Nations Environmental Programme) mission is to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations.

UNEP's programmatic priorities include:

1. environmental information, assessment and research, including environmental emergency response capacity and strengthening of early warning and assessment functions;
2. enhanced coordination of environmental conventions and development and development of policy instruments;
3. fresh water;
4. technology transfer and industry;
5. support to Africa.

The Global Environment Facility (GEF) was established to forge international cooperation and finance actions to address four critical threats to the global environment: biodiversity loss, climate change, degradation of international waters, and ozone depletion. Related work to stem the problem of land degradation is also eligible for GEF funding.

Launched in 1991 as an experimental facility, the GEF was restructured after the Earth Summit in Rio de Janeiro to serve the environmental interests of people in all parts of the world. The facility that emerged after restructuring was more strategic, effective, transparent, and participatory. In 1994, 34 nations pledged $2 billion in support of GEF's mission; in 1998, 36 nations pledged $2.75 billion to protect the global environment and promote sustainable development.

The GEF can succeed in its global environmental mission only as part of a worldwide movement toward sustainable development. GEF brings together 166 member governments, leading development institutions, the scientific community, and a wide spectrum of private sector and non-governmental organizations on behalf of a common global environmental agenda.

3 WHY GEOTHERMAL ENERGY?

Geothermal energy is a potentially significant contributor to the development and climate change objectives of the United Nations Environment Program and the Global Environment Facility.

Geothermal systems for electricity generation have proven to be reliable and flexible. Geothermal power plants are on-line an average of 97% of the time, while nuclear plants average 65% and coal plants 75%. Geothermal plants are modular, and can be installed in increments as needed. Construction time can be as short as 6 months for plants in the range 0.5 to 10 MW and as little as 2 years for clusters of plants totalling 250 MW or more.

On a life-cycle basis, geothermal energy costs are competitive with fossil fuels and many hydropower installations.

4 PRESENT SITUATION

Geothermal energy is commercially used today both for electricity generation and as a direct heat source. Due to the need for space heating, direct use of geothermal energy is more common in cold climates especially Central and East Europe and in Iceland.

Europe produces 10% of the electricity generated worldwide by geothermal energy but provides 52% of its direct uses. The reverse is true for the Americas, with 53% of the electricity generated and 10% of direct uses. For Asia, Oceania and Africa, the proportional share of the world total is similar for electricity and direct use.

Worldwide installed geothermal power generation capacity increased between 1995 and 2000 from 6833 MW to 8652 MW in 20 countries. Geothermal energy use is equivalent to the burning of 150 million bbl of oil per year.

During the period 1995–2000, the Philippines led the world by installing 682 MW. Indonesia showed the next greatest capacity increase with 280 MW built. Italy, New Zealand and Iceland's

Table 1. 2000 Electric generating capacity and population supported by geothermal energy (source: GEA Press Release, April 11, 2002).

Country	1990 capacity (MW)	2000 capacity (MW)	People supported
Australia	0.0	0.4	300
China	19.2	32.0	110,000
Costa Rica	0.0	142.5	670,000
El Salvador	95.0	161.0	1,490,000
France (Guadeloupe)	4.2	4.2	2000
Guatemala	0.0	33.4	1,060,000
Iceland	44.6	170.0	50,000
Indonesia	144.7	589.5	13,190,000
Italy	545.0	785.0	1,170,000
Japan	214.6	546.9	430,000
Kenya	45.0	57.0	3,859,786
Mexico	700.0	755.0	3,540,000
New Zealand	283.2	437.0	410,000
Nicaragua	70.0	70.0	820,000
Philippines	891.0	1909.0	18,610,000
Portugal (Azores)	3.0	16.0	20,000
Russia	11.0	25.0	10,000
Thailand	0.3	0.3	1500
Turkey	20.4	20.4	60,000
United States	2774.6	2898.0	1,239,000
20 countries	5865.8	8652.6	46,733,586

geothermal generation growth was significant at 153, 151 and 120 MW respectively, and Central American development increased with Costa Rica installing 87.5 MW, El Salvador 56 MW and Guatemala 33 MW. Ethiopia built its first plant (8.52 MW) in 1998 and Russia resumed geothermal power construction by installing 12 MW in the eastern Kamchatka region.

Data released recently by the US Geothermal Energy Association shows only a slight increase in geothermal production in the US and Europe during the past decade, but significant gains in other countries. During this period, geothermal production in Indonesia quadrupled from 144 to 589 MW. Japan nearly tripled its geothermal power from 214 to 546 MW. In the Philippines geothermal energy jumped from 891 MW over 1900 MW and now meets 25% of the country's total electricity needs. Three new countries joined the ranks of geothermal producers for the first time: Australia, Costa Rica and Guatemala. See Table 1 for details.

While geothermal energy currently meets the electricity needs of some 47 million people around the world, its ultimate potential is substantially greater. According to the Geothermal Energy Association (GEA), geothermal resources could serve the electricity needs of 865 million people, or 17 percent of world population. Thirty-nine countries could be 100-percent geothermal powered, mostly in Africa, Central and South America, and the Pacific Rim. These 39 countries had a total population of over 620 million in 1998.

5 KEY FACTORS

Factors influencing current interest and investment in development of geothermal energy worldwide are:

1. rising prices of oil, gas and other conventional energy sources;
2. increasing emphasis on reduction of greenhouse gases;

3. availability of financing to enable both governments and private sector companies to explore and develop geothermal resources;
4. technological developments that allow identification and development of new resources and reduce exploration and production costs;
5. awareness and acceptance of geothermal energy by political leadership worldwide and resulting positive changes in energy policy, legal frameworks and regulations;
6. increasing availability of technically skilled manpower and technology transfer programs in developing countries; and
7. expansion of the industry with greater standardization of equipment and use of field-proven technology, components and designs.

Initial risks and up-front capital costs for exploration and plant construction have been disuasive factors for both public and private sector geothermal investments. Also, governments may not be aware of geothermal's advantages and local energy policy, pricing, and legal structures may discourage private developers.

6 ENVIRONMENTAL ISSUES FOR WORLD GEOTHERMAL DEVELOPMENT

The world community is presently facing the competing goals of increased energy production and mitigating polluting gases. Some of the potential impacts of conventional thermal and large hydro power plant development and use include air emissions; noise and vibration; water quality and quantity, vegetation removal, habitat loss, visual impacts and population displacement. Because the production and use of energy imposes substantial and adverse impacts, a clear preference for renewable energy technologies, such as geothermal, has developed. Using geothermal resources to produce electricity and direct-use energy has significant environmental and land-use benefits, including:

1. requiring little land and enabling other land uses to take place in close proximity;
2. the production of little or no greenhouse gas emissions;
3. the production of minimal air and water pollution; and
4. with reinjection of effluents, an environmental impact that is a fraction of many other power sources.

7 INTERNATIONAL GEOTHERMAL PROJECT FINANCING

The key to increasing the use of geothermal energy is making financing available for power projects whose outputs can be integrated into the economies of a growing number of developing countries.

Private financing of power projects in developing countries is growing rapidly as a result of national power needs expanding more rapidly than the availability of public sector financing. Financing for power projects reached levels of nearly $50 billion during the 1994–1996 period (for approximately 47 GW). Most of the projects were financed on a limited-recourse basis in which lenders only security was the cash flow and other assets of the project. This level of investment is about three times the level in developing countries for all years prior to 1994 and has flowed mostly to power projects in Asia, Latin America and the Middle East.

As a result, new players are entering the field and markets are becoming more competitive. Also, public/private partnerships are increasing especially as they relate to risk allocation at the various stages of private power projects.

Public investment and other government involvement in geothermal development have been (and continues to be) necessary to secure private capital. Geothermal power plants are significantly more capital intensive and higher risk than more conventional oil or natural gas facilities. The up-front capital cost of a geothermal plant can be three to four times greater. Further, up to a third of the investment in a geothermal facility must be made before adequate definition of the resource can ensure targeted production and returns on investment. Finally, the market for geothermal power plant construction is too small to allow for economies of scale achieved by conventional plant developers. Though geothermal facilities provide consumers with clean, reliable, and economical power over their lifetime, investors most often seek to amortize their investments over relatively short-term periods.

A worldwide survey showed total investments in geothermal energy during 1973–1992 amounted to approximately $22 billion by nearly 50 countries. During the decade 1973–1982, public funding amounted to $4.6 billion, and private funding $3 billion. But during the following decade, public funding amounted to $6.6 billion and private funding to $7.7 billion, showing a dramatic decline in the rate of public investments dedicated to geothermal energy development.

Other emerging patterns that relate to financing of geothermal projects include:

1. long-term contract structures (as opposed to merchant plants that target market opportunities);
2. an increasing number of build-own-operate contract structures (over build-own-transfer);
3. increased risk-sharing between public and private sector entities;
4. increasing government policies that encourage private sector participation in energy markets.

For geothermal projects a number of different paths have promoted private-sector involvement. The participation of private operators in steam field development through BOT (Build, Operate and Transfer), BOO (Build, Own and Operate) contracts and JOC (Joint Operation Contracts) has increased the rate of geothermal development in the Philippines and Indonesia. The participation of private operators is presently ongoing or being considered in Costa Rica, Guatemala, Honduras, Nicaragua, Kenya, Djibouti, China and Vietnam. In El Salvador, the first-ever bidding was recently concluded on two concessions for private development of merchant geothermal power plants.

8 GENERAL CROSSCUTTING ISSUES AND POTENTIAL UNEP/GEF ROLES

When examining the conditions necessary for private investment in emerging market countries, it should be recognized that many issues are related to conditions conducive to private investment, in general, and are independent of the technology choice. UNEP and the GEF can fulfil a number of key roles to promote market acceleration for geothermal projects in relation to the following general power sector issues.

8.1 *Government policies and needs of the private sector*

International experience shows that government policy support is key to moving commercial renewable energy project development forward. Government-supported financial incentives have proven to play an important role in helping to develop commercial markets and reduce the financial life cycle costs of selected renewable energy technologies.

If a country chooses a competitive market system, the additional issues of transmission access and pricing mechanisms in the power sector need careful attention. Investors are unlikely to finance power plants without access to the grid, nor are they likely to build if their competitor is a state utility that controls the market (often offering subsidized energy prices). Other elements of policy support include realistic long-term planning, transparent establishment of priorities, coordinated programs for long-term R&D, and technology transfer involving concerned government and commercial institutions.

Governments need to establish "market rules" that guide and foster competition and provide a level playing field. Host country governments should provide clear parameters for the private sector to meet. These include procedures for environmental permitting and regulatory approval steps as well as terms and conditions for power sales and currency convertibility. In countries with little or no IPP (Independent Power Producers) experience, achieving this objective may require considerable time.

Potential UNEP/GEF Roles are:

1. UNEP/GEF should provide host country governments with advice to enable them to establish clear procedures for the private sector to follow. These include procedures for environmental permitting and following regulatory requirements as well as terms and conditions for power sales. In countries with little or no IPP experience, achieving this objective may require considerable time.
2. "Best Practices" for policy and regulatory-related issues should be collected, analysed, summarized and disseminated. Training seminars should be organized for key host country utility, policy, finance and regulatory personnel.

8.2 *Enforcement of power purchase agreements, political stability, and other investor concerns*

Both through their laws and behaviour, developers and investors need to feel secure that contracts will be honoured and enforced over time since alternative energy projects typically require 10 years or more for the investors to secure their targeted returns. Clear and enforced laws governing contracts are fundamental.

Power purchase and other agreements must be honoured and legally enforced in order to provide developers and investors with a degree of certainty they will receive fair returns on their investments. Market prices and risk premiums must also be factored into PPA negotiations and contracts. In emerging country markets, financiers will be hesitant to invest without a significant risk-premium until there is a history of market prices for power. Even then, they will be most likely to invest in energy sources with the quickest repayment, highest rate of investment return and lowest risk, which may not be the technology or mix of technologies that provide the best service and social/environmental values at a reasonable cost.

In competitive markets, governments have provided market-based incentives to promote fuel diversity, low-polluting fuel choices, and other public policy goals. In addition, several have employed renewable portfolio incentives to achieve specific market results.

Potential UNEP/GEF Roles are:

1. UNEP/GEF should identify risk insurance options and developers encouraged to use them when appropriate (although they will raise the price of projects). Risk insurance agencies, programs and costs should be catalogued and advertised.
2. UNEP/GEF should collect, analyse, summarize and disseminate "Best Practices" for policy and regulatory-related issues. Training seminars should be organized for key host country utility, policy, finance and regulatory personnel.

8.3 *Accurate costing of electric power from traditional resources*

In many countries, the true cost of power from traditional resources is unknown or is distorted by hidden subsidies (or both). In other cases, the elements that impact these costs are not recognized. As a result, the cost of energy generated from alternative sources is often compared to an artificially (or arbitrarily) low cost that is not based on reality.

Potential UNEP/GEF Roles are:

1. UNEP/GEF should envision preparation of handbooks that identify the elements to be included in power cost calculations and explain how they should be factored in for both traditional and geothermal projects. The handbooks should be distributed to energy ministry and utility company personnel.
2. A power cost calculation segment could be included as part of a "Best Practices" document and/or in spreadsheet form with linked explanations and instructions.
3. Training seminars should be organized in their use.
4. TA (Technical Assistance) should be provided in conjunction with cultivation of selected private power projects.

8.4 *Additional government signals to private sector*

Support from host country governments in a key factor in determining the success or failure of private power initiatives. The trade laws and infrastructure support of many countries are important signals that are noted by private developers and investors and can inadvertently discourage capital investment, particularly for geothermal projects. For example trade laws that impose duties on the import of equipment and services needed for alternative energy development but exempt competing fossil fuels are strong signals to developers. Offers of tax holidays and government construction of roads to alternative energy sites are strong investment enticements. Examples of positive signals should be identified, publicized and their impact analysed.

Potential UNEP/GEF Roles are:

1. A section on trade laws, infrastructure and other government incentives should be included in the "Best Practices" manual suggested above. Case studies from countries that have successfully reformed their power sectors and attracted strong private participation should be studied for "lessons learned" and used as models for others.
2. Training seminars should be organized on government incentives to alternative energy projects. TA should be provided in conjunction with cultivation of selected private geothermal projects.

9 ISSUES TO BE ADDRESSED TO INCREASE GEOTHERMAL DEVELOPMENT IN THE INTERNATIONAL MARKETPLACE AND PROPOSED UNEP/GEF ROLES

Assuming the general preconditions to private investment are addressed there are still several unique problems that geothermal development faces. These are presented below in the order of priority in which they are perceived by industry along with possible UNEP/GEF roles to address them.

9.1 *Lack of awareness among developers and financing institutions about near-term opportunities*

Even with host country interest in developing its geothermal resources, investing in the construction of a geothermal plant in a developing country can be an unnecessarily lengthy and expensive venture for both private companies and financial institutions when information is difficult to obtain. In order to identify a potential geothermal development opportunity and carry out the necessary "due-diligence", both private companies and financial institutions require information from various sources on a wide range of topics. These include the certainty, location, quality and size of country-specific geothermal resources, exploration work carried out to date, existing policy and judicial frameworks and infrastructure, financial solvency of the utility company and government, currency convertibility, electricity supply/demand pattern, taxation issues, etc.

Resource information based on research carried out by host country and international agencies is cumulative and, over time, can become increasingly valuable to potential developers if it's made available. However, collecting and collating this information can be time-consuming and costly. In many cases, the information is not available. In others, local entities may not wish to divulge it. The end result is that geothermal developers and financial institutions do not have access to the information required to enable them to make decisions about the commercial viability of a project opportunity.

Potential UNEP/GEF Roles are:

1. Existing or near term geothermal opportunities in selected developing countries with known geothermal resources suitable for power generation and/or direct uses (especially Eastern European countries) can be inventoried and prioritised by UNEP/GEF according to resource potential and government interest.
2. UNEP/GEF, in collaboration with host country, multi and bilateral agencies, can support development of country "geothermal master plans" for planning and decision-making by government agencies, private developers and lending institutions that bring together geologic, legal, policy and other information to support private geothermal development. The master plan approach could also foster the bundling of a number of projects in each country or region to achieve a significant critical mass that could potentially encourage larger international geothermal companies to participate.
3. Information on geothermal development opportunities could be communicated to members of the geothermal industry on a real-time basis. This could be carried out via the SANet website that is currently being established by the UNEP and the GEF to link solutions and partners with environmentally related needs.

9.2 *Lack of private sector participation due to high risk/high cost of resource exploration and assessment*

The geothermal resource constitutes the fuel source for a geothermal plant and should have an expected lifetime of at least 30 years. The most important (and highest risk) aspects of a geothermal project are the identification and measurement of the geothermal resource to be developed. Private sector interest is usually strongest where national authorities are actively involved in geothermal resource identification and testing. This decreases the risk faced by potential developers and financiers and the lead-times needed for development.

Potential UNEP/GEF Roles are:

1. UNEP/GEF should work with multilateral and bilateral financing and technical assistance agencies, export credit agencies, venture capital fund managers, equipment suppliers and host country governments to establish strategies to share the costs and risks of "upstream" geothermal exploration.
2. UNEP/GEF should encourage and facilitate host country governments becoming active participants in promoting geothermal development. This includes creating conducive policy and regulatory environments and participating in initial exploration and resource assessment efforts. This will serve to bring the private sector to the table and facilitate developer access to investment capital.
3. UNEP/GEF should remain informed about R&D carried out by bilateral agencies and scientific laboratories related to improved drilling, reservoir engineering and other techniques that can decrease exploration costs and risks.

9.3 *Lack of host country government awareness about geothermal energy and private sector participation*

In many cases, host country governments are not aware of the existence and advantages of geothermal energy including energy diversity, provision of clean, dependable, safe energy using little land, decreasing fuel importation, deforestation, foreign exchange expenditures and other issues.

They may also not be aware of the issues the private sector analyses prior to undertaking a geothermal development/investment project such as policy/regulatory environment, off-taker and sovereign credit ratings, risks of currency exchange fluctuation, economic and political crises, etc.

Lastly, Governments may also not know who the private sector developers are with proven geothermal experience and who are interested in investing and remaining involved in emerging market geothermal projects for significant periods of time.

As indicated above, significant investment is required for the upfront resource exploration and definition phases of a project to enable it to be considered "investment grade". Legal and policy frameworks that encourage exploration and development by providing specific rights of development and which reward risk through high returns on investment are essential.

Potential UNEP/GEF Roles are:

1. Regional geothermal conferences should be organized by UNEP with bilateral support to allow ministry, utility, geological survey, financing agency and private sector personnel to exchange experiential information, discuss their needs and establish professional contacts.
2. Geothermal developers interested in working in emerging market countries should be identified and their corporate capability statements collected, bound and translated into key languages. To carry out such an initiative, UNEP/GEF should work closely with national and international geothermal industry associations and their member companies.
3. In addition to a review of selected past geothermal projects, 2 3 pilot country projects should be selected for multilateral, bilateral and private financial support and issues, problems, and successes carefully documented. Three different types of market segments could be considered e.g. national grid applications, decentralized grid, and direct heat use systems. Potential country projects include Vietnam, Guatemala, Honduras, Russia, and Djibouti for electricity generation and Poland, Lithuania, Croatia and Slovenia for direct uses. UNEP/GEF (as well as other multi and bilateral agencies) should provide support in the pilot countries for establishment of optimal policy frameworks, long-term power planning, market integration through international collaboration, environmental impact and recommendations for obtaining private project financing.
4. In order to disseminate lessons learned from the previous and current pilot projects, a compendium of "Best Practices" should be prepared and published. This information should be updated on a regular basis as new experience is gained.

9.4 *Lack of private sector access to financing due to modest scale of geothermal projects*

Sizing of geothermal power projects is an important element that must be approached with both vision and realism. If new power projects are too large, they can constitute a debt burden that cannot be repaid from user revenues. This can create a drain on national budgets and put a private power developer out of business. The sizing of power projects too modestly can preclude economies of scale and needlessly increase the cost of electricity. It can also constitute a constraint to industrial development and hamper the provision of consumer, education and health-related services.

Most geothermal projects in developing countries are sized in the 30–65 MW range. This is most often due to the absorptive capacity of the market. It may also, however, be the result of the geothermal resource base of individual sites being limited and allowing only modest-size projects.

Historically, small geothermal projects have not interested large energy companies with capital for resource exploration and assessment activities. Smaller companies that are interested in 30–65 MW range projects are usually undercapitalized and must seek outside financing for both exploration/resource assessment and plant construction. In addition, costs/kWh costs are higher for small projects as fixed costs have a more significant overall financial impact.

Potential UNEP/GEF Roles are:

1. UNEP, in collaboration with other multilateral agencies and with GEF support, can promote the bundling of prospective geothermal projects within a country or region to achieve magnitudes of 50 MW+ to obtain economies of scale and facilitate access to project financing. Projects developed simultaneously could be offered for bid together. Alternatively, a series of projects could be proposed with sequenced time frames. UNEP/GEF can encourage and facilitate bundling of geothermal projects by offering technical assistance and agreeing to process the group of projects together to minimize delays and administrative costs.
2. For smaller projects, the GEF, through UNEP, could provide up front, long-term contingent project loans or guarantees to share the high initial exploration costs and risks. Such costs could be shared with the developer, bilateral agencies, equipment suppliers and private investment funds. Loans would be repaid from project revenues if the resource exploration is successful and after the private sector investors have received their targeted returns.

9.5 *Need for information on potential roles of bi and multilateral agencies and investment funds*

Information concerning the types of assistance and financing made available by various bi and multilateral agencies and investment funds is often lacking. A clear presentation is needed of all existing public and private initiatives, agencies and funding mechanisms that are being or could potentially be tapped to promote geothermal energy development. Their potential roles, capabilities and strengths in relation to geothermal projects should be presented.

Potential UNEP/GEF Roles are:

1. UNEP, with GEF support, can collect and present information from multi and bilateral agencies and investment funds that relates to the ability of each agency to participate in the financing of different aspects of geothermal projects. This information can be presented in a way that graphs the stages of geothermal projects against the missions and funds of each agency.

9.6 *Lack of adequate infrastructure*

Geothermal prospects are frequently located in rural areas without road, bridge and communication facilities. Moving heavy equipment into these areas can be time-consuming and costly.

Potential UNEP/GEF Roles are:

1. UNEP/GEF can endeavour to encourage cost-sharing arrangements between government and private geothermal developers to provide communications, roads and other necessary infrastructure to geothermal sites.

9.7 *Lack of trained host country personnel*

In order for developing country governments to feel confident that the development of geothermal energy is carried out in a way that protects their national interests, it is beneficial for them to be able to obtain the informed views of energy specialists who have expertise in a number of key areas and in whom they have political, commercial and technical confidence. These areas include policy-related aspects of geothermal energy as well as resource assessment, development, plant installation and maintenance. Historically, this expertise has been obtained from outside consultants who have been made available by private companies, bilateral or multilateral agencies for limited periods of time. From the developing country's point of view, this represents a less-than-ideal situation as the assistance can be costly, of uneven quality and be perceived as representing other-than-national interests.

Potential UNEP/GEF Roles are:

1. To expand the scale of geothermal use in the developing world, countries with proven or potential geothermal resources should have access to a minimum number of host country nationals with both theoretical and practical training in areas related to geothermal resource exploration and assessment, drilling and reservoir engineering, chemical analysis, power generation, and plant operation and maintenance.
2. UNEP, with the support of the GEF, can establish a strategy among industrialized and developing country geothermal agencies to assist developing countries with geothermal potential to build up groups of specialists with knowledge and experience in geothermal exploration and development. Both theoretical and practical training should be provided on an ongoing basis at a designated centre to provide training in areas such as geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, chemistry of thermal fluids, environmental studies, geothermal utilization, and drilling technology.
3. Trainees should be for engineers, technicians and scientists from energy ministries, universities, private companies and research institutions that have at least one year practical experience in geothermal (or 3–5 years of geological and/or power generation) work in their home countries. Short term (2 16 weeks) as well as long term (6 months) training programs could be organized. Study tours to geothermal installations and research centres could be included. If possible, participants could use data from their own countries as part of the training programs.
4. Training should also be provided for policy makers regarding the advantages of diversity in energy supply, comparative environmental benefits, and the need for laws pertaining specifically to private geothermal concessions/development. They could also be familiarized with the administrative and management aspects of private sector electric power regulation.

10 CONCLUSIONS

The conditions necessary for private sector-based geothermal development are broad-based and touch on fundamental aspects of national energy policy and the long and short-term commercial interests of private developers and investors. Related to these concerns are government regulation, project structure, debt and equity sources and development times. From a regulatory perspective, a strong government commitment to private power is a critical element in determining the success or failure of a private geothermal project. There also appears to be an increasing number of BOO project structures compared to BOT types.

Most private power projects to date have made use of debt-related financing and credit enhancements from export-credit agencies and multilateral development banks. Development times average 2–3 years with longer times in countries without previous private geothermal power experience.

Government participation in risk sharing is a key element. Important areas include resource exploration and risk assessment, utility performance, currency convertibility, inflation, uninsurable *force majeure* and political events. In more unstable country environments, governments are usually required to assume more risk. Increasingly other mechanisms are being used such as government loans, public insurance, local government support and commitments from utility off-takers. As markets open and private power projects become more common, host country governments will probably assume fewer risks.

UNEP and the GEF can play pivotal roles in promoting the development of private geothermal energy projects by serving as catalysts for other bi and multilateral agencies, host country governments and investment funds as well as private geothermal developers.

As UNEP and the GEF can work with all of the above types of agencies, it is in a unique position to forge international cooperation and finance actions to address the barriers described above.

UNEP and the GEF should carry out a review to assess the need for new forms of partnership between the private sector, where most technologies are developed, and financial organizations such as multilateral banks, bilateral organizations, and private investment funds, in order to overcome the initial financial obstacles associated with geothermal project development. UNEP/GEF can also play pivotal roles in promoting the establishment of government policy incentives to favour geothermal energy technologies, capacity building in the public and private sector, and fostering a comprehensive view of private power and environmental policies in conjunction with development and social objectives in a number of selected countries where use of geothermal energy can be increased in a significant manner.

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Small geothermal projects for rural electrification

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ABSTRACT: Opportunities for small geothermal projects exist in many areas of the developing world. Geothermal power plants with <5 MW of capacity could supply electricity where it is most needed: in remote areas. The technological feasibility of small geothermal power plants is proven, but their operational and economic feasibility for remote applications is less sure. An economical, effective geothermal resource exploration and characterization program is essential for successful small geothermal projects. Existing mini-grids are perhaps the most promising application for the small plants, where they could supplement or displace diesel generation. Companies from the United States, Europe, Japan, Iceland, New Zealand, and developing countries will compete for profitable small geothermal projects in remote areas. However, such plants would serve these markets almost exclusively in countries where strong government or regional policies help overcome the special financial and operational challenges associated with their small size.

1 INTRODUCTION

Demand for better electricity supplies in rural areas of developing countries is expected to grow rapidly in the coming years. Small geothermal power projects (defined here as <5 megawatts (MW) in size) could compete in this market, but they face many hurdles. This chapter examines these hurdles, especially in Latin America, the Caribbean, and the Philippines, where geothermal resources, dynamic electricity markets, and relatively low political risk converge. This overview of issues facing small geothermal projects may be useful especially for readers not already familiar with small geothermal opportunities. We hope that those readers more familiar with small geothermal projects can use this chapter as a starting point in determining the next steps to develop this market.

To describe opportunities to serve remote electricity markets with small geothermal power plants, we examine small geothermal systems and their current applications (Section 2), geothermal resource characterization (Section 3), rural energy needs (Section 4), technologies for rural energy markets (Section 5), private-sector participation (Section 6), rural electrification lessons learned (Section 7), and conclusions and recommendations (Section 8).

2 SMALL GEOTHERMAL SYSTEMS

Our technological focus defines small geothermal power plants, identifies their current applications, compares technologies for rural applications, and examines their costs.

2.1 *What are small geothermal projects?*

In this chapter, we consider small geothermal projects to be <5 MW. Financing criteria, previous definitions, and rural electricity supply criteria are considered in arriving at this definition. Small geothermal projects face financing challenges that larger projects do not, because of fixed costs that are independent of project size, and because project financing is unlikely to be available to small projects. For ease of financing, even a 5 MW project is undesirably small.

Previous definitions of small geothermal projects provide another perspective. Entingh et al. (1994a and b) refer to a range of 100–1000 kilowatts (kW). Recent work on using slim holes for small geothermal also defines "small" as 100–1000 kW (Pritchett 1998a).

Besides financing criteria and historical precedent, the size range of geothermal plants most useful for rural electricity supplies can be used to define "small". Efforts to provide electricity to unserved and underserved rural populations emphasize systems far smaller than 1 MW, reflecting more pressing need, larger number of possible sales, and higher cost of conventional energy sources as size decreases. With low per-capita electricity demands and geographic dispersion typical of rural people in developing countries, this market may be best served by several small generating units, rather than fewer, larger ones.

We will focus on rural markets for geothermal electricity systems <5 MW. This definition represents a compromise among financing, historical, and rural electrification criteria.

2.2 *Current applications of small geothermal plants*

Small geothermal power units are already common, though generally not in remote applications. Instead, they are used within larger geothermal developments, either because they are cost effective, because they fit with incremental development plans, or because they were installed early in a site's development. Current applications at large geothermal developments provide important experience with small plants, but remote applications would pose different challenges.

Examining size distributions of geothermal units throughout the world shows that small geothermal power units are numerous, that the number of units increases at smaller sizes, and that many units are smaller than 5 MW (Based on small geothermal units listed as "Operating" in the Geothermal Resources Council (GRC) geothermal project database, as of June 1998). However, most of the operating geothermal units 5 MW or smaller are installed at a site where the total generation is much larger. The sites where less than 5 MW of capacity has been developed are generally not remote; many are at sites near larger developments, at sites where there were plans for additional development to a much larger size (Huttrer 1995), or are not actually operational (Smith, pers. comm.) (See Table 1).

Small geothermal units are used at larger developments for several reasons. First, a modular approach can be less expensive overall because of shipping and handling costs. Second, small modules increase reliability and improve flexibility when adapting to changing well and system performance. Third, a small, remote well is sometimes located far from other wells because of reservoir characteristics, and a power plant at the remote well may cost less than transport pipes for the fluid.

A small geothermal unit may be installed at a site that has become, or is expected to become, much larger, to supply electricity during early phases (e.g. Dieng, Fang); (Ramingwong and Lertsrimongkol 1995). If development lags, a small plant may remain alone at the site for many years.

Table 1 shows four examples of operating small geothermal plants that are at remote locations, not at larger sites. The Ormat plant at Nagqu, Tibet, China, may be the only example of a small, operating, remote geothermal plant in a developing country. This 1-MW binary plant was constructed as a United Nations Development Program project (Ormat 1998).

Table 1. Small geothermal plants.

Power plant name	Country	Site	Geothermal field	MW at site	Status
Amedee Geo.	USA	California	Amedee H.S.	2	Operating
Dieng Monoblock	Indonesia	Central Java		2	Operational at different site (Sibayak)
Fang GT Demo plant	Thailand	Fang	Fang	<1	Expansion expected
Bouillante	France	Guadeloupe		4	Operating
Bjarnarfalg, Gufustoo	Iceland	Namafjall		3	Expansion expected
Copahue Power Station	Argentina	Neuquen Province	Copahue	1	Not operating
Empire Geo. Project	USA	Nevada	San Emidio KGRA	5	Expansion expected
Nagqu	China	Tibet		1	Operating
Pico Vermelho	Portugal	Pico Vermelho		3	Expansion expected
Kirishima Hotel	Japan	S Kyushu		<1	Near larger site
Wabuska	USA	Nevada		2	Operating

Source: GRC (1998), Smith (pers. comm.).

A critical distinction between the application of small geothermal plants within a larger site and application in a remote area is that a large geothermal site on a large electrical grid will serve base electrical load because of geothermal technologies' limited load-following ability and relatively high capital cost. Remote areas and small grids generally have low base loads, so the contrast between achievable capacity factors (and thus costs per kilowatt-hour [kWh]) for large versus small grid applications is striking.

Generally, the development of a large geothermal field has been the primary reason for installing small geothermal plants. The large number of small geothermal units installed shows that there is useful experience with small plants, at least in the 1 5-MW size range. These plants are technically sound, and data about their installation, operation, and maintenance could be relevant to remote geothermal sites. The same technologies could be used in remote locations, but the application of small plants at large sites is distinct from the small, remote geothermal niche. Small systems at large sites have advantages over remote ones in that the financing is secured for the entire project. The resource is confirmed for the large project, O&M (operation and maintanance) infrastructures are readily available, a grid either exists or is constructed for the large project, and sufficient base load is available. Therefore, the success of small systems at large project sites is insufficient to demonstrate their viability in remote locations.

3 GEOTHERMAL RESOURCE CHARACTERIZATION

A developer of small geothermal projects seeks usable geothermal resources that can be identified with relatively inexpensive exploration. After considering exploration cost issues, we briefly review the status of exploration.

3.1 *Usable geothermal resources*

Usable geothermal energy resources exist where geologic features produce temperatures sufficient for heating, cooling, and electricity production. In general, temperature increases with depth from the Earth's surface at an average rate of 25°–30°C/km (124°–138°F/mile)

(Fridleifsson and Freeston 1994). Economically competitive use of the geothermal resource for electricity generation requires a higher-than-average temperature gradient. The natural presence of water (a hydrothermal resource), and permeable or fractured rock that allows replenishment of that water are critical resource characteristics for electricity generation; without them, small geothermal power plants would be too expensive.

3.2 *The resource characterization process*

Geothermal resource characterization for exploration of prospective sites for geothermal electricity production proceeds from the initial steps of identifying geothermal areas to the ultimate goal of understanding the hydrologic, geologic, and thermal characteristics of a site. Wright (1991) describes the exploration process and the techniques it uses. Although exploration strategies are case specific, Wright outlines a generic exploration strategy consisting of several stages: reconnaissance, prospect selection, and detailed exploration and drilling. The resource data are derived from geological, hydrological, geochemical, and geophysical studies. The literature on geothermal resource characterization techniques is extensive, and Wright (1991) provides an overview.

Reconnaissance, prospect selection, and detailed exploration and drilling would need to be performed for a small geothermal power project, though at a less-detailed level than for a larger one. Reconnaissance is undertaken in regions where geothermal resources are likely: where geological data such as tectonic boundaries and surface manifestations, such as hot springs and geysers, suggest the presence of a resource. In addition, the literature may guide the selection of areas for reconnaissance based on ownership and regulatory status. Once an area for reconnaissance has been selected, the goal is to develop a conceptual model of the underlying geologic features that is sufficiently detailed to support the selection of prospects, or to determine that further exploration should not be done. If exploration continues into the prospect selection stage, additional data is gathered at each prospective site to develop and refine the model of the geologic features until likely drilling sites can be selected. Exploratory well drilling is an essential step in characterizing the resource.

3.3 *Exploration cost reduction for small geothermal projects*

Small geothermal projects require an exploration approach that costs less than exploration typically undertaken for larger projects. For the success of this small-scale exploration program, its uncertainties must be understood, and exploratory drilling costs must be low. The distribution of exploration costs between government and private industry, and among geothermal projects, also influences the viability of small geothermal projects. Using existing data during exploration is an important cost-reduction strategy for small projects.

To control costs, exploration efforts for small projects would follow a simpler approach than a conventional exploration program for large ones. This approach would identify several project sites, would almost certainly require government involvement, would use less detailed testing and drilling, and might proceed as follows. A goal of five small projects in a region might be selected. Geothermal and electrification experts would select perhaps 10 to 15 prospective sites based on existing geothermal data and electricity needs. Each site would be subject to brief reconnaissance studies and limited testing. A maximum of two shallow exploratory wells would be drilled at the most likely sites. Each well would be drilled with the goal of using it as a production well.

The cost of drilling exploratory wells is the largest expense in exploration, and "small" geothermal requires exploratory well-drilling costs that are much lower than in a conventional program.

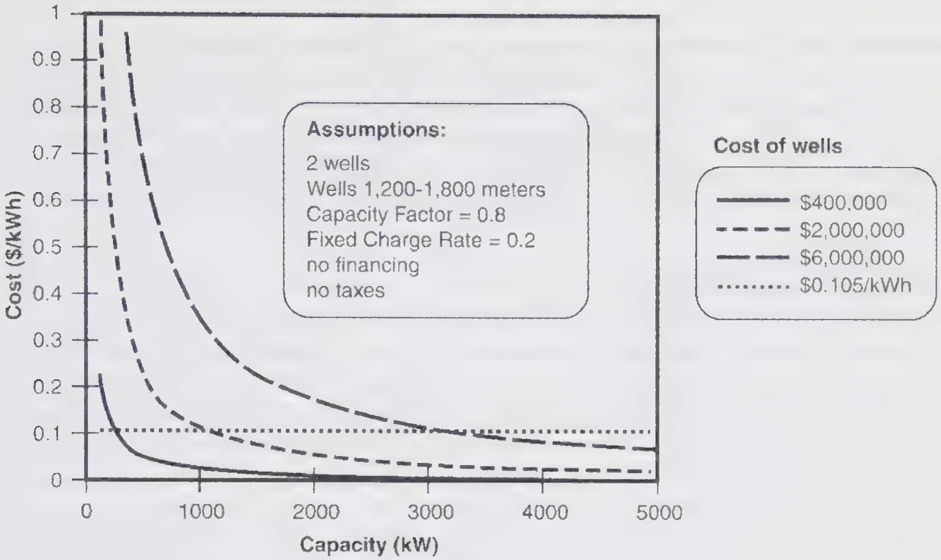


Figure 1. Well drilling cost per kWh versus capacity.

Exploratory drilling for large geothermal prospects would entail drilling at least three production-sized wells at each likely geothermal site (OLADE 1994). At $1 million to $3 million per well and a 25%–40% success rate (Finger 1998), exploratory well drilling costs could easily preclude competitive small geothermal systems. To illustrate this, Figure 1 shows an estimate of the levelized cost of energy associated with well costs alone at different costs per well.

Small geothermal plants could be considered where low costs per well can be achieved, either because of favorable geologic conditions or through the use of optimized drilling processes (Huttrer 1997, Pierce & Livesay 1994, Glowka et al. 1998) and drilling holes with smaller diameters.

The use of small-diameter ("slim") holes for geothermal exploration and production involves holes with a production zone diameter of 6 inches (152 mm) or less. Conventional production wells have a minimum production zone diameter of 8.5 inches (216 mm), with a 7-inch slotted liner in the production zone if needed (Pierce & Livesay 1994). Research suggests that 40%–60% exploration cost reductions can be achieved using slim holes, although some question remains about the accuracy of reservoir characterization data gathered from them (Finger 1998).

Current research efforts also are evaluating the use of slim holes for production (Pritchett 1998a). Slim holes are theoretically capable of producing sufficient geothermal fluid to support as much as several megawatts of capacity (Combs et al. 1997). Whether or not a slim hole supports artesian flow is an important factor in its economic viability for production, and in evaluating the alternatives of flash steam plants or binary plants. If the pressure in a slim hole is too low, then a downhole pump may be needed to produce geothermal fluid, or (especially in binary plants) to maintain pressure to keep the fluid in a liquid state. Availability of the right size of downhole pumps may be limited. The engineering economic evaluation of slim holes with downhole pumps depends on site-specific evaluation, that includes the parasitic load of the pump, its capital cost, and the generating capability of the slim hole with and without the pump (Pritchett 1997).

The distribution of the costs of exploration programs is an important consideration in determining the economic viability of small geothermal electricity generation. Publicly funded exploration subsidizes geothermal projects by distributing costs broadly. However, accounting for exploration costs is important to ensure appropriate priorities for public spending, even if the costs are not recovered through the project (Bradbury 1970). This is because the government incurs an opportunity cost equal to the value of activities that could have been funded instead of geothermal exploration. Another possible cost distribution would spread costs of regional or national exploration evenly among a large number of geothermal projects in the area, and so reduce the risk of excessive exploration costs on a single project. For example, Entingh et al. (1994b) assume "… an organized regional approach to exploration and test drilling, so that each stand-alone system does not bear all of the risk of exploration failure at any particular site".

3.4 *Resource characterization status*

The status of geothermal resource characterization, including what data exists and who supported its development, will be considered here to identify opportunities for small geothermal projects to use this valuable data. Some of the existing data that characterizes geothermal resources may be useful to reduce exploration costs of small geothermal projects. The funding sources that supported data development may have proprietary claims on the more specific, useful data, and also may be likely sources of funding for future exploration efforts.

Existing geothermal data ranges in detail from general locations of active geothermal regions to specific data about existing wells and conceptual models of geothermal resources. A global survey of thermal waters in the classic work by Waring (1965), "Thermal Springs of the United States and Other Countries of the World" provides basic data on geothermal surface waters for many countries. This information includes name and location, temperature, flow, total dissolved solids, principal chemical constituents, associated rocks, and descriptive notes. More extensive characterization of specific geothermal fields has been completed in those countries with more advanced geothermal development. Resource characterization in geothermal fields that are already developed is much more advanced than in unexplored areas.

Well-characterized resources at known geothermal fields are important to small-scale geothermal development for several reasons. First, known geothermal fields can be used to test small power plants. Second, if individual wells or entire known geothermal areas cannot support a large system, a small one may be appropriate, and would benefit from data that already had been gathered. Third, countries with extensive resource characterization and active geothermal development programs at known geothermal fields are much more promising for small-scale geothermal project development because of their in-country expertise and institutional commitment to geothermal energy.

In addition to using data from exploration of known large geothermal fields, earlier stages of exploration continue throughout the regions of interest. Examples of reconnaissance studies in Argentina, Mexico, El Salvador, Colombia, Guatemala, Peru, Chile, Bolivia, and the Caribbean are noted by Donovan (1985), World Geothermal Congress (1995), Smith (pers. comm.), and Huttrer (pers. comm.). The results of some of these studies are recorded in a Geographic Information System (GIS) that permits analysis with other important data, such as locations of roads and grids (Smith, pers. comm.).

Data from existing wells that were drilled for water, oil and gas, or large geothermal exploration may help geothermal exploration for small projects. For the more specific, useful data, proprietary concerns may arise, depending on funding and data ownership. National government and international funds have sponsored some exploration efforts, and exploration in developing countries often has been funded through international aid. For example, the United Nations Technical Assistance Programme funded initial geothermal exploration in some developing countries (Bradbury 1970), and subsequent United Nations funding also has been used (Donovan 1985). More recently, the U.S. Department of Energy funded reconnaissance studies in South America (Smith, pers. comm.). Similarly, the European Union and Italy recently funded reconnaissance and feasibility studies in Latin America and the Caribbean (Ducci 1995).

While information may be available from the exploration and development of large fields and ongoing exploration, this information is seldom publicly available or systematically assembled and so cannot be used to assess the overall potential for small systems. In addition, exploration has targeted large geothermal sites, possibly at the expense of exploring areas that might reveal opportunities for smaller projects. Thus, development of small geothermal power projects could be improved with better access to existing information and additional exploration.

4 RURAL ENERGY NEEDS

Small geothermal projects could provide electricity for rural energy needs in many areas of Latin America, the Caribbean, the Philippines, and other developing regions. These needs can be met with several technological alternatives under three rural electricity improvement approaches. In this section, we describe these approaches; and, in the next section, we describe the criteria for decisions among these alternatives.

4.1 *Rural energy needs*

Understanding current rural energy needs clarifies the role that electricity from small geothermal plants could play in improving those energy services. Rural energy uses, the status of rural electrification, and different approaches to rural electrification are described below.

Rural people in developing countries frequently lack access to modern energy technologies. The World Bank (1996) estimates that there are roughly 2 billion people without advanced energy sources. These people use traditional energy forms, such as burning biomass and using human labor. The World Bank (1996) summarizes information on rural energy use as shown in Table 2.

Table 2. Rural energy-use patterns in developing countries by end uses.

End Use	Household Income		
	Low	Medium	High
Household			
Cooking	Wood, residues, and dung	Wood, residues, dung, kerosene, and biogas	Wood, kerosene, biogas, LPG, and coal
Lighting	Candles, kerosene (sometimes none)	Candles, kerosene, and gasoline	Kerosene, electricity, and gasoline
Space heating	Wood, residues, and dung (often none)	Wood, residues, and dung	Wood, residues, dung, and coal
Other appliances	None	Electricity and storage cells	Electricity and storage cells
Agriculture			
Tilling	Hand	Animal	Animal, gasoline, diesel (tillers and tractors)
Irrigation	Hand	Animal	Diesel and electricity
Post-harvest processing	Hand	Animal	Diesel and electricity
Industry			
Milling & mechanical	Hand	Hand and animal	Hand, animal, diesel, and electricity
Process heat	Wood & residues	Coal, charcoal, wood, and residues	Coal, charcoal, wood, kerosene, and residues

Source: World Bank (1996).

Geothermal energy, as electricity or in direct-use applications, could improve energy services for many of these end uses. Lighting, appliances, irrigation, harvest processing, milling, and mechanical energy could be powered by electricity (the focus of this chapter); and space heat, harvest processing, and process heat could be supplied through direct use. Although direct use is not emphasized here, it could be an important source of energy for rural areas, either alone or in applications that employ geothermal fluid after it exits a geothermal power plant.

Much of the population that lacks access to electricity is in rural areas of developing countries. Table 3 shows the difference in developing country electrification rates between rural and urban people in 1970 and 1990.

Electricity use is expected to triple in developing countries, from 3 trillion kilowatt hours in 1996 to more than 9 trillion kilowatt hours in 2020, while use in industrialized countries almost doubles. Growth in Eastern Europe and the Former Soviet Union is stagnant over the same time period. This IEA reference case forecast assumes annual economic growth of 4.3% in Central and South America and 6.2% in developing Asia between 1995 and 2020, and does not consider electricity prices. It also assumes electric-sector reform (IEA 1998).

The rural energy needs, rural electrification rates, and projected growth in developing country electricity consumption show that providing electricity to rural areas supports development goals in growing markets. Overall, three approaches can improve rural electricity: extending or improving the national or regional grid; establishing, extending, or improving micro- or mini-grids; and establishing or improving individual systems. The decision among these different approaches should be based on cost, willingness and ability to pay, and future projections of each, so that the cost of the system will be recovered. The willingness and ability of rural households to pay for electricity services is an essential consideration in determining what type and level of service to offer. Level of service refers to the amount and hours of service of electricity available. Productive loads, such as industrial or commercial enterprises, enhance the ability to pay for electricity. Distance to the grid, number of households to be served, load density, and cost of generation determine the cost of grid service. Economic and population growth influence future ability to pay, as well as the costs of infrastructure per household.

Table 3. Urban and rural people connected to electricity in developing countries.

Region	Urban (%)		Rural (%)	
	1970	1990	1970	1990
North Africa and Middle East	65	81	14	35
Latin America and Caribbean	67	82	15	40
Sub-Saharan Africa	28	38	4	8
South Asia	39	53	12	25
East Asia and Pacific	51	82	25	45
All Developing countries	52	76	18	33
Total served (millions)	320	1100	340	820

Source: World Bank 1996.

Table 4. Approaches to rural electrification.

Approach	National or regional grid	Build or extend local mircro- or mini-grid	Install individual systems
Conditions			
Distance from local, national, or regional grid	Close to national or regional grid	Far from national or regional grid	Far from national or regional grid
Household service	High	High	Low

Table 4 shows the conditions under which each of the electrification approaches might be best. With the appropriate cost data, quantitative analysis could be performed to map the conditions under which each of the three rural electrification approaches in Table 4 would be economically justified.

5 TECHNOLOGIES FOR RURAL ENERGY MARKETS

Competitors of small-scale geothermal power production vary depending on which of the three electric-service improvement approaches best applies. We next consider the competition among technologies within these three markets, describe the types of geothermal technologies that could be selected, and characterize their costs.

5.1 *Describing the market for small geothermal*

Two factors define the niche for small geothermal systems in rural electricity markets: the electrification approach and the generation technology options. Electrification approaches divide rural electricity into three distinct markets: individual home systems, national grids, and mini-grids. Other technologies that compete with small geothermal systems include batteries and photovoltaic home systems in the individual system market; coal, hydropower, and oil in centralized generation for national grids; and diesel generators, gas turbines, mini-hydro, wind, and biomass in micro- and mini-grids. For purposes of our discussion, national governments, utilities, or private firms that have concessions for supplying rural electricity are assumed to make the choice among individual systems, national grids, and mini-grids, and to select an electricity-generation technology.

Current geothermal electricity-generation technologies are not small enough to supply individual systems, which are generally only tens to hundreds of watts in size. However, individual systems may be less expensive than grid-based technologies, once grid construction costs are included. Thus a national government, utility, or concessionaire could select individual systems as the least expensive method of electrification for some rural people. These decision makers compare the following two sums:

Generation ……….. + Transmission + Distribution + Operation + Maintenance
= Cost of Grid Technology

Generation + Operation + Maintenance = Cost of Individual System.

Of the technologies for individual systems, batteries are generally most expensive, with prices less than \$1.40/kWh cited as a goal for some projects (Bergey 1997). Batteries are competitive for the smallest systems, such as eight-hour area lighting (Cabraal et al. 1996). Photovoltaic home systems are best for slightly larger individual systems, and have achieved large demand, mostly in developing countries. In 1996, there were an estimated 400,000 individual photovoltaic home systems installed. Figure 2 shows approximate levelized capital costs per kilowatt-hour (adapted from Cabraal et al. 1996).

To justify building a small geothermal plant off the national grid, the distance from the national grid would have to be great enough that the capital cost of grid extension was, as a first approximation, the same as the capital cost of the plant. Figure 3 shows the distance from the national grid needed to justify different levels of capital investment. The grid extension costs are illustrative only, and depend on capacity needs and local conditions; they are roughly based on the range of estimated grid extension costs in Bolivia. There, a grid extension using a three-phase, 34.5-kV line that can carry 2 MW of power up to 77 km with a 7% voltage drop would cost \$11,000/km. A 69-kV line would cost about three times as much (Lilienthal 1998).

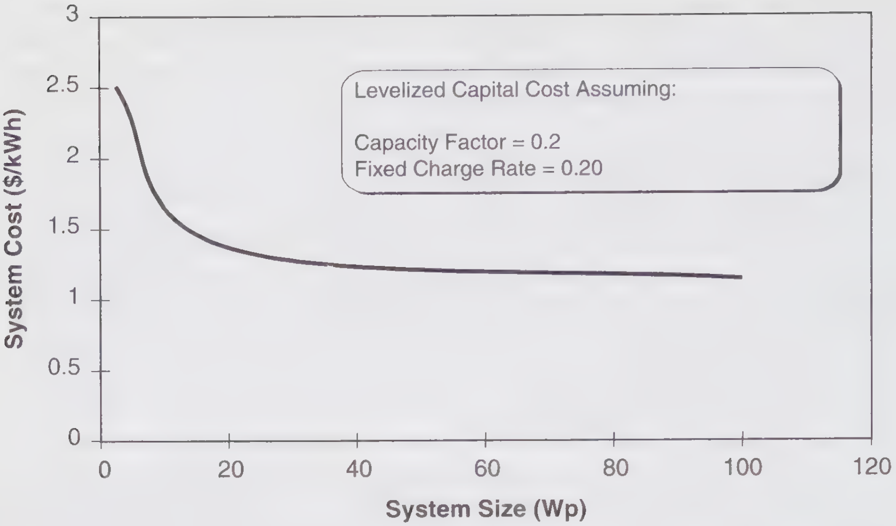


Figure 2. Photovoltaic home system cost per kWh versus size (adapted from Cabraal et al. 1996).

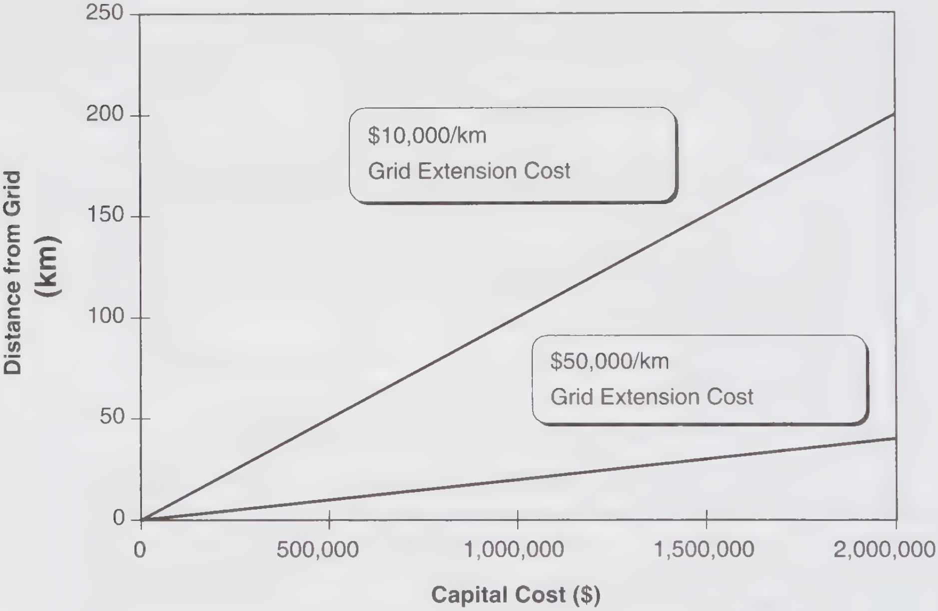


Figure 3. Distance from grid versus capital cost.

The service characteristics appropriate for an individual-system electrification approach are shown in Table 4. The boundary between these service characteristics and conditions appropriate to grid-based approaches can be changed through regional economic development, creating the higher numbers, service level, load density, productive load, and growth rate appropriate to a local grid or national grid extension. Small-scale geothermal power generation could then be employed.

The impact of individual systems markets on the small-scale geothermal market are that the costs of individual systems help to establish a limit on the price that it is reasonable to pay for grid electricity, and that economic development could transform individual system markets into grid-based markets where small geothermal power plants could compete. Increasingly, individual systems are used to provide rural electricity, but traditionally this has been less common than national grid extension or improvement. The high cost of grid extension in unelectrified or underserved areas ($0.12–$0.55/kWh [World Bank 1996]) is prompting the shift.

On the national grid, small geothermal plants would compete with a mix of fuels that varies within the geographic region, including hydropower, coal, oil, and natural gas. Within the national grid, small geothermal plants in remote locations could have value associated with generation that is distributed throughout the grid, closer to loads. This value arises because distributed generation may improve reliability and power quality, including voltage support and line control, and avoids energy-wasting line losses. However, distributed generation must be evaluated in comparison to other approaches to these problems, some of which should be taken first, such as basic maintenance of the grid. The distributed utility value of small geothermal power plants will depend on whether the national grid has capacity problems, reliability problems, power-quality problems, line-loss problems, or all of these – and on the options available to address them. If distributed generation were identified as the appropriate solution, installing a small geothermal plant could be the source of that distributed generation. To expand grid capacity, large geothermal is more likely to be competitive than small; but in remote regions of the distribution system, a small geothermal plant could make sense.

An example of the distributed utility application of a small geothermal project is the Copahue plant in a remote area of Argentina that is, nonetheless, connected to the national grid. Because of power needs for possible resort development plans in the area, bringing this plant back on line is under consideration (Smith, pers. comm.).

In addition to individual systems and national grid extension, establishing, extending, or improving a micro- or mini-grid is a third electricity-service improvement approach, and one that is considered the most likely niche for small geothermal projects. Here, small geothermal plants would compete with diesel, micro-hydro, wind, and biomass; diesel generators are the most widely used. The existing stock, sales, frequency distribution by size, and cost of electricity of small generators are important to determine opportunities for small geothermal projects to compete. The market for these generators is large and growing rapidly. World demand grew 4.5% to 386,000 in 1996, with most of the demand for sizes below 30 kW (AMPS 1997); India had 25% growth per year from 1992 to 1995, but growth in the very large category (500 kW-5 MW) was slow (Economic Times 1997).

The growth in demand for diesel generators shows that there is a promising market for small generation systems. The ability of small geothermal projects to compete in this growing market has not yet been demonstrated. Geothermal projects will have more difficulty as size decreases, which is where generator sales are most numerous and rapidly growing. However, capturing a small share of the generator market would represent dramatic market growth for small geothermal power plants.

To determine how many small geothermal plants could compete with existing diesel generation, data is required on the relative cost of diesel and geothermal generation at each site, given the load profile at the site. Comprehensive data of this nature for Latin America, the Caribbean, and the Philippines are not available, so estimates are based on data from Entingh, Easwaran, and McLarty (1994a and b), Lilienthal et al. (1998), and Abergas (1998). The cost of geothermal generation as a function of size was estimated using the GT-SMALL computer model (Entingh et al. 1994a and b) (See Table 6). Capital, operation, and maintenance costs of diesel generation as a function of size was estimated (Lilienthal et al. 1998) (See Table 5).

If diesel generators achieve the lifetime intended in their design, diesel fuel cost accounts for most of the cost of diesel generation. However, diesel lifetimes, and the resultant capital costs of diesel generation, are very dependent on the duty cycle and quality of maintenance in specific applications. Fuel cost also varies greatly depending on the cost of transporting it to specific

Table 5. Diesel generator costs.

Item	Units	Value
Diesel Fixed Capital Cost	US$	9600
Diesel Incremental Capital Cost	$/kW rated	140
Diesel Fixed O&M Cost	$/hr	0.136
Diesel Incremental O&M Cost	$/hr/kW rated	0.014

Source: Lilienthal et al. 1998.

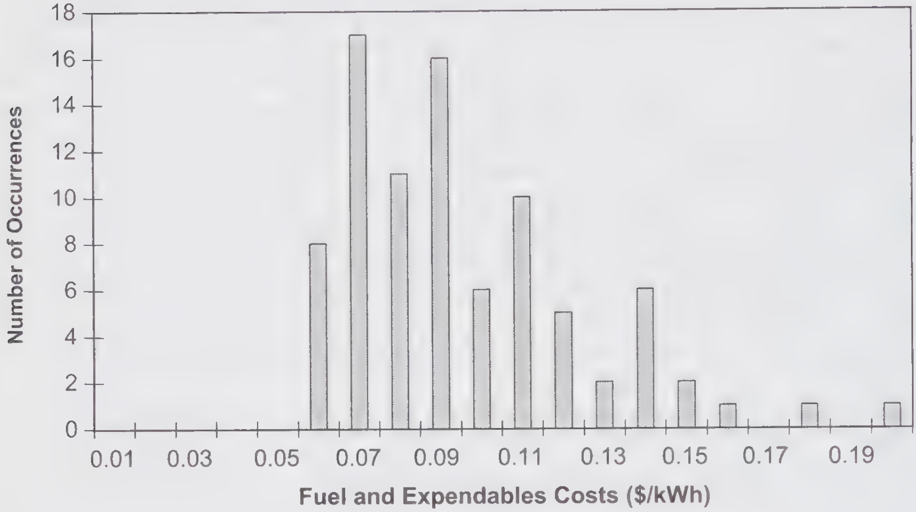


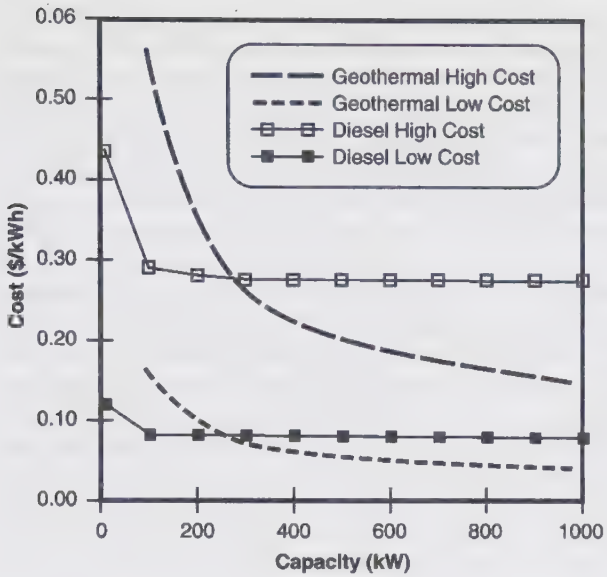
Figure 4. Frequency distribution of diesel fuel cost in the Philippines (adapted from Abergas 1998).

sites. Furthermore, each country has its own tax and subsidy systems, which are subject to rapid change during electric-sector reform. Fuel cost data used here are from the Philippines' remote power utility, the Strategic Power Utilities Group (SPUG). The data represent fuel and expendables costs, without taxes, at small diesel systems, on small islands, away from the main grid, and a frequency distribution of these grids is shown in Figure 4. An exchange rate of 30 pesos per U.S. dollar was assumed.

Combining these data yields the comparison of costs of geothermal and diesel as a function of size. As shown in Figure 5, the costs of electricity from small geothermal plants and diesel generators overlap in the 100–1000-kW size range. Overall, geothermal's chances improve at higher capacities. The example system that Entingh et al. (1994a and b) describe is 300 kW in size. Capital, operation, and maintenance costs for diesel are derived from data used in the Hybrid Optimization Model for Electric Renewables (HOMER) model (Lilienthal et al. 1998). A constant 80% capacity factor is assumed, although in practice this would generally decrease with decreasing size.

The geothermal lines in Figure 5 are not associated with the probability of finding the particular conditions that the line represents, and so do not account for exploration risk. The probability that a good geothermal resource is located close to an existing or prospective diesel mini-grid is not known, and improved estimates could be made with better geographic data.

Geothermal's relative advantage is not necessarily the greatest where diesel prices are very high. In general, the occurrence of very high diesel prices (more than $0.50/kWh) is most likely found in small system sizes. The transportation costs that drive up the cost of diesel generation



Assumptions:

Diesel High Cost
- capacity factor = 0.2
- diesel fuel cost = $0.2/kWh

Diesel Low Cost
- capacity factor = 0.8
- diesel fuel cost = $0.08/kWh

Note: This does not reflect the full range of diesel O&M costs that may occur, and these costs may be higher.

Geothermal High and Low Cost (see Table 6)

Figure 5. Cost of diesel generation and geothermal generation versus capacity (adapted from Entingh et al. 1994a and b, Lilienthal et al. 1988, Abergas 1998).

are also an indicator of challenging conditions for constructing and servicing a small geothermal power plant. Higher diesel costs occur where conditions such as low load density and remoteness are likely to raise costs of small geothermal projects as well. However, the incremental cost of geothermal caused by remoteness may be smaller than the incremental cost of transporting fuel to these locations.

Diesel generator stock, sales, frequency distribution, and costs characterize the opportunity for small geothermal plants to compete. The cost implications of the load profile in the target service area are a critical part of this competition. The GT-SMALL model assumes an 80% capacity factor for its example system. However, remote loads are notorious for their low base loads. Geothermal plants, though they have some load-following ability, are most economic as base load. The low base load could make an 80% capacity factor extremely difficult to achieve, and a lower capacity factor would raise the cost of energy from a small geothermal plant. In contrast, the cost penalty for a diesel system operating at lower capacity factor is relatively small if its primary expense is fuel. The relative shares of diesel generator capital and fuel costs, in turn, depend on actual diesel generator lifetime.

5.2 *Geothermal technologies for small systems*

The most likely technology choices for small geothermal power plants are flash steam and binary cycles. Dry steam systems are unlikely to be used in small geothermal plants because dry steam resources are thought to be rare.

Flash steam systems use steam produced from the geothermal fluid to drive a turbine, using backpressure or condensing designs. The simplest flash plants are backpressure units, in which the turbine exhausts to the atmosphere. Alternatively, in condensing units, the turbine exhausts to a condenser at sub-atmospheric pressure.

The advantages of flash steam systems in small applications include the relative simplicity and low cost of the plant. In contrast to binary plants, they require no secondary working fluid.

However, they pose a different set of maintenance, health, safety, and disposal problems (e.g. Forsha & Nichols 1997). Flash systems are most often used where higher resource temperatures (above 150°C [300°F]) are available, although a low-pressure turbine design for lower-temperature flash plants (110°C [230°F]) has been proposed (Forsha 1994), and feasibility of lower-temperature flash plants has been studied (Pritchett, pers. comm.).

Binary plants use the geothermal fluid to heat a secondary working fluid, which then drives a turbine. An advantage of binary technology is that, in small-size ranges, modular binary units are readily available. Because the geothermal fluid can be contained in a separate loop, precipitation and environmental effects of the geothermal fluid can be controlled. Conversely, secondary working fluids may be hazardous and difficult to supply. Other disadvantages of binary designs are the higher capital costs and greater complexity of plants (Forsha & Nichols 1997).

The choice between flash steam and binary designs for small geothermal plants will be site specific, and will depend on resource temperature, chemical composition of the geothermal fluid, and maintenance preferences. The site-specific characteristics of geothermal resources; the small number of small, remote, geothermal plants; and the limited amount of published data comparing operation and maintenance costs complicate the comparison between flash steam and binary designs.

5.3 *Costs of small geothermal plants*

Ultimately, the costs of small geothermal plants will determine their potential market. The two types of cost evidence here are reported costs from small geothermal plants at large geothermal developments and modeled cost estimates. Reported costs from small geothermal plants are rare. Few small units in the GRC database list initial power prices. Those that do are located at large fields and are in the \$0.05–\$0.07/kWh range, for units in the 1–5 MW range (GRC 1998).

Entingh et al. (1994a and b) developed a model called GT-SMALL for small, binary geothermal systems in the 100–1000-kW size range (Table 6, Fig. 6). The accuracy of GT-SMALL is difficult to evaluate given the scarcity of remote applications of small systems. The \$0.05–\$0.07/kWh prices reported in the GRC database are comparable to the modeled cost estimates at the 1-MW size.

Assumptions about the exploration costs, resource quality, and financing costs determine the modeled cost results. In their modeling study, Entingh et al. (1994a and b) describe an example system that serves as a reference point. The characteristics of the example system are shown in

Table 6. Major characteristics of example system from Figure 6 ("modal" system in the original papers).

COST: US \$0.105/kWh	Item	Units	Value
Technical	Resource temperature	°C	120
	System net capacity	kW	300
	Number of wells		2
	Capacity factor		0.8
Capital costs	Exploration	\$1000	200
	Wells	\$1000	325
	Field	\$1000	94
	Power plant	\$1000	659
O&M costs	Field	\$1000	32
	Plant	\$1000	26
	Backup system	\$1000	5

Table 6 and Figure 6. The probability of finding the conditions of the example system is not known, and could only be estimated after extensive resource characterization.

For a small geothermal plant, Entingh et al. (1994a and b) assume exploration costs of \$200,000 (averaged over many projects), and production well cost of \$195,000 (1993\$). Thus, the exploration cost could pay for drilling slightly more than one production-sized well to confirm the resource, which is consistent with the well success rate of 25%–40% cited elsewhere (Finger 1998) if exploration wells were sometimes used for production. Actual estimates of exploration costs would need to be adjusted to reflect site-specific estimates of drilling costs and the risk of unproductive exploratory wells.

Another critical input to GT-SMALL is the resource temperature and depth. The 120°C (248°F) temperature of the resource at 300 meters in the example system is comparable to well data for the western United States (NREL 1994). A lower rate of temperature increase with depth at the proposed site, or greater uncertainty, would raise costs compared to the example system results.

GT-SMALL's financing assumptions should be considered in light of small systems' financing challenges. The cost of capital (a fixed charge rate of 12%) in the example system is moderate, to reflect rates available with government participation. Government guarantees are critical because small projects would face higher costs with private finance. For example, one geothermal developer suggested that private financiers seek 30% rates of return on investment. The Geothermal Financing Workbook lists rates of return in the 15%–30% range (Battocletti 1998). Although the assumption of a \$200,000 charge for exploration represents an exploration risk pooled among many projects, other risks are not explicitly accounted for, and including these might increase financing charges (Entingh et al. 1994a and b).

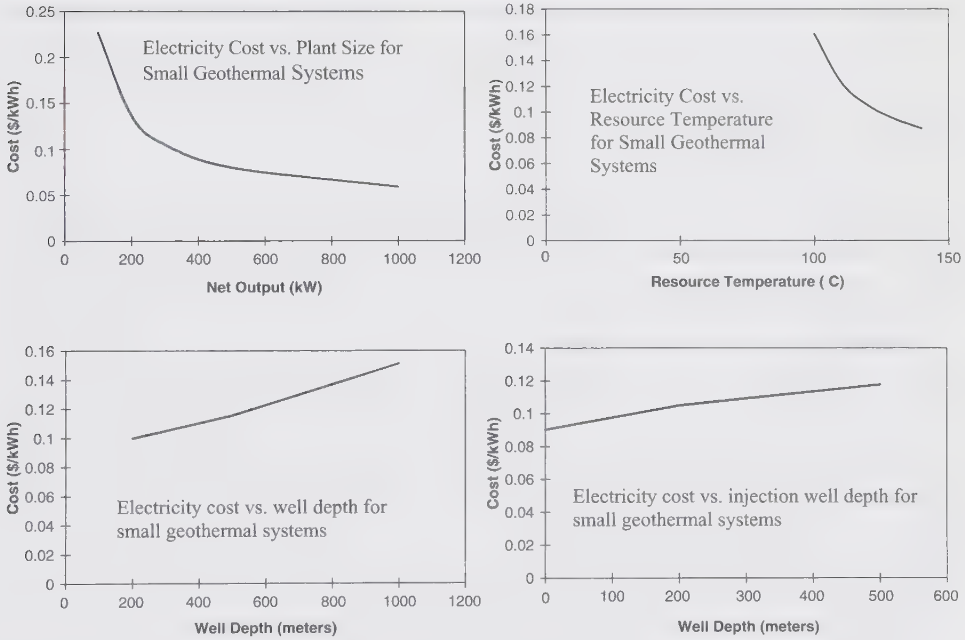


Figure 6. Modeling small geothermal plants; GT-SMALL: Economic evaluation of small geothermal electric systems for remote, off-grid locations (after Entingh et al. 1994a and b). Binary systems, 100–1000 kW in size, reservoir temperatures of 100°–140°C, production well depth of 200–1,000 meters, and injection well depth of 200–500 meters, were considered. The figures show cost variation with each of these independent variables. Technical costs at the busbar from this evaluation range from \$0.047–0.346/kWh. An example "modal" system costs \$0.105/kWh.

Although GT-SMALL did not include flash steam plants, these could be an alternative for small systems. Compared to the example system, flash steam plant capital costs probably would be lower. For example, estimated capital costs for binary plants in the United States were 1.2–3.1 times flash steam plants' costs (Petty et al. 1988). Cost comparisons between flash steam and binary plants are site specific, because operation and maintenance costs depend heavily on geothermal fluid quality.

The distribution of cost among major components of geothermal electricity in small projects in remote areas is not known. A rough approximation of the major technical cost components may be inferred from results of the IM-GEO model, which suggests that capital costs represent about 55%–80% of the cost of electricity generation, and operation and maintenance costs represent about 30%–45% (Entingh 1991).

Small geothermal power plants are one of many electricity generation technologies that could help meet rural energy needs. They could provide new grid electricity as part of economic development, improve electricity supply from remote parts of national grids, or enhance mini-grids, which are now mostly diesel fueled. To tap these potential markets, small geothermal projects will need institutional customers to buy the plants or the power they generate. These customers are considered next.

6 PRIVATE-SECTOR PARTICIPATION

Institutional customers will purchase the plant or the power that it generates. We now examine the effects of this institutional customer on small geothermal projects through an overview of the implications of electricity-sector structure and its reform for small geothermal projects, and the competitive opportunities for power plant manufacturers and developers within the geothermal industry.

6.1 *Electricity-sector structure and its reform*

The electricity sector in most countries historically has been viewed as a public service and, as such, government-owned or closely regulated, often with single major national utilities with close government relationships. These electric utilities are regulated, vertically integrated monopolies that are mandated to provide generation, dispatch, transmission, distribution, and customer service.

In national electric sectors dominated by utilities, independent power production is a common exception to the vertically integrated monopoly and can be a first step toward reform. Private companies may be allowed to build, own, and operate some generating facilities. The private company then sells its power to the utility under contracts that can take various forms. Countries within the regions of interest that allow private power projects include Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, the Dominican Republic, Guatemala, Honduras, Jamaica, Mexico, Panama, Peru, and the Philippines (Kozloff 1998). Major types of contractual arrangements for private power projects include Build-Own-Operate, Build-Operate-Transfer, and Build-Transfer-Operate.

Although independent power production and sales are a common initial step toward private participation, electricity-sector reform can extend far beyond this. Reform in the electricity sector is active throughout the world (e.g. Dussan 1996, Kozloff 1998). It may be categorized into three major types: commercialization, privatization, and restructuring. Commercialization refers to the introduction of private-sector principles to the operation of a public electric utility. For example, commercialization would eliminate government subsidies to the utility. Privatization means that the private sector performs fundamental functions of the utility, such as power sales, capacity construction, and generation ownership. Independent power projects and independent

Table 7. Effects of electricity sector reform on small geothermal projects (after Kozloff 1998).

Reform	Advantages for SG projects	Disadvantages for SG projects
Commercialization	• Removal of subsidies for competing technologies • Improved accounting for benefits of distributed generation • Improved opportunities for new technologies	• Removal of subsidies for small geothermal projects
Privatization	• Improved management and cost recovery in electric sector	• Private finance prefers lower share capital cost generation • Social objectives that may have justified geothermal are removed
Restructuring	• Consumer choice allows green marketing	• Environmental effects must be taken into account or consumers will just buy the least expensive
	• Geothermal won't pay intermittency penalties for transmission access	• No entity realizes distributed generation benefits

power sales are examples of privatization. Restructuring separates different functions of the vertically integrated utility and allows competition in each of these markets (Kozloff 1998). Dussan (1996) identifies the major issues that reform in the Latin American and Caribbean region has sought to address and the important attributes of effective reforms.

The implications of electric-sector reform for small geothermal projects are mixed, and include instability during regulatory transitions as well as changed competitive environments in the reformed market. Among these changes, mechanisms for rural electrification, governments' roles, and financing are especially important to small geothermal projects.

Once reform occurs, small geothermal projects face a changed competitive environment. Likely advantages and disadvantages of electric-sector reform to small geothermal projects are shown in Table 7 (based on Kozloff 1998). Of the changes arising from reform, treatment of electrification especially affects the remote markets considered in this chapter. No single method has emerged to improve rural electricity in a reformed market. Such methods must be established because utilities often subsidize electricity improvements (Kozloff 1998). Government contracts to private companies to serve rural areas are one mechanism. For example, Argentina grants concessions that designate an exclusive provider for a rural region. Rates are negotiated during bidding (Kozloff 1998). In contrast, the Philippines' reform does not privatize electrification and rural services. Instead, the part of the Philippines National Power Corporation responsible for remote areas, the SPUG, will be a subsidized independent government agency with a public service mission (IEA 1997).

Changes in government roles under reform also affect small geothermal projects. Now, national governments secure international financing for specific geothermal projects that they have requested. Under reform, the private sector is expected to invest a greater share of funds in capacity expansion, although the government still may obtain public development funds. Reform could reduce the ability of national government to help small geothermal projects because it reduces governments' role in setting electrical capacity expansion policy and coordinating funding of energy projects and programs. Despite this reform trend, countries placing high priority on geothermal resource development may retain a government role. For example, Nicaragua has a national master plan for geothermal energy to facilitate granting concessions for geothermal exploration and development (Zúñiga 1998). As an indigenous resource, geothermal energy can support government policy goals for energy self-sufficiency and allocation of foreign exchange, and such goals would lend support to a continued government role despite reform.

Reform also affects financing for geothermal projects. One goal of electric-sector reform is to increase private investment, which could create opportunities for small geothermal projects to compete in more open markets. Thus, challenges of attracting private investment are all the more important to address under reform. Midsized transactions of $1 million–$10 million, typical for small geothermal projects, are particularly difficult to finance (Battocletti 1998). Too large for informal micro-finance mechanisms, small geothermal projects also may be too small for traditional development bank-lending programs.

A reduced government role coupled with financing difficulties poses a challenge to small geothermal projects. National governments can improve financing prospects for small-scale geothermal developments, for example, by organizing exploration, bundling projects together for financing, or combining geothermal projects with economic development. However, unless government involvement is deliberately retained, electric-sector reform may leave competing private firms to select new capacity types. Private firms favor technologies with lower capital costs as a fraction of total cost because of the lower initial financial risk. Although technologies with relatively high capital costs and relatively low variable costs, such as geothermal, reduce or eliminate the risk of fuel price increase, these risks are less immediate than paying a large fraction of the cost of energy as initial capital cost. However, capital costs of diesel generation may be underestimated if in-use lifetimes for the expected duty cycle and operating conditions are not taken into account. A deregulated market may allow consumers to express a preference for specific types of generation, such as geothermal, because of advantages such as low environmental emissions. Price is likely to be the primary consideration for consumers, however, especially in developing countries.

In sum, electric-sector reform is shaping the customers for small geothermal plants. Geothermal projects must compete in electricity markets that are being transformed by commercialization, privatization, and restructuring. Implications of reform for rural electricity supply, national governments' roles, and private finance present challenges and opportunities for small geothermal projects. Experiences in rural electrification using other renewable energy technologies could help small geothermal power plants succeed.

6.2 *Geothermal industry capabilities and challenges*

Geothermal companies span a broad range of expertise, including geothermal development; exploration; drilling; power plant design, equipment, and construction; specialized scientific instruments for testing, monitoring, control, and logging equipment; heat exchange; and many different types of consultants (GRC 1998, GEA 1998). All of these industry sectors could work on small geothermal power plant projects. However, this examination of international competition will focus on the development and power plant segments of the geothermal industry.

The geothermal industry has experience with all of the major technology alternatives that might be used in small geothermal power plants including dry steam, flash steam, binary, topping/bottoming cycles, hybrids, and combinations with direct use. As discussed previously, flash steam and binary cycles are the most probable choices for rural electricity. The United States, Europe, and Japan are the most common location of companies listed in the GEA (1998) and GRC (1998) databases as project developers and power plant suppliers. Similarly, representatives of U.S. companies named Japanese and European firms as their most likely competitors in telephone interviews. Industry interviews with companies outside the United States were not conducted. Although Fuji is the only Japanese turbine manufacturer listed in the GRC database, U.S. company representatives noted that others, especially Mitsubishi and Toshiba, are strong competitors for geothermal equipment supply, so they could also participate in this market.

Although the geothermal industry can supply technologies for this market, improved small geothermal information and additional technology development is needed to cultivate the geothermal industry's capabilities to serve this market. Available operation and maintenance information includes the description by Forsha and Nichols (1997) of the Wineagle plant in California, which is presented as a model of what could be achieved in remote areas of developing countries. Its availability is reported as 98% during 11 years of operation, with "infrequent" unscheduled maintenance, periodic inspections, and yearly scheduled outages for maintenance. The plant has automatic control systems and is monitored by remote control. Remote control of geothermal plants also has been used in Italy to improve overall availability of large geothermal power plants from about 91% to 96% (Bracaloni et al. 1995).

For all sizes of geothermal plants, plant availability data are available from the GRC database. These data are incomplete, but show an average availability of 85%. Systematic identification of causes of outages for existing plants could be essential in achieving adequate performance and designing appropriate maintenance systems for remote areas.

Small-sized equipment manufacturing capability is a limitation on the growth of the small-scale geothermal market in a few respects. First, mass producing small plants as a package has been achieved only to a limited extent. Ormat probably approaches the goals of mass production and packaging most closely, with its modular binary systems. Producing large numbers of prepackaged small plants would reduce the cost of each plant if the small-scale market opportunities increased.

A second equipment availability limitation is the size range of units that are generally manufactured. Individual units are available in small sizes. Examples of small-sized units that are readily available include Geothermal Power Company's 500 kW steam units and Ormat's 300-kW binary turbines. Demonstration units have been prepared in even smaller sizes than this, but a significant shift in the economic size of geothermal power plants would be needed to increase manufacturing of smaller-sized units. In general, binary units have been manufactured in relatively small sizes, compared to steam systems.

A third equipment availability challenge for small plants is the limitations of other equipment and parts besides the power plant itself. For example, the highly portable, modern drilling rigs that Sandia National Laboratories examined to reduce drilling costs (Huttrer 1997) may be less available than older, less-efficient ones. Pritchett (1998a) also notes that the lack of a downhole pump small enough for slim holes is a current limitation, although one that could be overcome. A full systems study of each phase of development of a small power plant likely would reveal other equipment barriers to optimal development of these projects.

If there were a growing market for small, remote geothermal projects, international competition would come from several geographic areas. U.S., European, and Japanese companies probably have the best chance to successfully compete because of their international experience with geothermal projects and their international development programs. Iceland and New Zealand, with strong domestic experience, international training schools, and some international geothermal projects also have capabilities to serve this market.

In addition, several developing countries (Mexico and the Philippines, for example) already have significant expertise with specific aspects of geothermal power projects. If this market grows, the geothermal industry in developing countries could grow and become even more effective in competing or partnering with other international companies. Mexico and the Philippines could increase their exports of geothermal services to neighboring countries. An effective indigenous industry serving the small-scale geothermal market would be particularly likely in countries that already have significant industrial capabilities. A developing country is likely to provide strong political support for its own government or private-sector geothermal efforts. For example, PNOC's exploratory well data, and its status as a government corporation, could pose challenges for geothermal projects in the Philippines that did not have PNOC support. Japanese firms benefit in comparison to their international competitors because of the close cooperation between Japanese government and industry and the Japanese government's high profile as an international donor. Japan has used international development funds to support geothermal exploration. For example, the Japanese Overseas Economic Cooperation Fund provided the financing for feasibility studies for geothermal projects in Nicaragua, the Philippines, and Costa Rica (West JEC 1998). Japan provides "tied aid," in which development aid is packaged with contracts for Japanese businesses.

Similarly, the European Union, Italy, France, and Belgium have funded geothermal projects, from reconnaissance through construction, in Latin America and the Caribbean (Ducci 1995). The European Union funded the project, "Evaluation of the Capability for Managing Geothermal Resources in Latin America and the Caribbean". This project furthers international goals of the United Nations Economic Commission for Latin America and the Caribbean (UN CEPAL), and benefits European industry. For example, the project description explains that benefits to the European Community include improved information about geothermal resource potential, investment opportunities, technological and personnel requirements, and legal and financial conditions (CEPAL 1998). As in Japan, close ties between government and industry are shown in France, where CFG is a commercial subsidiary of a public agency (CFG 1998).

Development aid from national governments clearly plays a role in facilitating geothermal development. The relationship to business development in the country that provided aid may be a direct one, as with "tied aid," or an indirect one based on networking and building relationships between representatives from the geothermal industry of the donor country and decision makers in the recipient country.

7 RURAL ELECTRIFICATION: LESSONS LEARNED

Lessons learned from implementing other renewable energy technologies may apply to geothermal in remote areas. While some of these lessons are based on experience with projects in the individual system market, many apply to the small geothermal opportunity. The types of best practices here include financial arrangements, market infrastructure, performance safeguards, and government and donor support (Cabraal, Cosgrove-Davies, and Schaeffer 1996). Lessons learned are shown in Table 8.

Integrating renewable energy projects with economic development faces ongoing challenges. Electrification alone accomplishes much less than a broader rural economic development program (Taylor 1998). Electrification is not always well integrated with rural economic development, because different institutions and different funds support these activities. Better integration of energy projects with economic development would help geothermal energy

Table 8. Lessons learned in renewable energy for rural electrification.

Topic	Lessons learned
Financial arrangements	• Initial cost barrier must be overcome for small consumers • Innovative finance is needed • Long-term subsidies must be selected cautiously • Effects of politics on decisions should be examined
Market infrastructure	• Market infrastructure must include marketing, distribution, installation, maintenance, and revenue collection • Existing local infrastructures can be used • Local needs must be considered
Performance safeguards	• Rural conditions can be harsh • Reliability, ease of use, and maintenance are key • Quality control and managing user expectations are important
Government and donor support	• Support should facilitate expansion of market size • Governments and donors have a role in catalyzing private finance • Coordination is essential to leverage donor and government resources

because rural economic development plans that increase load and base load could be coordinated with plans for small geothermal projects. For example, such development plans could improve mini-grid load profiles by linking productive loads, such as agricultural water pumping, to mini-grids that now serve mostly residential loads.

8 CONCLUSIONS AND RECOMMENDATIONS

Small geothermal projects, less than 5 MW in size, could improve rural electricity supplies for the growing markets of Latin America, the Caribbean, and the Philippines. Small geothermal units could use either flash steam or binary technologies; these are technically proven and widely used in larger U.S. geothermal developments. However, their operational and economic feasibility in remote areas of developing countries is less well demonstrated. Investors in small geothermal projects will require documentation of performance in remote settings, including feasibility of plant designs and operation and maintenance plans. The choice between binary and flash will depend on site-specific characteristics. Small geothermal plants are potential competitors with diesel generators for rural electricity markets.

Exploration for small geothermal projects must be inexpensive so that the electricity from the project will be cost competitive. Understanding the effectiveness of small-scale exploration programs, and controlling drilling costs, present a significant challenge for small projects. Methods to reducing drilling costs include using slim holes for exploration and production, and advanced drilling systems. Geothermal resources have been characterized, to varying degrees, at many sites in Latin America, the Caribbean, and the Philippines. Using and adding to this knowledge base systematically could help small geothermal projects achieve low exploration costs. Existing wells may help geothermal exploration for small projects.

Rural people have pressing energy needs, and electricity from small geothermal plants could meet some of these needs. Individual systems, national grids, and mini-grids are used to provide rural electricity, and each type of system presents small geothermal projects with different competitors. Economic development could combine individual systems into a grid that small geothermal plants could serve. Small geothermal plants could provide distributed generation to remote parts of national grids. In mini-grids, a promising market for small geothermal plants, they would supplement or displace diesel generation. As electric sectors reform, private power producers become more likely customers for small geothermal power plants than public utilities. However, a continued public role may be important to catalyze small geothermal projects. Faced with competitive markets, small geothermal projects can benefit from lessons learned from other renewable technologies that supply rural markets: lessons about institutions to provide operation, maintenance, and other services; about innovative financing and technology performance; and about effects on market development of support from governments and financial institutions.

International firms from the United States, Europe, Japan, Iceland, New Zealand, and developing countries could develop small geothermal projects. These companies have the appropriate technologies for small projects, and have experience in international geothermal project development. The industry might respond to a growing small-scale geothermal market by tailoring power plants, drilling rigs, pumps, and other equipment to small applications. Better market infrastructure and innovative financing could improve industry success in these markets. National governments enhance the competitive position of their geothermal industries by funding international geothermal activities, supporting international trade, and requiring purchases in exchange for international aid.

Systematic, global exploration, including small and low-temperature resources, should be continued. Existing wells and known resources should be considered for small geothermal projects. Geothermal resource data should be integrated with other geographic data such as grids, pipelines, roads, population, and projections of each; diesel generator locations, fuel costs, and operation should be included. This could be an expansion of current efforts, an international effort, or an effort from a government to develop small-scale geothermal opportunities.

We recommend that all phases of small projects be systematically evaluated to identify and reduce costs. Such efforts have been initiated in the drilling phase, with studies of portable drill rigs and slim holes. Evaluations should be performed on other topics specific to small, remote geothermal, such as appropriate secondary fluids for binary plants in remote areas, small pumps for slim holes, and operations and maintenance procedures. This could occur under the auspices of geothermal industry associations or under confidential agreements between private firms and researchers.

The small, remote geothermal concept should be proven to support financing of projects and planning of a service infrastructure. This proof could include establishing standards for small, remote systems to facilitate testing and improvements and developing data on operation and maintenance of small systems. Geothermal industry associations could establish self-enforced standards, or standards could be developed as specifications for government-funded projects.

Computer models can help to determine the optimal size and location of geothermal plants and grids within a rural electrical system. To accomplish this, researchers could complete development of these models, and the private sector or governments could agree to apply them.

The problems for small projects associated with electric-sector reform should be addressed. A strategy should be developed to interest private power producers in geothermal. Methods to determine the sale price of electricity from a small geothermal plant to the grid or mini-grid should be established. To smooth the transition to a reformed electric sector, a government could designate a small geothermal ombudsman, and international financial institutions could develop international standards for regulation and pricing. Industry, donor governments, recipient governments, and international financial institutions could partner to address these issues.

The credibility of small geothermal projects should be strengthened with lenders. This could involve exploring major issues for these projects with lender representatives. Financing approaches and processes may need to be standardized for small geothermal projects, and project bundling should be explored. Industry, donor and recipient country governments, and international financial institutions could collaborate to address this issue.

Private-sector service models for small geothermal systems should be validated, by drawing on the expertise of existing geothermal personnel and other market development efforts. Other private industries' service logistics expertise could apply to small geothermal projects. Private industry could collaborate with public and financial players to design and validate these models.

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Direct heat utilization of geothermal resources

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ABSTRACT: Direct utilization of geothermal energy consists of various forms for heating and cooling instead of converting the energy for electric power generation. The major areas of direct utilization are (1) swimming, bathing and balneology, (2) space heating and cooling including district heating, (3) agriculture applications, (4) aquaculture applications, (5) industrial processes, and (6) heat pumps. Major direct utilization projects exploiting geothermal energy exist in about 60 countries, and the estimated installed thermal power is 16,200 MWt utilizing over 64,000 kg/s of fluid. The worldwide thermal energy used is estimated to be alt least 162,000 TJ/yr (45,000 GWh/yr) – saving 11.4 million TOE/yr. The majority of this energy use is for space heating (37%), and swimming and bathing (22%). In the USA, the installed thermal power is 5366 MWt, and the annual energy use is 20,300 TJ (5640 GWh). The majority of the use (59%) is for the heat pumps (both ground coupled and water source), with bathing and swimming, and fish farming each supplying about 13%.

1 INTRODUCTION

Direct or non-electric utilization of geothermal energy refers to the immediate use of the heat energy rather than to its conversion to some other form such as electrical energy. The primary forms of direct use include swimming, bathing and balneology (therapeutic use), space heating and cooling including district heating, agriculture (mainly greenhouse heating and some animal husbandry), aquaculture (mainly fish pond and raceway heating), industrial processes, and heat pumps (for both heating and cooling). In general, the geothermal fluid temperatures required for direct heat use are lower than those for economic electric power generation.

Most direct use applications use geothermal fluids in the low-to-moderate temperature range between 50°C and 150°C, and in general, the reservoir can be exploited by conventional water well drilling equipment. Low-temperature systems are also more widespread than high-temperature systems (above 150°C); so, they are more likely to be located near potential users. In the U.S., for example, of the 1350 known or identified geothermal systems, 5% are above 150°C, and 85% are below 90°C (Muffler, 1979). In fact, almost every country in the world has some low-temperature systems; while, only a few have accessible high-temperature systems.

2 UTILIZATION

Traditionally, direct use of geothermal energy has been on small scale by individuals. More recent developments involve large-scale projects, such as district heating (Iceland and France), greenhouse complexes (Hungary and Russia), or major industrial use (New Zealand and the U.S.). Heat exchangers are also becoming more efficient and better adapted to geothermal projects, allowing use of lower temperature water and highly saline fluids. Heat pumps utilizing very low-temperature fluids have extended geothermal developments into traditionally non-geothermal countries such as France, Switzerland and Sweden, as well as areas of the mid-western and eastern U.S. Most equipment used in these projects are of standard, off-the-shelf design and need only slight modifications to handle geothermal fluids (Gudmundsson and Lund, 1985, and Geo-Heat Center Quarterly Bulletin, 19(1), 1997).

Worldwide (Lund and Freeston, 2000), the installed capacity of direct geothermal utilization is 16,200 MWt and the energy use is about 162,000 TJ/yr (45,000 GWh/yr) distributed among 60 countries (Table 1). This amounts to saving an equivalent 11.4 million tonnes of fuel oil per year (TOE). The distribution of the energy use among the various types of use is shown in Figure 1 for the entire world, and for comparison, the U.S. (Figure 2). The installed capacity in the U.S. (2000) is 5366 MWt and the annual energy use is 20,300 TJ (5640 GWh), saving 3.94 million TOE (Lund and Boyd, 2000). Internationally, the largest uses are for space heating (37%) (3/4 of which is due to district heating), and for swimming, bathing and balneology (22%); whereas, in the U.S., the largest use is for geothermal heat pumps (59%). In comparison, Iceland's largest

Table 1. Summary of direct-use data from individual countries (blanks indicate no value reported).

Country	Flow kg/s	Capacity MWt	Annual TJ/yr	Utilization GWh/yr	Capacity factor	Wells drilled	Person-years	Funds million $
Algeria	516	100.0	1586	441	0.50		27	
Argentina	2515	25.7	449	125	0.55	9	202	6
Australia	90	10.4	294	82	0.90	0	60	
Austria	210	255.3	1609	447	0.20	17		
Belgium	58	3.9	107	30	0.87			
Bulgaria	1690	107.2	1637	455	0.48		85	0.13
Canada		377.6	1023	284	0.09			
Caribbean Islands		0.1	1	0	0.62	0	0	0.3
Chile		0.4	7	2	0.55			
China	12,677	2814.0	31,403	8724	0.35			
Columbia	222	13.3	266	74	0.63		68	6.15
Croatia	927	113.9	555	154	0.15	1	91	1.9
Czech Republic		12.5	128	36	0.33		106	0.3
Denmark	44	7.4	75	21	0.32			
Finland		80.5	484	134	0.19			
France	2793	326.0	4895	1360	0.48	1		
Georgia	894	250.0	6307	1752	0.80			
Germany	371	397.0	1568	436	0.13	16		
Greece	258	57.1	385	107	0.21	75	200	
Guatemala		3.4	107	30	1.00	1	10	
Honduras	12	0.7	17	5	0.76		14	
Hungary	677	328.3	2825	785	0.27	4	20	0.5
Iceland	7619	1469.0	20,170	5603	0.44	241	250	90
India	316	80.0	2517	699	1.00	73	14	
Indonesia		7.3	43	12	0.19			
Israel	1672	63.3	1713	476	0.86			
Italy	1656	325.8	3774	1048	0.37	1	50	10
Japan	1670	257.5	5836	1621	0.72			
Jordan	574	153.3	1540	428	0.32			
Kenya		1.3	10	3	0.25			
Korea	1054	51.0	1077	299	0.67	164	42	276

(*Continued*)

Table 1. *(Continued)*

Country	Flow kg/s	Capacity MWt	Annual TJ/yr	Utilization GWh/yr	Capacity factor	Wells drilled	Person-years	Funds million $
Lithuania	13	21.0	599	166	0.90	6	102	23.94
Macedonia	761	81.2	510	142	0.20	1	55	15
Mexico	4367	164.2	3919	1089	0.76	0	20	0
Nepal	25	1.1	22	6	0.66		8	0.007
Netherlands		10.8	57	16	0.17			
New Zealand	132	307.9	7081	1967	0.73	1	200	50
Norway		6.0	32	9	0.17			
Peru		2.4	49	14	0.65			
Philippines		1.0	25	7	0.79			
Poland	242	68.5	275	76	0.13		166	12
Portugal	49	5.5	35	10	0.20	7		
Romania	890	152.4	2871	797	0.60	14	181	24
Russia	1466	307.0	6132	1703	0.63	306	1043	
Serbia	827	80.0	2375	660	0.94	5	23	
Slovak Republic	623	132.3	2118	588	0.51	4	95	11.75
Slovenia	656	42.0	705	196	0.53	18	43	16.08
Sweden	455	377.0	4128	1147	0.35			
Switzerland	120	547.3	2386	663	0.14	4	58	230
Thailand		0.7	15	4	0.68			
Tunisia		19.7	174	48	0.28			
Turkey	700	820.0	15,756	4377	0.61	15	120	25
United Kingdom	25	2.9	21	6	0.23			
United States	4550	5366.0	20,302	5640	0.12	44	10	42
Venezuela		0.7	14	4	0.63			
GRAND TOTAL	54,416	16,210.7	162,009	45,006	0.32	1028	3363	841

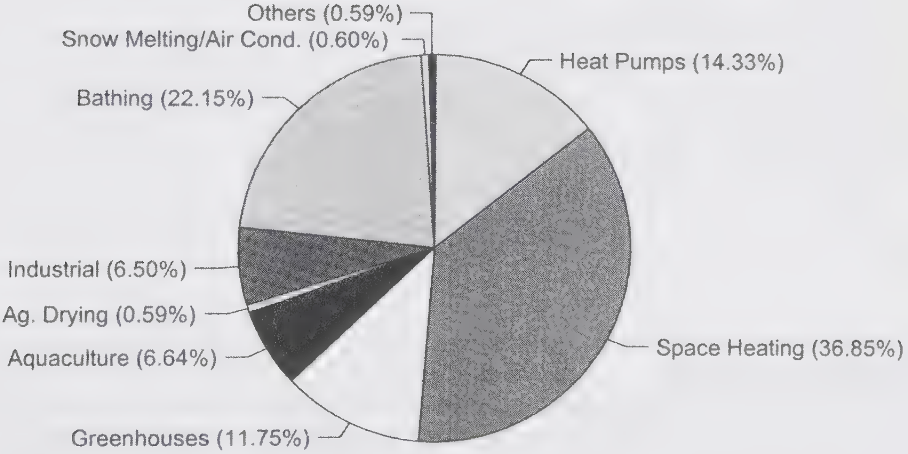

Figure 1. Distribution of geothermal energy use in the world.

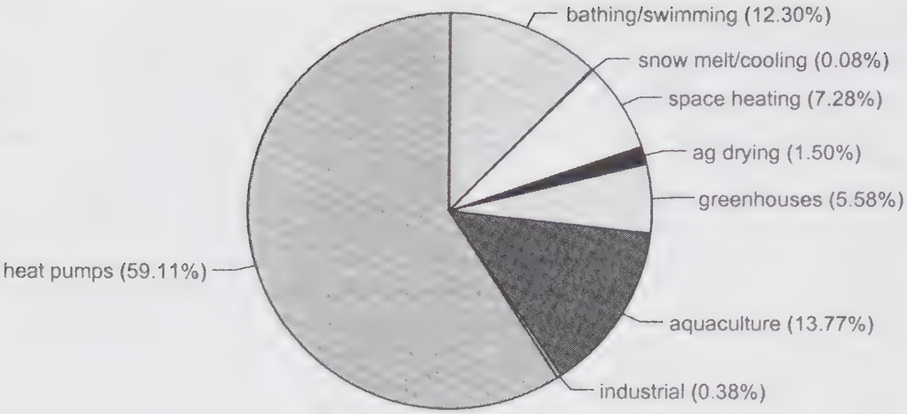

Figure 2. Distribution of geothermal energy use in the U.S.

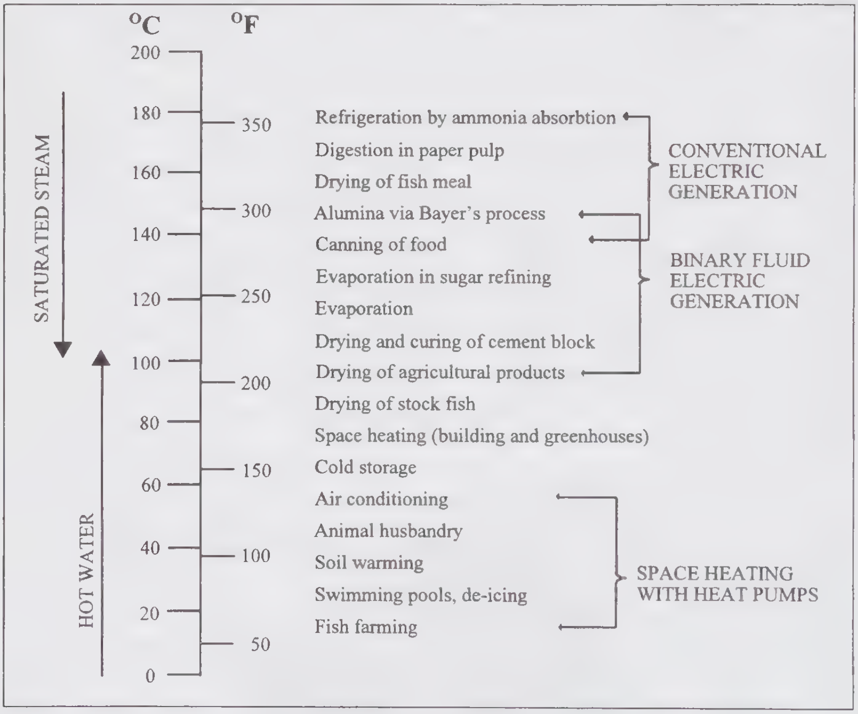

Figure 3. Lindal diagram.

geothermal energy use is 77% for space heating 15,600 TJ/yr (4334 GWh/yr) – primarily with district heating systems (Ragnarsson, 2000).

The Lindal diagram (Gudmundsson *et al.*, 1985), named for Baldur Lindal, the Icelandic engineer who first proposed it, indicates the temperature range suitable for various direct use activities (Figure 3). Typically, the agricultural and aquacultural uses require the lowest temperatures, with values from 25°C to 90°C. The amounts and types of chemicals such as arsenic and dissolved gases such as boron, are a major problem with plants and animals; thus, heat exchangers are often necessary. Space heating requires temperatures in the range of 50°C to 100°C, with 40°C useful in some marginal cases and ground-source heat pumps extending the range down to 4°C. Cooling and industrial processing normally require temperatures over 100°C. The leading user of geothermal energy, in terms of market penetration, is Iceland, where more than 86% of the population enjoys geothermal heat in their homes from 26 municipal district heating services, and 50% of the country's total energy use is supplied by direct heat and electrical energy derived from geothermal resources (Ragnarsson, 2000).

2.1 *Swimming, bathing and balneology*

Romans, Chinese, Ottomans, Japanese and central Europeans have bathed in geothermal waters for centuries. Today, more than 2200 hot springs resorts in Japan draw 100 million guests every year, and the "return-to-nature" movement in the U.S. has revitalized many hot spring resorts.

The geothermal water at Xiaotangshan Sanitarium, northwest of Beijing, China, has been used for medical purposes for over 500 years. Today, the 50°C water is used to treat high blood pressure, rheumatism, skin disease, diseases of the nervous system, ulcers and generally for recuperation after surgery. In Rotorua, New Zealand at the center of the Taupo Volcanic Zone of North Island, the Queen Elizabeth Hospital was built during World War II for U.S. servicemen and later became the national hospital for the treatment of rheumatic disease. The hospital has 200 beds, and outpatient service, and a cerebral palsy unit. Both acidic and basic heated mud baths treat rheumatic diseases.

In Beppu on the southern island of Kyushu, Japan, the hot water and steam meet many needs: heating, bathing, cooking, industrial operations, agriculture re-search, physical therapy, recreational bathing, and even a small zoo (Taguchi *et al.*, 1996). The waters are promoted for "digestive system troubles, nervous troubles, and skin troubles." Many sick and crippled people come to Beppu for rehabilitation and physical therapy. There are also eight Jigokus ("burning hells") in town showing various geothermal phenomena, used as tourist attractions.

In the former Czechoslovakia, the use of thermal waters has been traced back before the occupation of the Romans and has had a recorded use of almost 1000 years. Today, there are 60 spa resorts located mainly in Slovakia, visited by 460,000 patients usually for an average of three weeks each. These spas have old and well-established therapeutic traditions. Depending on the chemical composition of the mineral waters and spring gas, availability of peat and sulfurous mud, and climatic conditions, each sanitarium is designated for the treatment of specific diseases. The therapeutic successes of these spas are based on centuries of healing tradition (balneology), systematically supplemented by the latest discoveries of modern medical science (Lund, 1990).

Bathing and therapeutic sites in the U.S. included: Saratoga Springs, New York; Warm Springs, Georgia; Hot Springs, Virginia; White Sulfur Springs, West Virginia; Hot Spring, Arkansas; Thermopolis, Wyoming and Calistoga, California. The original use of these sites were by Indians, where they bathed and recuperated from battle. There are over 115 major geothermal spas in the U.S. with an annual energy use of 1500 TJ (Lund, 1996b).

2.2 *Space conditioning*

Space conditioning includes both heating and cooling. Space heating with geothermal energy has widespread application, especially on an individual basis. Buildings heated from individual are popular in Klamath Falls, Oregon; Reno, Nevada, and Taupo and Rotorua, New Zealand. Absorption space cooling with geothermal energy has not been popular because of the high temperature requirements and low efficiency. Geothermal heat pumps (groundwater and ground-coupled) have become popular in the U.S. and Switzerland, used for both heating and cooling.

An example of space heating and cooling with low-to-moderate temperature geothermal energy is the Oregon Institute of Technology in Klamath Falls, Oregon (Figure 4). Here, eleven buildings (approximately 62,000 sq. m of floor space) are heated with water from three wells at 89°C. Up to 62 L/s of fluid can be provided to the campus, with the average heat utilization rate over 0.53 MWt and the peak at 5.6 MWt. In addition, a 541 kW (154 tons) chiller requiring up to 38 L/s of geothermal fluid produces 23 L/s of chilled fluid at 7°C to meet the campus cooling base load (recently decommissioned) (Boyd, 1999).

2.3 *District heating*

District heating originates from a central location, and supplies hot water or steam through a network of pipes to individual dwellings or blocks of buildings. The heat is used for space heating and cooling, domestic water heating and industrial process heat. A geothermal well field is the primary source of heat; however, depending on the temperature, the district may be a hybrid system, which would include fossil fuel and/or heat pump peaking.

Geothermal district heating systems are in operation in at least 12 countries, including Iceland, France, Poland, Hungary, Turkey, Japan and the U.S. The Warm Springs Avenue project in Boise, Idaho, dating back to 1892 and originally heating more than 400 homes, is the earliest formal project in the U.S. The Reykjavik, Iceland, district heating system (Figure 5) is probably the most famous (Frimannsson 1991 and Lund, 1996a). This system supplies heat for a population of around 160,000 people. The installed capacity of 830 MWt is designed to meet the heating load to about −10°C; however, during colder periods, the increased load is met by large storage tanks and an oil-fired booster station (Ragnarsson, 2000).

In France, production wells in sedimentary basins provide direct heat to more than 500,000 people from 61 projects. These wells provide from 40°C to 100°C water from depths of 1500 to 2000 m. In the Paris basin, a doublet system (one production and one injection well) provides 70°C water, with the peak load met by heat pumps and conventional fossil fuel burners (Figure 6).

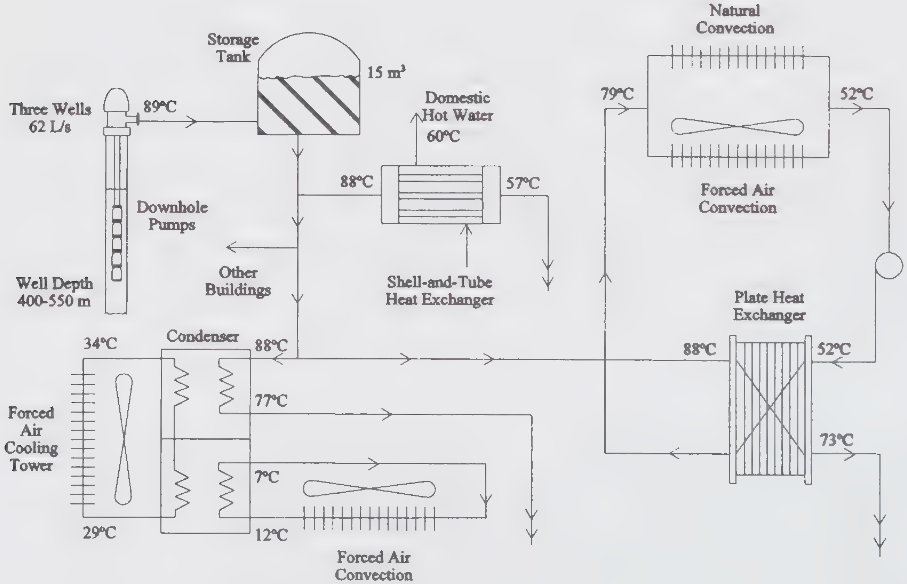

Figure 4. Oregon Institute of Technology heating and cooling system.

2.4 *Agribusiness applications*

Agribusiness applications (agriculture and aquaculture) are particularly attractive because they require heating at the lower end of the temperature range where there is an abundance of geothermal resources. Use of waste heat or the cascading of geothermal energy also has excellent possibilities. A number of agribusiness applications can be considered: greenhouse heating,

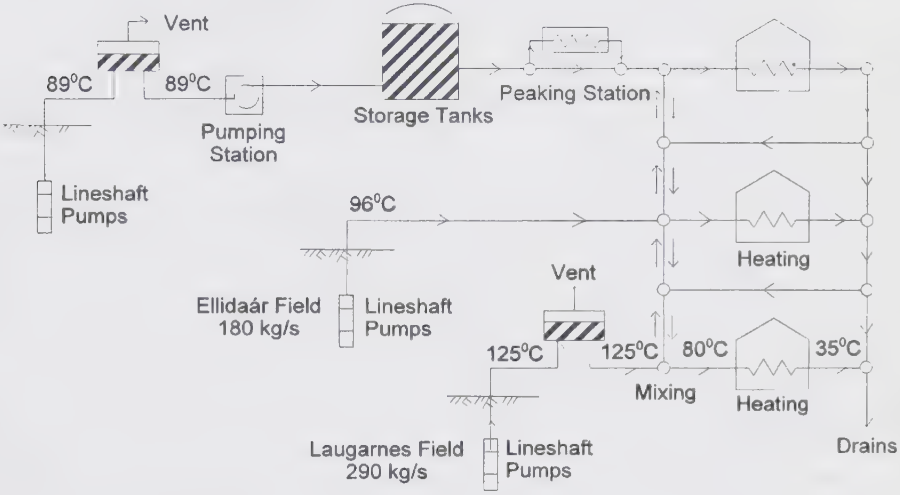

Figure 5. Reykjavik district heating system (prior to the Nesjavellir connection).

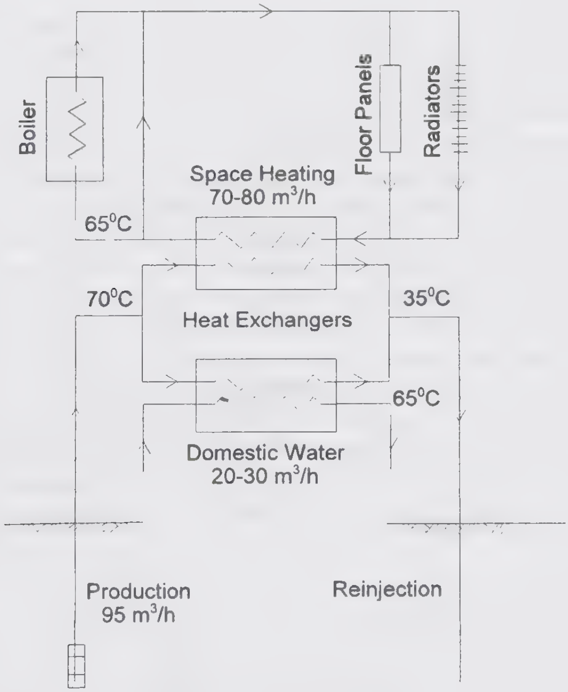

Figure 6. Melun l'Almont (Paris) doublet heating system.

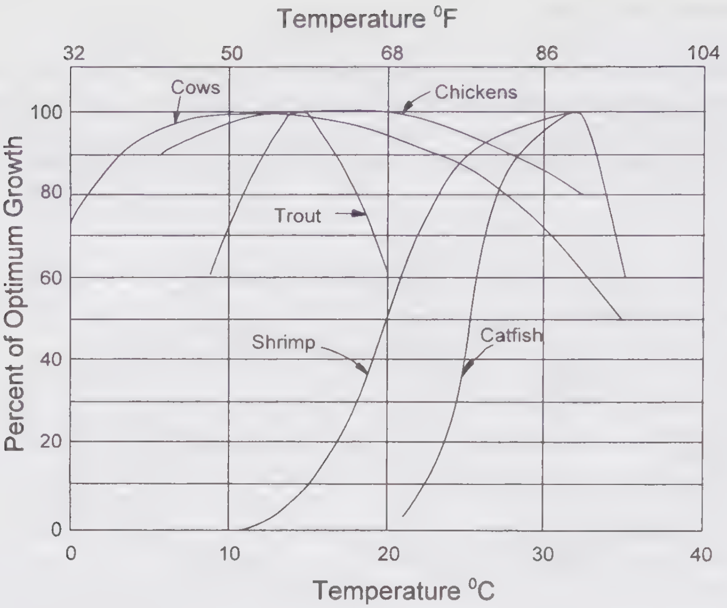

Figure 7. Effect of temperature on animal and fish growth.

aquaculture and animal husbandry, soil warming and irrigation, mushroom culture, and bio-gas generation.

Numerous commercially marketable crops have been raised in geothermally heated greenhouses in Hungary, Russia, New Zealand, Japan, Iceland, China and the U.S. These include vegetables, such as cucumbers and tomatoes, flowers (both potted and bedded), house plants, tree seedlings, and cacti. Using geothermal energy for heating reduces operating costs (which can account for 35% of the product cost) and allows operation in colder climates where commercial greenhouses would not normally be economical.

The use of geothermal energy for raising catfish, shrimp, tilapia, eels, and tropical fish has produced crops faster than by conventional solar heating. Using geothermal heat allows better control of pond temperatures, thus optimizing growth (Figure 7). Fish breeding has been successful in Japan, China and the U.S. A very successful prawn raising operation, producing 400 tons of Giant Malaysian Freshwater Prawns per year at US$ 17 to 27/kg has been developed near the Wairakei geothermal field in New Zealand (Lund and Klein, 1995). The most important factors to consider are the quality of the water and disease. If geothermal water is used directly, concentrations of dissolved heavy metals, fluorides, chlorides, arsenic, and boron must be considered.

Livestock raising facilities can encourage the growth of domestic animals by a controlled heating and cooling environment. An indoor facility can lower mortality rate of newborn, enhance growth rates, control diseases, increase litter size, make waste management and collection easier, and in most cases improved the quality of the product. Geothermal fluids can also be used for cleaning, sanitizing and drying of animal shelters and waste, as well as assisting in the production of bio-gas from the waste.

2.5 *Industrial applications*

Although the Lindal diagram shows many potential industrial and process applications of geothermal energy, the world's uses are relatively few. The oldest industrial use is at Larderello, Italy,

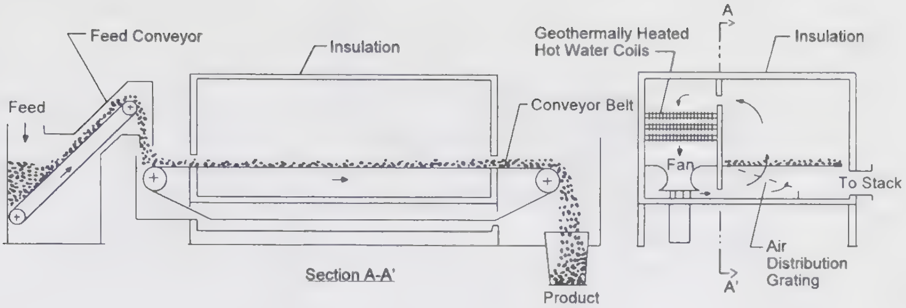

Figure 8. Continuous belt dehydration plant, schematic.

where boric acid and other borate compounds have been extracted from geothermal brines since 1790. Today, the two largest industrial uses are the diatomaceous earth drying plant in northern Iceland and a pulp, paper and wood processing plant at Kawerau, New Zealand. Notable U.S. examples are two onion dehydration plants in northern Nevada (Lund, 1995), and a sewage digestion facility in San Bernardino, California. Alcohol fuel production has been attempted in the U.S.; however, the economics were marginal and thus this industry has not been successful.

Drying and dehydration are important moderate-temperature uses of geothermal energy. Various vegetable and fruit products are feasible with continuous belt conveyors (Figure 8) or batch (truck) dryers with air temperatures from 40°C to 100°C (Lund and Rangel, 1995). Geothermally drying alfalfa, onions, pears, apples and seaweed are examples of this type of direct use. A new development in the use of geothermal fluids is the enhanced heap leaching of precious metals in Nevada by applying heat to the cyanide process (Trexler *et al.*, 1990). Using geothermal energy increases the efficiency of the process and extends the production into the winter months.

3 EQUIPMENT

Standard equipment is used in most direct-use projects, provided allowances are made for the nature of geothermal water and steam. Temperature is an important consideration, so is water quality. Corrosion and scaling caused by the sometimes unique chemistry of geothermal fluids, may lead to operating problems with equipment components exposed to flowing water and steam. In many instances, fluid problems can be designed out of the system. One such example concerns dissolved oxygen, which is absent in most geothermal waters, except perhaps the lowest temperature waters. Care should be taken to prevent atmospheric oxygen from entering district heating waters; for example, by proper design of storage tanks. The isolation of geothermal water by installing a heat exchanger may also solve this and similar water quality derived problems. In this case, a clean secondary fluid is then circulated through the used side of the system as shown in Figure 9.

The primary components of most low-temperature direct-use systems are downhole and circulation pumps, transmission and distribution pipelines, peaking or back-up plants, and various forms of heat extraction equipment (Figure 9). Fluid disposal is either surface or subsurface (injection). A peaking system may be necessary to meet maximum load. This can be done by increasing the water temperature or by providing tank storage (such as done in most of the Icelandic district heating systems). Both options mean that fewer wells need to be drilled. When the geothermal water temperature is warm (below 50°C), heat pumps are often used. The equipment used in direct-use projects represent several units of operations. The major units will now be described in the same order as seen by geothermal waters produced for district heating. Detailed discussion of equipment design and use can be found in Lund *et al.* (1998).

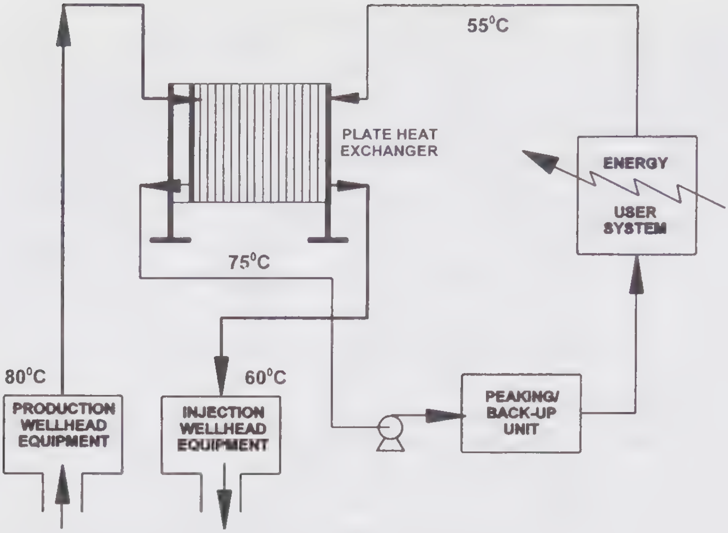

Figure 9. Geothermal direct-utilization system using a heat exchanger.

3.1 *Downhole pumps*

Unless the well is artesian, downhole pumps are needed, especially in large-scale direct utilization system. Downhole pumps may be installed not only to lift fluid to the surface, but also to prevent the release of gas and the resultant scale formation. The two most common types are: lineshaft pump systems and submersible pump systems.

The lineshaft pump system (Figure 10) consists of a multi-stage downhole centrifugal pump, a surface mounted motor and a long driveshaft assembly extending from the motor to the pump. Most are enclosed, with the shaft rotating within a lubrication column which is centered in the production tubing. This assembly allow the bearings to be lubricated by oil, as hot water may not provide adequate lubrication. A variable-speed drive set just below the motor on the surface, can be used to regulate flow instead of just turning the pump on and off.

The electric submersible pump system (Figure 11) consists of a multi-stage downhole centrifugal pump, a downhole motor, a seal section (also called a protector) between the pump and motor, and electric cable extending from the motor to the surface electricity supply.

Both types of downhole pumps have been used for many years for cold water pumping and more recently in geothermal wells (lineshafts have been used on the Oregon Institute of Technology campus in 89°C water for 45 years). If a lineshaft pump is used, special allowances must be made for the thermal expansion of various components and for oil lubrication of the bearings. The lineshaft pumps are preferred over the submersible pump in conventional geothermal applications for two main reasons: the lineshaft pump cost less, and it has a proven track record. However, for setting depths exceeding about 250 m, a submersible pump is required.

3.2 *Piping*

The fluid state in transmission lines of direct-use projects can be liquid water, steam vapor or a two-phase mixture. These pipelines carry fluids from the wellhead to either a site of application, or a steam-water separator. Thermal expansion of pipelines heated rapidly from ambient to geothermal

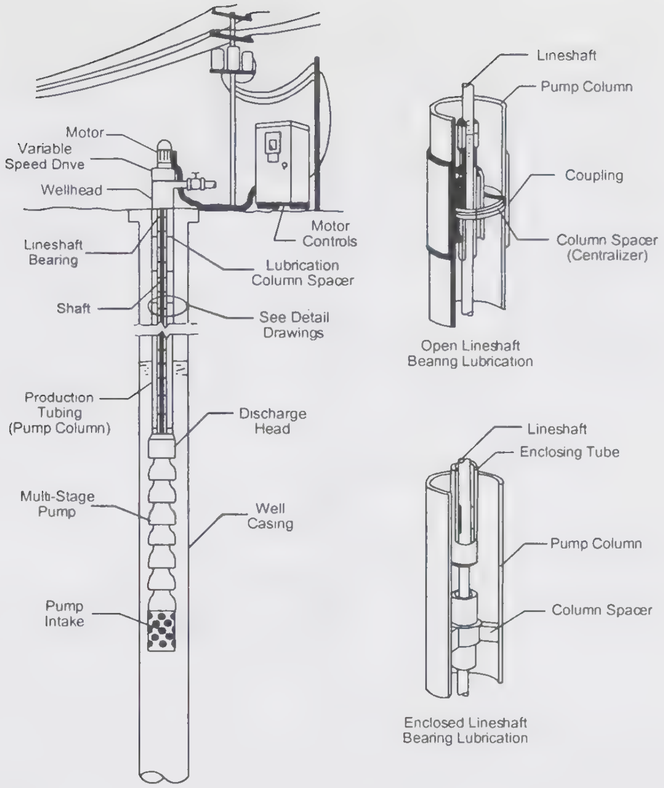

Figure 10. Lineshaft pump.

fluid temperatures (which could vary from 50 to 200°C) causes stress that must be accommodated by careful engineering design.

The cost of transmission lines and the distribution networks in direct-use projects is significant. This is especially true when the geothermal resource is located at great distance from the main load center; however, transmission distances of up to 60 km have proven economical for hot water (i.e., the Akranes project in Iceland Ragnarsson & Hrolfsson, 1998), where asbestos cement covered with earth has been successful (see Figure 13 later).

Carbon steel is now the most widely used material for geothermal transmission lines and distribution networks; especially if the fluid temperature is over 100°C. Other common types of piping material are fiberglass reinforced plastic (FRP) and asbestos cement (AC). The latter material, used widely in the past, cannot be used in many systems today due to environmental concerns; thus, it is no longer available in many locations. Polyvinyl chloride (PVC) piping is often used for the distribution network, and for uninsulated waste disposal lines where temperatures are well below 100°C. Conventional steel piping requires expansion provisions, either bellows arrangements or by loops. A typical piping installation would have fixed points and expansion points about every 100 m. In addition, the piping would have to be placed on rollers or slip plates between points. When hot water pipelines are buried, they can be subjected to external corrosion from groundwater and electrolysis. They must be protected by coatings and wrappings. Concrete tunnels or trenches have been used to protect steel pipes in many geothermal district heating systems. Although expensive (generally over US$ 300 per meter of length), tunnels and trenches have the advantage of easing future expansion, providing access for maintenance and a corridor for other utilities such as domestic water, waste water, electrical cables, phone lines, etc.

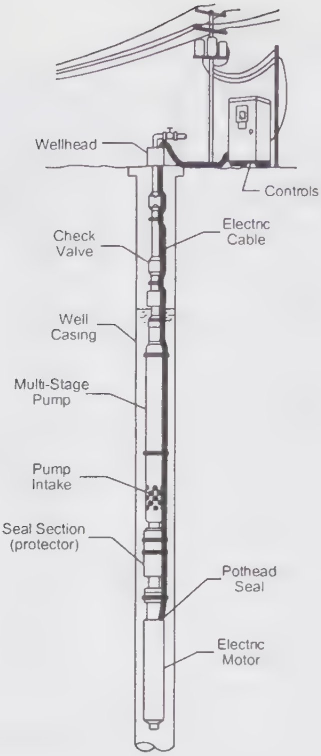

Figure 11. Submersible pump.

Supply and distribution systems can consist of either a single-pipe or a two-pipe system. The single-pipe is a once-through system where the fluid is disposed of after use. This distribution system is generally preferred when the geothermal energy is abundant and the water is pure enough to be circulated through the distribution system. In a two-pipe system, the fluid is recirculated so the fluid and residual heat are conserved. A two-pipe system must be used when mixing of spent fluids is called for, and when the spent cold fluids need to be injected into the reservoir. Two-pipe distribution systems cost typically 20 to 30 percent more than single-piped systems.

The quantity of thermal insulation of transmission lines and distribution networks will depend on many factors. In addition to minimize the heat loss of the fluid, the insulation must be waterproof and water tight. Moisture can destroy the value of any thermal insulation, and cause rapid external corrosion. Aboveground and overhead pipeline installations can be considered in special cases. Considerable insulation is achieved by burying hot water pipelines. For example, burying bare steel pipe results in a reduction in heat loss of about one-third as compared to aboveground in still air. If the soil around the buried pipe can be kept dry, then the insulation value can be retained. Carbon steel piping can be insulated with polyurethane foam, rock wool or fiberglass. Below ground, such pipes should be protected with polyvinyl chloride (PVC) jacket; aboveground, aluminum can be used. Generally, 2.5 to 10 cm of insulation is adequate. In two-pipe systems, the supply and return lines are usually insulated; whereas, in single-pipe systems, only the supply line is insulated.

At flowing conditions, the temperature loss in insulated pipelines is in the range of 0.1 to 1.0°C/km, and in uninsulated lines, the loss is 2 to 5°C/km (in the approximate range of 5 to 15 L/s flow for 15-cm diameter pipe) (Ryan, 1981). It is less for larger diameter pipes (i.e., less

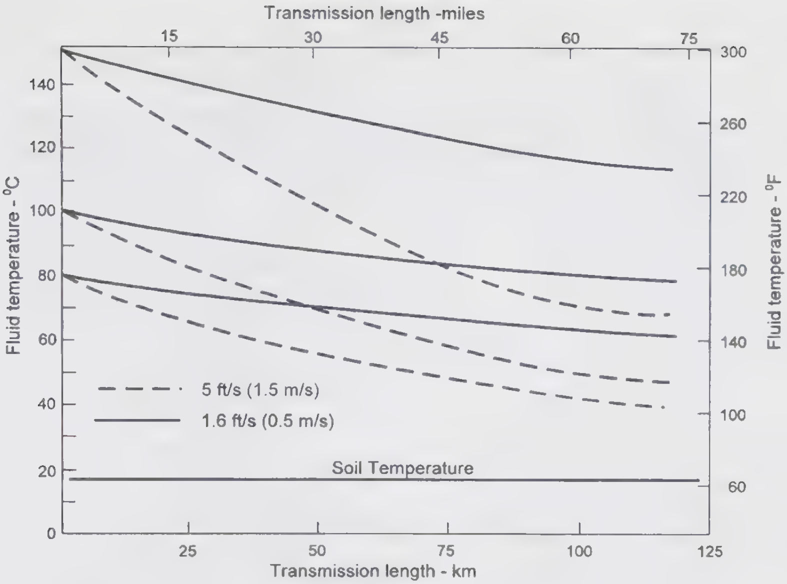

Figure 12. Temperature drop in hot water transmission line.

than 2°C loss is experienced in the new aboveground 29 km long and 80 and 90 cm diameter line (with 10 cm of rock wool insulation) from Nesjavellir to Reykjavik in Iceland. The flow rate is around 560 L/s and takes seven hours to cover the distance. Uninsulated pipe costs about half of insulated pipe, and thus, is used where temperature loss is not critical. Pipe material does not have a significant effect on heat loss; however, the flow rate does. At low flow rates (off peak), the heat loss is higher than at greater flows. Figure 12 shows fluid temperatures, as a function of distance, in a 45-cm diameter pipeline, insulated with 50 cm of urethane.

Several examples of aboveground and buried pipeline installations are shown in Figure 13.

Steel piping is shown in most case, but FRP or PVC can be used in low-temperature applications. Aboveground pipelines have been used extensively in Iceland, where excavation in lava rock is expensive and difficult; however, in the USA, below ground installations are more common to protect the line from vandalism and to eliminate traffic barriers. A detailed discussion of these various installations can be found in Gudmundsson and Lund (1985).

3.3 *Heat exchangers*

The principal heat exchangers used in geothermal systems are the plate, shell-and-tube, and downhole types. The plate heat exchanger consists of a series of plates with gaskets held in a frame by clamping rods (Figure 14). The counter-current flow and high turbulence achieved in plate heat exchangers, provide for efficient thermal exchange in a small volume. In addition, they have the advantage when compared to shell-and-tube exchangers, of occupying less space, can easily be expanded when addition load is added, and cost 40% less. The plates are usually made of stainless steel; although, titanium is used when the fluids are especially corrosive. Plate heat exchangers are commonly used in geothermal heating situations worldwide.

Shell-and-tube heat exchangers may be used for geothermal applications, but are less popular due to problems with fouling, greater approach temperature (difference between incoming and outgoing fluid temperature), and the larger size.

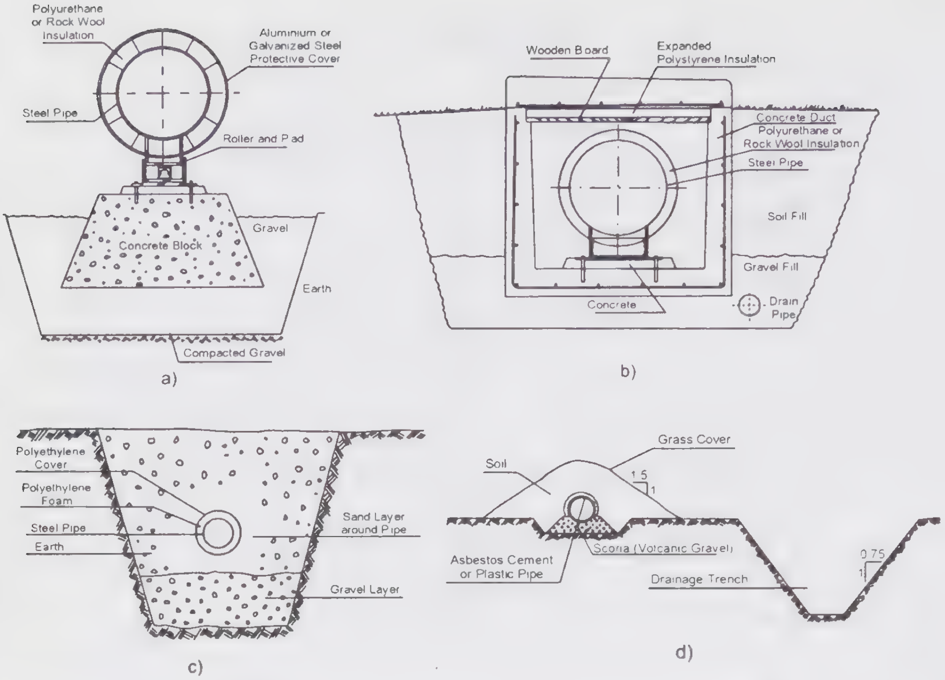

Figure 13. Examples of above and below ground pipelines: a) aboveground pipeline with sheet metal cover. b) steel pipe in concrete tunnels, c) steel pipe with polyurethane insulation and polyethylene cover and d) asbestos cement pipe with earth and grass cover.

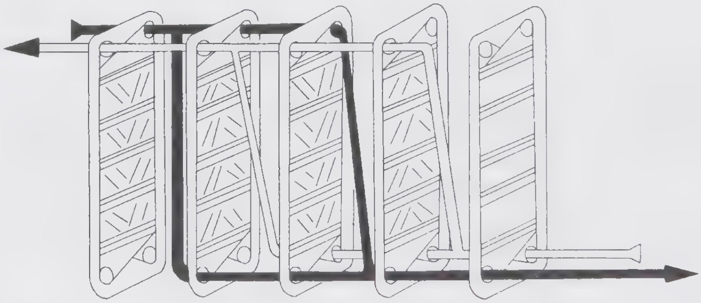

Figure 14. Plate heat exchanger.

Downhole heat exchangers eliminate the problem of disposal of geothermal fluid, since only heat is taken from the well. However, their use is limited to small heating loads such as the heating of individual homes, a small apartment house or business. The exchanger consists of a system of pipes or tubes suspended in the well through which secondary water is pumped or allowed to circulate by natural convection (Figure 15). In order to obtain maximum output, the well must be designed to have an open annulus between the wellbore and casing, and perforations above and below the heat exchanger surface. Natural convection circulates the water down inside the casing, through the lower perforations, up in the annulus and back inside the casing through the upper perforations (Culver and Reistad, 1978; GHC Quarterly Bulletin, Vol. 20, No. 3, 1999). The use of a separate pipe or promoter, has proven successful in older wells in New Zealand to increase the vertical circulation (Dunstall and Freeston, 1990).

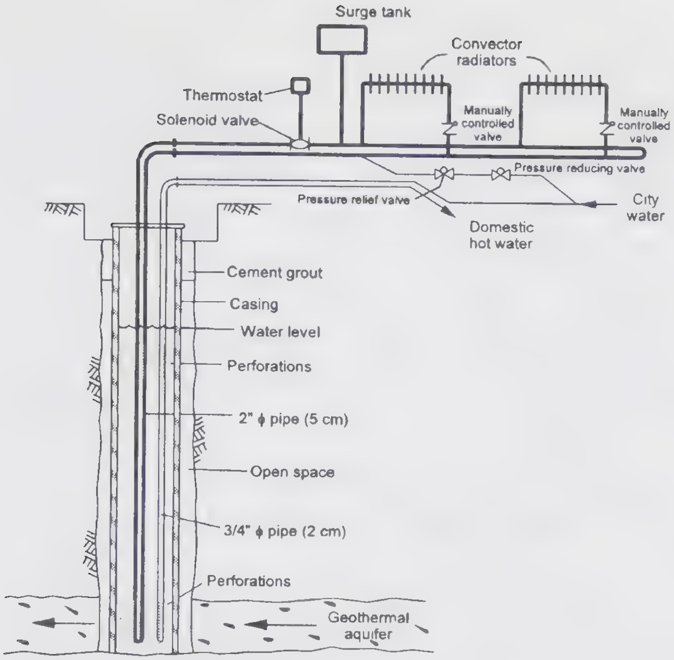

Figure 15. Downhole heat exchanger (typical of Klamath Falls, Oregon).

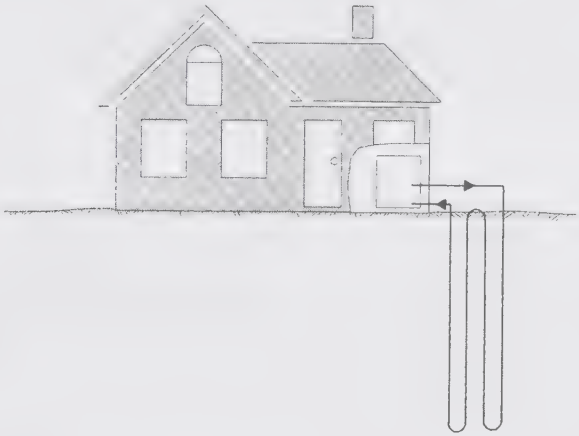

Figure 16. Typical ground-source heat pump installation.

3.4 *Heat pumps*

At the present time, ground-coupled and groundwater (often called ground-source or geothermal) heat pump systems are being installed in great numbers in the United States, Switzerland and Germany (Kavanaugh and Rafferty, 1997; Rybach and Sanner, 2000). Groundwater aquifers and soil temperatures in the range of 5°C to 30°C are being used in these systems. Ground-source heat pumps (GSHP) utilize groundwater in wells or by direct ground coupling with vertical heat exchangers (Figure 16). Just about every state in the USA, especially in the mid-western and

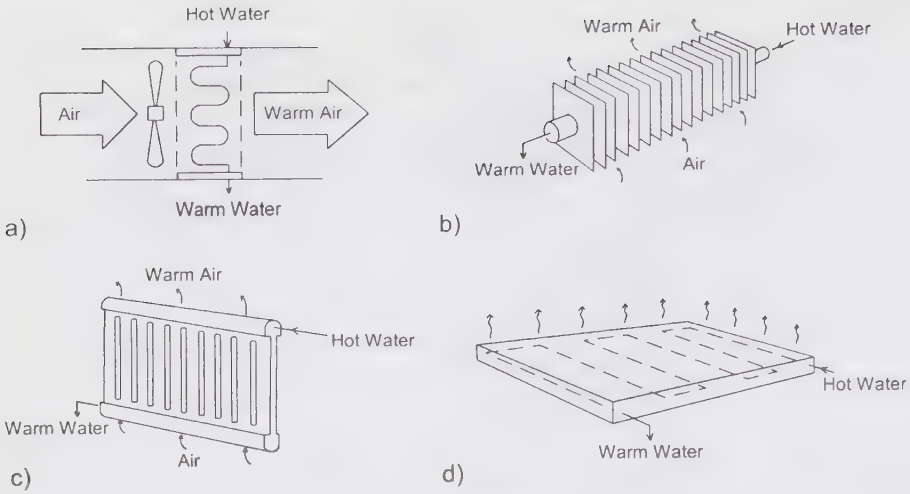

Figure 17. Convectors: a) forced air, b) material convection (finned tube), c) natural convection (radiator), and d) floor panel.

eastern states are utilizing these systems in part subsidized by public and private utilities. It is estimated that almost 60,000 groundwater systems, and more than 184,000 closed-loop vertical and 152,000 horizontal systems are already in use.

Like refrigerators, heat pumps operate on the basic principle that fluid absorbs heat when it evaporates into a gas, and likewise gives off heat when it condenses back into a liquid. A geothermal heat pump system can be used for both heating and cooling. The types of heat pumps that are adaptable to geothermal energy are the water-to-air and the water-to-water. Heat pumps are available with heating capacities of less than 3 kW to over 1500 kW.

3.5 *Convectors*

Heating of individual rooms and buildings is achieved by passing geothermal water (or a heated secondary fluid) through heat convectors (or emitters) located in each room. The method is similar to that used in conventional space heating systems. Three major types of heat convectors are used for space heating: 1) forced air, 2) natural air flow using hot water or finned tube radiators, and 3) radiant panels (Figure 17). All these can be adapted directly to geothermal energy or converted by retrofitting existing systems.

3.6 *Refrigeration*

Cooling can be accomplished from geothermal energy using lithium bromide and ammonia absorption refrigeration systems (Rafferty, 1983). The lithium bromide system is the most common because it uses water as the refrigerant. However, it is limited to cooling above the freezing point of water. The major application of lithium bromide units is for the supply of chilled water for space and process cooling. They may be either one- or two-stage units. The two-stage units require higher temperatures (about 160°C); but, they also have high efficiency. The single-stage units can be driven with hot water at temperatures as low as 77°C (such as at Oregon Institute of Technology – see Figure 4). The lower the temperature of the geothermal water, the higher the flow rate required and the lower the efficiency. Generally, a condensing (cooling) tower is required, which will add to the cost and space requirements.

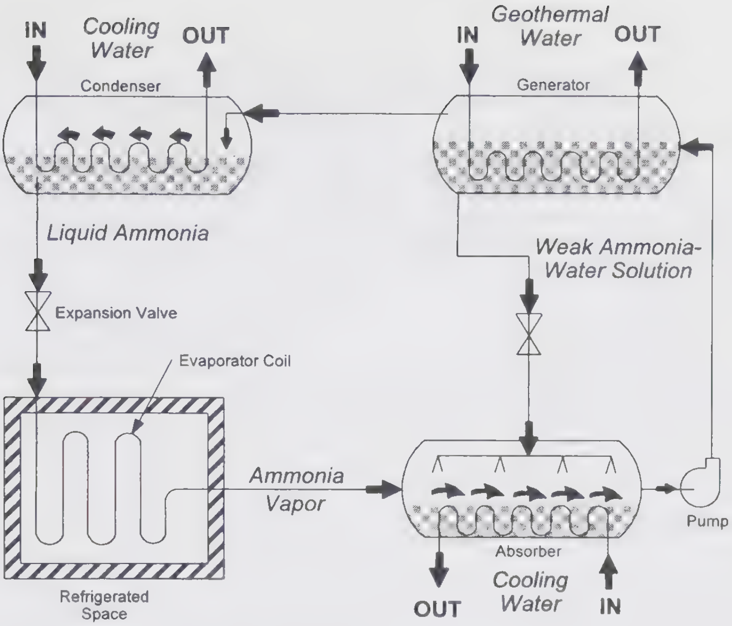

Figure 18. Geothermal absorption refrigeration cycle.

For geothermally-driven refrigeration below the freezing point of water, the ammonia absorption system must be considered. However, these systems are normally applied in very large capacities and have seen limited use. For the lower temperature refrigeration, the driving temperature must be at or above about 120°C for a reasonable performance. Figure 18 illustrates how the geothermal absorption process works.

4 ECONOMIC CONSIDERATIONS

Geothermal projects require a relatively large initial capital investment, with small annual operating costs thereafter. Thus, a district heating project, including production wells, pipelines, heat exchangers, and injection wells, may cost several million dollars. By contrast, the initial investment in a fossil fuel system includes only the cost of a central boiler and distribution lines. The annual operation and maintenance costs for the two systems are similar, except that the fossil fuel system may continue to pay for fuel at an every-increasing rate; while, the cost of the geothermal fuel is stable. The two systems, one with a high initial capital cost and the other with high annual costs, must be compared.

Geothermal resources fill many needs: power generation, space heating, greenhouse heating, industrial processing, and bathing to name a few. Considered individually, however, some of the uses may not promise an attractive return on investment because of the high initial capital cost. Thus, we may have to consider using a geothermal fluid several times to maximize benefits. This multistage utilization, where lower and lower water temperatures are used in successive steps, is called cascading or waste heat utilization. A simple form of cascading employs waste heat from a power plant for direct use projects (Figure 19).

Geothermal cascading has been proposed and successfully attempted on a limited scale throughout the world. In Rotorua, New Zealand, for example, after geothermal water and steam

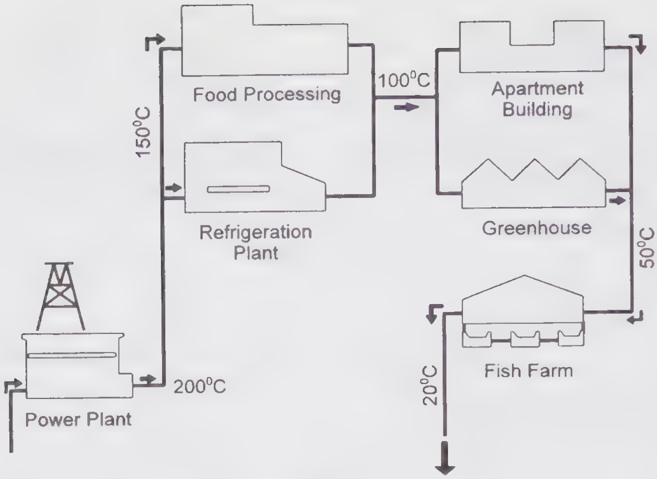

Figure 19. An example of cascading.

heat a home, the owner will often use the waste heat for a backyard swimming pool and steam cooker. At the Otake geothermal power plant in Japan, about 165 tonnes per hour of hot water flows to downstream communities for space heating, greenhouses, baths and cooking. In Sapporo, Hokkaido, Japan, the waste water from the pavement snow melting system is retained at 65°C and reused for bathing.

Recent estimates (1990 data) of the capital cost for various direct use projects in the U.S. are as follows:

Space heating (individual):	US$ 463/kW of installed capacity
District heating:	US$ 386/kW of installed capacity
Greenhouses:	US$ 120/kW of installed capacity
Aquaculture:	US$ 26/kW of installed capacity

Recent international data (Freeston, 1996) gives US$ 270/kW of installed capacity for all projects reported, with a range from US$ 40 to US$ 1880/kW. In the U.S., the annual operation and maintenance cost is estimated at 5% of the installed cost.

5 FUTURE DEVELOPMENTS

There appears to be a large potential for the development of low-to-moderate enthalpy geothermal direct use across the world which is not currently being exploited due to financial constraints and the low price of competing energy sources. Given the right environment, and as gas and oil supplies dwindles, the use of geothermal energy will provide a competitive, viable and economic alternative source of renewable energy.

Future development will most likely occur under the following conditions:

1. Collocated resource and uses (within 10 km apart),
2. Sites with high heat and cooling load density (>36 MWt/sq. km).
3. Food and grain dehydration (especially in tropical countries where spoilage is common),
4. Greenhouses in colder climates,
5. Aquaculture to optimize growth – even in warm climates, and
6. Ground-coupled and groundwater heat pump installation (both for heating and cooling).

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Introduction to geothermal greenhouse design

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1 INTRODUCTION

A number of commercial crops can be raised in greenhouses, making geothermal resources in cold climates particularly attractive; however, growth can even be optimized in warmer climates. These include vegetables, flowers (potted and cut), house plants, and tree seedlings. As an example, the optimum growth temperature of cucumbers, tomatoes, and lettuce is shown in Figure 1 below (Barbier and Fanelli, 1997). Cucumbers grow best in the temperature range 25–30°C, tomatoes near 20°C, and lettuce at 15°C and below. The growing time for cucumbers is usually 90 to 100 days; while, the growing cycle for tomatoes is longer, in the range 9 to 12 months. The use of geothermal energy for heating can reduce operating costs (which can amount for up to 35 percent of the product cost) and allows operation in colder climates where commercial

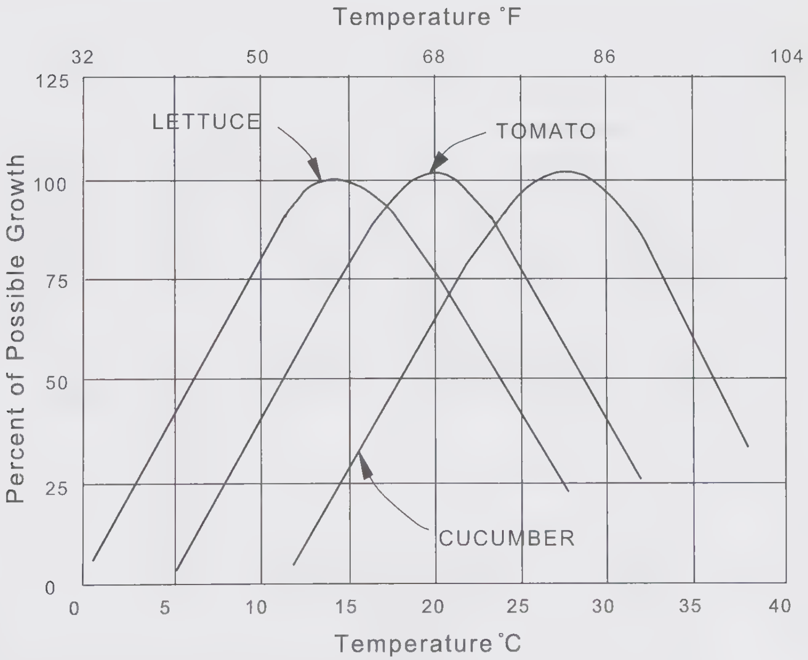

Figure 1. Optimum growing temperature for selected agricultural products.

greenhouses would not normally be economical. In addition, greenhouses are suited to large quantities of relatively low-grade heat. Furthermore, better humidity control can be derived to prevent condensation (mildew), botritis, and other problems related to disease control (Schmitt, 1981).

Greenhouses are one of the largest low-enthalpy energy consumers in agriculture; thus, geothermal energy can provide the necessary heating for greenhouses (Popovski, 1998). Some of the advantages of using geothermal energy are:

- Good correlation between the sites of greenhouse production area and low-enthalpy geothermal resources,
- Low-enthalpy geothermal resources are common in many countries,
- Geothermal energy requires relatively simple heating installations, but advanced computerized installations can later be added for total conditioning of the inside climate in the greenhouses,
- The economic competitiveness of geothermal energy for greenhouse heating, especially in colder climates,
- Strategic importance of energy sources that are locally available for food production, and
- Using a geothermal resource in combination with and existing fossil fuel system for peak heating.

2 EXAMPLES OF GEOTHERMALLY-HEATED GREENHOUSES

There are numerous uses of geothermal energy for greenhouse heating throughout the world, estimated at 19,240 TJ/year (5345 GWh/yr)(1998). In the USSR, it is reported that over 2500 ha of agricultural land are heated by geothermal of which 25 ha are covered by greenhouses. In Hungary, over 170 ha of greenhouses are heated geothermally. Many of these greenhouses are built on rollers, so they can be pulled from their location by tractors, the ground cultivated with large equipment, and then the greenhouse returned to its location. In addition, to minimize the cost, much of the building structure pipe supporting system also acts as the supply and radiation system for the geothermal fluid. Greenhouses cover about 40 ha in Japan where a variety of vegetables and flowers are grown. Individual greenhouses, operated by farmers and covering 300 1500 m^2 use 70–100°C geothermal water. Many large greenhouses totaling about half a hectare, are operated as tropical gardens for sightseeing purposes. New Zealand has numerous greenhouses using geothermal hot water and steam. At the Land Survey Nursery in Taupo, greenhouses are heated by geothermal steam and soil is sterilized (pasteurized) at 60°C to kill insects, fungi, worms, and some bacteria. In Iceland, over 18 ha are heated, including a greenhouse, restaurant, and horticulture college at Hveragerdi. Everything from bananas, coffee beans, cacti, and tropical flowers to the standard tomatoes and cucumbers are grown in these greenhouses. Studies of the economic feasibility of greenhouses in Iceland have been based on theoretical 33.5-ha facility, which would grow asparagus on 10 ha, flower seedlings on 1 ha, and cucumbers on 0.5 ha. Projected profit on the initial investment would amount to 11 percent before taxes, and the greenhouses would provide jobs for 250 persons (Hansen, 1981).

The largest geothermal greenhouse operations in the world by country are (Popovski, 1998):

• Hungary	170 ha
• China	116 ha
• Macedonia	59 ha
• Italy	57 ha
• USA	50 ha
• Japan	40 ha
• Romania	34 ha
• Russia	25 ha
• Spain	25 ha

France	24 ha
Turkey	20 ha
Iceland	18 ha
Greece	17 ha
Bulgaria	16 ha
Yugoslavia	10 ha
New Zealand	10 ha

Numerous geothermally-heated greenhouses exist in the USA; several examples are described as follows. In Salt Lake City, Utah, a 23,000 m^2 greenhouse is using 12.6 L/s of 49°C water for heating. Utah Roses, Inc., is producing cut roses for a national floral market. The 1200-m geothermal well has replaced a natural gas/oil heating system. Twenty-four kilometer south of Klamath Falls, Oregon, on the Liskey ranch, approximately 4600 m^2 of greenhouses are heated with 90°C water from a 82-m deep well. One of the greenhouses consists of four 13-m by 46-m buildings connected to form one large complex. Initially, seedlings were raised for federal and private agencies. More recently succulents, cacti, and potted plants are raised. All plants are grown in trays on raised tables, with the heat supplied by pipes under each table (Laskin, 1978; Lund, 1994). A Honey Lake, California, near Susanville, over 30 9-m by 38-m quonset-design greenhouses were used to raise cucumber and tomatoes. The vegetables are raised by hydroponics, with the heat being supplied by forced-air heaters. Production rates were about 680 kg of cucumbers per unit per week and 358 kg of tomatoes per unit per week. The cover of each greenhouse consisted of two layers of 6-mil sheeting (plastic). A small electric air blower continually inflated the area between the two layers and maintained an air space of about 15 cm, resulted in heat savings of approximately 40 percent over conventional coverings. The savings, using geothermal heat as compared to conventional fuel, averages $11,100/ha/year (Boren and Johnson, 1978). A similar analysis has been made for a greenhouse provided in La Grande, Oregon. The double 6-mil polyethylene covering required 45 percent less heating than single layer (Higbee and Ryan, 1981) (Fig. 2).

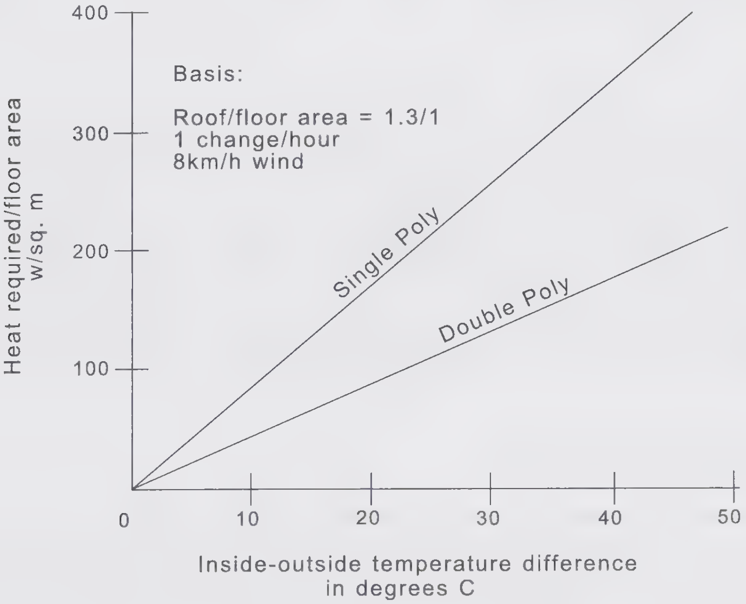

Figure 2. Example of heat requirement for greenhouses in La Grande, Oregon (outside design temperature = −17°C).

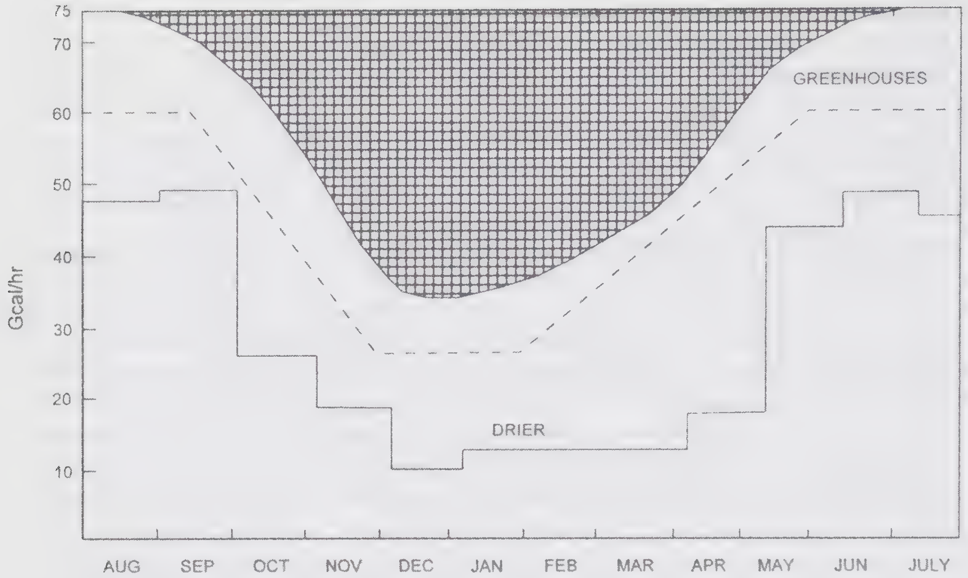

Figure 3. Geothermal energy consumed by greenhouses and drier at Mt. Amiata, Italy.

Table 1. The three leading greenhouse locations in the USA.

Location	Annual energy (TJ/GWh)	Capacity (MWt)	Load factor (%)	Area (ha)	Product
Animas, NM	220/61.2	32.8	21	13.0	Cut roses & bedding plants
Newcastle, UT	145/40.3	18.4	25	8.6	Potted plants
Radium Springs, NM	126/34.9	13.3	30	5.3	Potted plants

One of the world's largest geothermally-heated greenhouse operations is near Mt. Amiata, Italy. Approximately 22 ha of greenhouses are used to produce potted plants and flowers. Waste heat is supplied from a 15-MWe power plant. The greenhouse is operated in conjunction with an experimental drier that operates during the summer months when greenhouse heating is low. This combination maximizes the utilization of the geothermal heat as shown in Figure 3 (Lund, 1987).

Approximately 50 ha of greenhouses are heated geothermally in the USA. The largest single greenhouse operation is at Animas, in southwestern New Mexico, where 13 ha are used for raising cut roses. The three leading greenhouses locations are shown in Table 1. Additional details of geothermal greenhouse development in the USA is summarized by Lienau (1997).

3 GENERAL DESIGN CRITERIA

Greenhouse heating can be accomplished by (1) circulation of air over finned-coil heat exchangers carrying hot water, often with the use of perforated plastic tubes running the length of the greenhouse in order to maintain uniform heat distribution, (2) hot-water circulating pipes or ducts located in (or on) the floor, (3) finned units located along the walls and under benches, or (4) a combination of these methods. A fifth approach is using hot water for surface heating. Surface-heated greenhouses were developed several decades ago in the USSR. The application of a flowing layer

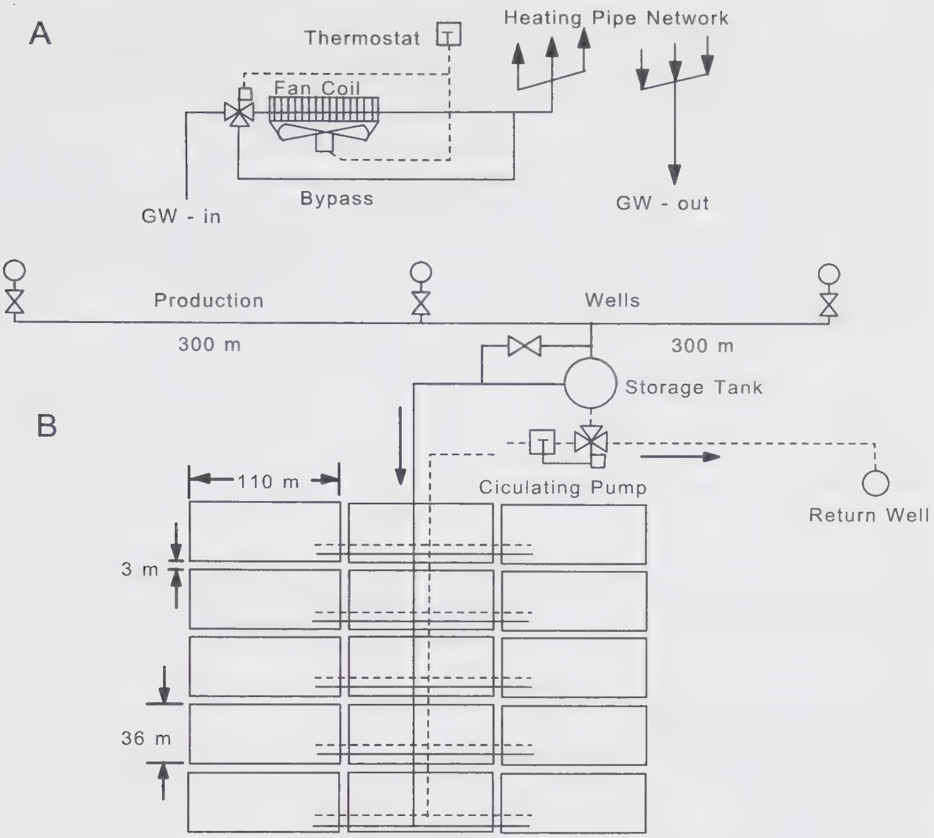

Figure 4. a) Unit heating system design (three per house); b) six-hectar greenhouse complex.

of warm water to the outside surface of the greenhouse can provide 80–90% of the energy needed. The flowing layers of warm water prevent snow and ice from accumulating.

The most efficient and economical greenhouse development consists of large structures covering 0.2–0.4 ha (Fig. 4). A typical size would be 36 by 110 m constructed of fiberglass with furrow-connected gables. Heating would be from a combination of fan coils connected in series with a network of horizontal pipes installed on outside walls and under benches. A storage tank would be required to meet peak demand and for recirculation of the geothermal water to obtain the maximum temperature drop. Approximately 6.3 L/s of 60–82°C water will be required for peak heating. The average is much less. Fortunately, most crops require lower nighttime than daytime temperatures. Greenhouse construction and outfitting will run from \$54 to \$108 per m^2.

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Introduction to geothermal aquaculture use

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1 INTRODUCTION

1.1 *Background*

Aquaculture involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates. The main species reared in this way are carp, catfish, bass, tilapia, frogs, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone.

It has been demonstrated that more fish can be produced in a shorter period of time if geothermal energy is used in aquaculture rather than water dependent upon the sun for its heat. When the water temperature falls below the optimal values, the fish lose their ability to feed because their basic body metabolism is affected (Johnson, 1981). A good supply of geothermal water, by virtue of its constant temperature, can therefore "outperform" even a naturally mild climate.

Ambient temperature is generally more important for aquatic species than land animals, which suggests that the potential of geothermal energy in aquaculture may be greater than in animal husbandry, such as pig and chicken rearing (Barbier and Fanelli, 1997). Figure 1 shows the

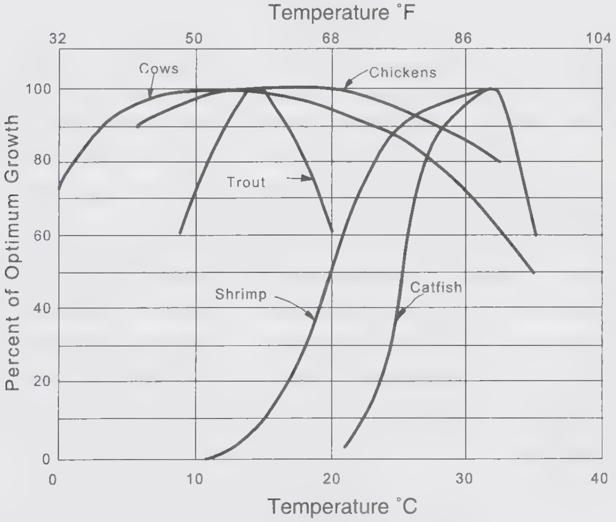

Figure 1. Optimum growing temperatures for selected animal and aquatic species (Beall and Sammels, 1991, modified).

growth trends for a few land and aquatic species. Land animals grow best in a wide temperature range, from just under 10°C and up to about 20°C. Aquatic species such as shrimp and catfish have a narrower range of optimum production at a higher temperature, approaching 30°C. Trout and salmon, however, have a lower optimum temperature, no higher than 15°C.

2 EXAMPLES OF GEOTHERMAL PROJECTS

Fish breeding is a successful business in Japan where carp and eels are the most popular species raised. Eels are the most profitable and are reared in earthenware pipes 25 cm in diameter and 0.9 m long. Water in the pipes is held at 23°C by mixing hot spring water with river water. The adult eels weight from 100 to 150 grams, with a total annual production of 3800 kg. Alligators and crocodiles are also reared in geothermal water, but these reptiles are bred purely for tourism. In combination with greenhouses exhibiting tropical flora, alligator farms are becoming even more popular, making a significant contribution to the growth of the domestic tourist industry (J.G.E.A., 1974). In Iceland, 610,000 salmon and trout fingerlings are raised annually in geothermal water in 10 fish hatcheries, in a new and fast-growing industry (Hansen, 1981; Georgsson and Fridleifsson, 1996).

In the USA, aquaculture projects using geothermal water exist in Idaho, Oregon and California. Fish Breeders of Idaho, Inc., located near Buhl, have been rearing channel catfish in high-density concrete raceways for over 15 years. The water is supplied by artesian geothermal wells flowing at 380 L/s at 32°C. Cold water from springs and streams is used to cool the hot water to 27–29°C for the best production temperature. Normal stocking densities are from 80 to 160 kg of fish per cubic meter. The maximum recommended inventory for commercial production is about 1.6 to 2.4×10^5 kg per cubic meter per second of water. Yearly production will usually be three to four times the carrying capacity. Oxygen and ammonia are the principal factors limiting production (Ray, 1979).

Giant freshwater prawns (Macro brachium rosenbergii) were raised at Oregon Institute of Technology (OIT) from 1975 to 1988. Some research in trout culture and mosquito fish (Gambuzia affinis) has demonstrated that a tropical crustacean can be grown in cold climate as low as -7°C if the water temperature is maintained at the optimal growing temperature for this species of 27–30°C. Initially, two smaller outdoor ponds (1.2 m deep) were uses, before building another two of 0.2 ha each (Fig. 2). A selected brood stock was held in a small spawning building where larvae were hatched in artificial saltwater and reared to the post-larva stage, which made the facility self-supporting. Growth rates of 2 cm per month were maintained (twice that obtained in tropical climates) with a 900-cm^2 of surface area per animal maximum density. The plumbing system of the ponds consisted of perforated diffuser pipes, control valves and thermostats to maintain an optimum temperature in the pond, which provided an even distribution of geothermal energy throughout the pond (Johnson, 1978 and 1981; Smith, 1981).

A very successful catfish raising operation has been launched by the Indian community at Fort Fidwell in northeastern California. Geothermal well water at 40°C is mixed with cold water to produce 27°C water, which is then piped into raceways 7.6 m long × 2.4 m wide × 1.2 m deep. Two sets of parallel raceways use 57 to 63 L/s. A 0.3 m drop between raceways is used to aerate the water. The initial stock of 28 g fish at 3000 per raceway produced a surviving 2000 fish at 0.9 kg each in five months. Construction of the raceways and well cost $100,000. The fish are sold live at the source for $6.60 to $8.80 per kg. Production cost at Fort Bidwell is approximately $1.32/kg (Johnson, 1990).

In a tropical fish raising operation near Klamath Falls, Oregon (Lund, 1994), the effluent water from a greenhouse operation is used to heat 37 shallow tropical fish ponds. These ponds are 30 m long and 4 m wide and vary from 1.0 to 1.4 m in depth. They are kept at a constant 23°C temperature. At present, the owner raises 85 varieties of cichlid fish for pet stores in San Francisco

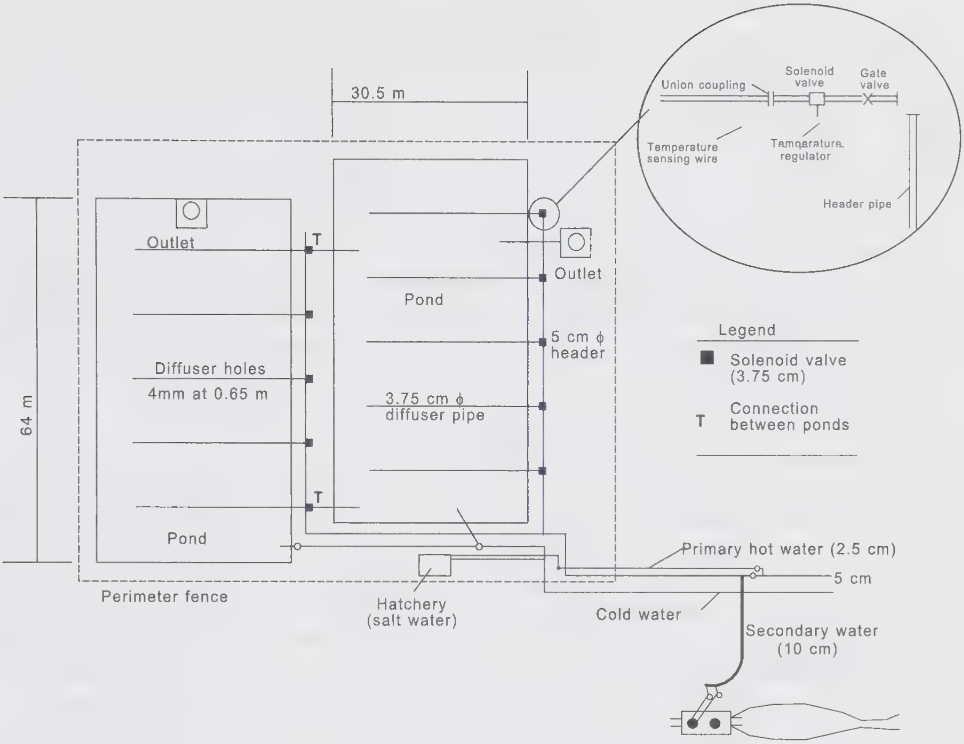

Figure 2. The geothermal aquaculture research project at Oregon Institute of Technology (Smith, 1981).

Table 1. The leading concentration of fish farms in the United States.

Location	Annual use TJ – MWt	Load factor (%)	Product
Buhl, ID	310.2–12	80	Catfish
Mecca, CA	750.0–10	25	Prawns
Waushka, NV	13.8–2	25	Catfish/Tropicals
Ft. Bidwell, CA	12.1–1	80	Catfish
Paso Robles, CA	11.8–1	50	Catfish

and Portland. Approximately 1000 fish 7.5 to 10 cm in length are shipped each week from the local airport. The geothermal heat is a real advantage, as the greatest demand for the fish is during the winter months.

A summary of the leading concentrations of fish farms in the United States is given in Table 1.

In 1987, one of the largest and most successful freshwater prawn farms was established on North Island, New Zealand, to take advantage of geothermal waste heat from the Wairakei power generating field. At present, the farm has 19 ponds varying in size from 0.2 to 0.35 ha and from 1.0 to 1.2 m in depth. The ponds are kept at a temperature of 24°C, with a variation of 1°C from one end of the pond to the other. The farm is currently capable of producing up to 30 tonnes of prawns per year. The adult prawns are harvested at about nine months, averaging 30 to 40 per kg, and sold at US$ 17/kg wholesale, and US$ 27/kg retail. Ninety percent of the harvested prawns are sold to a restaurant on the property, which caters to about 25,000 tourists each year. In the near future, another 40 ha will be added on the other side of the Wairakei power plant, using

Table 2. Crops that are good candidates for aquaculture.

Species	Growth period (months)	Water temperature (°C)
Tropical fish	2–3	23–27
Catfish	4–6	27–29
Trout	4–6	13–18
Prawns	6–9	27–30

waste cooling water from a proposed binary power generator. The farming operation could then well become the third largest freshwater prawn producer in the world, at 400 tonnes per year, which would mean an income of more than US$ 6.7 million annually (Lund and Klein, 1995).

3 GENERAL DESIGN AND CONSIDERATIONS

Based on experience at Oregon Institute of Technology, ponds for raising shrimp, gambusia and trout are best constructed with 0.1 ha of surface area. A size of 15 by 61 m is ideal for harvesting. A minimum-sized commercial operation should have 3 to 4 ha under development (water surface area), or about 30 to 40 ponds. The maximum surface area that should be considered for a single pond is 0.2 ha. Figure 2 illustrates the geothermal pond design of Oregon Institute of Technology. Recent trends are to use circular holding tanks constructed of either metal of fiberglass of six to 10 meters in diameter. An example of this type of geothermal installation for tilapia is found in Imperial Valley, CA (Rafferty, 1999). The optimum size and shape is a function of the specie.

The most important items to consider are quality of the water and disease. If geothermal water is to be used directly, evaluation of heavy metals such as fluorides, chlorides, etc., must be undertaken to determine if the fish or prawns can survive. A small test program is often a wise first step. An aeration pond proceeding the stocked ponds will often solve the chemical problem.

Crops that are a good candidate for aquaculture are listed in Table 2.

Tropical fish (goldfish) are generally the easiest to raise, and have a low investment and high yield. Smaller ponds can also be used. An average of 150,000 fish per year can be raised from 0.4 ha pond area requiring the lowest temperature water; thus, they can better use low-temperature resources of cascaded water. Freshwater prawns generally have a high market value, with marketable sizes being 35 to 44 tails to the kilogram. Channel catfish are also popular, especially as fillets. Production rates depend upon water quality and flow rates.

Ponds require geothermal water of 38–66°C and a peak flow of 19 L/s for 0.4 ha of uncovered surface area in colder climates. The long axis of the pond should be constructed perpendicular to prevailing winds to minimize wave action and temperature loss. The ponds are normally constructed of excavated earth and lined with clay or plastic where necessary to prevent seepage loss. Temperature loss can be reduced, thus reducing the required geothermal flow, by covering the pond with a plastic bubble. Construction cost, exclusive of geothermal wells and pipelines, will run to $75,000–$125,000 per hectare.

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Introduction to geothermal heat pumps

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1 INTRODUCTION

Heat pumps are used where geothermal water or ground temperatures are only slightly above normal, generally 10 to 30°C. Conventional geothermal heating (and cooling) systems are not economically efficient at these temperatures. Heat pumps, at these temperatures, can provide space heating and cooling, and with a desuperheater, domestic hot water. Two basic heat pump systems are available, air-source and ground-source.

Water- and ground-coupled heat pumps, referred to as geothermal heat pumps (GHP) or ground-source heat pumps (GSHP), have several advantages over air-source heat pumps. These are: (1) they consume about 35% less annual energy, (2) they tap the earth or groundwater, a more stable energy source than air, (3) they do not require supplemental heat during extreme high or low outside temperatures, (4) they use less refrigerant (freon), and (5) they have a simpler design and consequently less maintenance.

The main disadvantage is the higher initial capital cost, being about 33% more expensive than air-source units. This is due to the extra expense and effort to burying heat exchangers in the earth or providing a well for the energy source. However, once installed, the annual cost is less over the life of the system, resulting in a net savings. The savings is due to the coefficient of performance (COP) averaging around 4 for GHP as compared to 2 for air-source heat pumps.

2 TYPES OF GEOTHERMAL HEAT PUMP SYSTEMS

Two major types exist: earth-coupled or water-source. The earth-coupled uses a buried earth coil with circulating fluid in a closed loop of horizontal or vertical pipes to transfer thermal energy to and from the earth. The water-source uses a well or an open pond to provide an energy source or sink. Earth-coupled systems have been used in northern Europe for many years, but were not used on a commercial scale in the U.S. until 1980. Earth coupling is used where insufficient well water is available; where the quality of well water is a problem; where drilling and casing of wells are expensive, or where disposal of well water is restricted.

In the horizontal mode of the earth-coupled system, pipes are buried in trenches spaced a minimum of 1.5 m apart and from 1 to 2 m deep. This allows for minimum thermal interference between pipes; however, this system is also affected by solar radiation. Solar radiation will affect the earth to a depth of about 10 m, causing a cycling of soil temperatures, that lags in time and decreases with depth due to the insulating properties of the soil (Figure 1); however, the temperature is much more stable than for air-source units. Moist soil will have greater temperature swings than

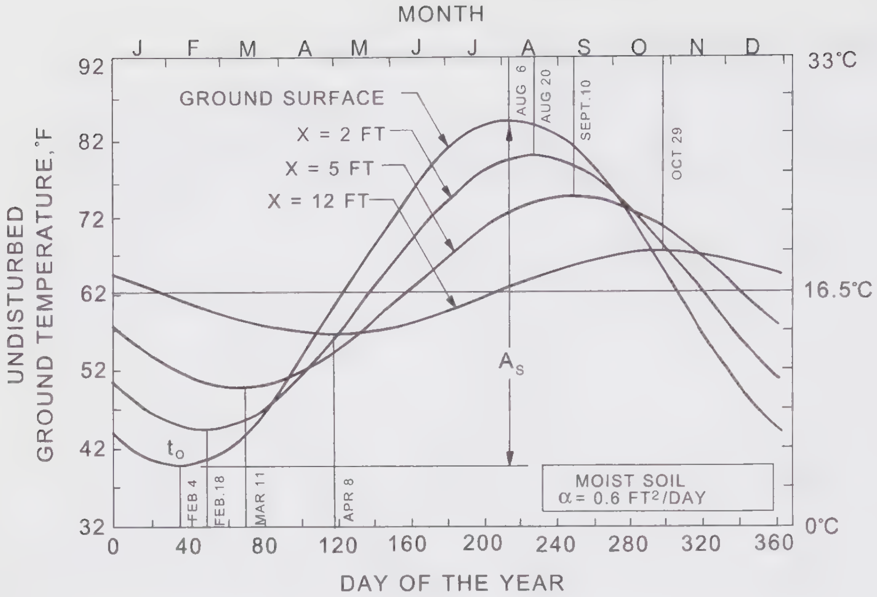
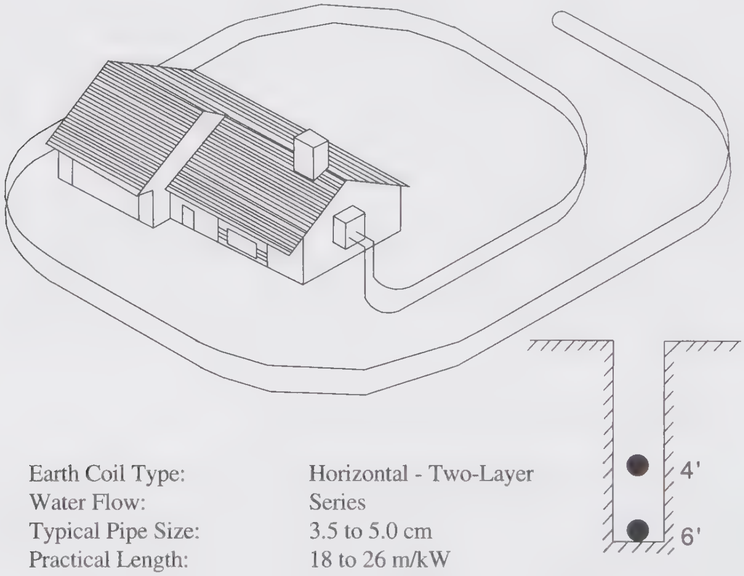


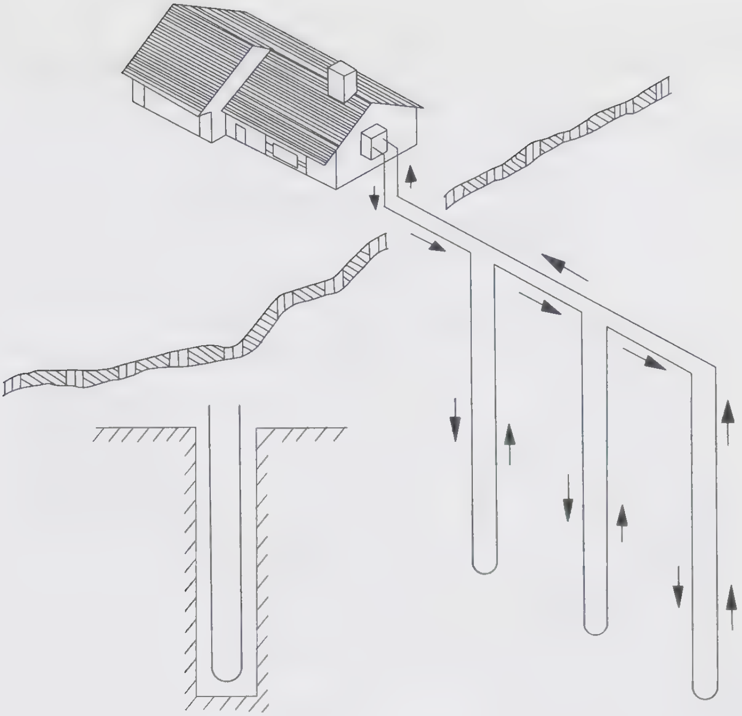
Figure 1. Annual soil temperature variation, Stillwater, OK (Source: Oklahoma State University).



Earth Coil Type:	Horizontal - Two-Layer
Water Flow:	Series
Typical Pipe Size:	3.5 to 5.0 cm
Practical Length:	18 to 26 m/kW 36 to 52 m/kW
Burial Depth:	1.2 to 1.8 m

Figure 2. Two-pipe horizontal ground heat exchanger (Source: Oklahoma State University).

dry soil. The loops can be placed in a double layer as shown in Figure 2. Vertical installation (Figure 3) of the coils are used where land space is limited or trenching would disturb the surface landscape, and drilling costs are reasonable. Holes are drilled approximately 50 m deep and 4 to 6 m apart.



Earth Coil Type:	Vertical - Single U-Bend
Water Flow:	Series
Pipe Sizes:	2.5 to 5.0 cm
Bore Length:	14 to 17 cm/kW
Pipe Length:	28 to 34 m/kW

Figure 3. Series vertical ground heat exchanger (Source: Oklahoma State University).

Computer programs have been developed (Dexheimer, 1985) to calculate the length of horizontal earth coils for heating and cooling. Polyethylene pipes are the most popular in use, and along with socket-fusion joining, are usually guaranteed for over 50 years.

Whereas, horizontal loops are affected by solar radiation, rain and wind; the vertical loops are controlled by the mean-annual temperature of the area and the geothermal gradient and thus, have a more stable temperature environment. Computer design for vertical loops can be found in Kavanaugh & Rafferty (1997).

Water wells are usually used where one is already available, such as for domestic water supply. Normally, a minimum diameter of 15 cm and a production of about 0.05 L/s per kW of heat pump capacity is required. 10.5 kW, a typical residential load, requires about 0.5 L/s. The 15 cm diameter well casing is required to place the pump and return lines, placed in an injection well, or disposed on the surface such as irrigation. Pipes have also been anchored to the bottom of surface ponds (minimum depth of 2 m); however, the heating and cooling capacities are affected by solar radiation and other surface weather factors similar to the horizontal loops. Installation is cheaper and heat transfer is more efficient; however, ponds do not maintain a constant temperature as wells do and the pipes are more vulnerable to accidental damage.

The operation of the heat pump unit is the same for air-source and ground-source configuration. The main difference is that the air-source requires an outside unit (accumulator and fan) which

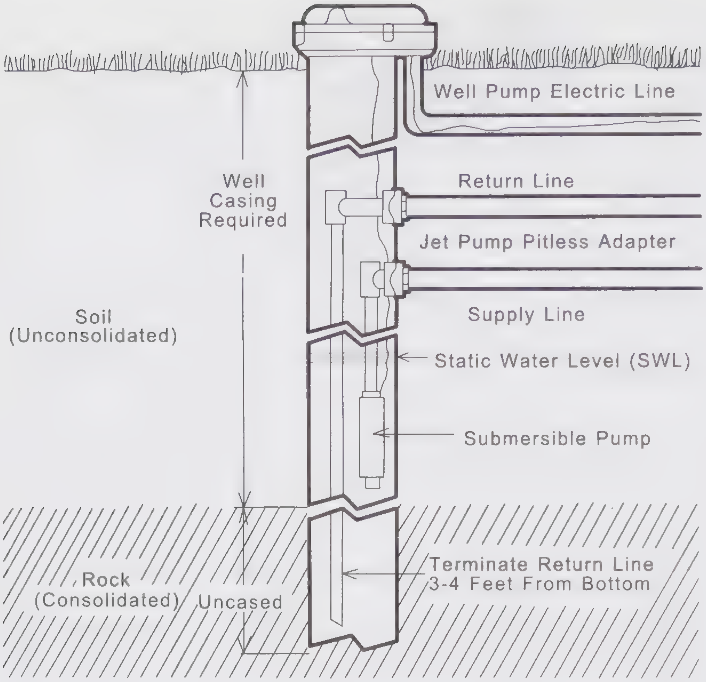


Figure 4. Cross-section view of geothermal well (Source: Water Source Heat Pump Book).

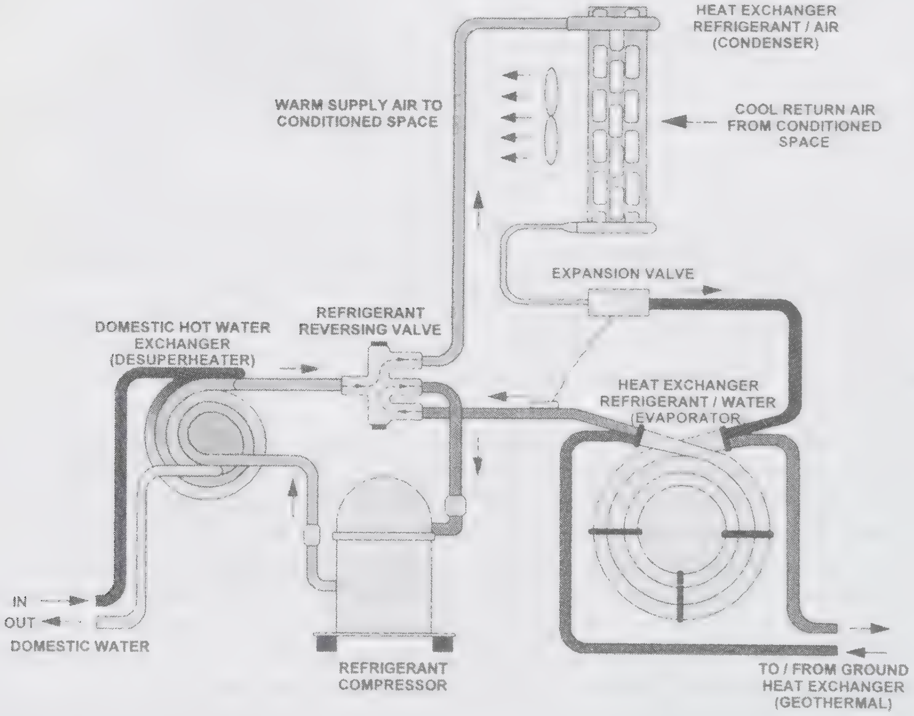


Figure 5. Heating cycle (Source: Oklahoma State University).

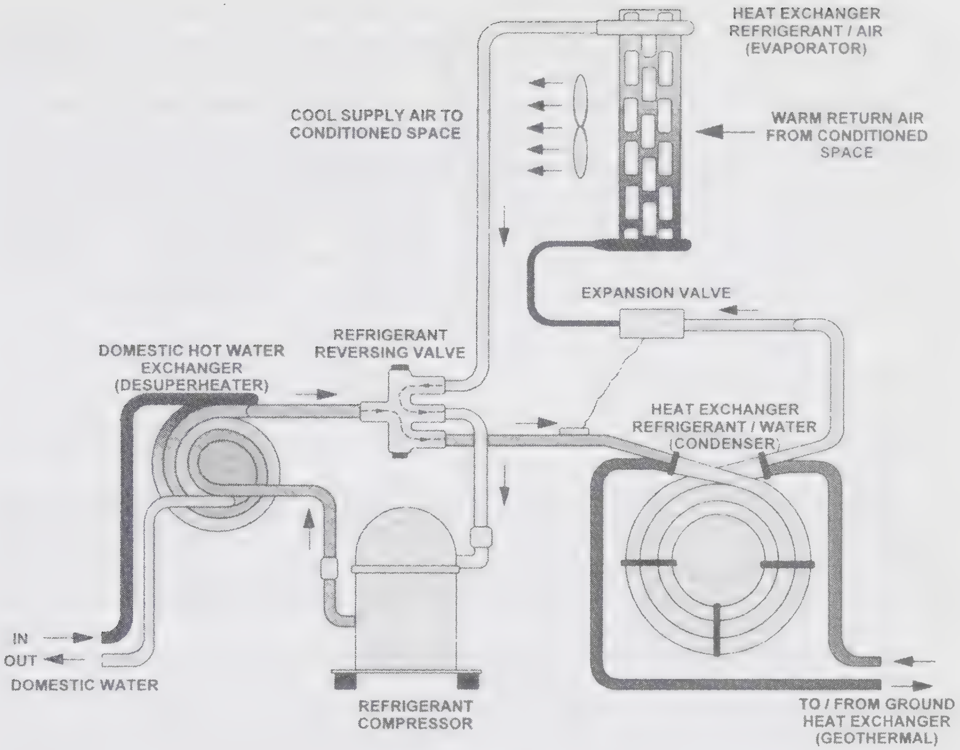


Figure 6. Cooling cycle (Source: Oklahoma State University).

may frost up in cold weather, requires frequent defrosting. They also require a backup heating source (electric or gas) when outside temperatures are too low for efficient operation. The operation and cycle in both heating and cooling mode of the heat pump are shown in Figures 5 and 6 (Oklahoma State University, 1988).

3 HEAT PUMP GROWTH POTENTIAL

It is estimated that 2.5 million heat pump units (of all kinds) are presently installed annually in the United States, with sales growth of 10 to 15% annually. Of these, 45,000 per year are geothermal installations. By 2010, geothermal units will have captured 15% of the heat pump market. Presently, there are around 450,000 geothermal units installed in the U.S. (Lund 1988 and 2001).

Depending upon incentives provided by utilities, state and federal governments, such as tax credits, installations subsides, etc., the total increase of geothermal heat pump installations will be between 10% (a 7-fold increase) and 18% (a 27-fold increase) over the next 20 years.

As an example of incentives for geothermal heat pump installations, mainly to overcome the initial capital investment, the Public Service Company of Indiana (PSI) paid residential developers the added cost of a geothermal heat pump over air-source heat pumps (the horizontal or vertical piping loop cost). To reduce the initial cost, PSI "mass produces" the installation of the geothermal heat pump by installing the system when the subdivision is under construction. This cut the increment cost by about 50%. PSI considered this a good investment as it reduces the peak load, improves the load curve by adding winter demand, and reduces the need for costly new power plants. This program was also considered by other utilities throughout the nation.

Market penetration of geothermal heat pumps can be accelerated dramatically, if utilities have a profit motive for cost-effective conservation investments. One industry representative predicts that if the geothermal heat pump's first cost was equal to the air-source heat pump, their sales would soar to 400,000 annually, 50% of today's heat pump market. Assuming an increasing share of utilities promote geothermal heat pumps as capacity is required, the market share of geothermal heat pumps may reach 5 to 10% of the housing market by 2010, similar to the air-source heat pump market penetration over the past 15 years. The overall energy savings is estimated to reach 30,000 GWh/yr (3,000 MW) by 1995, and over 180,000 GWh/yr (20,000 MW) by 2010 (Sources: EIA, USDOE).

There are presently 27 countries, worldwide, who have documented installations of geothermal heat pumps (Lund, 2001). These provide 6,453 GWh annually from over 500,000 installed units.

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Agri-business uses of geothermal energy

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1 INTRODUCTION

Food production to meet the demands of the world population is becoming an important issue confronting governments today. This is especially true in developing countries where preserving, packaging and transporting food products are difficult and expensive. The problem is compounded in warm climates where spoilage occurs rapidly, and crops cannot be stored for long periods of time.

Drying (dehydration) of food and crops reduces the moisture content which has a number of benefits (modified from Andrejevski and Armenski, 1999):

1. Long storage time without deterioration
2. Early harvesting, which reduces field losses
3. Higher prices for products
4. Food available out-of-season
5. Better quality

Most drying is done by direct contact with warm air at relatively low temperatures (35 to 80°C). Thus, low-temperature geothermal fluids are good candidates for drying food and agricultural products.

The temperature of the warm air usually has to be below a certain value to prevent damage to the product. For example, cracking and checking can occur in cereal grains, especially corn and rice, if the temperature is too high. The drying temperature is also a function of the equilibrium relative humidity of the air and the type of grain as illustrated in Table 1 (Andrejevski and Armenski, 1999).

The drying temperature is also dependent on the moisture content of the grain. For example, grain used for seed and baking have recommended critical kernel temperature as follows (Andrejevski and Armenski, 1999).

Table 1. Critical kernel temperature (°C) as a function of equilibrium relative humidity.

Grain	Relative humidity (%)			
	60	70	80	90
Oats	59	55	50	–
Wheat	63	62	58	52
Corn	52	45	48	46
Rye	53	50	63	41

Table 2. Critical kernel temperature (°C) of wheat as a function of moisture content.

	Moisture content %						
Grain Use	27	25	23	21	19	17	15
Seed	49	51	52	55	56.7	60	63
Baking	49.4	52.2	55	57.2	60	63.3	67.2

Most agricultural crops must be dried to, and maintained at, a moisture content of 12 to 13% wet basis, depending on the specific crop, storage temperature and length of storage. Mold growth and spoilage are functions of elapsed storage time, temperature, and moisture content above a critical value. Grain to be sold through commercial markets is priced according to a specific moisture content, with discounts for moisture varying from this value (Lienau and Lund, 1998).

2 SYSTEMS FOR DRYING (LIENAU AND LUND, 1998)

The systems used for drying can be divided into two general methods:

1. Batch dryers
2. Continuous dryers

2.1 *Grain and rice drying*

Grain dryers are either full bin (batch) dryers or vertical column (continuous) dryers. In the case of batch dryers, the dryer is typically a deep bed dryer. This type of equipment consists of (a) a fan to move the air through the product, (b) a controlled heater to increase the ambient air temperature to the desired level, and (c) a container to distribute the drying air uniformly through the product. The exhaust air is vented to the atmosphere. Where the climate and other factors are favorable, unheated air is used for drying, and the heater is not used.

Several operating methods for drying grain in storage bins are in use. They may be classified as full-bin drying, layer drying and batch drying. The deep bed dryer can be installed in any structure that will hold grain. Most grain storage structures can be designed or adapted for drying by providing a means of distributing the drying air uniformly through the grain. This is most commonly done by either a perforated false floor (Figure 1) or duct system placed on the floor of the bin.

Full-bin drying is generally done with unheated air or air heated 5 to 10°C above ambient. A humidistat is frequently used to sense the humidity of the drying air and turn off the heater if the weather conditions are such that heated air would cause over drying.

The depth of grain (distance of air travel) is limited only by the cost of the fan, motor, air distribution system and power required. The maximum practical depth appears to be 6 m for corn and beans, and 4 m for wheat. Grain stirring devices are used with ful-bin systems. These devices typically consist of one or more open, 5-cm diameter, standard pitch augers suspended from the bin roof and side wall, and extending to near the bin floor.

Conversion of the deep bed dryer to geothermal energy is accomplished by simply installing a hot water coil in the inlet duct using geothermal fluid in the 40 to 50°C temperature range.

Of all the grains, rice is probably the most difficult to process without quality loss. Rice containing more than 13.5% moisture cannot be safely stored for long periods. When harvested at a moisture content of 20 to 26%, drying must be started promptly to prevent the rice from souring. Deep-bed or columnar dryer could be used; a columnar dryer will be described next.

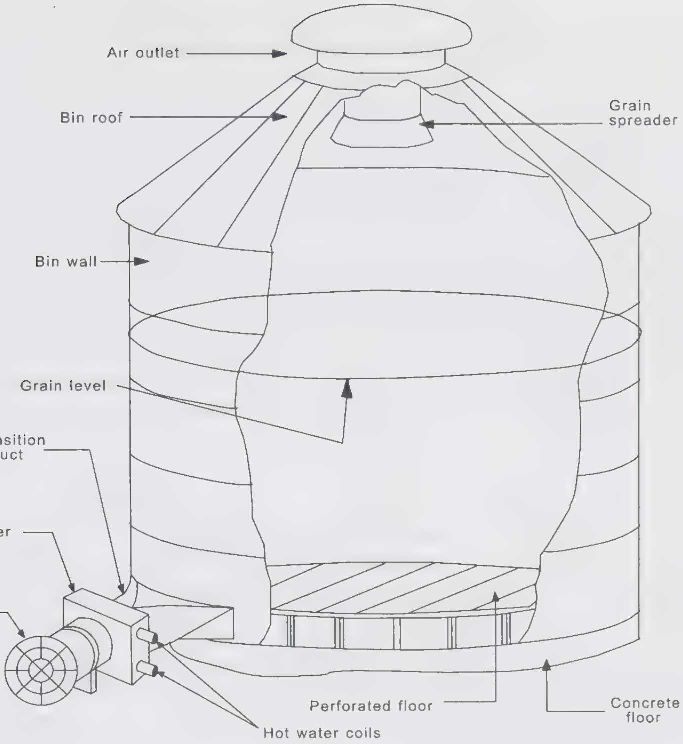

Figure 1. Perforated false floor system for bin drying of grain.

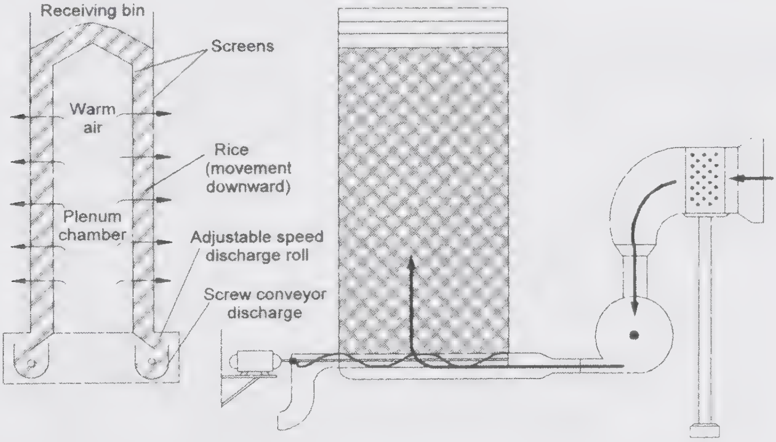

Figure 2. Columnar grain dryer (Guillen, 1987).

Grain is transferred from the storage bins to the top of the columnar dryer by conveyors. The column must be completely filled before the drying operation start. The grain screw conveyor, located at the bottom of the column, as shown in Figure 2.

The two important variables in the drying operation are the air-mass flow rate and the temperature at the inlet to the dryer. Hot air is blown from the bottom and a static pressure is maintained between columns. Air temperature is controlled by regulating the burner output from several thermocouples installed inside the column to monitor the air and kernel temperature.

Rice is loaded in the dryer at approximately 21 to 22% moisture content and the drying cycle is normally completed after three to four passes. The final moisture content should be below 15% before it can be safely stored in the warehouse. After each pass, partially dried rice is tempered to equalized internal moisture content, thus minimizing thermal stresses and avoiding breakage of kernels. Kernel temperature is normally maintained at 40°C when the moisture content is approximately 21% and at lower moisture content, 17%, the temperature is limited to 35°C. At a constant grain temperature of 40°C, air is heated to 80 to 90°C during cold weather and approximately 60 to 80°C during the warm season.

Converting the columnar dryer to geothermal fluids involves the installation of a hot water coil upstream of the blower fan to obtain uniform temperature inside the plenum chaber. The air flow pattern is shown in Figure 2 and there is no air recirculation because of the presence of dust on the down stream side.

Air flow could be maintained at a constant rate; then the only variable would be the flow rate of the grain.

A rice drying facility has been installed at Kotchany in Macedonia using geothermal water at 5 L/min (Figure 3). The unit has a capacity of 10 tonnes/hour (Popovski, et al., 1992). The geothermal fluid enters at 75°C and exits at 50°C. The air temperature in the dryer unit inlet is 35°C. The rice enters at 20% moisture content and exits at 14%. The cooling (ambient) air is 15°C with a relative humidity of 60%. A regulator keeps the air drying temperature below 40°C in order to avoid cracking the rice grains. The heating capacity of the dryer is 1360 kW. The heat exchangers consist of square finned copper pipes in three row perpendicular to the flow. It is modified from a standard one which is designed for 90/70°C temperature drop for use in the geothermal system at 75/50°C.

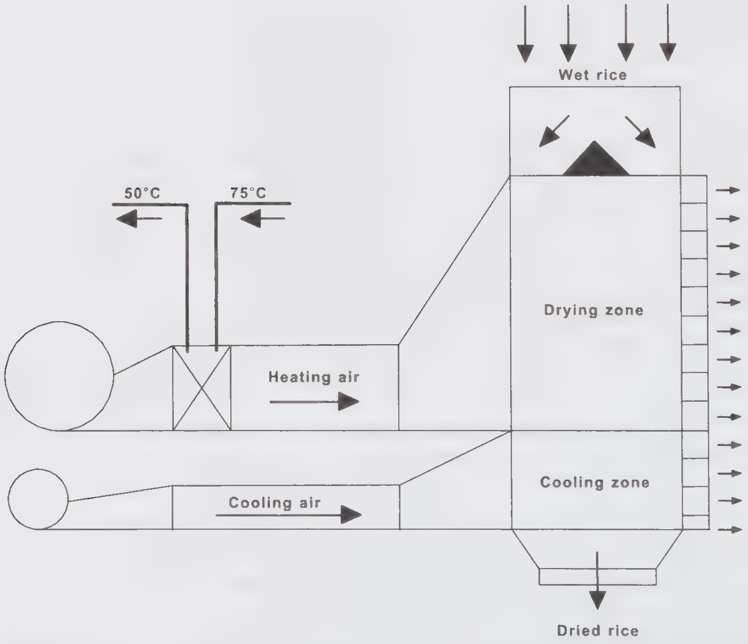

Figure 3. A schematic flow diagram of the geothermal rice drying plant in Kotchany, Macedonia.

The drying process starts with the wet rice entering the dryer at the top. By a system of simple flow regulators, it moves down the sloping grate cascading at a constant velocity. By gravity, it flows from the upper to the lower grates through a cross flow of heated air. After passing through the drying section, the rice moves to the cooling section; where, the temperature is equalized to the ambient one. At the end of the drying process, the rice discharges into sacks via a variable-speed discharger at the bottom of the dryer (Popovski, et al., 1992).

Another specialized fibrous plant dehydration method using geothermal energy is that used for alfalfa (lucerne) drying and pelletizing developed in New Zealand (Pirrit and Dunstall, 1995). Near Taupo, on the edge of the Broadlands geothermal field, geothermal steam and hot water is used from drying the alfalfa into "De-Hi" produced from the fibrous part of the plants, and "LPC" (lucerne protein concentrate) which is a high protein product produced from extracted juice. Dried timber is also produced on the site in a separate batch operation. What was originally a pilot plant operation has been developed into a full-scale production plant producing approximately 3000 tonnes per annum of dried products for New Zealand and Australian markets.

2.2 *Vegetable and fruit dehydration*

Vegetable and fruit dehydration involves the use of a tunnel dryer, or a continuous conveyor dryer using fairly low-temperature hot air from 40 to 105°C. Geothermal examples of these types of dryers can be found in Lund (1994); Lund & Lienau (1994a; 1994b); Lund & Rangel (1995); Chua & Abito (1994), and Merida (1999).

A tunnel dryer is an enclosed, insulated housing in which the products to be dried are placed upon tiers of trays or stacked in piles in case of large objects, as shown in Figure 4. Heat transfer may be direct from gases to products by circulation of large volumes of air, or indirect by use of heated shelves or radiator coils.

Because of the high labor requirements usually associated with loading and unloading the compartments, they are rarely used except in the following cases:

1. A long heating cycle is necessary because of the size of the solid object or permissible heating temperature requires a long hold-up for internal diffusion of heat or moisture.
2. The quantity of material to be processed does not justify investment in more expensive continuous equipment. This would be the situation for a pilot plant.

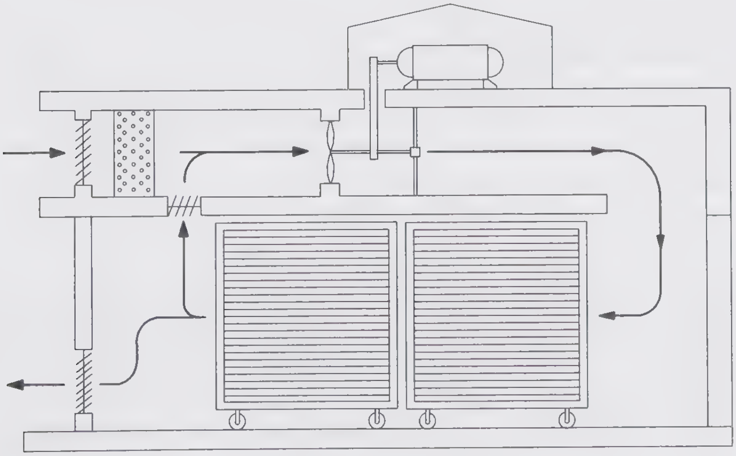

Figure 4. Tunnel dryer air flow pattern (Guillen, 1986).

A drawing of a conveyor dryer, which is typical of onion and garlic dehydration in Nevada, USA (Lund and Lienau, 1994a) is shown in Figure 5. The energy requirements for the operation of a conveyor dryer of this type will vary because of difference in outside temperature, dryer loading, and requirements for the final moisture content of the product. A single-line conveyor, approximately 64 meters long × 3.8 meters wide can handle 4,500 kg of raw products per hour (mainly onions and garlic) and produce 680 to 816 kg of dried product. This unit will require 22.1 GJ/hr, or for an average season of 150 days, 80 TJ/season, using approximately 35 MJ/kg of dry product.

In general, four stages (A through D) are preferred; however, if the ambient air humidity is below approximately 10%, Stage D can be eliminated. Also, temperature and number of compartments in each stage may vary. Figure 6 is a flow diagram of a geothermally-heated process with an outside air temperature of 4°C requiring 27.4 GJ/hr. If the outside air temperature was

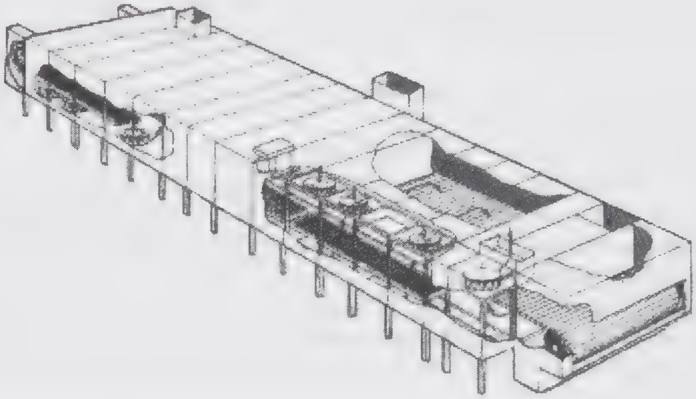

Figure 5. Typical continuous belt dryer (Proctor and Schwartz, Inc., Horsham, PA).

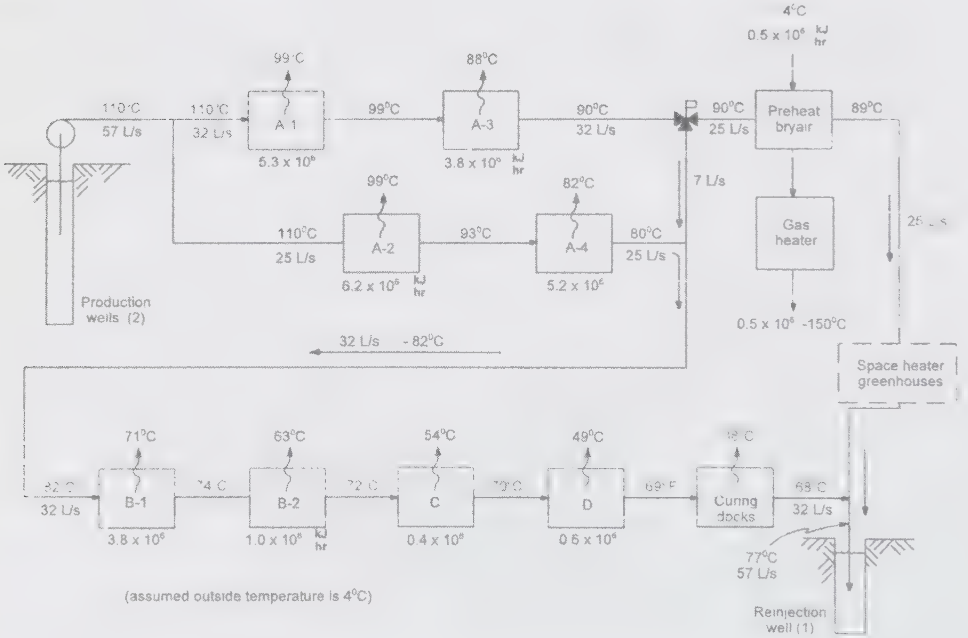

Figure 6. Flow diagram of a multi-stage conveyor dryer using 110°C geothermal fluid and 4°C ambient air.

18°C instead, the total energy requirements would be reduced to 22.1 GJ/hr. Using an 11°C minimum approach temperature between the geothermal fluid and process air, this process would require a geothermal well flow of 57 L/s at 110°C.

The line shown in Figure 6 is split between compartments A-1 and A-2, because both require 99°C air. This first-stage air temperature can be as low as 80°C; however, temperatures above 90°C are desirable. The Bryair desiccator in Stage D requires 150°C on the reactor side; thus, only half of the 1.0 million kJ/hr energy requirements can be met by geothermal energy. Geothermal fluid will be used for preheating to 79°C, with natural gas or propane used to boost the air to 150°C. The waste water from the Bryair preheater has a temperature of 89°C; thus, this could be used for cascaded uses. The waste water could be returned to the reservoir by means of an injection well.

In compartments A-1, A-2, A-3 and A-4, four finned air-water heat exchangers in parallel would be required to satisfy the energy requirement and water velocity flows. The remaining stages would require from one to two heat exchangers in each compartment, depending upon the energy requirements.

If lower temperature geothermal fluids were encountered (below 90°C), then not all the energy could be supplied to Stage A by geothermal fluid. Geothermal fluid would then be used as a preheater, with natural gas providing the energy for the final temperature rise.

A recent study by Geothermal Development Associates of Reno, NV, made the following rough cost comparison of investing in a geothermal binary power plant vs. an onion dehydration.

The following assumptions were made:

1. 150°C geothermal resource temperature
2. 20 MWe net binary power plant (90% availability)
3. US$0.07 per kWh power sales price
4. 10-month dehydration plant operation
5. 13.6 million kg annual dryer production (two dryers similar to the ones shown in Figure 5)
6. US$2.20 per kg of dried product wholesale price.

Based on the above assumptions, the following cost analysis was made:

	Power Plant	Dehydration Plant
Capital Expenditure	US$50 million	US$15 million
Gross Revenue	US$11 million	US$30 million
Resource Requirements	760 L/s	76 L/s
Number of Employees	15	75

The benefits by investing in the dehydration plant over the power plant is less capital expenditure and higher gross revenue along with less geothermal resource needed. The employment could be looked at as a benefit, by employing more people especially in areas of high unemployment, but at the same time costing more for salaries. O&M costs are not included, as well as the transportation costs to supply onions to the plant. Pumping costs would be more for the power plant. Thus, it appears the dehydration plant is the better investment.

2.3 *Lumber drying*

Drying lumber in batch kilns is standard practice for most upper grade lumber in the western U.S. and other countries (Scott and Lund, 1998; Lund, 1999). The two basic purposes of drying are to set the sap and to prevent warping. This in turn enhances the value of the lumber, increasing the market for the product.

The sap normally sets at 57 to 60°C. Warping is prevented by establishing uniform moisture content throughout the thickness. Lumber left to dry under ambient conditions loses its moisture from exposed surfaces at a faster rate than internally. This differential drying rate sets up stresses

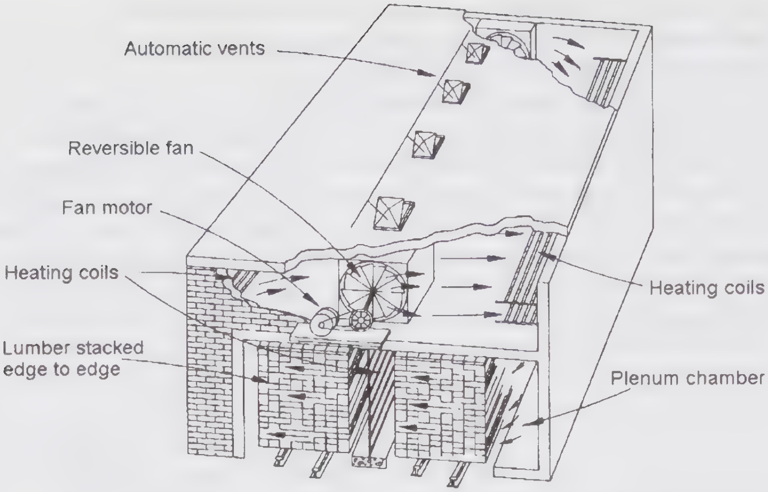

Figure 7. Long-shaft, double-track, compartment kiln with alternately opposing internal fans.

that cause warping. Moisture occurs in wood in cell cavities and cell walls. The majority of the moisture is first lost from the cavities. This loss is not accomplished by changes in the size of the cell or in warpage. When water is lost from the cell walls, however, shrinkage of the wall fibers takes place setting up the stresses that cause warping (VTN-CSL, 1977).

In the kiln drying process, the evaporation rate must be carefully controlled to prevent these stresses. The allowable drying rates vary from species to species and decreases with thick cut sizes (i.e., they take longer time to dry). Kiln drying is usually carried out as a batch process. The kiln is a box-shaped room with loading doors at each end (Figure 7). It has insulated walls and ceiling and has fans to recirculate the air at high velocity through the lumber. The sawn lumber is spaced and stacked to assist the free air movement. When fully loaded, either by fork lift or on rail cars, the doors are closed and the heating cycle is started. Make-up air, preheated to temperature consistent with the drying schedule, enters the kiln where it recirculates through the stacked lumber by reversible fans and picks up moisture. Exhaust fans draw the moist air from the kiln and discharges the moist air outside. The rates of flow and temperature are adjusted so that the temperature and the humidity in the kiln will retard the drying rate sufficiently to prevent warping. During the drying cycle, the lumber loses a large portion of its weight from evaporation of water, 50 to 60% for many species.

Drying schedules are specific for each species of lumber and for size. The larger the size, the more tightly the moisture is held in the wood fiber, and slower the schedule. Drying schedules range from less than 24 hours to several weeks per batch. Typical temperature used in the kiln are below 100°C, but recent work in New Zealand and elsewhere have accelerated the drying schedule by using temperatures above 100°C (Scott and Lund, 1998). In most cases, the lumber has to be cured in humid air after drying to bring the entire board to a uniform moisture content. Examples of drying schedules can be found in Knight (1970).

Geothermal energy can be adapted to kiln drying by passing air over finned heat exchanger tubes carrying hot water or steam. The finned tube heat exchangers are placed inside the kiln so that the air recirculation path passes over the heat exchanger. The water temperature must be at least 10 to 20°C above the ambient operating temperature of the kiln. This would mean a geothermal supply temperature of 90 to 115°C would be required.

The geothermal discharge fluid from this application would have temperatures ranging from 70 to 80°C, and would be available for other applications at the mill, such as heating of office buildings, keeping log ponds ice free in winter, greenhouse heating, or other cascaded uses.

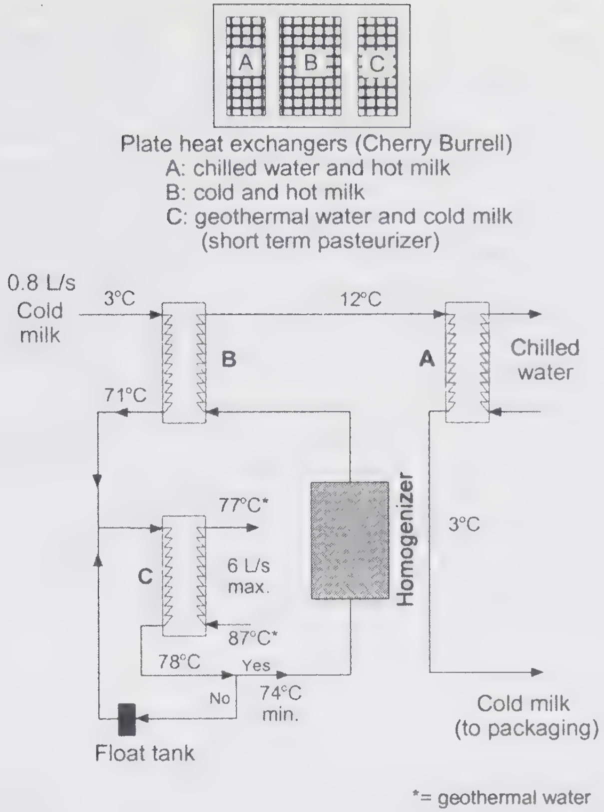

Figure 8. Medo-Bell milk pasteurization flow diagram.

2.4 *Milk pasteurization with geothermal energy*

Milk pasteurization with geothermal energy has been reported in three locations in the world: Klamath Falls, Oregon; Oradea, Romania and Iceland (Lund, 1997; Thorhallsson, 1988).

The Medo-Bell Creamery, in Klamath Falls, Oregon, is the only creamery in the U.S. known to have used geothermal heat in the milk pasteurization process (Lund, 1976, 1996; Belcastro, 1979). This process, using 82°C water from a 233-m deep well with artesian flow of about 2 L/s, will be described in detail. Unfortunately, the business is no longer in operation.

2.4.1 *Details*

The pasteurization process involved pumping up to 6.3 L/s of geothermal fluid into the building and through a short-time pasteurizer (Cherry Burrell plate heat exchanger of stainless steel construction) (Figure 8). The geothermal water was pumped from the well at 87°C into the building and through a three-section plate heat exchanger, the incoming cold milk at 3°C was heated by milk coming from the homogenizer in one section of the plate heat exchanger. The milk was then passed to the second section of the plate heat exchanger where the geothermal fluid heated the milk to a minimum temperature of 78°C, the short-time pasteurizer automatically recirculated the milk until the required exposure was obtained. Once the milk was properly pasteurized, it was passed through the homogenizer and then pumped back through the other side of the first section of the plate heat exchanger where it was cooled to 12°C by the incoming cold milk. It was finally chilled to 3°C by cold water in the third section of the plate heat exchanger, where the milk went into the cartons with no chance of cook on. This insured both flavor and longer shelf life. As an added bonus, the outgoing heated milk was cooled somewhat by passing it by the incoming cold milk and the cold milk was in turn heated slightly by the outgoing milk. Milk was processed at a rate of 9.84 L/s, and a total of 225,000 kg were processed each month. Some steam was necessary in the process to operate equipment; thus, geothermal water was heated by natural gas to obtain the required temperature. Geothermal hot water was also used for other types of cleaning.

In addition to the milk pasteurizing, some batch pasteurizing of ice cream mix was carried out by geothermal heat. A 950-liter storage tank was used to mix geothermal hot water and process steam to a temperature of 121°C. This heat was then used to pasteurize the ice cream mix at 63°C for 30 minutes. This was the original milk pasteurizing method used at the creamery.

This geothermal water had slightly over 800 mg/L dissolved solids of which approximately half were sulfate, a quarter sodium and a tenth silica. The pH of the water was 8.8. Minimum corrosion was evident in the well, requiring the jet pump to be replaced only once in the 30-year period (1974). The original pump was rated at 0.7 kW (one hp) and a new pump was rated at 5.6 kW (7.5 hp). The corrosion had also been minimum in the area heaters and did not affect the stainless-steel plate heat exchanger. Corrosion was substantial in the pipelines.

The annual operational cost of the system was negligible. However, the savings amounted to approximately $1,000 per month as compared to conventional energy costs. Geothermal hot water was also used to heat the 2,800 m^2 building, which amounted to a substantial savings during the winter months.

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Geochemical and geophysical methods in geothermal exploration

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ABSTRACT: Geochemical survey on thermal spring areas all over the World have been largely used in the past to assess the potentiality of a promising region for the development of geothermal energy.

Before conducting any expensive geochemical and geophysical prospecting campaign, a preliminary reconnaissance survey describing the location, geological setting of thermal emergences, and type of manifestation should be conducted.

Once the occurrence and type of thermal manifestations is known, a strategy on what type of chemical prospecting is better for the area under investigation should be planned.

Chemical investigation of steam condensates, thermal waters, gas vents and mineral phases, precipitated at the orifice of thermal discharges should include both isotopic and chemical analysis, whose number is limited by the available budget.

The geochemical prospecting of natural thermal (and for comparison cold) fluids discharged at the surface of a promising area should precede any future geophysical investigation.

Among possible geophysical investigations, geoelectrical prospecting and the drilling of shallow wells to measure the geothermal gradient seem to be the more useful tools to decide if a potential geothermal area deserve to be investigated by deep drillings.

1 INTRODUCTION

The main evidence of the potential presence of deep exploitable geothermal fluids (energy) in a region is the presence, at the surface, of thermal features such as thermal springs. It is evident that the presence of the most spectacular thermal emergences, such as: steam emissions, gaysers and/or boiling mud pools, is even more promising. Quantity (in number and flow rate), quality and spatial distribution of thermal manifestations in an area are extremely variable. This varies according to the size of the hydrothermal system at depth that leak fluids to the surface, as well as the permeability of formations lying above the hydrothermal system. The presence of low permeable formations above buried high temperature hydrothermal systems is of fundamental importance to prevent massive inflow of cold meteoric-originated waters into the system that would cool the hydrothermal system itself, very fast.

Hydrothermal systems that form and develop in a geological sequence, where permeable formations are prevalent over impermeable formations are sometimes able to seal themselves over a period time due to water-rock interaction processes. These hydrothermal solutions, which are generally saline and rich in silica and CO_2 (the concentration of silica in solution is dependent upon temperature), during their ascent to the surface (or flowing laterally from the system) precipitate silica (and/or carbonates due to loss of CO_2) at cooler, near surface regions. The precipitation of secondary minerals as veins in cooler boundary areas is able to seal the top and lateral parts of their mother hydrothermal systems. This is what happens at The Gaysers geothermal field, in California, where both the "real" reservoir under exploitation and the cap-rock are located in the "Franciscan Formation", a tectonic melange made up of a thick sequence of ophiolite-bearing graywackes and metagraywackes.

In general, what is applicable for large regions characterized by anomalous heat flow (such as the circum-pacific ring of fire), is also locally valid for volcanic areas. In volcanic areas self-sealing processes are even more common due to the ascending high salinity volcanic fluids generated by the continuous steam loss from the top craters of volcanoes. As a consequence of such sealing processes, sometimes (often), in Quaternary volcanic areas, thermal manifestations at surface can be completely absent. The concept of self-sealing as a tool nature has to form and preserve buried and sometimes hidden geothermal system was developed and described by Facca and Tonani (1967).

Another important parameter that affects the presence of natural thermal features at the surface is the topography. If there are hot hydrothermal solutions spreading from an active hydrothermal system and laterally flowing underground, it is more likely that they will find a way (fault, fracture, overflow ... etc.) of discharge in a ragged topography rather than in a flat topography. In areas with flat topography, the emission of deep fluids is strictly associated with prevailing fracture and fault systems (Person and Baumgartner, 1995 and references therein).

2 TYPES AND IMPORTANCE OF SURFACE THERMAL MANIFESTATIONS

In a wild (undiscovered from a geothermal point of view) area where there are several thermal manifestations at the surface, it is very important to classify the different types of thermal features. The most promising thermal manifestations at surface are steam vents. In volcanic areas the presence of steam fumaroles at temperatures around 160°C are quite common. In volcanic areas, such as those at Solfatara volcano in the Neapolitan area, Italy; at Mt. Usu in Japan, S. Lucia Island, West Indies, as recorded by the author, presence of fumaroles with temperature of about 160°C are quite common. This type of fumaroles at the surface is due to the presence, at depth, of a hydrothermal system at the maximum enthalpy for water (in the Mollier diagram at about 236°C and 32 bars). If such a system pumps steam quickly to the surface, the adiabatic expansion of steam will produce, at surface, at atmospheric pressure, a steam fumaroles (or a fumarolic field) with temperatures of about 160°C (associated with low temperature fumaroles as well).

It is more common to find, especially in the crater areas of volcanic cones, weak steam emissions, especially from lavas. Temperature of these steaming areas is variable: from 30–40°C, up to the boiling point of water at the altitude of emission. Although sometimes their presence can lead to misinterpretations (steaming at 30–40°C can be derived by the evaporation of 2–3 km thick convective unconfined aquifers at near boiling temperature), in general the presence of fumaroles gives clear indication of the presence of a high temperature hydrothermal systems at depth.

Thermal springs (up to boiling temperature for water) are another common feature of active geothermal areas. They can be classified in terms of temperature (boiling or below boiling temperature) and the presence of an associated gas phase. The gas phase can be either N_2 or CO_2 rich (more rarely CH_4 and H_2 rich), but the presence of CO_2 (and H_2S) is a better indication of active hydrothermal systems at depth. Salinity and flow rate of springs are additional parameters that can give preliminary information on their source zone. The genetic scheme of thermal spring emergence can be visualized as follows:

a) very high temperature springs (up to near boiling temperature), with high flow rate (up to several m^3/sec), high salinity (up to several g/L), neutral to alkaline *p*H (up to 11), N_2 (generally with no H_2S) as main associated gas component (up to 99% by vol.), high concentration of total He (up to several % by vol.), low $^3He/^4He$ ratio (less than the air ratio);

b) lower temperature springs (30 70°C), low-to-very-low flow rate (as low as 1 L/m), low salinity (even <100 mg/kg), neutral to acidic *p*H (up to 2), CO_2 (sometimes with H_2S) as main gas component ($>99\%$ by vol.), low concentration of total He (<1 mg/kg) and contemporary high $^3He/^4He$ ratio ($>>$ than the air ratio).

Although high flow rate, high temperature springs are much more spectacular than lower temperature springs, the presence of type (a) springs, especially if they are isolated and the only thermal emergence in a large area, is not a good indication of the presence of a high enthalpy system at depth. On the contrary, they are more likely to represent the ascending arm of a large and thick convective system located along a fault that carries, fast to the surface, a deep fluid whose source zone can be a deep saline reservoir at 3–5 km in depth. Such deep reservoirs hosting long circulating regional waters are rich in atmospheric N_2 where no CO_2 is produced through active water-rock hydrothermal processes. The high concentration of total He (^4He, up to several % by vol.) in type (a) spring is a consequence of the long circulation of water in the crust, where ^4He is continuously produced by the radioactive decay of U-Th-rich minerals. Such springs (type – a) are also quite common in cratonic areas, and have been defined as "intracratonic thermal fluids" (Minissale et al., 2000).

By contrast, the presence of lower-temperature, lower-salinity springs is, sometimes, a good indication of the presence of a high enthalpy system at depth. Such springs sometimes can hardly be distinguished chemically and isotopically from the usual, common, cold Ca-HCO_3 groundwaters occurring in the same area. The reason why they are hot, in spite of having the main composition as groundwaters, is due to the fact that the heat flow in the area is so high that they are heated, locally, by conduction. This is what happens in the famous Larderello geothermal field, in Italy, where the chemical composition of the thermal springs is similar to the shallow groundwaters (Duchi et al., 1986). Sometimes the condensation of steam rising from a high temperature system in shallow cold aquifers can occur. Especially if the permeability of shallow aquifers is low, such condensation can generate thermal springs with very low salinity, but high concentration of volatile components, such as NH_4, quite often the only saline component (together with CO_2) carried on by steam (Tonani, 1970). The total concentration of He in the gas phase associated with the springs with good promising geothermal characteristics is generally very low (sometime less than 1 mg/kg). This is due to the dilution with CO_2 which is continuously produced inside the geothermal systems through reactions between carbonate and silicate phases, such as the conversion of calcite in epidote at temperature $>200°C$:

$$\text{calcite} + SiO_2 = \text{epidote} + CO_2$$

As mentioned above, in active geothermal areas, gases are generally associated with thermal springs. Sometimes, especially in the case of hydrothermal systems hosted by limestones aquifers at greater depth, "dry" CO_2-rich gas emissions at surface is the main hydrothermal evidence of the presence of a degassing hydrothermal system at depth. This is particularly evident in areas where the topography affects the discharge of fluids at surface and where a phase separation can occur at depth between the liquid phase and the gas phase. In rugged topographic areas, gas vents (sometimes associated with genetic shallower cold waters) are located at higher elevations while thermal springs discharge at lower elevations.

A particular feature of several active hydrothermal and/or volcanic areas in the World is the presence of cold CO_2-rich gas bubbling mud pools, even where there are no emergence of thermal springs. In fact, quite often, "primary" liquid phases and/or steam condensates and/or thermal circulating waters are not able to reach the surface while the separated gas phase continuously ascend to the surface. These mud pools are generated by the spot discharge of gases at the surface and even able to carry small quantity of water (gas lift) and mud, especially where clay-rich material is present in the shallower part of the rising duct. The continuous flow of the gas phase to the surface (especially if H_2S is associated to CO_2) renders the stagnant solution in the pools extremely acidic resulting in kaolinization of bedrock in the discharge point as well as along the flow channels of the rising water column. Sometimes, where CO_2 emissions occur in clay rich formations (Neogene basins) these mud pools can have the shape of mud volcanoes, typical surface CH_4 emissions of areas rich in oil and gas fields.

3 GEOCHEMISTRY APPLIED TO GEOTHERMAL PROSPECTING

3.1 *Field and laboratory procedures*

If the shape and type of topography associated with thermal emissions in an area under exploration can roughly suggest the presence of a high enthalpy system at depth, then, the chemical composition of the emerging fluids can definitely suggest whether that area deserves to be further investigated through geophysical methods and eventually through deep drilling.

The geochemical prospecting of natural thermal manifestations is generally not very expensive and it may give information on the geothermal potential of large territories. In general the application of chemical geothermometers in liquid and gas phase gives reliable estimates of temperature of the sources of fluids, whose depth cannot generally be derived by the geochemical prospecting.

Exploratory field campaigns for sampling generally consist of thermal water and gas samples, either associated with the springs or as dry emissions, as well as hydrothermal deposits eventually present around the orifices of the fluid emergences.

In silicic formations thermal springs, at the surface, generally precipitate silica (sinter deposits) and Fe-hydroxides. Sometimes, travertine precipitates from thermal (and sometimes cold) springs, such as those areas located along the Tethys orogenic belt (from Italy to Himalaya, Pentecost, 1995; Ford and Pedley, 1996), giving rise to huge deposits, sometimes hundred meters thick.

When a spring is sampled, temperature, *p*H, electrical conductivity, as well as the concentration of HCO_3 must be determined in the field and a special bottle must be used for silica. In fact, since hot springs generally precipitate silica after cooling, and silica is really an important parameter of geochemical exploration, thermal spring water is generally stored diluted 1:10, in a separate plastic bottle to avoid silica precipitation during the time span between sampling and the analysis. Ammonia, another important parameter during geothermal prospecting, should be analyzed in the field, using portable spectrophotometers. If this is not available, a fraction of the sampled water must be acidified to prevent both oxidation of ammonia and oxidation of other cations, as well as Ca, Fe … etc. precipitation as $CaCO_3$, $Fe(OH)_3$ … etc.

The sampling of gas phases during the exploration stage of a promising area is much more important than the springs. With respect to spring waters, that undergo easily dilution and mixing during underground motion, that quite often do not allow to assess the real composition of the original deep hydrothermal solutions, the gas phase rising the crust is less sensitive to dilution and mixing with shallow gases (i.e. atmospheric). Sampling techniques for gases are nowadays quite well developed (Giggenbach, 1975) and during sampling what we have to do is to avoid air contamination.

There are a large number of components that can be measured in both liquid and gas phase. The geothermal prospector's minimum requirement in liquid phase is: i) main components (Ca, Mg, Na, K, HCO_3, SO_4, Cl), ii) minor components (SiO_2, NH_4, B, Br and Sr in decreasing order of importance), iii) isotopic ratios of $^{18}O/^{16}O$ and D/H and, in the gas phase is: i) main components (CO_2, N_2, H_2S, CH_4), ii) minor components (He, Ar, Ne, H_2) and iii) some isotopic ratios, such as the $^{13}C/^{12}C$ ratio in CO_2 and CH_4 and the $^3He/^4He$ ratio.

3.2 *Methods to interpret chemical data during hydrogeochemical prospecting*

The fundamental concept of a geochemical prospecting and the reliability of the application of chemical geothermometers to liquid and gas phases is that the composition and equilibrium attained by the fluids in a hydrothermal system at depth do not change considerably during their transfer from the system to the surface. This is generally possible only if, and where, the geothermal systems are very shallow in the crust and well covered by an effective cap rock, like the one at Larderello geothermal field in Italy (Minissale, 1991). Larderello is a very rare geothermal system having superheated steam (lower pressure with respect to temperature in the water saturation curve) in the reservoir. It does not leak liquid phases to the surface, but both steam and gases discharged in the areas of natural emission have a composition quite similar to the steam and gases hosted by the geothermal reservoir (Duchi et al. 1992). For this reason empirical gas geothermometry applied to natural gas/steam vents at Larderello has proved to be very effective (D'Amore and Panichi, 1980).

In general, chemical components analyzed in both liquid and gas phase can be divided into two groups: i) tracers and ii) geoindicators. Tracer components are chemical species that are markers of the system in which they are produced and/or they flow through. Since they are conservative elements, they do not re-equilibrate (precipitate) with decreasing temperature or have no effect on dilution by low salinity shallow solutions during their rise to the surface. Typical conservative elements in liquid phase are: Cl, B, Br, whereas in the gas phase the noble gases are typically conservative elements. On the other hand typical geoindicators in liquid phase are SiO_2, Na, K, Ca, Mg and CO_2, H_2, H_2S, CH_4 in the gas phase.

While tracers in fluid (both liquid or gas) phase are not sensitive to the internal parameters (such as: temperature, total pressure, Pco_2... etc), the geoindicators are very sensitive to variation in temperature and pressure of the system where they are produced and the environment through which they travel. Moreover, their concentration (their chemical potential) in solution is largely dependent by the presence of other elements, and more generally by the "redox" conditions existing in the system.

In general, the concentration of geoindicators in both liquid and gas phases are dependent upon deep chemical equilibria and temperature. The most commonly used equilibrium in liquid phase to assess deep temperature from the analysis of chemical components in surface manifestation is the equilibrium of feldspars:

$$\text{Na-felspar} + K^+ = \text{K-fedspar} + Na^+$$

In the early 60's K/Na ratio of geothermal fluids was recognized to be proportional to the deep temperatures measured in producing wells in New Zealand and several functions have been calibrated and proposed over a period of time by several workers (both empirical and theoretical functions are shown in Fig. 1). More or less during the same period Fournier (Fournier and Rowe, 1966) presented theoretical and laboratory solubility diagrams showing the temperature dependence of the various silica phases present in the hydrothermal systems (Fig. 2, quartz, chalcedony, opal... etc.; redrawn after Fournier, 1991). Because hydrothermal fluids can be in equilibrium with one of the several phases of silica according to the rock composition through which the fluids flow (reservoir), the application of one silica function or another is not always very easy to decide. A general rule is to apply the appropriate silica geothermometer to the more soluble phase with which a thermal fluid is saturated. This procedure avoids potentially overestimation of the source temperature from which the sampled solution is derived from.

Several geothermometers have been proposed in time, both in liquid (see Fournier, 1991 for a review) and gas (see Giggenbach, 1991 for a review) phases. Some of them are based on slow-re-equilibrating reactions (such as the K/Na geothermometer) some others are based on fast re-equilibrating reactions (such as the silica concentration in solutions). Slow re-equilibrating geothermometers are theoretically more effective, in terms of real assessments of deep temperatures, but they are often affected by shallow processes. For example, the K/Na geothermometer is really unreliable when applied to thermal springs that emerge after having undergone mixing with shallow cold waters circulating in aquifers hosted in pyroclastic K-rich alkaline formations (Dall'Aglio et al., 1994). On the other hand, fast re-equilibrating geothermometers, in case of

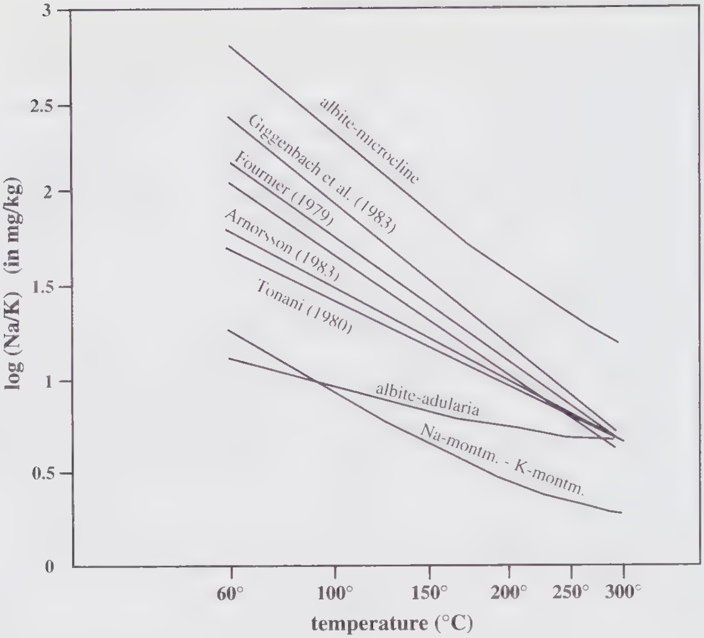

Figure 1. Variation of log(Na/K) as a function of temperature. Theoretical curves for albite-microcline, albite-adularia, Na-montmorillonite-K-montmorillonite and various empirical Na/K geothermometric functions are shown (after Fournier, 1991).

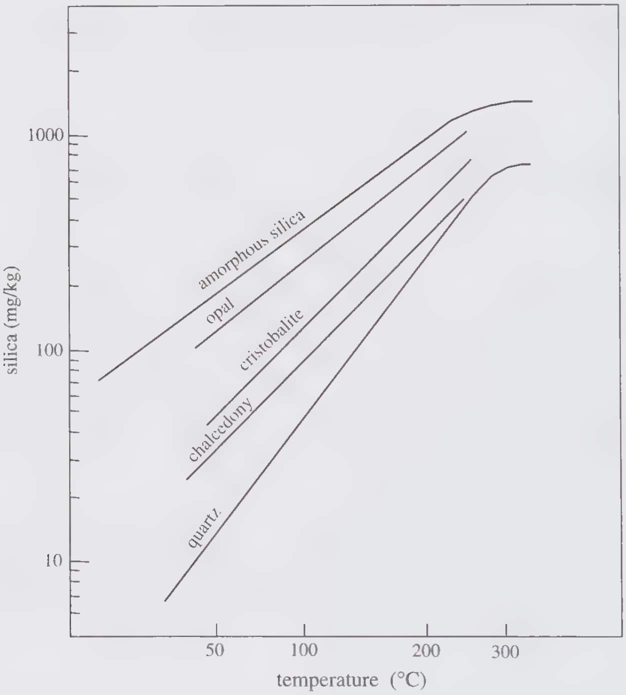

Figure 2. Solubility of various silica phases in water at the vapor pressure of the solutions with increasing temperature (after Fournier, 1991).

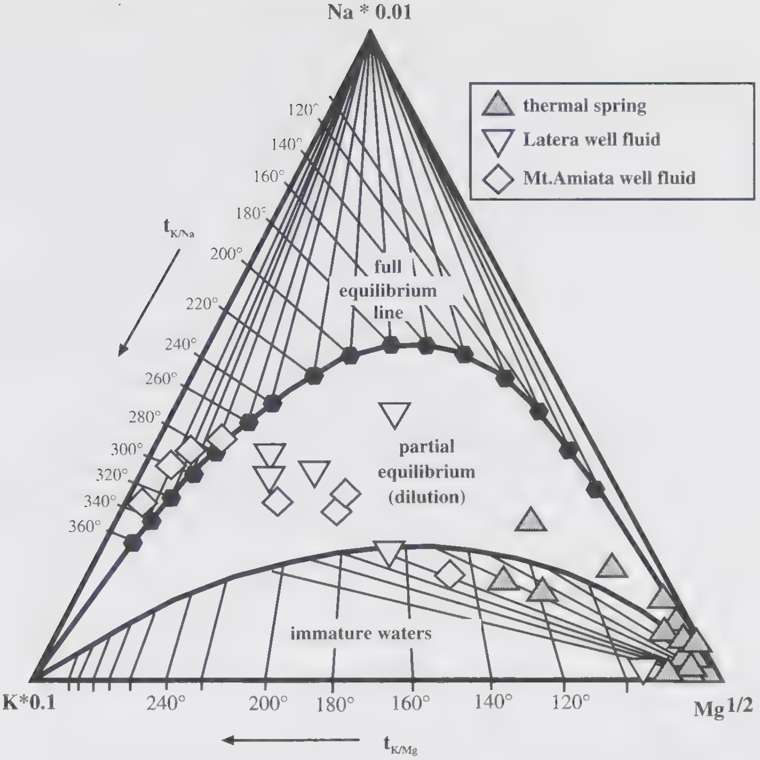

Figure 3. K(*0.01)-Na(*0.001)-$Mg^{1/2}$ ternary diagram (Giggenbach, 1988) showing relative cation ratios and K/Na and K/Mg geothermometric functions (Giggenbach et al., 1983) in the Mt. Amiata (Italy) geothermal area (after Minissale et al., 1997).

slow-moving solutions from the hydrothermal source to the surface, quite often give estimated deep temperatures sometimes much lower than the real temperatures.

The ternary Na-K-Mg diagram in Figure 3 proposed by Giggenbach (1988) is based on hydrothermal systems where the compositions of deep high-temperature fluids (full equilibrium line) is the result of isochemical recrystallization, after hydrothermal alteration, of a primary rock (of average crustal composition) into a secondary assemblage. This diagram compares slow re-equilibrating Na/K geothermometer (proposed by Giggenbach et al., 1983) with the fast re-equilibrating K^2/Mg geothermometer (Giggenbach et al., 1983; Mg is a fast re-equilibrating element whose concentration in hydrothermal fluids is very low because of formation of chlorite).

By applying such technique to natural fluids in the Mt. Amiata and Latera geothermal areas in central Italy (Fig. 3; Minissale et al., 1997) it is seen that, although there are several thermal springs in the area (gray triangles), they do not keep record of the relative Na-K-Mg ratios of fluids sampled in the geothermal wells (white triangles and diamonds). In particular, even between deep hot samples, there are only 5 fluid samples from geothermal wells lying along the full equilibrium line, whereas the remaining deep fluids are aligned along a mixing line (in the "partial equilibrium-dilution" sector of the diagram) pointing towards the Mg corner. Most of the thermal springs in the area align along the right ascending "cold" arm of the equilibrium line, suggesting very low K^2/Mg deep temperatures (<100°C) compared to the deep ones, the latter varying between 260 and 320°C. Only three spring samples, lying in a hypothetical mixing line with the more "contaminated" well samples seems to have undergone some mixing with deep hydrothermal solutions.

What is described for the thermal springs discharging in the Mt. Amiata area in Italy, a quite well understood geothermal area in terms of temperatures and pressures, is quite typical of many geothermal areas in the World. The application of chemical geothermometers to thermal springs quite often under estimates the deep real temperatures. The reason for this is due to the fact that leaking fluids from the geothermal reservoir towards the surface is flushed by the laterally continuous flowing of meteoric-originated waters (groundwaters). The resulting mixed solutions re-equilibrate at the resulting dilution temperature, modify their relative cations and anions ratios according to the ratios prevailing in the shallow aquifers and the degree of dilution.

As suggested by Tonani (1970) sometimes, rather then trusting on chemical geothermometers applied to a selected number of thermal springs, it is better to look for anomalous concentrations of volatile geothermal elements (such as NH_4 and Hg) in the shallow cold water table in a large number of shallow water samples. In this case, presence of shallow sources of these geothermal elements (such as evaporitic material, mineralized ore bodies ... etc.) must be excluded.

Dilution of deep ascending geothermal fluids by descending meteoric waters affects the composition of rising hydrothermal gases much less than hydrothermal liquid phases. Descending meteoric waters in fact transfer underground only low quantity of atmospheric N_2 and Ar. Because of low solubilities of gases at higher temperatures, these atmospheric gases have little effect on the gases present in the rising thermal fluids. This is the reason geothermometric techniques applied to gas manifestations are generally more reliable than geothermometric techniques applied to thermal springs.

3.3 *Gas components and geothermometry in the gas phase*

The most part of geothermal systems in the World are located at plate boundaries where the intrusion of mantle magmas in the crust and volcanic activity are common features. Geothermal fields are generally located near active or recent volcanic areas where magmatic fluids move from the magma chambers into geothermal reservoirs which are eventually formed. Fluid phases moving from magmatic system into geothermal systems undergo drastic changes. Condensation of water causes dissolution of very acidic magmatic components, such as SO_2, HCl and CO_2 and the *p*H of geothermal fluids becomes very low. Such acidic solutions cause alteration (sericitization, kaolinization ... etc.) of country rocks (primary neutralization, Figure 4, redrawn after Giggenbach, 1988) and this alteration increases the *p*H of parent magmatic fluids. Near neutral, or slightly acidic Na-Cl brines form and generate permanent geothermal systems in places where the permeability is high. Eventually a steam phase can form and the condensation of such steam at the boundaries of geothermal systems causes gas separation that migrates into shallower aquifers.

Compared to natural liquid thermal discharges (thermal springs) natural gases (either associated with thermal springs or emerging as "dry" gas vents) have three advantages:

i) apart from CO_2 and H_2S which are weakly soluble in water, CH_4, H_2 as well as noble gases, once formed, tend to be more stable in solution underground;
ii) they do not have a diluting component formed at shallow level in the crust apart from small quantities of N_2 and Ar carried as air underground by rainfall;
iii) relative ratios between components at surface are much more representative of deep equilibria than components in liquid phase.

In fact, although being affected by increased dissolution in shallow cold aquifers and although the fact that solubility of gas components is different for individual components with decreasing temperature, the gases preserve their deep signature better.

Several geothermometers based on singular gas components or ratios between gas components have been proposed in the past (D'Amore and Panichi, 1980; Taran, 1986; Arnorsson and Gunnlaugsson, 1985; Giggenbach, 1980; Giggenbach, 1991). In particular Giggenbach has

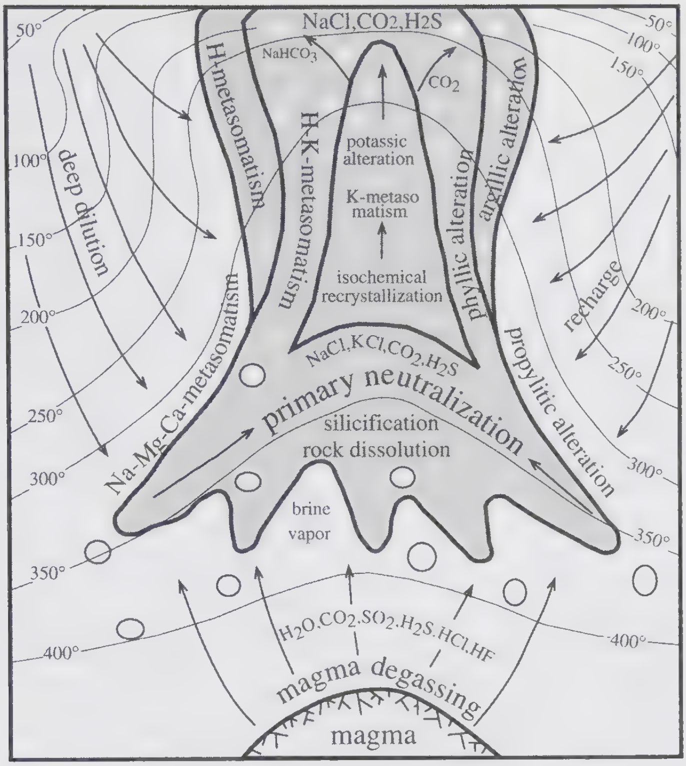

Figure 4. Schematic representation of a typical hydrothermal system showing distribution of temperatures and main alteration processes (redrawn after Giggenbach, 1988).

developed several gas geothermometers based on the relative H_2, CH_4, CO, CO_2 and Ar concentrations. Hydrogen, CH_4, CO_2, CO are typical geoindicators because they are involved in several gas–gas reactions such as:

$$CH_4 + 2H_2O = CO_2 + 2H_2$$

whose equilibrium constants and relative ratios between components are temperature dependent and also dependent on their relative solubility (fractionation factor) in water and steam (y = steam fraction; Giggenbach, 1980).

By the application of some of these geothermometric functions to the Mt. Amiata and Latera natural gases associated with both thermal and cold emissions and geothermal wells, some interesting conclusions can be drawn. In Figure 5 (after Giggenbach, 1991) the log ratio of CO/CO_2 concentrations of the Mt. Amiata and Latera gases have been plotted against the log ratio of CH_4/CO_2. Two main redox buffers constraining the composition of gases, either in vapor or liquid phase, are considered: i) that involving di and trivalant Fe ions of the rock, marked $(FeO)/(FeO_{1.5})$ and ii) that involving the coexistence of H_2S and SO_2 of the magmatic vapor phase. If the $(FeO)/(FeO_{1.5})$ buffer (the main mineralogical buffer in both magmatic and hydrothermal environments) is a valid assumptions for natural systems ranging from room temperature to magmatic temperature (1200°C), the $\log(fH_2/fH_2O)$ (another important redox buffer constraining the composition of gases in geothermal environments), in a fully equilibrated system, can be considered to be one single value of -2.8 (Giggenbach, 1987).

Opposite to what shown in Figure 3 by liquid phases, where the relative Mg-Na-K concentrations of thermal spring waters were almost completely out of the equilibrium line at the temperatures

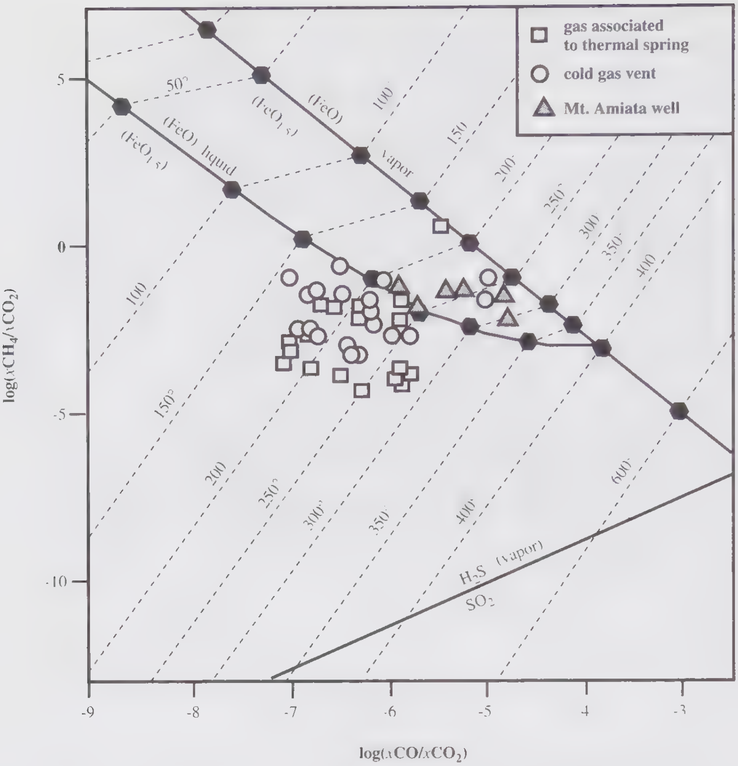

Figure 5. Geothermometric functions log(xCO/xCO$_2$) versus log(xCH$_4$/xCO$_2$) in gas phases from surface gas emissions and gases from geothermal wells in the Mt. Amiata geothermal area (after Minissale et al., 1997).

existing at depth inside the Mt. Amiata geothermal system, the natural gas phases plot in the log(xCH$_4$/xCO$_2$) – log(xCO/xCO$_2$) diagram of Figure 5 not far from the full equilibration line for gases derived from a geothermal system in liquid phases at temperatures in the range of 180 280°C. The Mt. Amiata (and Latera) geothermal system is, in fact, a liquid-dominated system with deep temperatures varying from 200 to 350°C and located in two different reservoirs: i) a shallower one in Mesozoic carbonate formations at <1000 m depth, with temperature <200°C and ii) a deeper one (>3000 m) in Paleozoic metamorphic formations where temperature is >300°C. Even if samples are not aligned along the full equilibration line for liquid-dominated systems, they suggest deep equilibration temperature ranging from 160°C, for the more "air contaminated" samples, up to 285°C for the "less air-contaminated ones" (Minissale et al., 1997). Alternatively, they suggest their provenance from one of the two existing (shallow and deep) geothermal reservoirs. It is also interesting to note that gas samples derived from producing wells (gray triangles) plot in the area between the lines delimiting equilibrium between liquid and vapor phases (i.e. two phases zone). This is in line with boiling of the rising fluid within the producing casing, with partial steam loss at the orifice of wells, and this is what actually happening in the production wells (Ceccarelli, personal comunication).

3.4 *The ^{3}He/^{4}He ratio in the gas phase*

It is well known that the ^{3}He/^{4}He ratio in gas phases, both measured in free gas vents and/or in the gas stripped from liquid phases (extracted under vacuum), is a real sensitive parameter to detect the

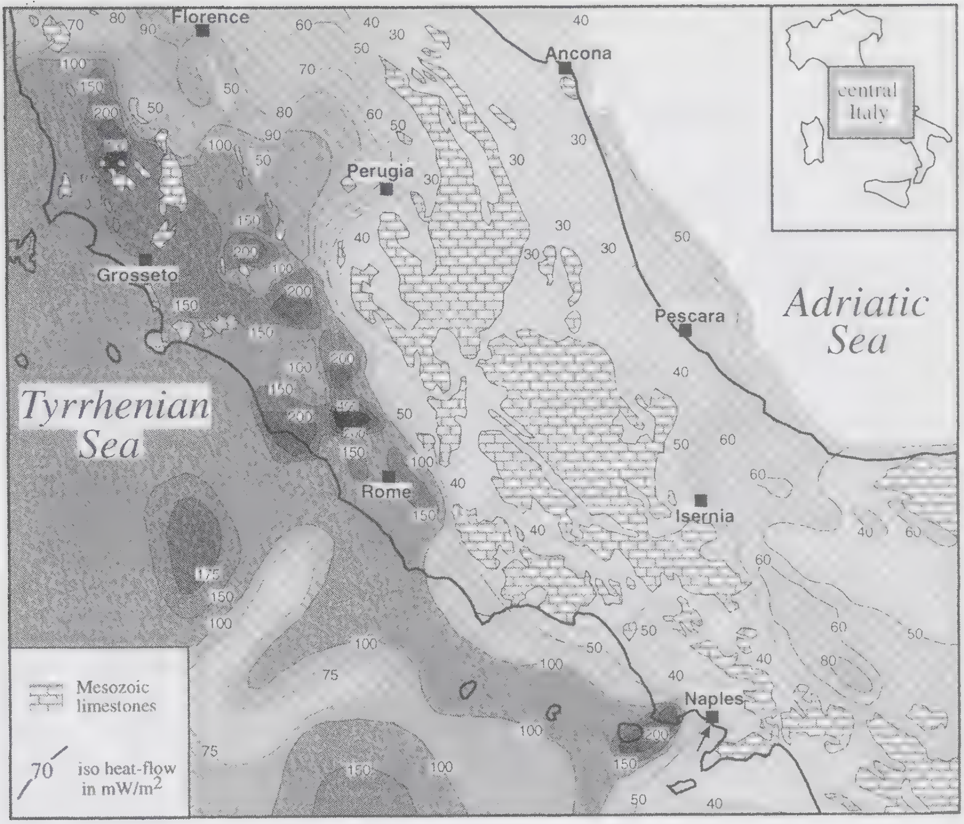

Figure 6. Heat flow map of central Italy (Minissale, 2002).

presence of mantle magma intrusions in the crust (Craig et al., 1978). It is also a useful chemical tool to understand how developed (thick) is the crust in an area (O'Nions and Oxburg, 1988). In fact, the more thick is the crust the more is the production of crustal ^{4}He from radioactive decay of U and Th.

The Earth's mantle is considered to be the principal reservoir for primordial ^{3}He degassing. The ^{3}He/^{4}He ratio, (generally reported as R/Ra where R is the ratio in the sample and Ra is the ratio in the atmosphere; Ra $= 1.39 \times 10^{-6}$ in air) varies from about 0.02 in the crust up to 15 in the mantle. Gases derived from MORB and from andesites typically have a R/Ra ratio = 8.0 (Craig et al., 1978).

During the geothermal prospecting phase of remote areas determination of such parameter in the gas phase is very important. In fact, in spite of the fact that sometimes high ^{3}He flux can simply be derived by the cold rising of mantle gas from deep faults crossing the crust, such as the San Andreas fault in California (Kennedy et al. 1997), in general ^{3}He anomalies are related to areas of active and/or Quaternary Volcanism (Polyak et al., 2000). The contemporary presence of Quaternary volcanism, thermal springs and ^{3}He anomalies is often sufficient to decide that an area is really interesting for further geothermal investigations.

A typical example of such multiple association can be seen in Italy. By considering a large sector of central Italy in the western Tyrrhenian sector, the area with the maximum heat flow (Fig. 6) is characterized by the presence of Quaternary and active volcanism as well as the presence of many thermal springs and several discovered geothermal fields (Fig. 7). In terms of ^{3}He/^{4}He ratio in the gas phase, the isodistribution map reported in Figure 8 shows that all active volcanic areas

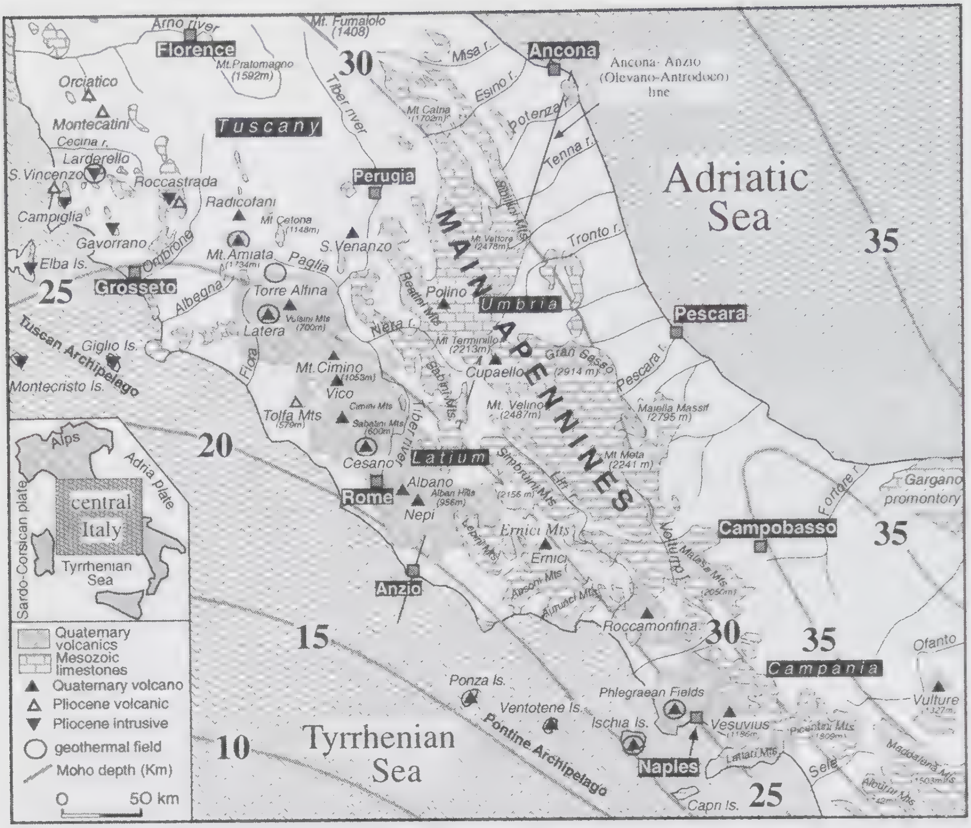

Figure 7. Schematic geological map of central Italy showing the main Mesozoic carbonate reservoir of central Italy as well as Pliocene-Quaternary intrusive and volcanic rocks and active volcanic and geothermal areas (Minissale, 2002).

(in the Neapolitan region) as well as other more northern areas (around Rome) have anomalous ^{3}He discharges (R/Ra > 2). The northernmost of these anomalies characterizes the natural gas discharged at surface in a large region well encompassing the Larderello geothermal area.

4 GEOPHYSICAL PROSPECTING

Geophysical methods for geothermal energy prospecting generally follow the geochemical methods and are mostly devoted to the decision of the place where it is less risky to drill the first exploratory wells. In the following discussion we will see with only two very commonly employed techniques to verify the presence of shallow anomalies (or the presence of thermal fluids at shallow depth) whose presence has been identified by the geochemical prospecting.

4.1 *Geoelectrical prospecting*

This technique of geothermal prospecting was widely used in the 70's by geophysicists through the determination of a physical parameter (electrical conductivity), a parameter highly related to the chemical characteristics of geothermal fluids. Hot geothermal fluids hosted in liquid-dominated

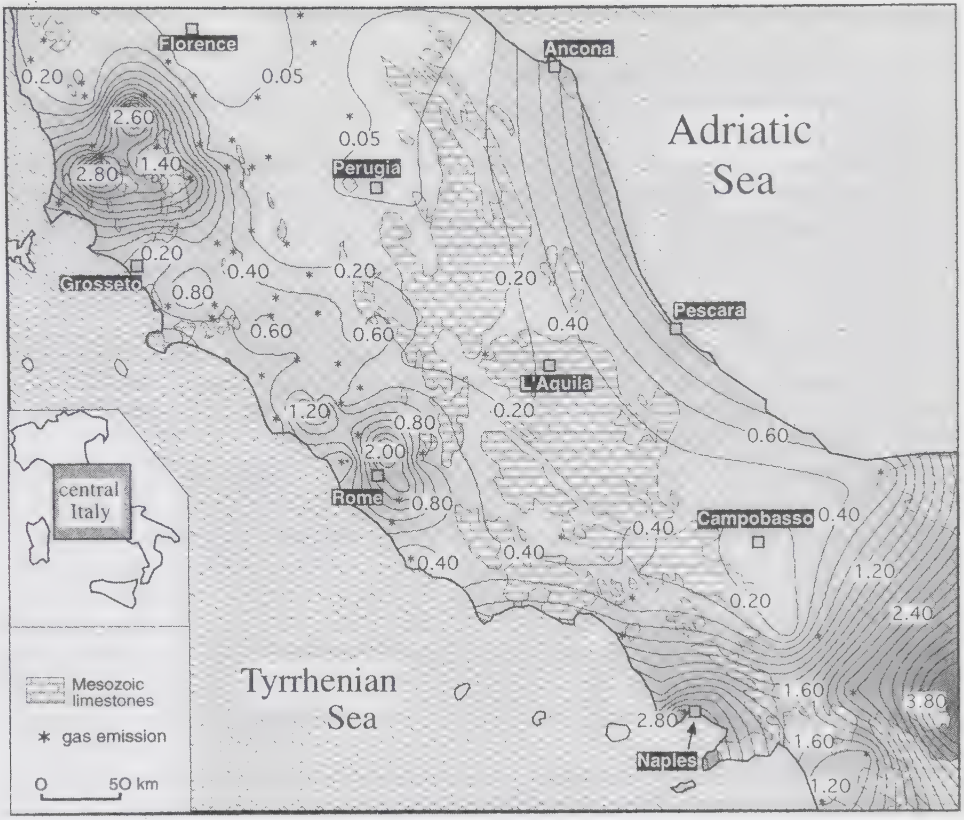

Figure 8. Isocontour map of $^3He/^4He$ ratio in gas manifestations from central Italy (Minissale, 2002).

systems (hydrothermal reservoirs) are in fact generally characterized by having a relatively high salinity. For this reason, such reservoirs have, with respect to low salinity fluids bordering the geothermal system, well enhanced electrical conductivity. In a geological situation where deep seated geothermal fluids are surrounded by local low-salinity meteoric originated waters, their presence will de easily recognized.

By performing a geoelectrical survey on a relatively homogeneous geological environment, the presence of geothermal fluids will be revealed, at the surface, with closed areas of electrical anomalies. On a regional scale if the geochemical prospecting has suggested the presence of deep hydrothermal fluids, such electrical anomalies are the best places for further investigations through drilling. If the geological setting where the geoelectrical prospecting is carried out is not homogeneous (for example a rugged orogenic areas where massive limestone formations or granite bodies alternate with flysch facies) the interpretation of electrical signals can be much more difficult. Clay-rich material, and more generally unconsolidated sedimentary formations, rich in saline connate waters have, in fact, higher electrical conductivity compared to crystalline and limestone and sandstone formations because of the presence of circulating fluids. According to such features, sometimes the presence of an electrical anomaly can be either related to the presence of hot deep geothermal fluids or shallow or deep unconsolidated material rich in connate waters. This is particularly evident in syn-orogenic and post-orogenic basins, where recent evaporitic material is a common deposit and where the interpretation of the electric signals can be easily misunderstood.

4.2 *Geothermal prospecting through wells for measuring geothermal gradients*

It is well known that the Earth is not in a steady thermal state. It is still cooling at an average rate of 1.2 μcal/sec/cm^2 and volcanic and geothermal areas are the most spectacular places where such cooling is taking place.

The rate of heat transfer varies from region to region and is a function of the thermal conductivity of the ambient rock. The average heat flow of tectonically stable continental regions is about 60 mW/m^2. High enthalpy areas in active orogenic belts may have values up to 400 mW/m^2. The expression describing the heat flow is:

$$\Phi_c = k\ \delta T/\delta z$$

where k is the thermal conductivity coefficient of rock material and δT/δz is the geothermal gradient. Although thermal conductivity of rocks varies from 3 cal/cm∗sec∗$10^{\ 3}$ in schist up to 16 cal/cm∗sec∗10^{-3} in quartzites, as an approximation it is apparent that Φ_c for a given region is directly proportional to the geothermal gradient.

Measurements of geothermal gradients can be conveniently carried out through the drilling shallow wells (from about 50 to 200 m deep), in impermeable formations, where the presence of cooling shallow aquifer waters has been excluded through observation that no water loss occurred during drilling.

The best way to measure δT inside the drilled wells is to put two thermometers (electric thermocouples) at 10 m distance from each other, little above the bottom of the well. For example, if the well is 100 m deep the two thermometers can be placed at 80 and 90 m depth. After having placed the thermometers, sufficient time should be given for temperature stabilization (several months). Once this is attained, the true thermal gradient can be obtained and can be used for geophysical prospecting.

The best use of geothermal gradient can be made in areas where a potential (from a lithological point of view) geothermal reservoir has already been assessed with geological methods and where depth of such potential reservoir is known (for example after the application of geoelectrical, magneto-telluric and/or seismic surveys). In such cases the geothermal gradient measured at near surface in a prospecting well can be extrapolated up to the presumed depth and the likely temperature can be calculated.

This type of geophysical prospecting has been widely used in the 60s and 70s to find out the best sites for drilling deep wells in the Mt. Amiata area (central Italy) where the depth of the potential reservoir located in Mesozoic Formation was already known through geoelectrical prospecting. In fact, because of convection and fluid motion inside a given geothermal system, local heat-flow inside the convective system falls close to zero (in places even negative). If a convective system is confined or coincides with a geological horizon, such as the Mesozoic limestones in several areas of central Italy (Fig. 7), it is reasonable to suppose that the temperature calculated at the top of the convective system (top of the limestone series) is similar. This temperature will follow the top of the real reservoir and the thermal gradient measured by the shallow prospecting wells will be the highest where the reservoir is located at the shallower depths and viceversa.

Limitations and drawbacks of prospecting through drilling for thermal gradient wells can be found in the fact that sometimes, shallow thermal waters in suspended aquifers, not related to the presence of active hydrothermal systems, can simulate the presence of high anomalous thermal gradients at the surface. Deep-seated fluids, convectively rising along deep faults (such as the N_2- and He-rich thermal waters described in the geochemical section) and spreading in shallow aquifers can in fact simulate the presence of high thermal shallow gradients. In such cases, extrapolation of the gradients to greater depths will be misleading. In such cases, such as where hot fluids are strictly confined to faults, negative thermal gradients can be encountered below the aquifers that cause the anomalous thermal gradients measured by the exploratory wells. This is the reason why, as described above, the geochemical prospecting on natural thermal discharge must precede future geophysical prospecting.

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Optimisation of the exploration and evaluation of geothermal resources

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ABSTRACT: As a renewable source of energy, geothermal energy is a viable alternative. It could become much more competitive provided quantitative, cost-effective, reliable, and efficient methods using an interdisciplinary approach were routinely applied. Therefore, quantitative aspects of geothermal research are critically examined in this chapter. A proposal is made to apply an integrated methodology involving geology, geochemistry, and geophysics, in conjunction with statistical methods and quantitative modelling. Most, if not all, relevant concepts are briefly reviewed. Information is provided on the current state of Mexican geothermal development. Mexico's long experience about the exploitation of geothermal energy for electricity production is reflected in the year 2000, by a total installed capacity of about 855 MW. This installation represents about 2.4% of total installed capacity of all kinds of electric power plants. Interestingly, in the year 2000 the geothermal power plants in Mexico produced a considerably greater percentage of electricity (about 3.1% of all produced electricity in Mexico). In spite of these positive results, the quantitative integrated approach outlined in this chapter is recommended to be used during both exploration and exploitation stages in all geothermal fields. This would certainly cut down costs of exploration and exploitation of geothermal resources, and would provide more reliable results than those obtained by qualitative and semi-quantitative methods.

1 INTRODUCTION

Geothermal energy as a renewable source is already a viable alternative to other options, but it could even become a better alternative provided more-efficient, reliable, and cost-effective methods are developed for their routine application during both the exploration and exploitation stages.

The developments that took place during the past three or four decades include, among other events, the following: the First United Nations Symposium on the development and utilization of geothermal resources in 1970, Pisa, Italy; the Second United Nations Symposium in 1975, San Francisco, U.S.A.; International Symposium on geothermal energy in 1985 and numerous other symposia organized by the Geothermal Resources Council and other similar societies; a series of publications "Geothermal Resources Council Transactions"; workshops on "Geothermal Reservoir Engineering", Stanford University; World Geothermal Congress 1995 in Florence, Italy; World Geothermal Congress 2000 in Kyushu and Tohoku, Japan; as well as a series of courses and workshops on different aspects of geothermics organised in several countries such as Italy, Iceland, New Zealand, Mexico, and U.S.A.

A new peer-reviewed journal "Geothermics" was launched in 1972 by Italian workers on a periodic basis; in fact, a special issue was published somewhat earlier (in 1970) and contained contributions from the First United Nations Symposium of Pisa. Similarly, a new interdisciplinary

Elsevier journal "Journal of Volcanology and Geothermal Research" (JVGR), commenced its publication in the year 1976. The very existence and the flourishing of this journal have clearly shown that geothermal energy and volcanology are intimately related, and a multi-disciplinary approach is, in fact, required for a proper exploration and exploitation of this renewable resource. These journals (JVGR and Geothermics), along with other reputed journals such as "Geochimica et Cosmochimica Acta", "Chemical Geology", "Journal of Geophysical Research", "Geochemical Journal", etc., have become important sources of information related to the field of geothermics.

A basic set of methodologies for geothermal exploration, particularly in volcanic fields, was developed, about twenty years ago, by a group of international experts for Latin American energy development (O.L.A.D.E. 1983). This proposal, once again, pointed out the need for a multi-disciplinary approach. Some books (e.g. Wohletz & Heiken 1992) and articles (e.g. Verma 1984a, 1985a, 1990) also stressed this relationship between volcanoes and geothermal energy, and more importantly, the need for a quantitative approach than that normally exercised in geothermal exploration and exploitation.

For any quantitative evaluation of resources, uncertainty estimates of the inferred parameters will necessarily be required. These uncertainties will, in fact, facilitate any decision-making for future investments. Clearly, the uncertainties of the final parameters depend on the uncertainties of the input variables; these will have to be estimated for a quantitative and reliable evaluation of geothermal resources. These uncertainties, if unduly or unacceptably large, will have to be reduced using new improved or optimised methods. Therefore, an integrated, quantitative, statistical approach should be used for a better estimation of geothermal energy resources, in order to put this type of resource on a more competitive basis. This chapter briefly describes the various procedures to apply a quantitative approach to a geothermal study. It must be stated, however, that this is not a comprehensive description of all the ideas and concepts but rather an indication of the more important research areas, particularly the statistical methods involving error propagation theory, which should prove beneficial in geothermal research.

2 QUANTITATIVE APPROACH

In a multi-disciplinary approach, successive and interactive application of geology, geochemistry, and geophysics, along with proper statistical methods, is required for a better understanding of the origin and evolution of volcanic and geothermal systems.

2.1 *Basic statistical methods and error propagation theory*

This section briefly reviews the main statistical principles and methodologies that may prove useful in geothermal research. Emphasis is made on relevant methods to improve data-quality and to provide error estimates on all variables of interest. Full details on the relevant methods, robust statistics, outlier theory, and related topics of statistical tests can be found in Bevington (1969), Shaw (1969), Ebdon (1988), Miller & Miller (1988), Taylor (1990), Miller (1991), Barnett & Lewis (1994), Jensen et al. (1997), Verma (1997, 1998a), Verma et al. (1998a), Otto (1999), Velasco-Tapia et al. (2001), and Verma et al. (2002a), as well as in the references cited in these books and articles. Great care is, however, required when dealing with compositional data (Aitchison 1986; Woronow & Love 1990; Barceló et al. 1996).

2.1.1 *Analytical errors and data handling*

It is well known that all experimentally measured parameters are subject to analytical errors or uncertainties associated to them (e.g. Bevington 1969; Taylor 1990; Otto 1999). One class of errors originates from mistakes or blunders in computations or measurements. These errors, called illegitimate errors, are generally recognised either as incorrect data points or as results not "reasonably" close to the expected values, and can, therefore, be corrected by performing the erroneous arithmetic, computational or experimental operation correctly.

Besides the illegitimate errors, there are two other types of errors: systematic errors or bias and random errors. The systematic errors result from faulty calibration of equipment or from bias on the part of an observer. Such errors must be estimated from an analysis of the experimental conditions using proper reference materials or standards, and must then be corrected, as is commonly done in isotope geochemistry, see for example, work related to Sr and Nd isotopic ratios (e.g. Faure 1986, 2001; Verma 1992). In this context, it is rather surprising to note that such a simple operation as weighing may be subject to significant systematic errors, because the balance to be used, although probably a precise instrument, may not be accurate for this purpose, and may require a set of reference (calibrated) weights to correct this problem.

Random errors, whether of human or instrumental origin, are always present, and impossible to eliminate. In fact, measuring instruments inevitably generate random errors (Miller & Miller 1988). Therefore, an effort should be made to minimize them and to estimate them properly, along with some kind of mean or central value of the physical, chemical or geological parameter under study.

Several different types of parameters for central tendency exist: arithmetic mean, median, mode, geometric mean, harmonic mean, trimmed mean, Winsorized mean, among others. Likewise, the dispersion parameters could include: standard deviation, standard error of the mean, relative standard deviation, range, mean deviation, confidence limits, etc.

Because of the presence of random errors (likely to be "normally" distributed) in any experiment for estimating a physical or chemical parameter, the mean value can be estimated by the arithmetic mean of all "univariate" (single variable) data.

Let $x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n$, be the initial data (number of individual data $= n$), and $x_{(1)}, x_{(2)}, x_{(3)}, \ldots, x_{(n-2)}, x_{(n-1)}, x_{(n)}$, an ordered array of these data where $x_{(1)}$ is the lowest observation and $x_{(n)}$ the highest one. First, the n data can be plotted in a histogram using a window w (depending on n; Otto 1999) as follows:

$$w \cong \frac{x_{(n)} - x_{(1)}}{\sqrt{n}} \quad \text{for } 30 < n \leq 400 \tag{1}$$

or

$$w \cong \frac{x_{(n)} - x_{(1)}}{20} \quad \text{for } n > 400 \tag{2}$$

If statistically sufficient number of multiple observations are available for a given parameter (at least about 30; see the range of n values in the above two equations), it is useful to plot them in a histogram and to check if the data represent a Gaussian i.e., a normal distribution (a symmetrical bell-shaped distribution), if they present a skewed distribution (see below the sample skewness parameter), or if they show the presence of possible outliers or aberrant observations.

When a normal distribution is shown, it is recommended to obtain the mean value (arithmetic mean; also known as the first moment), defined as:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{3}$$

and the sample standard deviation is given by:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{(n - 1)}} \tag{4}$$

Similarly, the sample variance (also known as the second moment) is defined as:

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{(n - 1)} \tag{5}$$

The third moment, called sample skewness (a measure of symmetry), can be estimated as follows:

$$s_k = \frac{n^{1/2}\left\{\sum_{i=1}^{n} (x_i - \bar{x})^3\right\}}{\left\{\sum_{i=1}^{n} (x_i - \bar{x})^2\right\}^{3/2}} \tag{6}$$

For a symmetrical distribution (normal), the sample skewness s_k ideally should be zero ($s_k = 0$). If there is a tail towards the right of the histogram, it is called a positively-skewed distribution ($s_k > 0$); on the other hand, if tailed towards the left, it is a negatively-skewed distribution ($s_k < 0$).

Finally, the fourth moment, called sample kurtosis (a measure of excess), can be calculated as follows:

$$k = \frac{n\left\{\sum_{i=1}^{n} (x_i - \bar{x})^4\right\}}{\left\{\sum_{i=1}^{n} (x_i - \bar{x})^2\right\}^{2}} \tag{7}$$

For a normal distribution, the sample kurtosis k is ideally close to 3. The presence of "excess" data at the centre of the distribution renders $k > 3$; on the contrary, a deficit of data at the centre of the histogram gives $k < 3$. A modified kurtosis k' is sometimes used in order to make it similar to s_k, and ideally close to 0 for a normal distribtion.

$$k' = k - 3 \tag{8}$$

So far, we have discussed the sample mean as the only location parameter. Besides this arithmetic mean, other types of central tendency indicators or location parameters are useful, particularly when the distribution departs from a normal distribution or when outliers are present. The other location parameters are:

Geometric mean G is useful when the data are log-normally distributed.

$$G = \sqrt[n]{(x_1 \cdot x_2 \cdot x_3 \cdot \ldots \cdot x_n)} \tag{9}$$

Similarly, harmonic mean is defined as:

$$H = \frac{n}{\sum_{i=1}^{n} (1/x_i)} \tag{10}$$

A general relationship between the above measures of central tendency (location parameters) seems to be: $H \leqslant G \leqslant \bar{x}$.

Other robust measures of central tendency are the median and mode. For an ordered array of data $x_{(1)}, x_{(2)}, x_{(3)}, \ldots, x_{(n-2)}, x_{(n-1)}, x_{(n)}$, the median is the central value $x_{((n+1)/2)}$, when the number of observations is an odd number. Otherwise for an even number of observations, the median is the mean of two central values $x_{(n/2)}$ and $x_{((n/2)+1)}$.

The median is apparently not affected by the presence of outliers. Similarly, the mode being the most frequently observed value in a set of observations, can be inferred from an ordered array of data or from the examination of a histogram plot. Sometimes, more than one mode may be present in a data set.

Concerning measures of dispersion, sample standard deviation has already been explained. Other measures also exist. The range (total dispersion of the data) is defined as:

$$R = x_{(n)} - x_{(1)} \tag{11}$$

The coefficient of variation is:

$$s_v = \frac{s}{\bar{x}} \tag{12}$$

The s_v expressed in % is a useful parameter called relative standard deviation (*RSD*):

$$s_v(\%) = RSD = 100 s_v \tag{13}$$

The standard error of the mean is defined as:

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \tag{14}$$

For the definition of other measures such as quartiles, confidence limits, etc., see standard textbooks on the subject cited above.

2.1.2 *Error propagation theory*

Errors on individual parameters are propagated or combined according to certain laws or equations (Bevington 1969; Taylor 1990). Let x be an arbitrary function of two variables u and v with respective errors σ_u and σ_v; a and b be positive constants; and σ_{uv} the covariance of the variables u and v. Then, for random errors, the error propagation theory predicts errors for specific formulas as follows (Bevington 1969):

$$\text{For } x = \mathrm{a}u \pm \mathrm{b}v: \quad \sigma_x^2 = \mathrm{a}^2\sigma_u^2 + \mathrm{b}^2\sigma_v^2 \pm 2\mathrm{ab}\sigma_{uv}^2 \tag{15}$$

$$\text{For } x = \pm \mathrm{a}uv: \quad \frac{\sigma_x^2}{x^2} = \frac{\sigma_u^2}{u^2} + \frac{\sigma_v^2}{v^2} + 2\frac{\sigma_{uv}^2}{uv} \tag{16}$$

$$\text{For } x = \pm\frac{\mathrm{a}u}{v}: \quad \frac{\sigma_x^2}{x^2} = \frac{\sigma_u^2}{u^2} + \frac{\sigma_v^2}{v^2} - 2\frac{\sigma_{uv}^2}{uv} \tag{17}$$

$$\text{For } x = \mathrm{a}u^{\pm\mathrm{b}}: \quad \frac{\sigma_x}{x} = \mathrm{b}\frac{\sigma_u}{u} \tag{18}$$

$$\text{For } x = \mathrm{a}\,\mathrm{e}^{\pm\mathrm{b}u}: \quad \frac{\sigma_x}{x} = \mathrm{b}\sigma_u \tag{19}$$

$$\text{For } x = \mathrm{a}\ln(\pm\mathrm{b}u): \quad \sigma_x = \mathrm{a}\frac{\sigma_u}{u} \tag{20}$$

where (for all above equations 15–20),

$$\sigma_u^2 = \lim_{n \to \infty} \frac{1}{n} \left\{ \sum_{i=1}^{n} (u_i - \bar{u})^2 \right\} \tag{21}$$

$$\sigma_v^2 = \lim_{n \to \infty} \frac{1}{n} \left\{ \sum_{i=1}^{n} (v_i - \bar{v})^2 \right\} \tag{22}$$

and

$$\sigma_{uv}^2 = \lim_{n \to \infty} \frac{1}{n} \left\{ \sum_{i=1}^{n} \{(u_i - \bar{u})(v_i - \bar{v})\} \right\} \tag{23}$$

Generally σ_u and σ_v are unknown (particularly because an infinitely large number of observations are not actually available for any given variable), but in order to use the above equations, they can be replaced by their estimates, the sample standard deviations s_u and s_v respectively. In this respect, Monte Carlo type simulations are also much useful, for which adequate random number generators, such as linear congruent generators (LCG) or more complex generators, are required (Law & Kelton 2000).

On the other hand, concerning systematic errors it is advisable to try to eliminate them. But if it were not possible to do so, systematic errors can also be propagated according to certain principles (Miller & Miller 1988).

Let s_{e_x}, s_{e_u}, and s_{e_v} be the systematic errors on the variables x, u, and v respectively. Then

$$\text{For } x = au \pm bv: \quad s_{e_x} = as_{e_u} \pm bs_{e_v} \tag{24}$$

$$\text{For } x = \pm auv: \quad s_{e_x} = \frac{s_{e_u}}{u} + \frac{s_{e_v}}{v} \tag{25}$$

$$\text{For } x = \pm \frac{au}{v}: \quad s_{e_x} = \frac{s_{e_u}}{u} - \frac{s_{e_v}}{v} \tag{26}$$

and, in general,

$$\text{For } y = f(x): \quad s_{e_y} = \left| s_{e_x} \frac{dy}{dx} \right| \tag{27}$$

where s_{e_y} is the systematic error on the variable y.

Some geological or geochemical applications of the error propagation theory have been discussed by, e.g. Santoyo & Verma (1993), Criscenti et al. (1996), Verma & Santoyo (1997), Karpov et al. (1999), and Verma (1998b, 2000a). On the basis of these studies, I strongly recommend a generalised application of this theory to all experimental work.

2.1.3 *Statistical tests for univariate samples*

When the data distribution somewhat differs from a normal distribution, proper statistical tests involving outlier detection and elimination (Table 1) can be applied to the data set. It is obvious that extreme observations have an extreme effect on the value of a sample variance and standard deviation (Barnett & Lewis 1994). Therefore, either the outlier detection and rejection or robust methods should be used to handle such data.

The outlier procedure is particularly suited for processing geochemical data for reference samples (Verma 1997, 1998a; Verma et al. 1998a; Velasco-Tapia et al. 2001; Guevara et al. 2001). The relevant statistical tests are of five major types (see Table 1 for more details): (1) Deviation/spread statistics (using in the numerator a measure of the distance of an outlier from some central tendency parameter of the data); (2) Sum of squares statistics (ratios of sums of squares for the restricted and total samples) or Grubbs type; (3) Range/spread statistics (the numerator is the sample range); (4) Excess/spread statistics (ratios of differences between an outlier

Table 1. Discordancy tests for normal univariate samples (modified after Barnett & Lewis 1994; Verma 1997, 1998a; Verma et al. 1998a).

Statistic type*	Test label**	Description of test***	Test statistic****	Test significance$	Value(s) tested$$	Test$$$	
						n_{min}	n_{max}
Deviation/spread statistics	N1	Upper	$(x_{(n)} - \bar{x})/s$	Greater	$x_{(n)}$	3	147
		Lower	$(x - x_{(1)})/s$	Greater	$x_{(1)}$	3	147
	N2	Extreme	$Max: \{(x_{(n)} - \bar{x})/s, (\bar{x} - x_{(1)})/s\}$	Greater	$x_{(n)}$ or $x_{(1)}$	3	20
	N3	k = 2 Upper	$(x_{(n)} + x_{(n-1)} - 2\bar{x})/s$	Greater	$x_{(n)}, x_{(n-1)}$	5	100
		k = 3 Upper	$(x_{(n)} + x_{(n-1)} + x_{(n-2)} - 3\bar{x})/s$	Greater	$x_{(n)}, x_{(n-1)}, x_{(n-2)}$	7	100
		k = 4 Upper	$(x_{(n)} + x_{(n-1)} + x_{(n-2)} + x_{(n-3)} - 4x)/s$	Greater	$x_{(n)}, x_{(n-1)}, x_{(n-2)}, x_{(n-3)}$	9	100
		k = 2 Lower	$(2\bar{x} - x_{(1)} - x_{(2)})/s$	Greater	$x_{(1)}, x_{(2)}$	5	100
		k = 3 Lower	$(3\bar{x} - x_{(1)} - x_{(2)} - x_{(3)})/s$	Greater	$x_{(1)}, x_{(2)}, x_{(3)}$	7	100
		k = 4 Lower	$(4\bar{x} - x_{(1)} - x_{(2)} - x_{(3)} - x_{(4)})/s$	Greater	$x_{(1)}, x_{(2)}, x_{(3)}, x_{(4)}$	9	100
Sums of squares statistics	N4	k = 1 Upper	$S^2_{(n)}/S^2$	Smaller	$x_{(n)}$	4	50
		k = 2 Upper	$S^2_{(n),(n-1)}/S^2$	Smaller	$x_{(n)}, x_{(n-1)}$	4	149
		k = 3 Upper	$S^2_{(n),(n-1),(n-2)}/S^2$	Smaller	$x_{(n)}, x_{(n-1)}, x_{(n-2)}$	6	50
		k = 4 Upper	$S^2_{(n),(n-1),(n-2),(n-3)}/S^2$	Smaller	$x_{(n)}, x_{(n-1)}, x_{(n-2)}, x_{(n-3)}$	8	50
		k = 1 Lower	$S^2_{(1)}/S^2$	Smaller	$x_{(1)}$	4	50
		k = 2 Lower	$S^2_{(1),(2)}/S^2$	Smaller	$x_{(1)}, x_{(2)}$	4	149
		k = 3 Lower	$S^2_{(1),(2),(3)}/S^2$	Smaller	$x_{(1)}, x_{(2)}, x_{(3)}$	6	50
		k = 4 Lower	$S^2_{(1),(2),(3),(4)}/S^2$	Smaller	$x_{(1)}, x_{(2)}, x_{(3)}, x_{(4)}$	8	50
Sums of squares statistics	N5	Upper-Lower	$S^2_{(n),(1)}/S^2$	Smaller	$x_{(n)} x_{(1)}$	4	100
	N16 (k = 1 to k = 4)	Upper, Lower, or mixed k	Tietjen and Moore's Statistic	Smaller	$x_{(n)}$ or $x_{(1)}$, combinations	4	50
Range/spread statistics	N6	Upper-Lower	$(x_{(n)} - x_{(1)})/s$	Greater	$x_{(n)}, x_{(1)}$	3	100
Excess/spread statistics	N7	Upper	$(x_{(n)} - x_{(n-1)})/(x_{(n)} - x_{(1)})$	Greater	$x_{(n)}$	3	30
	N8	Extreme	$Max: \{(x_{(n)} - x_{(n-1)})/(x_{(n)} - x_{(1)}), (x_{(2)} - x_{(1)})/(x_{(n)} - x_{(1)})\}$	Greater	$x_{(n)}$ or $x_{(1)}$	6	30
	N9	Upper	$(x_{(n)} - x_{(n-1)})/(x_{(n)} - x_{(2)})$	Greater	$x_{(n)}$	4	30
		Lower	$(x_{(2)} - x_{(1)})/(x_{(n-1)} - x_{(1)})$	Greater	$x_{(1)}$	4	30
	N10	Upper	$(x_{(n)} - x_{(n-1)})/(x_{(n)} - x_{(3)})$	Greater	$x_{(n)}$	5	30
		Lower	$(x_{(2)} - x_{(1)})/(x_{(n-2)} - x_{(1)})$	Greater	$x_{(1)}$	5	30
	N11	Upper pair	$(x_{(n)} - x_{(n-2)})/(x_{(n)} - x_{(1)})$	Greater	$x_{(n)}, x_{(n-1)}$	4	30
		Lower pair	$(x_{(3)} - x_{(1)})/(x_{(n)} - x_{(1)})$	Greater	$x_{(1)}, x_{(2)}$	4	30

(Continued)

Table 1. (*Continued*)

Statistic type*	Test label**	Description of test***	Test statistic****	Test significance$	Value(s) tested$$	Test$$$	
						n_{min}	n_{max}
	N12	Upper pair	$(x_{(n)} - x_{(n-2)})/(x_{(n)} - x_{(2)})$	Greater	$x_{(n)}, x_{(n-1)}$	5	30
		Lower pair	$(x_{(3)} - x_{(1)})/(x_{(n-1)} - x_{(1)})$	Greater	$x_{(1)}, x_{(2)}$	5	30
	N13	Upper pair	$(x_{(n)} - x_{(n-2)})/(x_{(n)} - x_{(3)})$	Greater	$x_{(n)}, x_{(n-1)}$	6	30
		Lower pair	$(x_{(n)} - x_{(1)})/(x_{(n-2)} - x_{(1)})$	Greater	$x_{(1)}, x_{(2)}$	6	30
Higher-order moment statistics	N14	Extreme	$\left[\dfrac{n^{1/2}\left\{\sum_{i=1}^{n}(x_i - \bar{x})^3\right\}}{\left\{\sum_{i=1}^{n}(x_i - \bar{x})^2\right\}^{3/2}}\right]$	Greater	$x_{(n)}$ or $x_{(1)}$	5	1000
	N15	Extreme	$\left[\dfrac{n\left\{\sum_{i=1}^{n}(x_i - \bar{x})^4\right\}}{\left\{\sum_{i=1}^{n}(x_i - \bar{x})^2\right\}^{2}}\right] - 3$	Greater	$x_{(n)}$ or $x_{(1)}$	5	2000

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*Classification suggested by Tietjen & Moore (1972) and Barnett & Lewis (1994).

**The test labels are after Barnett & Lewis (1994), and have been used earlier for geochemical applications by Verma and colleagues (e.g. Verma 1997, 1998a; Verma et al. 1998a).

***Type of observation(s) being tested; k = number of data to be tested at a time (1 to 4). I recommend to use, in general, only the k = 1 and k = 2 options; the other variants (k = 3 and k = 4 or more, see Barnett & Lewis 1994 for the critical value tables) should be used only for large data sets (high n), probably for n ≫ n_{min}. urthermore, caution is required for use of the tests for upper-lower combinations, such as N5, N6, and N16. Similarly, note test N16 is a direction independent test with k = 1 to k = 4, and must be used with caution.

****Parameters to be computed for a given test; a spread-sheet or a computer programme (SIPVADE; Verma et al. 1988a) can be used to compute them. Note modified kurtosis (k′) used in test N15. See Tietjen & Moore (1972) and Barnett & Lewis (1994) for the explanation of the test statistic in N16. This column indicates whether the test statistic should be greater or smaller than the 1% critical value for a successful detection of an outlier (note my suggestion to use these tests at a high confidence level of 99%, equivalent to the 1% significance level).

$This column indicates whether the test statistic should be greater or smaller than the 1% critical value for a successful detection of an outlier (note my suggestion to use these tests at a high confidence level of 99%, equivalent to the 1% significance level).

$$Type of value(s) being tested by a given statistic, e.g. highest observation $x_{(n)}$ or lowest observation $x_{(1)}$, or a combination.

$$$Range of observations that can be tested by a given statistic, due to the availability of 1% criticalvalues. Note the serious limitations in the availability of critical values for many of the tests (see n_{max} column). These deficiencies must be overcome for a better application of these tests by generating new tables from proper simulation methods such as those given by Law & Kelton (2000).

and its nearest or next-nearest neighbour to the range, or some other measure of spread of the sample) or Dixon type; (5) Higher-order moment statistics (measures of skewness and kurtosis).

The tests are recommended to be applied at the 99% confidence level (Verma 1997, 1998a; Verma et al. 1998a), and not at the less-strict 95% level as is usually done by other workers (e.g. Dybczynski 1980). Critical value tables for 1% significance level (corresponding to 99% confidence level) are reported by Barnett & Lewis (1994). After detection and elimination of outliers, the remaining data have a normal distribution and can be used to compute sample mean and standard deviation values.

2.1.4 *Robust methods*

Alternatives to the outlier rejection method are the so called robust or accommodation methods that can be used to obtain good estimates of central tendency (location parameter), in spite of the presence of outliers (Huber 1981; Barnett & Lewis 1994). These methods are, in a way, insensitive to outliers, and include two distinct processes: trimming and Winsorizing.

Suppose we have an initial statistical sample of experimental observations (n ordered data):

$$x_{(1)}, x_{(2)}, x_{(3)}, \ldots, x_{(n-2)}, x_{(n-1)}, x_{(n)}$$

We wish to trim (i.e. to cut or "temporarily" eliminate) or Winsorize (i.e. to replace by the nearest neighbour observations) $r + s$ observations (r observations from the lower end and s from the higher end) from this sample. Then, the (r, s)-fold trimmed mean is

$$x^T_{r,s} = \frac{x_{(r+1)} + \ldots + x_{(n-s)}}{(n - r - s)} \tag{28}$$

whereas, the (r, s)-fold Winsorized mean is

$$x^W_{r,s} = \frac{rx_{(r+1)} + x_{(r+1)} + \ldots + x_{(n-s)} + sx_{(n-s)}}{n} \tag{29}$$

Often, the amounts of lower-tail and upper-tail trimming or Winsorizing are the same, i.e. $r = s$; r-fold symmetrically trimmed or Winsorized means can be obtained from equations (28) and (29), simply by putting $r = s$.

Equivalently to r-fold trimmed or Winsorized mean, we can speak of α-trimmed or Winsorized mean, where α refers to a given proportion of the sample to be trimmed or Winsorized, at either end; α can take values such as 0.1, 0.2, etc. When α takes a value of 0.5, the trimmed and Winsorized means will be identical to the median value explained above in this chapter.

The α-trimmed and Winsorized means are:

$$x^T_{(\alpha,\alpha)} = \{(1 - f)x_{(r+1)} + x_{(r+2)} + \cdots + x_{(n-r-1)} + (1 - f)x_{(n-r)}\}/(n(1 - 2\alpha)) \tag{30}$$

and

$$x^W_{(\alpha,\alpha)} = \{rx_{(r+1)} + x_{(r+1)} + \cdots + x_{(n-r)} + rx_{(n-r)}\}/n \tag{31}$$

where

$$\alpha n = r + f; \text{ for which } r \text{ is an integer and } f \text{ a fraction; } 0 < f < 1 \tag{32}$$

Clearly, 0-trimmed or Winsorized mean is equal to the sample mean, whereas ½-trimmed or ½-Winsorized mean is the sample median. Similarly, ¼-trimmed mean is called mid-mean. A basic problem with the use of a trimmed or Winsorized mean is choosing the extent of trimming or Winsorization. Should we apply an asymmetric ($r \neq s$) or symmetric ($r = s$) scheme? How should r, s, or α be chosen? There are no simple answers to these questions (Barnett & Lewis 1994).

2.1.5 *Other important statistical tests*

Other very useful tests include, among others, the Student's t-test (mean value test), F-ratio test, or ANOVA (analysis of variance), χ^2 test, and estimation of linear correlation coefficient (r).

Student's t-test is a parametric test of the difference between two samples, with the null hypothesis (H_0) being that the two sets of data are random samples from a common, normally distributed population, or from two identical, normally distributed populations. The alternative hypothesis (H_1) is that there exists a difference between the means of the two populations, which is accurately reflected in the samples under study. I recommend to use a significance level of 0.01 or better (0.001; see the tabulated two-tailed t-values in a text book on statistics; e.g. Ebdon 1988).

The test-statistic, t, should first be calculated using the following equation (the two samples consist of respectively n_x and n_y data, with the respective means $\bar{x}$ and $\bar{y}$ and the standard deviations s_x and s_y):

$$t = \frac{|\bar{x} - \bar{y}|}{s\left(\sqrt{(\frac{1}{n_x} + \frac{1}{n_y})}\right)} \tag{33}$$

where $|\bar{x} - \bar{y}|$ is the absolute difference between the two means, and s is the combined standard deviation of the two samples as follows:

$$s = \sqrt{\frac{\sum_{i=1}^{n_x}(x_i - \bar{x})^2 + \sum_{i=1}^{n_y}(y_i - \bar{y})^2}{(n_x + n_y - 2)}} \tag{34}$$

Alternatively, if the individual data are not available, and the respective standard deviations must be used, then

$$s = \sqrt{\frac{(n_x - 1)s_x^2 + (n_y - 1)s_y^2}{(n_x + n_y - 2)}} \tag{35}$$

Note that $(n_x + n_y - 2)$ gives the degrees of freedom for the t-value. The hypothesis H_0 is to be rejected (i.e. alternative hypothesis H_1 is to be accepted) if the computed t-value (using equations 33 and 34, or 33 and 35) is greater than the tabulated two-tailed Student's t-value for a chosen significance level (e.g. 0.01 or 0.001). Otherwise, the null hypothesis H_0 is taken to be true.

The ANOVA or F-ratio test is the standard parametric test of difference between three or more samples. Such a test can also be applied between pairs of samples (Student's t test). The two hypotheses (null H_0: samples come from a common population, and alternative H_1: samples come from different populations) are similarly defined. The rationale of the analysis of variance is to find out whether there is more variation between the samples than within them. Under the null hypothesis H_0 it is reasonable to expect that the variation within the samples is about the same as the variation between the samples. Two estimates of the variance of the hypothesized common population are first made: the within samples variance estimate, and the between samples variance estimate.

Thus, if κ is the number of samples, n_i is the number of individual data in each sample (i.e. $n_1, n_2, \ldots, n_k$ data respectively), and $\bar{x}_1, \bar{x}_2, \ldots, x_\kappa$ are the respective mean values, the *within samples variance estimate* is:

$$\hat{s}_W^2 = \frac{\sum_{i=1}^{n_1}(x_i - \bar{x}_1)^2 + \sum_{i=1}^{n_2}(x_i - \bar{x}_2)^2 + \cdots + \sum_{i=1}^{n_\kappa}(x_i - \bar{x}_\kappa)^2}{N - \kappa} \tag{36}$$

where N is the total number of individual data values in all samples, and $(N-\kappa)$ the degrees of freedom for the within samples variance.

The *between samples variance estimate* is:

$$\hat{s}_B^2 = \frac{n_1(\bar{x}_1 - \bar{x}_g)^2 + n_2(\bar{x}_2 - \bar{x}_g)^2 + \cdots + n_\kappa(\bar{x}_\kappa - \bar{x}_g)^2}{\kappa - 1} \tag{37}$$

where $\bar{x}_g$ is the grand mean of all the data values (mean of all data in κ samples put together), and $(\kappa-1)$ are the degrees of freedom for the between samples variance.

Having calculated the two estimates of variance, the F ratio is calculated as:

$$\mathrm{F} = \frac{\hat{s}_B^2}{\hat{s}_W^2} \tag{38}$$

The critical value of F at the chosen significance level (e.g. 0.01 or 0.001) with $(\kappa-1)$ and $(N-\kappa)$ degrees of freedom (see Ebdon 1988 or other standard text book for a list of critical values) is compared with the computed F value. Reject H_0 if the computed F-value is greater than the critical value.

The χ^2 (Chi square) test is a flexible nonparametric test. It must be applied when the conventional t-test is not applicable, for example when the data do not represent "normal" samples. The reader is referred to Ebdon (1988) for details.

The linear correlation coefficient (r), also known as product-moment correlation coefficient, is a useful guide to infer the degree of linear correlation between n observations of two variables x and y, and is estimated as follows:

$$r = \frac{\sum_{i=1}^{n}\{(x_i - \bar{x})(y_i - \bar{y})\}}{\sqrt{\left\{\sum_{i=1}^{n}(x_i - \bar{x})^2\right\}\left\{\sum_{i=1}^{n}(y_i - \bar{y})^2\right\}}} \tag{39}$$

where $-1.0 \leqslant r \leqslant +1.0$.

Value of r (also known as Pearson's correlation coefficient) is a measure of linear relationship between the two variables x and y (although linearity tests are required; see the references cited in this chapter). If the computed r value is greater than the critical r-value for a given number (n) of observations and at a given significance level (e.g. 0.01 or 0.001), the $x-y$ linear relationship can be considered significant at that particular significance level. More details on this and other tests can be found in standard books cited in this chapter.

2.2 *Geology*

For any geological model of a geothermal area, "proper" quantitative geological data are required. Therefore, such geological information should be of a quantitative nature, and not just a qualitative type as is generally the case.

2.2.1 *Surface geology data*

Exploration of geothermal energy resources in volcanic fields should be based primarily on an understanding that the volume and physical and chemical characteristics of pyroclastic rocks are fundamental indicators of the presence, size, and location of a potential hydrothermal system (Wohletz & Heiken 1992). In fact, I would suggest that such physical and chemical characteristics of all other rock types from that particular area are equally important to understand the geothermal problem. During field geology campaigns, therefore, volume estimates of different geological units or formations should be routinely carried out, and representative sampling undertaken, whenever possible, for future laboratory work. This work should include, besides a conventional petrographic study, detailed analysis and interpretation of major and trace elements, mineral compositions, geochronology, and radiogenic and possibly stable isotopes.

2.2.2 *Drillhole geology*

Whenever wells have been drilled, the corresponding information on lithology, stratigraphy, and rock-types should be used to infer a three-dimensional geological model, and to put constraints on the final geothermal model. Drill cuttings and cores can also be used in a detailed geochemical study.

2.3 *Geochemistry*

As discussed earlier, representative rock, water, and gas samples must be collected and analysed to learn more about the magmatic-hydrothermal system. Special care must be exercised in analytical work, especially in establishing optimum experimental conditions, in evaluating the precision and accuracy (or trueness) of the methods, and in evaluating errors throughout the different steps (right from the field to the laboratory and all through the models).

In fact, new, efficient, and cheaper methods, such as those involving chromatographic and electrophoresis techniques (e.g. Verma 1991; Verma et al. 2000; Santoyo et al. 2001, 2002), should be further explored and standardized for use in geothermal research.

2.3.1 *Instrumental calibrations in geochemistry*

Most analytical methods require a proper calibration of the instruments to be used (Potts 1987). In instrumental calibrations, particular care should be taken in preparing proper regression curves and estimating uncertainties on the regression parameters (e.g. Miller 1991). These uncertainties can then be combined with other uncertainties to obtain the total uncertainty in the measured experimental parameter (Bevington 1969; Taylor 1990; see the statistics section above).

Instrumental calibration procedures deserve special mention in this discussion. As is well known, for most analytical instruments proper calibration curves must be prepared. This is usually done using materials with known element concentrations, called geochemical reference materials (GRM) or certified GRM (e.g. Potts et al. 1992; Verma 1997, 1998a). The instrument signal or response value (y-axis) is plotted against the element concentration value (x-axis) and a regression curve, usually a "least squares" unweighted (equal weight) line, is prepared from the data. For such an unweighted regression several assumptions must be fulfilled (e.g. Draper & Smith 1966; Miller 1991): (i) all the errors occur in the y-direction; (ii) y-errors are normally distributed; (iii) variation in y-direction errors is the same for all x values.

The regression calibration line for n data points (x_i, y_i) can be expressed as:

$$y = bx + a \tag{40}$$

where the slope b is

$$b = \frac{\sum_{i=1}^{n}\{(x_i - \overline{x})(y_i - \overline{y})\}}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{41}$$

and the intercept a is

$$a = \overline{y} - b\overline{x} \tag{42}$$

There will be random errors (expressed as standard deviation values) in the calibration itself, i.e., both on the slope and on the intercept, as follows:

$$s_b = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y_i)^2}{(n-2)\sum_{i=1}^{n}(x_i - \overline{x})^2}} \tag{43}$$

and

$$s_a = \sqrt{\frac{\left\{\sum_{i=1}^{n}(y_i - y_i)^2\right\}\left\{\sum_{i=1}^{n}x_i^2\right\}}{n(n-2)\sum_{i=1}^{n}(x_i - \overline{x})^2}} \tag{44}$$

where y_i is the measured signal value (ith data point) and $\hat{y}_i$ is the value of y on the fitted straight line at the same value of x, i.e. $(y_i - \hat{y})$ is the residual of y_i.

Hence, the confidence limits on the slope and the intercept can be estimated respectively as $b \pm ts_b$ and $a \pm ts_a$, where t is the Student's t value at the desired confidence level (two-tailed values) and with $(n-2)$ degrees of freedom (see any standard text book or Ebdon 1988, for a listing of t-values).

Our aim is to estimate the resulting total error in a measurement of an unknown sample. If y_0 is the mean y-value (measured signal) for an unknown or test sample (result of m determinations), its concentration x_0 can be estimated from equation (40) after rearrangement and corresponding standard deviation S_{x_0} can be computed as follows:

$$s_{x_0} = \frac{1}{b}\sqrt{\frac{\left\{\sum_{i=1}^{n}(y_i - y_i)^2\right\}}{(n-2)}\left\{\frac{1}{m} + \frac{1}{n} + \frac{(y_0 - \overline{y})^2}{b^2\sum_{i=1}^{n}(x_i - \overline{x})^2}\right\}} \tag{45}$$

The confidence limits on x_0 can be estimated by $x_0 \pm ts_{x_0}$ where, once again, t is the Student's t value at the desired confidence level (two-tailed values) and with $(n-2)$ degrees of freedom.

Thus, it is possible to have a good estimate of total propagated errors for the unknown sample. Miller (1991) has discussed important criteria for minimizing these errors, as well as for carrying out tests for linearity.

The unweighted least squares regression method presented above is not really appropriate: (i) if y-errors are not normally distributed, (ii) if both x and y have errors as is usually the case, (iii) if the errors vary for different values of x (heteroscedastic errors), or (iv) if possible outliers are present. Then robust and nonparametric methods should be used.

One such method is to obtain slope b from the median of the slopes of all possible lines joining pairs of points (there are $n(n + 1)/2$ possible independent estimates for n data points). The median is the middle value for odd observations of slopes arranged in ascending order.

On the other hand, for even observations it is the mean of two middle values. After b is determined, n estimates of the intercept, a, can be obtained by equation $a_i = y_i - bx_i$. The median of the n values of a is taken as the intercept estimate.

A modified robust weighted method has also been proposed (e.g. see Miller 1991) because slope estimates with well-separated points should be given more weight than those with close-by points.

Alternatively, weighted linear regression methods are required. One such method is to assign a weighting factor w_i to each point (x_i, y_i), which is inversely proportional to the combined variance s_i of x_i and y_i.

$$w_i = \frac{s_i^{\;2}}{\left\{\sum_{i=1}^{n}(s_i^{\;2})\right\} \Big/ n} \tag{46}$$

The weighting is scaled, so that

$$\sum_{i=1}^{n} w_i = n \tag{47}$$

The coefficients of the weighted regression equation are

$$b = \frac{\left(\sum_{i=1}^{n} w_i x_i y_i\right) - n\bar{x}_w \cdot \bar{y}_w}{\sum_{i=1}^{n}(w_i x_i^2) - n\bar{x}_w^2} \tag{48}$$

$$a = \bar{y}_w - b\bar{x}_w \tag{49}$$

and the weighted centroid is:

$$\bar{x}_w = \frac{\sum_{i=1}^{n} w_i \bar{x}_i}{n} \tag{50}$$

$$\bar{y}_w = \frac{\sum_{i=1}^{n} w_i \bar{y}_i}{n} \tag{51}$$

The weighted regression line must pass through this point. The corresponding standard deviation for an unknown sample is

$$s_{x_{0w}} = \frac{s_{(y/x)_w}}{b}\left(\sqrt{\frac{1}{w_0} + \frac{1}{n} + \frac{(y_0 - \bar{y}_w)^2}{b^2\left\{\left(\sum_{i=1}^{n} w_i y_i^2\right) - n\bar{x}_w^2\right\}}}\right) \tag{52}$$

where

$$s_{(y/x)_w} = \sqrt{\frac{\left(\sum_{i=1}^{n} w_i y_i^2 - n\bar{y}_w^2\right) - b^2\left(\sum_{i=1}^{n} w_i x_i^2 - n\bar{x}_w^2\right)}{(n-2)}} \tag{53}$$

The confidence limits for the concentration of the unknown can be easily calculated as explained earlier in this chapter.

Although weighted linear regression can be applied to most calibration applications, a curvilinear regression, such as the following equation, may sometimes be required

$$y = a + bx + cx^2 + dx^3 + ex^4 + \cdots \tag{54}$$

If this were the case, an attempt should be made to keep the number of terms to the minimum necessary for a satisfactory fit of the data. Quadratic and cubic fits are frequently excellent when linear regression is not satisfactory (Miller 1991; Otto 1999).

2.3.2 *Rock geochemistry*

First of all, the rock types should be inferred from internationally accepted criteria. For volcanic rocks, the IUGS Subcommission on Systematics of Igneous Rocks (Le Bas et al. 1986; Le Bas 2000) recommended a chemical classification scheme based on total alkalis versus SiO_2 diagram and CIPW normative minerals. This has been incorporated in a new computer programme SINCLAS (Verma et al. 2002b), which can be used for a proper and efficient classification. For other types of igneous rocks, a mineralogical classification has been recommended (Le Bas 2000).

Trace elements and isotopes have proved invaluable for understanding magmatic processes. Key trace elements should include members from different groups: LILE (large ion lithophile elements) such as Rb, Cs, Ba, Sr, etc.; REE (rare earth elements) or lanthanides La to Lu, HFSE (high field strength elements) such as Nb, Zr, etc., and compatible elements such as Ni, Cr, etc. Age data are also very useful and must be obtained, whenever possible, using standard radiometric dating techniques (e.g. Faure 1986). Radiogenic isotope ratios, such as $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$, should be used in conjunction with the major and trace elements, to constrain the magma genesis and evolution processes (Rollinson 1993).

Using these known-quality geochemical and isotopic data, quantitative models must be applied to obtain a well-constrained magma chamber model (Gast 1968; Shaw 1970; DePaolo 1981; McKenzie & Bickle 1988; Rollinson 1993; Albaréde 1995; Williamson et al. 1995; Verma et al. 1998b; Verma 2000b, 2001a, 2001b; Spera & Bohrson 2001; Bohrson & Spera 2001). Inversion techniques should be useful whenever applicable (Albarède 1983; Ormerod et al. 1991; Feigenson and Carr 1993; Maaløe 1994; Caroff et al. 1997; Velasco-Tapia & Verma 2001).

Application of the error propagation theory to such models will be required in order to have uncertainty estimates, which can be input in the magma chamber thermal modelling. As an example, error propagation equations have been derived for geochemical modelling for mixing of two or more components, which should prove useful for better constraining the mixing process (inferring error estimates) if this were the controlling mechanism (Verma 1998b, 2000a).

2.3.3 *Fluid geochemistry*

Representative samples of fluids (water, fumaroles, etc.) should be collected from the magmatic-hydrothermal systems, and carefully analysed in laboratory for chemical and isotopic compositions, including radioactive isotopes such as ^{222}Rn (e.g. Henley et al. 1984; Santoyo et al. 1991, 2001, 2002). Chemical and isotopic parameters determined using well-standardized methods are useful for their classification and geothermometric applications. Careful calibration of the instrument and evaluation of experimental errors as well as achievement of lower values for limits of detection (or increased sensitivities) should undoubtedly form an integral part of a geochemical study. Besides other applications, fluid chemical data can be used to infer subsurface temperatures from geothermometric equations.

2.4 *Geothermometers*

Chemical and isotope geothermometers are routinely used to infer subsurface temperatures from the composition of fluids from thermal springs, fumaroles, and geothermal wells (Henley et al. 1984). They are of great value during both exploration stage as well as exploitation of geothermal resources (D'Amore & Arnórsson 2000).

A compilation of chemical geothermometers shows the plethora of equations that are available for this purpose (Tables 2 and 3). Great caution is required while using any of these geothermometric equations not only because of such a diversity of equations but also because of the different measurement units for the input data and the geochemical conditions that need to be considered. Furthermore, note that earlier compilations of geothermometric equations (e.g. Arnórsson 1991; Fournier 1991; D'Amore & Arnórsson 2000) contain some serious errors, which have been corrected in the present compilation. However, an attempt should be made to critically evaluate these equations before using them in routine work. It is also important to read carefully the footnotes of these tables, and to examine the original reference(s), in order to rectify any errors that might still persist in Tables 2 to 4.

As an example, we see that for the Na-K geothermometer, there are at least ten equations (55 to 64; Table 2); three of them (equations 55, 61, and 64) need Na and K concentrations in molal unit (mol/kg), whereas the remaining equations require them in the conventional mg/kg unit. Note that although only the Na/K ratio is involved (and not the actual concentrations), the use of molal unit would differ from the mg/kg unit by a factor equal to the ratio of the atomic weights of K and Na. In future, therefore, it would be worthwhile to recast all equations with the same units in order to make them directly comparable, and also to propose equations with smaller propagated errors. In this regard, it is interesting to observe that the Na/K concentration (mg/kg) ratio is unaffected by transient boiling or condensation, and is affected only slowly by conductive cooling (Apps & Chang 1992). Also note that although error estimates are available for only a few of these equations (Tables 2 and 3; see, e.g. Verma & Santoyo 1997), it would be highly recommended to estimate them for other equations, if possible to do so.

Other geothermometers proposed are: K-Mg with three equations (65 to 67); Li-Mg two equations (68 and 69); Na-Li five equations (70 to 74); Na-Ca one equation (75); K-Ca one equation (76); Na-K-Ca two equations (77–78); Na-K-Mg one equation (79); and Na-K-Ca-Mg two equations (80–81). Besides geothermal fields, some of these geothermometric equations have also been applied to oil fields.

There are numerous equations (82 to 97) proposed for SiO_2 geothermometers (Table 3). Such a diversity is really puzzling; however, this is a rather complex thermodynamic system whose research is still underway (e.g. Gunnarsson & Arnórsson 2000; M.P. Verma 2000a, 2000b).

Gas geothermometers based on thermodynamic data or empirical considerations are presented in Table 4 (equations 98 to 114). These geothermometers require validity of many assumptions.

For example, they generally assume the existence of some kind of equilibrium of gases with mineral buffers, or in other words, equilibrium within the gas, water, and rock system (e.g. Arnórrson & Gunnlaugsson 1985; Taran 1986; Giggenbach 1991).

Application of more than one geothermometer or geothermometric equation often produces divergent results, which must be properly evaluated and explained in terms of not only the field geology and thermodynamic considerations but also on statistical grounds. Each and every geothermometric equation has errors associated to it. These errors come from at least two different sources: the first related to the errors in the regression coefficients and the other in the determination of the chemical species.

Table 2. Diversity of chemical (Na, K, Ca, Mg) geothermometers for geothermal exploration.

Geothermometer Eq.#	Equation (t°C)*	Ref.**	
Na-K (Fournier-Truesdell)	$\{777/\log([Na]/[K])) + 0.700)\} - 273.15$	FT73	(55)
Na-K (Truesdell)	$\{855.6/(\log(Na/K) + 0.8573)\} - 273.15$	T76	(56)
Na-K (Fournier)	$\{1217(\pm 93.9)/\log(Na/K) + 1.483(\pm 0.2076))\} - 273.15$	F79	(57)
Na-K (Tonani)	$\{833/\log(Na/K) + 0.780)\} - 273.15$	T80	(58)
Na-K (Arnórsson1)	$\{933/\log(Na/K) + 0.993)\} - 273.15$	A83	(59)
Na-K (Arnórsson2)	$\{1319/\log(Na/K) + 1.699)\} - 273.15$	A83	(60)
Na-K (Nieva-Nieva)	$\{1178/\log([Na]/[K]) + 1.239)\} - 273.15$	NN87	(61)
Na-K (Giggenbach)	$\{1390/\log(Na/K) + 1.75)\} - 273.15$	G88	(62)
Na-K (Verma-Santoyo)	$\{1289(\pm 76)/)\log(Na/K) + 1.615(\pm 0.179))\} - 273.15$	VS97	(63)
Na-K (Arnórsson)	$733.6 - 770.55(\log([Na]/[K])) + 378.189(\log([Na]/[K]))^2$ $-95.753(\log([Na]/[K]))^3 + 95.44(\log([Na]/[K]))^4$	A00	(64)
K-Mg (Giggenbach)	$\{4410/(14.0 - \log(K^2/Mg))\} - 273.15$	G88	(65)
K-Mg (Fournier1)	$\{2230/(7.35 - \log(K^2/Mg))\} - 273.15$	F91	(66)
K-Mg (Fournier2)	$\{1077/(4.033 + \log(K^2/Mg))\} - 273.15$	F91	(67)
Li-Mg (Kharaka-Mariner-1)	$\{2200/(5.47 - \log(Li/\sqrt{Mg}))\} - 273.15$	KM89	(68)
Li-Mg (Kharaka-Mariner-2)	$\{1910/(4.63 - \log(Li/\sqrt{Mg}))\} - 273.15$	KM89	(69)
Na-Li (Kharaka-Mariner)	$\{1590/(\log(Na/Li) + 0.779)\} - 273.15$	KM89	(70)
Na-Li (Fouillac-Michard-1)	$\{1000(\pm 47)/(\log([Na]/[Li]) + 0.38(\pm 0.11))\} - 273.15$	FM81	(71)
Na-Li (Fouillac-Michard-2)	$\{1195(\pm 75)/(\log([Na]/[Li]) - 0.19(\pm 0.25))\} - 273.15$	FM81	(72)
Na-Li (Verma-Santoyo-1)	$\{1049(\pm 44)/(\log([Na]/[Li]) + 0.44(\pm 0.10))\} - 273.15$	VS97	(73
Na-Li (Verma-Santoyo-2)	$\{1267(\pm 35)/(\log([Na]/[Li]) + 0.07(\pm 0.10))\} - 273.15$	VS97	(74)
Na-Ca (Tonani)	$\{1096.7/(3.080 - \log(Na/\sqrt{Ca}))\} - 273.15$	T80	(75)
K-Ca (Tonani)	$\{1930/(3.861 - \log(Na\sqrt{Ca}))\} - 273.15$	T80	(76)
Na-K-Ca (Fournier-Truesdell)	$\{1647/((\log([Na]/[K]) + \beta \log([\sqrt{Ca}]/[Na]) + 2.06)$ $+2.47)\} - 273.15$	FT73	(77)
Na-K-Ca (Kharaka-Mariner)	$\{1120/((\log([Na]/[K]) + \beta \log([\sqrt{Ca}]/[Na]) + 2.06)$ $+1.32)\} - 273.15$	KM89	(78)
Na-K-Mg (Nieva-Nieva)	$\{11140/(6 \log([Na]/[K]) + \log([Mg]/[Na^2])$ $+18.30)\} - 237.15$	NN87	(79)
Na-K-Ca-Mg (Nieva-Nieva-1)	$\{16000/(3 \log([Na]/[K]) + 3 \log([Ca]/[Na^2])$ $-\log([Mg]/[Na^2]) + 44.67)\} - 273.15$	NN87	(80)
Na-K-Ca-Mg (Nieva-Nieva-2)	$\{10080/(5 \log([Na]/[K]) + 2 \log([Ca]/[Na^2])$ $-\log([Mg]/[Na^2]) + 16.65)\} - 273.15$	NN87	(81)

*Concentrations of Na, K, Li, Ca, and Mg are in mg/kg (element symbols are used for this purpose). Concentrations in molal unit are indicated by square brackets, viz. [Na], [K], [Li], [Ca], and [Mg].

**Reference (Ref.) abbreviations, along with pertinent comments, are given here.

FT73 = Fournier & Truesdell (1973); the equations were apparently not reported by the authors explicitly but were inferred by Fournier (1991) and Arnórsson (1991); concentrations are in molal (mol/kg) unit; $\beta = 4/3$ for $t < 100$°C, and $\beta = 1/3$ for $t > 100$°C and $\log(Ca^{0.5}/Na) < 0$; Mg correction is recommended for Na-K-Ca (Fournier-Truesdell) geothermometer (see D'Amore & Arnórsson 2000, for details).

T76 = Truesdell (1976) cited in Henley et al. (1984); applicable for temperatures 100–275°C.

F79 = Fournier (1979); applicable for temperatures >150°C; certainly not recommended for temperatures <100°C when this geothermometer might give anomalously high temperatures; note the errors on the regression coefficients were reported by Verma & Santoyo (1997).

T80 = Tonani (1980); this Conference Proceedings reference was not available to me and, therefore, their correctness could not be checked; these equations were reported by Fournier (1991), Arnórsson (1991), and D'Amore & Arnórsson (2000), from where they have been reproduced.

A83 = Arnórsson et al. (1983); the first equation (Arnórsson1) is applicable for 25–250°C, whereas the second (Arnórsson2) is for 250–350°C.

Table 2. *(continued)*

NN87 = Nieva & Nieva (1987); the abbreviations are: TMEQ = Na + K + Ca + Mg, all in milliequivalents/kg; %Mg = 100Mg/TMEQ; the conditions are: (a) for Na-K (Nieva-Nieva) geothermometer, TMEQ $>$ 8.0, %Mg $\leqslant$ 3.5, $t_{\text{Na-K}} > 125$°C; (b) for Na-K-Mg (Nieva-Nieva), TMEQ $<$8.0, %Mg $>$3.5, $\text{Mg}^{0.5}/\text{Na} \leqslant 1.7$, $\text{Ca}^{0.5}/\text{Na} \leqslant 2.6$, $t_{\text{Na-K}} \leqslant 125$°C; (c) for Na-K-Ca-Mg (Nieva-Nieva-1), TMEQ $<$ 8.0, %Mg $>$ 3.5, $\text{Mg}^{0.5}/\text{Na} > 1.7$, $t_{\text{Na-K}} \leqslant 125$°C; (d) for Na-K-Ca-Mg (Nieva-Nieva- 2), TMEQ $<$ 8.0, %Mg $\leqslant$ 3.5, $\text{Mg}^{0.5}/\text{Na} > 1.7$, $\text{Ca}^{0.5}/\text{Na} > 2.6$, $t_{\text{Na-K}} \leqslant 125$°C.

G88 = Giggenbach (1988); for Na-K (Giggenbach) geothermometer, the pair Na-K reaches equilibrium slower than the pair K-Mg used for the K-Mg (Giggenbach).

VS97 = Verma & Santoyo (1997); note that errors were estimated for each regression parameter in this and other equations; Na-Li (Verma-Santoyo-1) geothermometer is for Cl $<$ 0.3 mol/kg, Na-Li (Verma-Santoyo-2) geothermometer is for Cl $>$0.3 mol/kg.

A00 = Arnórsson (2000); temperature range 0–350°C, directly applicable for dilute to moderately saline waters.

F91 = Fournier (1991); K-Mg (Fournier1) geothermometer is applicable for $\log(\text{K}^2/\text{Mg}) > 1.25$, whereas K-Mg (Fournier2) is for $\log(\text{K}^2/\text{Mg}) < 1.25$.

KM89 = Kharaka & Mariner (1989); the concentrations are in mg/L (which is close to, but not identical to mg/kg); Li-Mg (Kharaka-Mariner-1) is for all waters; Li-Mg (Kharaka-Mariner-2) is particularly useful for oil-field waters; use Na-K-Ca (Kharaka-Mariner) geothermometer only when no Mg data are available, $\beta = 1/3$ for all samples.

FM81 = Fouillac & Michard (1981); Na-Li (Fouillac-Michard-1) geothermometer is applicable for Cl $<$ 0.3 mol/kg, Na-Li (Fouillac-Michard-2) for Cl $>$ 0.3 mol/kg; note the errors on the regression coefficients were reported by Verma & Santoyo (1997).

Table 3. Diversity of chemical (SiO_2) geothermometers for geothermal exploration.

Geothermometer	Equation (t°C)*	Ref.**	Eq.#
Quartz (Fournier1)	$\{1309/(5.19 - \log S)\} - 273.15$	F77	(82)
Quartz (Fournier2)	$\{1522/(5.75 - \log S)\} - 273.15$	F77	(83)
Quartz (Fournier-Potter)	$-42.198(\pm 1.345) + 0.28831(\pm 0.01337)S - 3.6686 \cdot 10^{-4} (\pm 3.152 \cdot 10^{-5}) S^2 + 3.1665 \cdot 10^{-7}(\pm 2.421 \cdot 10^{-7} S^3 + 77.034(\pm 1.216) \mathit{log}\, S$	FP82	(84)
Quartz (Arnórsson1)	$-53.5 + 0.3659S - 5.3954 \cdot 10^{-4}S^2 + 5.5132 \cdot 10^{-7}S^3 + 74.360\, \mathit{log}\, S$	A85	(85)
Quartz (Arnórsson2)	$-55.3 + 0.3659S - 5.3954 \cdot 10^{-4}S^2 + 5.5132 \cdot 10^{-7}S^3 + 74.360\, \mathit{log}\, S$	A00	(86)
Quartz (Verma-Santoyo-1)	$-\{44.119(\pm 0.438)\} + \{0.24469(\pm 0.00573)\} S - \{1.7414 \cdot 10^{-4}(\pm 1.365 \cdot 10^{-5})\} S^2 + \{79.305(\pm 0.427)\} \mathit{log}\, S$	VS97	(87)
Quartz (Verma-Santoyo-2)	$\{140.82(\pm 0.00)\} + \{0.23517(\pm 0.00179)S$	VS97	(88)
Quartz (M.P. Verma)	$\{\{1175.7(\pm 31.7)\}/(\{4.88(\pm 0.08)\} - \log S)\} - 273.15$	V00	(89)
Chalcedony (Fournier)	$\{1032/(4.69 - \log S)\} - 273.15$	F77	(90)
Chalcedony (Arnórsson)	$\{1112/(4.91 - \log S)\} - 273.15$	A83	(91)
Chalcedony (Arnórsson)	$\{1182/(5.09 - \log S)\} - 273.15$	A91	(92)
Moganite (Gíslason)	$-30.7 + 0.53113S + 1.2578 \cdot 10^{-4}S^2 - 5.9241 \cdot 10^{-7}S^3 + 19.576 \log S$	G97	(93)
α-Cristobalite (Fournier)	$\{1000/(4.78 - \log S)\} - 273.15$	F77	(94)
β-Cristobalite (Fournier)	$\{781/(4.51 - \log S)\} - 273.15$	F77	(95)
Amorphous silica (Fournier)	$\{731/(4.52 - \log S)\} - 273.15$	F77	(96)
Amorphous silica (Gunnarsson-Arnórsson)	$-121.6 + 0.2694S - 1.8101 \cdot 10^{-4}S^2 + 7.5221 \cdot 10^{-8}S^3 + 55.114 \log S$	DA00	(97)

*S is the concentration of SiO_2 are in mg/kg unless otherwise indicated.

**Reference (Ref.) abbreviations along with pertinent comments are given here.

Table 3. *(continued)*

F77 = Fournier (1977); all geothermometers given by this author are applicable for 0–250°C; Quartz (Fournier1) for no steam loss; Quartz (Fournier2) for maximum steam loss (silica concentrations in water initially in equilibrium with quartz after adiabatic boiling to 100°C.

FP82 = Fournier & Potter (1982); applicable for 20–330°C; note the errors on the regression coefficients were reported by Verma & Santoyo (1997).

A85 = Arnórsson (1985); slightly modified Fournier and Potter (1982) equation.

A00 = Arnórsson (2000); applicable for 0–350°C.

VS97 = Verma and Santoyo (1997); Quartz (Verma-Santoyo-1) is applicable for 20-210°C, whereas Quartz (Verma-Santoyo-2) should be used for 210–330°C.

V00 = M.P. Verma (2000a); silica value should be corrected iteratively for the vapour fraction in the geothermal reservoir.

A83 = Arnórsson et al. (1983); applicable for 25–180°C.

A91 = Arnórsson (1991); based on Fournier (1977); after steam loss by adiabatic boiling to 100°C.

G97 = Gíslason et al. (1997); the equation is given by D'Amore & Arnórsson (2000); applicable for 0–200°C.

GA00 = D'Amore & Arnórsson (2000); applicable for 0–350°C.

Table 4. Diversity of gas geothermometers for geothermal exploration.

Geothermometer	Equation (t°C)*	Ref.**	Eq.#
CO_2-H_2S-H_2-CH_4 (D'Amore-Panichi)	$\{24775/2\log(CH_4/CO_2) - 6\log(H_2/CO_2) - 3\log(H_2S/CO_2) + 7\log P(CO_2) + 36.05)\} - 273.15$	DP80	(98)
H_2-CO_2 (Nehring-D' Amore)	$190.3 + 55.97\{\log(H_2) + 0.5\log(CO_2)\} - 0.14\{\log(H_2) + 0.5\log(CO_2)\}^2$	ND84	(99)
CO_2-H_2 (Arnórsson-Gunnlaugsson-1)	$341.7 - 28.57\log(CO_2/H_2)$	AG85	(100)
CO_2-H_2 (Arnórsson-Gunnlaugsson-2)	$311.7 - 66.72\log(CO_2/H_2)$	AG85	(101)
H_2S-CO_2 (Nehring-D'Amore)	$\{194.3 + 56.44\{\log(H_2S) + (\log(CO_2)/6)\} + 1.53\{\log(H_2S) + (\log(CO_2)/6)\}^2$	ND84	(102)
CO_2 (Arnórsson-Gunnlaugsson)	$-44.1 + 269.25\{\log(CO_2)\} - 76.88\{\log(CO_2)\}^2 + 9.52\{\log(CO_2)\}^3$	AG85	(103)
CO_2 (Arnórsson et al.)	$4.724\{\log(CO_2)\}^3 - 11.08\{\log(CO_2)\}^2 + 72.012\{\log(CO_2)\} + 121.8$	A98	(104)
H_2S (Arnórsson-Gunnlaugsson-1)	$246.7 + 44.8\log(H_2S)$	AG85	(105)
H_2S (Arnórsson-Gunnlaugsson-2)	$173.2 + 65.04\log(H_2S)$	AG85	(106)
H_2S (Arnórsson et al.)	$4.811\{\log(H_2S)\}^2 + 66.152\{\log(H_2S)\} + 177.6$	A98	(107)
H_2 (Arnórsson-Gunnlaugsson-1)	$277.2 + 20.99\log(H_2)$	AG85	(108)
H_2 (Arnórsson-Gunnlaugsson-2)	$212.2 + 38.59\log(H_2)$	AG85	(109)
H_2 (Arnórsson et al.)	$6.630\{\log(H_2)\}^3 + 5.836\{\log(H_2)\}^2 + 56.168\{\log(H_2)\} + 227.1$	A98	(110)
H_2S-H_2 (Arnórsson-Gunnlaugsson)	$304.1 - 39.48\log(H_2S/H_2)$	AG85	(111)
H_2-Ar (Giggenbach)	$70\{2.5 + \log(H_2/Ar)\}$	G91	(112)
CO_2-Ar (Giggenbach)	$\log(CO_2/Ar) = 0.032 + 0.0277T + 2048/T$	G91	(113)
CH_4-CO_2 (Giggenbach)	$\{4625/(10.4 + \log(CH_4/CO_2))\} - 273.15$	G91	(114)

*Equations are explicitly given for all cases, except one CO_2-Ar (Giggenbach) geothermometer.

**Reference (Ref.) abbreviations along with pertinent comments are given here.

DP80 = D'Amore & Panichi (1980); gas concentrations in vol%; selection of partial pressure of CO_2 is rather arbitrary; this geothermometer is good for fumaroles, because it is supposed to give temperatures close to those encountered in wells.

Table 4. (*Continued*)

ND84 = Nehring & D'Amore (1984); gas concentrations in mole% (or vol%); the equations are those reported by D'Amore & Arnórsson (2000).
AG85 = Arnórsson & Gunnlaugsson (1985); gas concentrations in mmol/kg; CO_2-H_2 (Arnórsson-Gunnlaugsson-1), H_2S (Arnórsson-Gunnlaugsson-1), H_2 (Arnórsson-Gunnlaugsson-1), and H_2S-H_2 (Arnórsson-Gunnlaugsson) geothermometers are for all waters above 300°C and waters in the range 200–300°C if chloride content >500 ppm; CO_2 (Arnórsson-Gunnlaugsson) geothermometer is for all waters above 300°C; the remaining geothermometers reported by these authors are for all waters below 200°C and waters in the range 200–300°C if chloride content <500 ppm.
A98 = Arnórsson et al. (1998) cited in D'Amore & Arnórsson (2000); all gases are in mmol/kg units; equations are valid for gases in steam at atmospheric pressure (100°C);
G91 = Giggenbach (1991); gas concentrations are molal units; for CO_2-Ar (Giggenbach) geothermometer the equation can be solved numerically, T is in Kelvin, the equation is slightly modified here as compared to that given by the author.

An evaluation of geothermometric equations has been carried out for only a few geothermometers (Na/K, Na/Li, and SiO_2; Santoyo & Verma 1993; Verma & Santoyo 1995, 1997; M.P. Verma 2000a). In fact, the latter (quartz) geothermometer has been the subject of extensive study from both statistical and thermodynamic points of view (Verma & Santoyo 1997; M.P. Verma 2000a, 2000b; Gunnarsson & Arnórsson 2000).

Dowgiallo (2000) used some of the chemical geothermometers listed in Tables 2 and 3, for a study of thermal waters in Poland. This was criticised by Yalcin & Suner (2001) because of wrong concentration units in one of the equations used by him. This example clearly shows that extreme caution is required while using this kind of tool in geothermal or petroleum research. In this context, it would be very useful to write a computer programme that could facilitate the use of these equations and provide additional constraints about propagated errors on the predicted temperatures. In fact, this work is presently being carried out in our group, and a suitable code should be available in the near future.

Much care is similarly required in the use of gas geothermometers. In fact, a series of isotopic geothermometers are also available, but are not discussed in this chapter due to space limitations; the reader is referred to relevant sources (e.g. Henley et al. 1984; Nuti 1991; Truesdell 1991; D'Amore & Arnórsson 2000).

2.5 *Temperature estimates*

Subsurface temperature estimates and heat flow studies are essential to any geothermal research (e.g. Jessop 1990). When no drillholes are available in a given area, first temperature estimates come from the use of geothermometers. Depending on the type of thermal manifestations, one or more kinds of geothermometers can be applied, and subsurface temperatures and corresponding error estimates can be obtained.

When wells have been drilled, actually measured temperatures have to be extrapolated to infer undisturbed formation temperatures (Kutasov 1999). This extrapolation must be done using proper statistics-based methodology. Computer code is available for calculating such static formation temperatures in geothermal wells (Santoyo et al. 2000a). As an example, this is an important area of geothermal research where the error propagation theory should prove useful to obtain uncertainty estimates on the undisturbed or stabilised temperatures.

Drill cuttings and cores are used to obtain information on the mineralogy of the volcanic rocks that are normally hydrothermally altered to different degrees, leading to temperature estimates of the hydrothermal system (e.g. González-Partida et al. 2000). Similarly, geochemical studies can also be carried out on these products and compared with fresh, probably less altered volcanic material (e.g. Torres-Alvarado & Satir 1998). Great care should, however, be taken while interpreting these data;

a simple comparison of mean values, without reference to the corresponding standard deviations and without assuring the validity of inherent basic assumptions, is not really meaningful. If there is strong evidence that the two statistical samples may have been drawn from the same or identical populations, F- and t-tests should be carried out to obtain statistically significant conclusions.

2.6 *Magma chambers*

Depending on the results of a detailed geological, volcanological, and geochemical study of a geothermal area, a preliminary model for the primary, deep heat source, in terms of a magma chamber, has proved valuable for simulation of temperature field distributions. Examples of preliminary studies exist from Mexican geothermal areas (location map is not shown because of space limitations; for locations and more information on these geothermal areas, see e.g. Verma 1985a, 2001a; Anguita et al. 2001), Los Humeros caldera (M.P. Verma et al. 1990; Castillo-Román et al. 1991); Los Azufres caldera (Verma & Andaverde 1996); La Primavera caldera (Verma & Rodríguez-González 1997), as well as from some other areas outside Mexico, for example, Phlegraean magmatic system in Italy (Wohletz et al. 1999) and Clear Lake magmatic-hydrothermal system in U.S.A. (Stimac & Wohletz 2001). Similarly, an application of thermal modelling to the study of contact metamorphism was reported by Furlong et al. (1991).

These attempts should be updated by incorporating more complex simulation models and statistical methodologies to obtain well-constrained results on the heat source in a given geothermal area. Work is in progress in our group to test a new integrated methodology for magma chamber modelling, and thus obtain more reliable estimates of subsurface temperatures.

3 CASE HISTORIES

Mexican geothermal areas are mainly concentrated in the Mexican Volcanic Belt (MVB), southern Mexico (for location of the MVB see any paper on this area, such as Verma 1985a, 1999, 2000b, 2000c, 2001a, 2001b), although the most important geothermal field (Cerro Prieto) of Mexico is located in northwestern Mexico, close to the Mexico-U.S.A. border. The MVB has been studied from different points of view (social, economic, anthropological, volcanic risk, and scientific, in general; Verma 1987). Its study is now considerably intensified because of the recent debates on the origin of this important Miocene-Recent, E-W oriented, volcanic province (e.g. see discussions in Sheth et al. 2000; Verma 1999, 2000b, 2000c, 2001a; Márquez et al. 2001; Velasco-Tapia & Verma 2001), whether it is subduction-, plume- or rift-related. The classical subduction-related model for the MVB seems to be superseded by a rift-related model, at least for the central and eastern parts of the MVB that correspond to the subduction of the Cocos plate. An integrated approach such as the one suggested here should prove useful to solve such scientific controversies, and consequently, provide a better estimate of the available thermal resources in this volcanic area (MVB), where a large number of interesting circular features exist (Anguita et al. 2001). Many of these features probably house geothermal systems.

Geothermal resources in Mexico are used mostly to produce electrical energy; direct uses are practically restricted to bathing and swimming pools (Quijano-León & Gutiérrez-Negrin 2000). Mexico has nearly 30 years of experience producing electricity from geothermal resources; the first geothermal power units of Cerro Prieto started commercial operation in 1973 (Hiriart & Andaluz 2000). The geothermal installed capacity in Mexico (a total of about 855 MW by the year 2000; Quijano-León & Gutiérrez-Negrín 2001) represents about 2.4% of the total capacity of electricity generation using different resources. Interestingly, as compared to this installed capacity of about 2.4%, the geothermal energy represents an even greater proportion of electricity generation in Mexico (about 3.1%), with the other sources being fossil fuels (about 75.3%), hydroelectricity (about 17.3%), nuclear (about 4.3%), and wind (a very minor amount, about 0.004%). This implies that the geothermal power plants in Mexico are run with a better efficiency than other types of power plants. Furthermore, generating costs for electricity from geothermal resources in Mexico are competitive with the costs of generation by means of fossil fuels (Hiriart & Andaluz 2000). I suggest that the geothermal costs can be further lowered if optimised methods were used for the exploration and evaluation of geothermal resources. As a summary, about 422 deep wells have been drilled in Mexico amounting to a total of about 856,954 drilled meters, excluding some thermal gradient and shallow slim holes (Quijano-León & Gutiérrez-Negrín 2000).

3.1 *Cerro Prieto*

This is the largest electricity-producing geothermal field in Mexico; it has an actual installed capacity of about 720 MW distributed in four sectors (Quijano-León & Gutiérrez-Negrín 2000, 2001). It is also probably the best studied geothermal field in Mexico (e.g. Elders et al. 1984; Nehring & D'Amore 1984; Schiffman et al. 1984; Valette-Silver et al. 1985; Silver & Valette-Silver 1987; Mercado & Fernández 1988; Lippmann et al. 1991; M.P. Verma 1997). Cerro Prieto has a long history (since 1973) of producing electricity from geothermal resources. During the year 2000, it produced about 5104 GWh of electricity (Quijano-León & Gutiérrez-Negrín 2001).

3.2 *Los Azufres*

Los Azufres, located in the central part of the MVB, is the second largest electricity-producing geothermal field, with an installed capacity of about 93 MW (Quijano-León & Gutiérrez-Negrín 2001). There are many studies on this geothermal field as well (e.g. Dobson & Mahood 1985; Kruger et al. 1985; Santoyo et al. 1991; Pradal & Robin 1994; Campos-Enriquez & Garduño-Monroy 1995; Torres-Alvarado et al. 1995; Verma & Andaverde 1996; Torres-Alvarado & Satir 1998; Torres-Alvarado 2000; Garcia-Estrada et al. 2001). Geothermal electricity generation here began in 1982. During the year 2000, this field produced about 586 GWh of electricity (Quijano-León & Gutiérrez-Negrín 2001).

3.3 *Los Humeros*

This is the third important geothermal field in Mexico, actually producing electricity with an installed capacity of about 42 MW (Quijano-León & Gutiérrez-Negrín 2001). This area has been studied in detail by many workers (e.g. Verma & Lopez M. 1982; Verma 1983, 1984a, 1984b, 1985a, 1985b, 2000b; Ferriz & Mahood 1984, 1987; Ferriz 1985; M.P. Verma et al. 1990; Castillo-Román et al. 1991; Ascencio 1992; Campos-Enríquez & Arredondo-Fragoso 1992; Tello-Hinojosa 1992; Andaverde et al. 1993; Quijano-León & Torres R. 1995). This field began producing electricity in 1990. During the year 2000, Los Humeros produced about 211 GWh of electricity (Quijano-León & Gutiérrez-Negrín 2001).

3.4 *Other fields*

There are several other fields in Mexico that have been studied to some extent. Two of them are: La Primavera in the western part of the MVB (with a number of studies: e.g. Mahood 1981a, 1981b; Mahood et al. 1983; Mahood & Halliday 1988; Alatorre-Zamora & Campos-Enríquez 1991; Yokoyama & Mena 1991; Verma & Rodríguez-González 1997) and Las Tres Vírgenes in

Baja California peninsula (with an ongoing project of about 10 MW capacity to be installed according to Quijano-León & Gutiérrez-Negrín 2001; see also Santoyo et al. 2000b; other studies were mostly published in a local Mexican journal).

Other promising areas of the MVB that have been geothermally explored to some extent include: Pathé, Acoculco caldera, Los Negritos, and Sanganguey volcano, among others (geothermal studies were mostly published in a local Mexican journal; but see Verma & Nelson 1989; Quinto et al. 1995; Carrillo Martínez 1998; Quijano-León & Gutiérrez-Negrín 2000; Verma 2001a).

4 CONCLUSIONS

Basic methodology for a quantitative evaluation of a geothermal resource is outlined. The most important aspects of statistical principles and tests are briefly reviewed. References to existing case histories are given that use at least part of the methodology outlined in this chapter. Mexican geothermal experience is briefly described. An integrated approach involving geology, geochemistry, geophysics, and statistics should be used to study geothermal fields. I consider this statistics-based integrated approach of vital importance for providing us with a successful geothermal research programme, for reducing electricity generation costs from geothermal resources, and consequently, making the geothermal energy a better alternative to other more conventional sources of energy.

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Geochemical techniques in geothermal development

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ABSTRACT: A comprehensive review on fluid geochemistry for geothermal resources exploration-exploitation is presented. The calculation of deep reservoir physical-chemical parameters is first step in geochemical modeling. Besides many limitations, quartz geothermometer is the only reliable geochemical tool to estimate deep reservoir temperatures. Knowing the reservoir temperature, the chemical parameters in the vapor and liquid phases are calculated using the conservation of enthalpy and mass. The conservation of alkalinity is used to calculate the reservoir pH. Additionally, a numerical simulation for heating H_2O-CO_2 in a reaction vessel is carried out to relate the extracted fluid characteristics with the reservoir fluid characteristics. The pressure is first controlled by CO_2, then by water vapor and in last again by CO_2. On extracting vapor, CO_2 transfers to vapor phase except for highly alkaline fluids, while on extracting liquid, CO_2 in the extracted fluid decreases in acidic to neutral reservoir fluids but increases in alkaline reservoir fluids.

1 INTRODUCTION

Fluid geochemistry is a valuable tool in the evaluation of energy prospects of geothermal systems in the exploration and exploitation stages. Ellis & Mahon (1977) reviewed the geochemical studies on the determination of reservoir parameters like temperature, pressure, state of water-rock interaction, mineral deposition potential of fluid, natural heat flow, fluid flow pattern, recharge zone, high upflow permeability, injection feasibility, size of the reservoir, etc. The effect of the cooling processes of the fluid during ascent to the surface due to heat conduction and admixtures with cold waters or steam losses may be evaluated by means of changes introduced in the chemical and isotopic composition (Giggenbach et al. 1983). In order to obtain these reservoir parameters and to evaluate reservoir processes from fluid chemistry, various theoretical approaches have been developed; the first step in these approaches is to determine the deep reservoir fluid composition from fluids, separated water and steam obtained from drilled wells and/or natural manifestations using the principles of conservation of energy and mass. Mahon (1970) developed a method to estimate minimum underground water temperature from the chloride concentrations in boiling springs and processes such as boiling, dilution with low chloride waters. Fournier & Truesdell (1973) and Truesdell & Fournier (1975) improved the calculation of deep temperatures and hot water fraction for mixed and diluted springs at boiling temperature. Arnórsson et al. (1982) presented a numerical approach to calculate pH and contents of gaseous species in a geothermal reservoir with using mass and enthalpy balance equations. Henley et al. (1984) compiled the studied on chemical calculation and presented the approach, systematically. Verma (1997) presented a two-phase flow approach to calculate the concentration of the dissolved species in the liquid phase in the reservoir except pH.

Various computer programs have been written for chemical modeling of the equilibrium state of multi-component fluids in order to interpret water chemistry in nature as well as in the laboratory, and to trace the reaction mechanisms and processes for water-bodies evolution (Nordstrom et al. 1979, Plummer et al. 1988, Bethke 1992). Some of the existing software like SOLMNEQ (Kharaka & Barnes 1973), MINEQ (Westall et al. 1976), WATEQX (van Gaans 1989) and EQ3NR (Wolery 1983), deal chemical speciation using input parameters as dissolved species concentration, temperature and pH; while others WATEQ (Truesdell & Jones 1974), WATCH (Arnorsson et al. 1982), CHILLER (Reed 1982) and EQQYAC (Barragan & Nieva 1989) may recalculate the pH using charge balance or H^+ mass-balance. NETPATH (Plummer et al. 1991) and "The Geochemist's Workbench" (Bethke 1992, 1994) can also take into account mixing, dilution and evaporation processes. Nordstrom et al. (1979) reviewed over 30 chemical modeling programs and concluded that every modeling program had been developed for specific purposes with its own individual capacities and limitations. Fundamental limitations were the form of alkalinity input and non-carbonic alkalinity correction, and pH calculation. These limitations are still not resolved completely in the improved versions of these commercial computer-programs (Verma 2000a, Verma & Truesdell 2001).

This chapter presents systematically the approach of chemical modeling of geothermal systems, which is basically the evaluation of reservoir fluid-mineral equilibrium-state from the surface natural manifestation and well discharge chemistry. We measure the dissolved species including pH in separated water at weirbox and the non-condensable gaseous species in vapor phase at separator. The chemical composition of reservoir fluid is reconstructed as a mixture of separated water and vapor. It contemplates the calculation of temperature, pH and chemical composition of both vapor and liquid phases in the reservoir. The concentration calculation of the total discharge dissolved species (like Na^+, K^+, Cl^-, etc.) is performed using mass and enthalpy balance equations (Henley et al. 1984). The reservoir pH is calculated through the conservation of alkalinity (Verma 2000a, Verma & Truesdell, 2001). The methodology is discussed in respect to develop the reservoir conceptual models during the exploration and exploitation of geothermal systems. Additionally, a numerical simulation of heating H_2O-CO_2 in a geothermal reservoir is carried for predicting the reservoir fluid characteristics from the variation of CO_2 in production fluid.

2 STRUCTURE AND CLASSIFICATION OF GEOTHERMAL SYSTEMS

Geothermal systems are generally found in a wide range of geological settings at the active tectonic plate boundaries such as subduction zones (e.g. Pacific Rim), spreading zones (e.g. Mid Atlantic) and rift zones (e.g. East Africa) and within orogenic belts (e.g. Mediterranean, Himalayas) and are defined and classified on the basis of their geological, hydrological, and heat transfer characteristics (Nicholson 1993). Thus there exist many types of classifications. However, all the geothermal systems have four common basic components: heat source, fracture rock reservoir, working fluid (water) and caprock (Ellis & Mahon 1977, Henley et al. 1984).

Nicholson (1993) presented a broad classification based on reservoir equilibrium state, fluid type and temperature as following

1. Convective geothermal systems (dynamic systems)
    a. High temperature: liquid- and vapor-dominated
    b. Low temperature
2. Conductive geothermal systems (static systems)
    a. Low temperature
    b. Geo-pressurized

The high-temperature geothermal systems are often volcanogenic, with the heat provided by intrusive masses of rhyolitic-andesitic composition and associated with calderic or graben structures like Los Azufres, Los Humeros, and Cerro Prieto, Mexico (Henley et al. 1984, Nicholson 1993). High temperature chloride springs are found within the geothermal field. The features of these systems are: recharge by meteoric waters, heat input at depth, convective upflow, deep mixing with meteoric cold water, transfer of steam to the surface and its interaction with groundwater, and the flow of deep fluid direct to the surface or its dilution and outflow to some hydraulic base level like river or lake (Henley et al. 1984). These are also known as vertical flow geothermal systems.

Some systems are formed on the flanks of young volcanoes (e.g. Ahuachapán, El Salvador; Kamojang, Indonesia). In these systems the same basic processes occur, but the chloride water springs found several kilometers from the hot upflow part of the system (Henley et al. 1984, Nicholson 1993) and are known as lateral flow geothermal systems.

White et al. (1971) classified as the vapor- and liquid-dominated geothermal systems in order to understand the production characteristics and geochemistry of reservoirs. Some authors consider the presence of both vapor and liquid (White et al. 1971, Truesdell & White 1973) in a vapor-dominated reservoir, while others accept the existence of only superheated steam (Donaldson & Grant 1981, Economides & Miller 1984). The PVT characteristics of water are helpful to enlighten the definition of vapor- and liquid-dominated geothermal systems.

2.1 *Pressure, volume and temperature (PVT) characteristics of water*

Verma (1997, 2000b) discussed the PVT characteristics of pure water through a numerical simulation study for heating different amount (mass) of water in a constant volume reaction vessel. The results are summarized in Figure 1. In Figure 1a the vaporization curve is locus for the values of temperature and pressure where liquid and vapor coexist in equilibrium and it terminates at the critical point (T_C, P_C). The fluid region, existing at higher temperatures and pressures, is shown by dashed lines, which do not represent phase changes but depend on arbitrary definitions of what constitutes liquid and vapor phases (Smith & van Ness 1975).

It is possible to draw a path (e.g. the path I from A to B) from the liquid region to the vapor region that does not cut a phase boundary (Figure 1a). This path represents a gradual phase transition from the liquid to vapor, rather than the path II from A to B that passes through the boundary (vaporization curve) of abrupt change in properties. There is no phase change on moving from the liquid region to the fluid region, similarly from the fluid region to the vapor region (Smith & van Ness 1975). Thus there should exist a gradual phase change within the fluid region, as water is liquid at point A and vapor at point B. Thus a supercritical fluid is composed of compressed liquid or superheated vapor depending on the conditions of pressure and temperature.

Figure 1b shows the PV relation for pure water. The volume is plotted in logarithmic scale in order to show the vapor and liquid in same figure. There coexist both vapor and liquid at the conditions of pressure and volume within the dome-shaped curve. There will be only saturated liquid on the left part of the curve up to the critical point and saturated vapor on the right part of the curve.

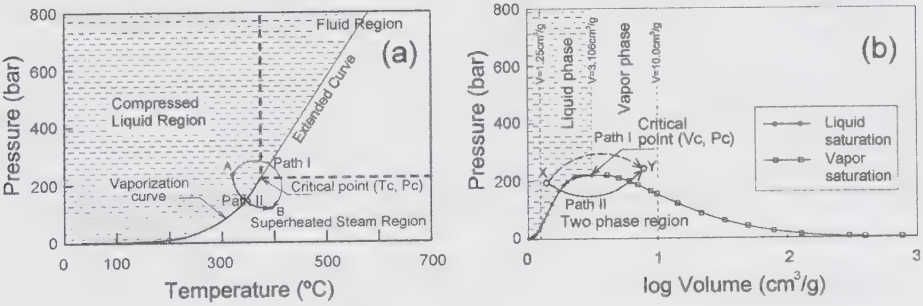

Figure 1. PVT characteristics of pure water. The extended curve in Figure (a) is the separation boundary between liquid and vapor phases in the fluid region, similarly the V = 3.106 cm^3/g line after the critical point of water in Figure (b).

The vertical lines (isochors) corresponding to the total specific volume, V = 1.25, 3.103 and 10.0 cm^3/g shows the heating of given amount (mass) of water in a constant volume reaction vessel. If the total specific volume is less than the critical specific volume of water (e.g. V = 1.25 cm^3/g), there will be first vapor and liquid, than saturated liquid and in the last there will be compressed liquid. Similarly in case of V = 10.0 cm^3/g there will be first vapor and liquid, then saturated vapor and in the last there will be superheated steam. In case of V = 3.106 cm^3/g (i.e. equal to the critical volume of water) there will be vapor and liquid up to the critical point. Above the critical point there will not be any distinction between liquid and vapor along the V = 3.106 cm^3/g isochor, but there will be compressed liquid at any point on the left and superheated steam on the right of the isochor. Thus the V = 3.106 cm^3/g line above critical point is a separation boundary between compressed and superheated steam. Similarly, it is possible to draw a path I from X to Y (liquid region to vapor region) that represents a sudden change of liquid to vapor. There is slow change from liquid to vapor along the path II from X to Y.

The above discussion can be generalized. For cases when the total specific volume is greater than the critical specific volume of water (3.106 cm^3/g), there is only vapor in the container at a certain high temperature ($T < T_C$). To the contrary, when the total specific volume is less than the critical specific volume of water, there is only liquid at a certain high temperature ($T < T_C$). On the other hand, if the total specific volume of water is just equal to the critical volume of water, there will be liquid and vapor along the liquid-vapor saturation curve up to the critical point. After the critical point there is no distinction between liquid and vapor along the critical isochor (V = 3.106 cm^3/g), but there is compressed liquid at any point above this isochor and superheated steam below it even in the supercritical fluid region. In other words there is compressed liquid above the saturation curve and the extended curve, and superheated steam below them in the PT diagram in Figure 1a. This is equivalent to having the compressed liquid in the left and the superheated steam in the right of the V = 3.106 cm^3/g line except in the two-phase region.

Thus a supercritical fluid is composed of compressed liquid or superheated vapor depending on the conditions of pressure and temperature. The "extended curve" or the V = 3.106 cm^3/g isochor above the critical point of water is the boundary separating liquid and vapor in the fluid region.

2.2 *Thermodynamic definition of vapor and liquid dominating geothermal reservoir*

Verma (1997) demonstrated that there was no unanimous definition of vapor- and liquid-dominated geothermal reservoirs. If superheated steam reservoirs are vapor-dominated, then compressed liquid systems will be liquid-dominated. Why should two-phase reservoirs be considered liquid-dominated? A two-phase reservoir can produced only vapor or liquid, depending on well taping. If both phases can be present together in the vapor- and liquid-dominated reservoirs, the proportion of phases becomes important to distinguish between vapor- and liquid-dominated geothermal reservoirs.

According to the PVT characteristics of water, a geothermal system can be classified as vapor- or liquid-dominated depending on whether the specific volume of the fluid in the reservoir is smaller or greater than the critical volume, respectively. Both types of reservoir can produce vapor only at the wellhead. Thus it is incorrect to define the type of geothermal reservoir by the characteristics of geothermal fluid at the wellhead. It is necessary to calculate the deep reservoir fluid specific volume from the fluid characteristics at the wellhead to classify a geothermal system.

2.3 *Fluid production from a geothermal reservoir*

To relate the production fluid characteristics with the type of reservoir, let us assume a geothermal reservoir as a constant volume container of 1000 ml. There are two extreme cases when the

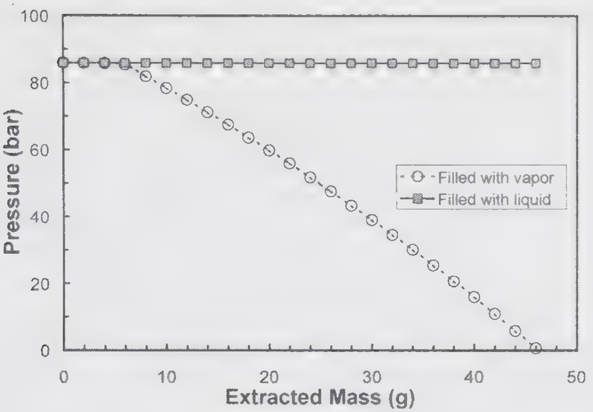

Figure 2. Pressure variation on extracting fluid from a container (1000 ml) completely filled with saturated vapor or liquid at 300°C.

container is completely filled with saturated vapor or liquid at a given temperature (say 300°C). Figure 2 shows the pressure variation on extracting fluid from the container for the two cases. Pressure decreases substantially when the container is filled with vapor only. It means that there should be an entry of some fluid in order to maintain the pressure constant. It is assumed here that there is sufficient heat transfer from the rock to the fluid for converting into vapor. Thus a vapor-dominated reservoir also has liquid phase in the reservoir. There is one more point to be emphasized that the conversion of liquid into vapor means extensive boiling. So there should be highly concentrated geothermal brine in some part of the reservoir, if it is producing only vapor.

3 SAMPLING AND ANALYTICAL DATA QUALITY

Sampling techniques for geothermal natural manifestations like springs, fumaroles and hot pools and drilled wells have been well documented by Ellis & Mohan (1977) and Giggenbach & Goguel (1986). Recently, D'Amore & Arnórsson (2000) restated the sampling techniques together with updated analytical procedures to measure chemical constituents in the samples.

In order to predict the quality of analytical data, Ellis (1976) conducted the first interlab comparison of chemical analysis of geothermal waters involving many countries. The scatter in the results during this study revealed serious deficiencies in analytical accuracy and the need for general improvement and standardization of analytical procedures (Giggenbach et al. 1992). In 1985 the International Atomic Energy Agency, Vienna (IAEA) initiated interlab calibrations of geothermal waters within the framework of the "Coordinated Research Program on the Application of Isotope and Geochemical Techniques in Geothermal Exploration". Since then the IAEA has conducted four interlab calibrations for geothermal waters (Giggenbach et al. 1992, Gerardo-Abaya et al. 1998, Alvis-Isidro et al. 1999, 2000). Eight water samples (i.e. two samples in each calibration) were analyzed among the geochemistry laboratories involved in geothermal developments around the world. The parameters electrical conductivity, pH, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, F^-, SiO_2, B and As were analyzed.

Figure 3 shows a relation between concentration and percentage error for all the chemical parameters. The percentage error increases with decreasing concentration for all the chemical parameters except for SiO_2 and the analytical error is of the same order of magnitude for concentration lower than 1 ppm. The overall error in the analytical data for geothermal waters is ±13% and there is no appreciable improvement in the analytical quality in the successive interlab

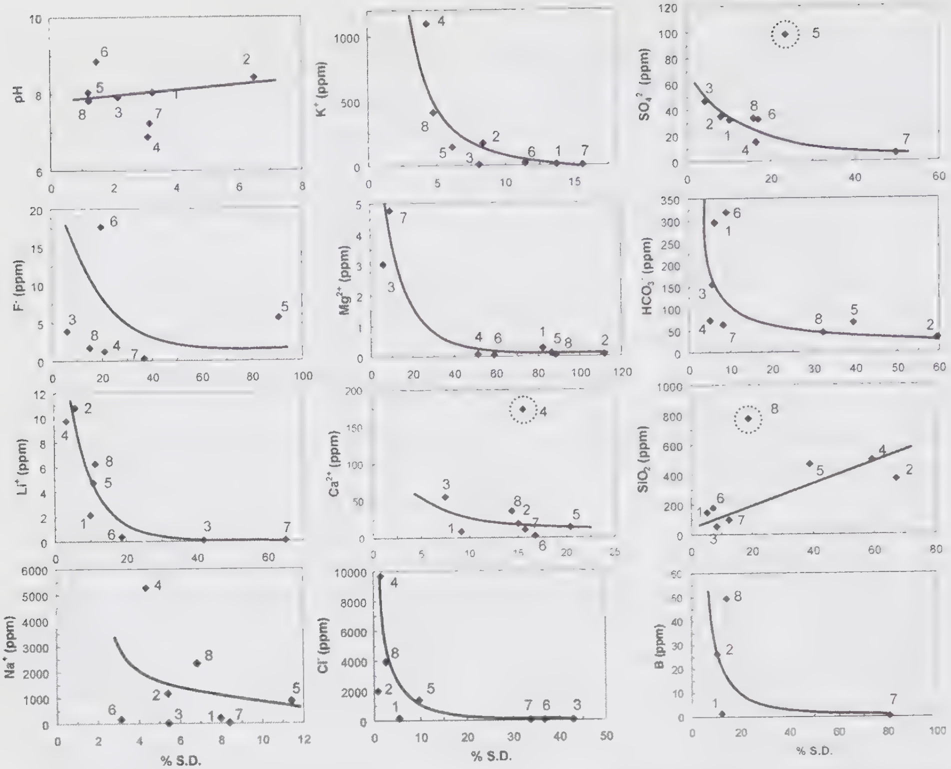

Figure 3. A relation between analytical value and percentage error for all the chemical parameters analyzed under the IAEA interlaboratory calibration program. The data points with circle around them were not included in deriving the trends (modified after Verma & Santoyo 2002).

calibrations, probably due to the existence of systematic errors in the measurements from some laboratories (Verma & Santoyo 2002). There were some serious problems with sampling and analytical procedures for SiO_2 and HCO_3^-.

Verma et al. (2002a) conducted an interlab calibration for silica analysis using commercial standards as samples. The results were similar to the IAEA interlab calibrations; however they provided some understanding on the analytical uncertainty. There is higher random error on direct injection to the atomic absorption spectrometer for higher concentration samples. Similarly, high dilution of samples also produces high systematic and random errors. A need of performing further interlab calibration to optimize the dilution factor for silica analysis was suggested.

It can be stated that there is in general an average error of 10% for concentration >10 ppm, 20% for concentration between 10 to 1 ppm and >80% for concentration <1 ppm for all the parameters except SiO_2 and HCO_3. There is the need of running some common commercial standards for each species together with samples in the participating laboratories to the interlaboratory calibration program (Verma et al. 2002a). The propagation of errors must be considered in developing geochemical models of geothermal systems.

4 CALCULATION OF GEOTHERMAL RESERVOIR FLUID PARAMETERS

The procedure for back calculating the deep reservoir physical-chemical parameters from the chemistry of surface manifestations like springs, fumaroles and drilled wells is based on the conservation of mass and enthalpy (Henley et al. 1984). As the geothermal fluid flows up in a

Table 1. Regression equations for the distribution constant (B) of gaseous species (Giggenbach 1980). The parameter t is temperature in °C.

$$\begin{aligned}
\log B_{NH_3} &= 1.4113 - 0.00292\,t \\
\log B_{H_2S} &= 4.057 - 0.00981\,t \\
\log B_{CO_2} &= 4.7593 - 0.01092\,t \\
\log B_{CH_4} &= 6.0783 - 0.1383\,t \\
\log B_{N_2} &= 6.2283 - 0.01403\,t \\
\log B_{N_2} &= 6.4426 - 0.01416\,t
\end{aligned}$$

well, it flashes within the well and in the separator. The separated water is flashed further in the weirbox at the atmospheric pressure or passed through a cooling coil attached to the separator to collect the sample. Samples of water from the weirbox and steam from the separator are, generally, collected to analyze geochemical constituents. The reconstruction of deep reservoir chemical composition in the vapor and liquid phases is possible through the conservation of mass and enthalpy and the distribution coefficient of certain species between the vapor and liquid phases.

During the formation of natural manifestations like hot springs and fumaroles the geothermal reservoir fluid undergoes many processes like boiling, mixing, dissolution-precipitation and losing of some part the geothermal component. Thus the reconstruction of deep fluid composition from natural manifestations has certain limitations. Here a combined approach including the contribution from all the manifestations will be discussed later.

4.1 *Conservation of mass and enthalpy*

As the geothermal fluid ascends to surface it separates into vapor and liquid. Assuming adiabatic steam separation (i.e. heat loss or gain by the fluid from its surroundings is negligible) the distribution of reservoir fluid enthalpy between the liquid and vapor phases is expressed by

$$H_{res} = y\,H_v + (1 - y)H_l \tag{1}$$

Where H is enthalpy, y is the fraction of vapor by weight in the separator and sub-indices res, v and l stand for reservoir, vapor and liquid, respectively. Similar equation can be written for the concentration of any chemical species, i as

$$C_{i,res} = y\,C_{i,v} + (1 - y)C_{i,l} \tag{2}$$

The non-volatile species like Na^+, Cl^+, etc. resides only in the liquid phase (i.e. their concentration in the vapor phase is zero). In this way the equations 1 and 2 are sufficient to calculate the concentration of reservoir fluid from the separated water concentration and vice versa. But in case of volatile species like CO_2, H_2S, N_2, CH_4, etc. there is need to know the distribution coefficient for the species between the liquid and vapor phases. The distribution coefficient B for a species, i is defined as the concentration ratio of the species in the vapor and liquid phases.

$$B_i = \frac{C_{i,v}}{C_{i,l}} \tag{3}$$

Giggenbach (1980) derived the regressions equations for the distribution coefficient of certain gaseous species of geothermal interest valid from 100 to 340°C (Table 1). Thus the reconstruction of deep reservoir chemical composition in the vapor and liquid phases is possible through the conservation of mass and enthalpy and knowing the values of the distribution coefficient of gaseous species. The approach is applicable only for the species, which do not convert to other aqueous species like N_2, H_2, CH_4, etc. However, there is also need to know alkalinity and pH in case of species like CO_2 and H_2S which transform to other aqueous species. For example, it is well known on adding CO_2 to an aqueous solution, some CO_2 converts to HCO_3^- and CO_3^{2-} and vice versa. For knowing the distribution of total CO_2 we have to consider alkalinity and pH. The approach will be extended later.

4.2 *Fluid geothermometry*

Geothermometers are the principal geochemical tools for the exploration and development of geothermal resources. These are also used in monitoring the response of geothermal reservoirs to the production load and elucidating chemical reactions occurring in the zone of depressurization around wells that result from boiling and/or cooling by recharge cold water (D'Amore & Arnórsson 2000). There are two types of geothermometers: *chemical* and *isotope geothermometers*. The chemical geothermometers are further subdivided as *water or solute geothermometers* and *steam or gas geothermometers*. The application of water geothermometers will only be discussed here. Two types of water geothermometers have been devised: *the cation-exchange geothermometers* and *the silica (quartz) solubility geothermometers*. The use of water geothermometers is presently an integral part of almost all the geochemical investigations of geothermal systems around the world.

4.2.1 *Cation exchange geothermometers*

Most of the cation-exchange geothermometers were developed from the mid-1960s to the mid-1980s and are tabulated in the recent books on the geochemistry of geothermal systems (Henley et al. 1984, D'Amore 1991, Nicholson 1993, D'Amore & Arnórsson 2000). Most commonly used cation geothermometers based on the concentration of Na^+, K^+, Ca^{2+} and Mg^{2+} are from Fournier & Truesdell (1973), Truesdell (1976), Fournier (1979), Tonani (1980), Arnórsson (1983), Nieva & Nieva (1987) and Giggenbach (1988). Recently, Verma & Santoyo (1997) applied a statistical data treatment method and the theory of error propagation in improving the Na^+/K^+ geothermometer equation. Arnórsson (2000) presents a thermodynamic calibration for the Na^+/K^+ geothermometer equation. However, there is a need to demonstrate thermodynamically that the Na^+/K^+ concentration ratio is only a function of temperature in geochemical reactions (i.e. to establish valid fundamental concepts beyond the development of cation-exchange geothermometers). For example, a cation-exchange reaction between Na^+ and K^+ can be written in general as following

$$zNa^+ + Na_{1-z}K_zX = zK^+ + Na_zK_{1-z}X \tag{4}$$

where the capital X represents an anion and z denotes the stoichiometric coefficient. The equilibrium constant for this reaction is given by

$$K = \exp\left(-\frac{\Delta G_F^{T,P}}{RT}\right) = \frac{\left(a_{K^+}\right)^z\left(a_{Na_zK_{1-z}X}\right)}{\left(a_{Na^+}\right)^z\left(a_{Na_{1-z}K_zX}\right)} \tag{5}$$

where $\Delta G_F^{T,P}$ is the difference in the Gibbs' free energy of formation of the participating species at any temperature (T) and pressure (P), subscript F stands for formation (see for definition, Chatterjee, 1991), R is the gas constant, and "a" is the activity of respective species. The activity coefficient is considered to unity in case of dilute solution. Similarly, the activity of solid phases is also taken as unity in developing the geothermometers. Thus the equilibrium constant is reduced to

$$K = \left(\frac{[K^+]}{[Na^+]}\right)^z \tag{6}$$

where square brackets [ ] represent the molal concentration of the species. We will further be presenting the concentration without square brackets. The mixed-minerals like $Na_zK_{1-z}X$ are

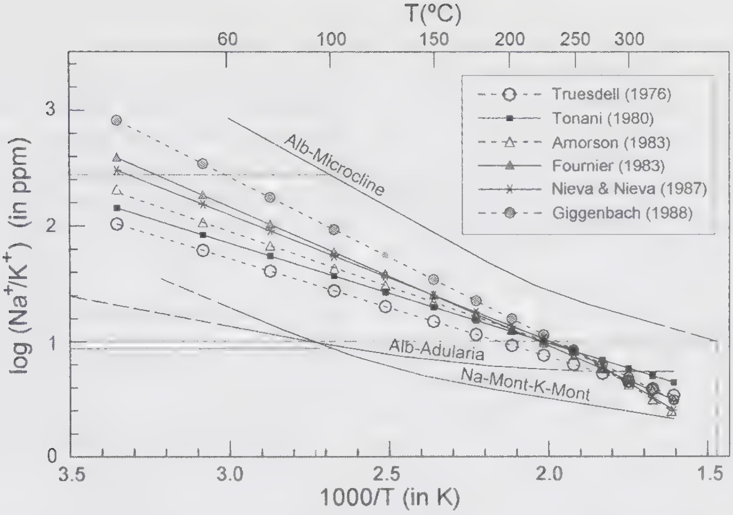

Figure 4. Variation of log (Na^+/K^+) as a function of 1000/T for the theoretical curves for low albite – microcline, low albite – adularia, and Na^+ – montmorillonite – K-montmorillonite together with the (Na^+/K^+) ratio for various geothermometers (modified after Fournier 1989).

not pure phases, so their activity cannot be considered as unity. To avoid the situation the end members of mixed-minerals are considered. It means that we are indirectly considering the solubility of NaX and KX. Then the concentration Na^+/K^+ ratio will not only depend on temperature, but also on the type and concentration of anion X^-. Additionally, to reach the solubility equilibrium, the concentration of Na^+ and K^+ will be very high as can be observed in seas and oceans.

According to the cation-exchange theory, the Na^+/K^+ ratio in a solution is a function of temperature, the type of minerals and the Na^+/K^+ ratio in the mineral phases (Garrels & Christ 1965). The Na^+/K^+ ratio of reservoir rocks, which are in equilibrium with the fluid, is not known and is not included in any cation-exchange geothermometer.

Additionally, Fournier (1989) simplified the equations for various cation-exchange geothermometers to the Na^+/K^+ geothermometer. Then he plotted log (Na^+/K^+) versus 1000/T for base exchange between albite and adularia, albite and microline and Na^+- and K^+-montorillonites together with the values of log (Na^+/K^+) for the empirical equations (Figure 4). There is a wide range of values for log (Na^+/K^+) at a given temperature and vice versa. For example, at temperature 100°C, log (Na^+/K^+) varies in the range 0.95 to 2.25 for different equations. Similarly, for log (Na^+/K^+) = 1.00, the temperature range is 90 to 410°C. Thus one can get a wide range of temperature values using different geothermometer equations for a given ratio of Na^+/K^+.

In summary the cation exchange geothermometers are merely empirical and different geothermometer equations provide different values of temperature. There are no fundamental criteria to justify superiority of one equation over others. There is need of re-evaluating the concepts of cation-exchange geothermometer including the reservoir rock-types.

4.2.2 *Quartz solubility geothermometer*

White et al. (1956) identified that the silica content could be used as a geochemical indicator of geothermal reservoir temperature, as the silica concentration in hot springs at Steamboat, Nevada was very close to the experimental solubility of amorphous silica. Since then enormous contributions have been made to gather more evidence and to create a systematic approach to understand the geothermal reservoir characteristics from the fluid geochemistry of silica.

Verma (2000a, 2001) analyzed critically the existing quartz solubility data. Silica is found naturally in many stable phases including quartz, chalcedony, tridymite, cristobalite, coesite, stishovite and amorphous silica. The dissolution-precipitation equilibration of such multi-phase minerals depends upon the solution-mineral contact time, and it requires an understanding of mineral solubility kinetics (Stumm & Morgan 1981). Quartz is the most stable phase and has the lowest solubility, whereas amorphous silica is the least stable phase and has the highest solubility. Thus quartz and amorphous silica must represent two extreme cases of silica dissolution-precipitation equilibria in hydrothermal systems. The solubility of others silica phases will be in between the two extreme solubilities. The resident time for geothermal reservoir fluid is high enough to reach in equilibrium with quartz. Therefore, we will be here concerned only with the solubility of quartz.

Figure 5 shows the temperature and pressure behavior of all the existing experimental quartz solubility data (after Walther & Helgeson 1977, Manning 1994). The quartz solubility increases with temperature and/or pressure. Figure 6 shows the behavior of quartz solubility data along the saturation curve (Verma 2002a). There is a decrease in quartz solubility along the water-vapor saturation curve above 320°C. Similar behavior is found in compressed liquid region near to the critical point of water (Figure 5(a)). If the quartz solubility increases with both temperature and pressure, it is implicit that either quartz solubility decreases with temperature above 320°C or with pressure above the corresponding pressure (112.7 bar). Thermodynamically, if the decrease is true, there should be a phase transition (Chatterjee 1991) in aqueous silicic species or in water or in quartz. There is no phase transition in quartz and water at 320°C (or at pressure equal to 112.7 bar). Then there should be a phase transition in aqueous silicic species. A phase transition in an aqueous species is not known. If it is true, there will be two types of aqueous silicic species: one below and other above 320°C.

Let us examine the thermodynamics of silica solution chemistry in order to understand such behavior of quartz solubility along the saturation curve. The dissolution of quartz results in the formation of silicic acid according to the following reaction

$$SiO_{2(qz)} + 2H_2O = H_4SiO_4 \tag{7}$$

According to equation (5) the equilibrium constant for the reaction (7) is

$$K_{qz} = \exp\left(\frac{-\Delta G_F^{T,P}}{RT}\right) = \frac{a_{H_4SiO_4}}{a_{qz} \cdot a_{H_2O}} \cong a_{H_4SiO_4} \cong \left[H_4SiO_4\right] \tag{8}$$

If we assume water and solid quartz as pure phases, the equilibrium constant is equal to the activity of H_4SiO_4. Further, on assuming the activity coefficient for H_4SiO_4 as unity, the equilibrium constant (K_{qz}) reduces to the molal concentration of H_4SiO_4. In the case of aqueous solutions the undissociated silicic acid species (H_4SiO_4) is the dominating species, therefore the total dissolved silicic species concentration ($SiO_{2(aq)}$) is equal to $[H_4SiO_4]$ and may be written as

$$\log SiO_{2(aq)} = \frac{1}{2.303}\left(\frac{-\Delta G_F^{T,P}}{RT}\right) = \frac{1}{2.303}\left(\frac{-\Delta H_F^{T,P}}{RT}\right) + \frac{1}{2.303}\left(\frac{-\Delta S^{T,P}}{RT}\right) \tag{9}$$

At lower temperatures the changes in enthalpy and entropy of the reaction are constant, therefore it represents a straight line between log SiO_2 and 1/T. There could be small deviation from the linear behavior of quartz solubility at high temperature and pressure.

The thermodynamic variables, temperature, pressure, volume, Gibbs free energy, internal energy, enthalpy and entropy (represented by T, P, V, G, U, H and S, respectively) are state functions. A state function should be single valued and continuously differentiable unless there is a phase transition (Chatterjee 1991). For example, if we define G for a phase as a function of T at constant P, the function G(T) should be single valued and continuously differentiable with respect to T and vice versa.

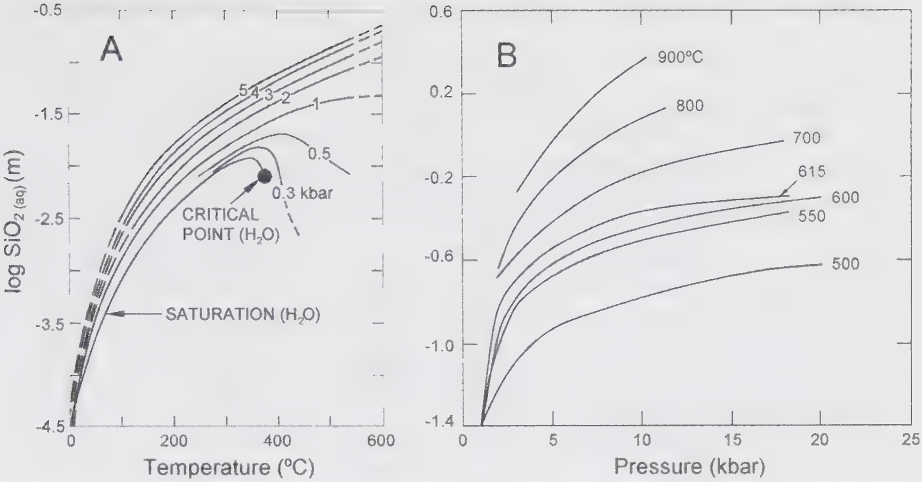

Figure 5. Temperature and pressure dependence of quartz solubility data (modified after Walther & Helgeson (1977) and Manning (1994)).

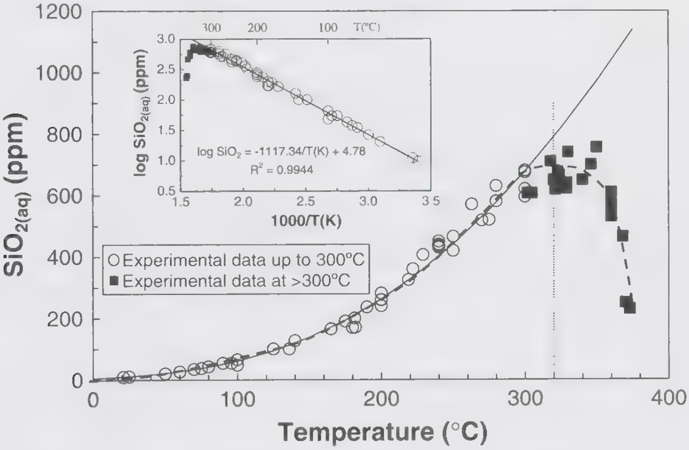

Figure 6. Quartz solubility data along liquid-vapor saturation curve. A linear regression relation between log $SiO_{2(aq)}$ vs. 1000/T for the data up to 300°C is plotted as an insert in the figure. Similarly, a curve corresponding to the straight line is shown with solid line. The curve (dashed) is for all the data and shows a maximum around 320°C.

Similarly, the equilibrium constant (K) defined according to equation (5) is also a state function of T and P. Along the water-vapor saturation curve there is increase in T and P. If K (K_{qz} = $SiO_{2(aq)}$) increases with T and decreases with P and vice versa, the behavior of K is possible as shown in Figure 6 with the dashed curve for all quartz solubility data. If K increases with both T and P, it cannot decrease with T or P. The quartz solubility in aqueous solution increases with T and/or P (see behavior of experimental data in Figure 5). Thus the behavior of quartz solubility along the saturation curve may be interpreted implicitly that the quartz solubility increases initially with T (or P) and then decreases with T above 320°C (or corresponding P). Thus T (or P) is not a state function of K. In other words the behavior of quartz solubility along the saturation curve is against the basic laws of thermodynamics.

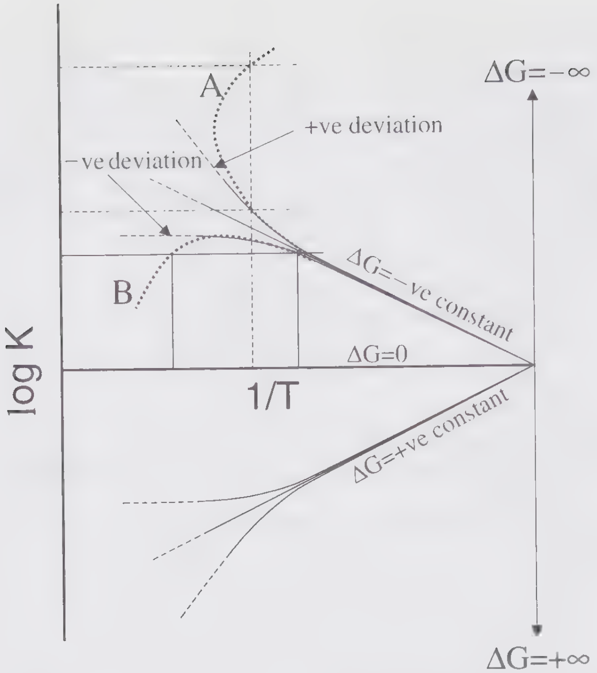

Figure 7. A schematic diagram for the variation of log K with inverse of absolute temperature.

The concept is further illustrated in Figure 7. It shows a schematic diagram for the variation of log K with the inverse of T at constant P. At lower temperatures, the values of Gibbs free energy ($\Delta G_F^{T,P}$) or enthalpy ($\Delta H_F^{T,P}$) and entropy ($\Delta S^{T,P}$) for the first order of approximation are constant and the variation of log K with 1/T is a straight line. There could be positive or negative deviation from the linear trend at higher temperatures, but the function should only be single valued (i.e. the trend of log K may be asymptotic at higher temperatures).

Let us consider two other behaviors of log K as shown with dotted curves (A and B) in Figure 4. In case A there are two values of log K at a given T and in case B there are two values of T for a value of log K. Thus K(T) in case A and T(K) in case B are not single valued functions. In other words either T or K is not thermodynamic state function in the respective cases. As discussed above K and T are thermodynamic state functions, therefore the behavior (represented with curves A and B) of log K is against the basic laws of thermodynamics. In summary the decrease in quartz solubility with temperature at 320°C along the saturation is against basic laws of thermodynamics, when the solubility increases with P and T. Therefore the following linear regression for the quartz solubility data along the liquid-vapor saturation curve is valid for the whole range of temperature (0–374°C)

$$\log SiO_{2(aq)}(in\ ppm) = \frac{-1117.34(\pm 13.05)}{T(in\ K)} + 4.78(\pm 0.03) \tag{10}$$

We will use this equation as a geothermometer to estimate deep geothermal reservoir temperature.

4.3 *pH calculation through alkalinity*

Reed & Spycher (1984) pointed out that the previous methods for calculating pH at high temperature from the analyses at low temperature, without the use of equilibrium among minerals

(Truesdell & Jones 1974, Merino 1979, Arnórsson et al. 1982) were based on the estimate of "total ionizable hydrogen", which they considered an ill-defined quantity compared to the abundance of hydrogen ion. Reed & Spycher (1984) used the total moles H^+ as conservative quantity in order to calculate pH with temperature change. They had to adjust the concentration of Cl^- in their datasets in order to get initial charge balance condition. In other words one has to justify that the analysis of Cl^- was only incorrect in the datasets, considered by Reed & Spycher (1984). Some of the problems encountered in these approaches may be avoided by use of alkalinity.

A base-neutralizing capacity (BNC) or acid-neutralizing capacity (ANC) is the equivalent sum of all the acids or bases that can be titrated with a strong base or acid to a preselected equivalence point (Stumm & Morgan, 1981). The BNC and ANC are more commonly known as alkalinity and acidity, respectively. Both of these terms are defined for certain pertinent equivalence points (EPs) for the system. Acidity is the negative of alkalinity for the same reference EP. In carbonate systems there are three equivalence points called the H_2CO_3EP, $NaHCO_3$EP and $Na_2CO_3^{2-}$ EP. Alkalinity could be defined with respect to either EP. However, the geothermal fluids also have other weak acids and bases and the alkalinity is defined (Verma 2000a) as

$$\begin{aligned} \boldsymbol{alk} &= \left[OH^-\right] + \left[HCO_3^-\right] + 2\left[CO_3^{2-}\right] + \left[B(OH)_4^-\right] + \left[H_3SiO_4^-\right] \\ &\quad + \left[HS^-\right] - \left[NH_4^+\right] - \left[H^+\right] \\ &= \left[OH^-\right] + C_{Tcar}\left(\alpha_1 + 2\alpha_2\right) + C_{TB}\left(\alpha_{1B}\right) + C_{TSi}\left(\alpha_{1Si}\right) \\ &\quad + C_{TS}\left(\alpha_{1S}\right) - C_{TN}\left(\alpha_{1N}\right) - \left[H^+\right] \end{aligned} \tag{11}$$

where the α's identify the ionization fraction (Stumm & Morgan 1981) and C_T is the total dissolved concentration of the subscripted constituent, i.e., carbonic acid (car), boric acid (B), silicic acid (Si), hydrogen sulfide (S) and ammonia (N), respectively. Chemical speciation can be reconstructed introducing in equation (11) pH, alkalinity and total dissolved concentrations of relevant constituents.

It is important to point out here that we are interested in the dissolution-exsolution of NH_3, but not of NH_4^+ or its salts like NH_4Cl (Verma & Truesdell 2001). Therefore we defined the alkalinity with respect to the instead of NH_3EP in equation (11). The procedure of writing the alkalinity expression for different types of reactions in a system is explained by Stumm & Morgan (1981). Thus the alkalinity defined here does not change upon dissolution or exsolution of CO_2 (H_2CO_3) and other gases, such as H_2S and NH_3. On the other hand, the addition or removal of $CaCO_3$ or other carbonate minerals, and $Ca(OH)_2$ or other hydroxides, will increase or decrease alkalinity.

There are three types of equations for an aqueous solution: *mass balance, charge balance and proton balance*. But out of the three equations two are independent and the third can be derived as an algebraic sum of the other two equations (Verma & Truesdell 2001). Theoretically, a solution should be electrically neutral, but the electro-neutrality condition is rarely satisfied, even in best quality analyses. Thus the alkalinity approach is safer for the pH calculation of hydrothermal fluids.

4.4 *An example to illustrate the geochemical calculations*

The stepwise geochemical calculations for well M-19A, Cerro Prieto, Mexico are illustrated in Table 2. The analytical data for the vapor and liquid phase are taken from Henley et al. (1984) and water production at the weirbox from Verma (1997). The vapor production at the separator is adjusted through the conservation of mass and enthalpy. The calculated results are presented up to three decimal places for comparison purposes, although the accuracy of these results depends on the quality of analytical data.

Table 2. Physical-chemical parameters of geothermal fluid at various positions in the well M-19A at Cerro Prieto. The analytical data are taken from Henley et al. (1984). The calculated concentrations are in mmole/kg of water or steam and are reported up to 3 decimal points for the sake of comparison. The actual accuracy depends on the analytical data quality (modified after Verma 2000a).

Parameter	Analytical data		Weir box					Separator		Wellhead	Reservoir
	Separated water	Condensed vapor	At 25°C	At 100°C	Lost vapor	Lost vapor correction	At separator	From vapor	Corrected		
Press. sep.	7.55 bar										
Press. wellhead	35 bar										
Q_{liq} weirbox	97.8 t/hr										
Q_{vap} separator	44.95 t/hr										
Enthalpy (J/g)	1203							1203.004	1203.004	1203.003	1203.014
Pressure (Bar)	1			1.000	1.000	1.000	7.550	7.550	7.550	35.000	42.614
Temperature (°C)	25		25.000	100.000	100.00	100.000	168.060	168.060	168.060	242.300	254.134
Q_{liq} (ton/hr)	97.8		97.800	97.800		142.720	142.720	142.720		16.484	10.867
Q_{vap} (ton/hr)					44.920			44.946	44.946	171.182	176.799
Vapor fraction					0.315			0.240	0.240	0.088	0.058
Liquid phase											
Li^+	200 ppm		28.814	28.814		19.745	19.745		19.745	16.462	15.939
Na^+	7370 ppm		320.577	320.577		219.678	219.678		219.678	183.153	177.334
K^+	1660 ppm		42.457	42.457		29.094	29.094		29.094	24.257	23.486
Mg^{2+}	0.4 ppm		0.016	0.016		0.011	0.011		0.011	0.009	0.009
Ca^{2+}	438 ppm		10.928	10.928		7.489	7.489		7.489	6.243	6.045
Cl^-	13800 ppm		389.248	389.248		266.735	266.735		266.735	222.386	215.321
SO_4^{2-}	18 ppm		0.187	0.187		0.128	0.128		0.128	0.107	0.104
$C_{T(carbonic)}$			0.958	0.958		271.101	271.101		0.770	5.753	10.366
$H_2CO_3^*$			0.105	0.185		270.480	270.480	0.321	0.321	5.301	9.971
HCO_3^-	52 ppm		0.852	0.772		0.621	0.621		0.449	0.452	0.395
CO_3^{2-}			0.001	0.001		0.000	0.000		0.000	0.000	0.000

SiO_{2T}	808 ppm		13.448	13.448		9.215	9.215		9.215	7.683	7.439
H_4SiO_4			13.410	13.331		9.215	9.215		9.215	7.648	7.420
H_3SiO_4			0.038	0.116		0.000	0.000		0.000	0.035	0.019
B_T	14.4 ppm		1.332	1.332		0.913	0.913		0.913	0.761	0.737
$B(OH)_3$			1.318	1.316		0.913	0.913		0.913	0.759	0.736
$B(OH)_4$			0.014	0.016		0.000	0.000		0.000	0.002	0.001
NH_{3T}									1.039	2.803	0.116
NH_4^+									0.131	0.118	0.006
NH_3								0.908	0.908	2.685	0.110
H_2S_T									0.243	1.389	1.709
H_2S								0.102	0.102	1.243	1.616
HS									0.141	0.146	0.092
N_2								1.44E−4	1.44E−4	0.004	0.010
H_2								0.001	0.001	0.037	0.081
CH_4								0.002	0.002	0.065	0.141
H^+			5.37E−8	9.10E−8		1.66E−4	5.13E−5		8.41E−8	2.51E−7	4.06E−7
OH			1.91E−7	6.04E−6		3.32E−9	6.23E−8		3.80E−5	2.48E−5	1.54E−5
pH	7.27		7.270	7.270		3.781	4.290		7.075	6.601	6.392
Alkalinity (meq/l)			0.906	0.906		0.621	0.621		0.621	0.518	0.501
Vapor phase											
X_g		5.88*									
CO_2		822[$]			859.260			269.139	269.139	680.781	954.620
H_2S		79.1						25.899	25.899	58.296	82.510
NH_3		23.1						7.563	7.563	0.519	43.052
N_2		5.1						1.670	1.670	4.509	6.752
CH_4		39.8						13.031	13.031	34.877	51.638
H_2		28.6						9.364	9.364	25.159	37.427

*Gas fraction in vapor phase is in mmol of total gas/mol steam.

[$] Gas concentrations are in mmoles/mole total gases.

The speciation of carbonic, silicic and boric species may be obtained with knowing pH and concentration of one of the species. For example, the concentrations of all carbonic species are calculated from the analytical values of pH and HCO_3^-. Similarly, the speciation of silicic and boric species is obtained from their total concentration and pH. Then the alkalinity is determined using equation (11). This water is heated up to 100°C to get the chemical speciation of flashed water at the weirbox. Alkalinity does not change on heating a solution.

The fraction of lost vapor at the weirbox is calculated through the conservation of enthalpy and mass. The concentrations of dissolved gaseous species like H_2S, NH_3, H_2, CH_4, etc. are not measured in the flashed water. From the concentration of dissolved CO_2 (H_2CO_3) as calculated above in the flashed water at the weirbox, the concentration of CO_2 in the lost vapor could be calculated according to equation (3), considering equilibrium between the water and vapor phases. The data are reported in the column "lost vapor" in Table 2. On mixing the flashed water and lost vapor, the speciation of separated water at 100°C is calculated and reported as "lost vapor correction" at the weirbox. Then this water is heated to 168.060°C (i.e. corresponding separator pressure 7.55 bar) to get the chemical speciation of separated water at the separator.

There is an alternative way to know the concentration of dissolved gaseous species in the liquid phase at the separator with considering equilibrium between water and vapor. The data are reported in the column "from vapor" in Table 2. It can be observed that the concentrations of dissolved CO_2 are quite different from the two approaches. If there is equilibrium between water and vapor at the weirbox, it means a substantial discharge of CO_2 into the atmosphere from a geothermal system. It has been noted that most of the CO_2 remains in the liquid phase on flashing at low temperature (i.e. kinetic of the reaction is important). Other possibility for this discrepancy in the calculated CO_2 concentrations could be analytical errors. Here it assumed that the equilibrium between the liquid and vapor phases at the separator is more reliable. Accordingly, the corrected data at the separator are used for further calculations and are reported in Table 2. Then the water and vapor at the separator are mixed together and heated up to the wellhead conditions.

In order to calculate the reservoir temperature it is assumed that the residence time of geothermal fluid in the Cerro Prieto reservoir is sufficiently high to achieve a chemical equilibrium between the liquid phase and quartz. Therefore the quartz solubility regression equation (10) is used as a geothermometer for calculating the reservoir temperature. The vapor fraction in the reservoir is obtained through the mass and enthalpy balance equations. Based on these vapor fraction and reservoir temperature, chemical constituents are redistributed between the coexisting vapor and liquid phases. Throughout the approach the alkalinity is considered as conservative entity.

The propagation of analytical errors should be considered in these calculations. However, there are presently many approximations and corrections, which needed to be justified first. There will be substantial variation in the calculated pH values due to small error in the concentration of CO_2, silica, boron, H_2S, or NH_3, when the system is near to one of the equivalence points. Here the geothermal waters are considered as dilute solutions, which may not be true in all types of geothermal waters. Thus the activity coefficient for all the species should be taken into consideration for concentrated geothermal brines.

5 GEOCHEMICAL MODELING OF GEOTHERMAL SYSTEMS

The approach developed so far will be discussed briefly to predict the reservoir conditions of the Los Azufres geothermal field, Mexico. The well location map is shown in Figure 8. The chemical and isotopic data are taken from the works of Ramírez et al. (1988), Verma et al. (1989), González et al. (2000) and Tello & Suárez (2000).

Table 3 presents the analytical data, reservoir enthalpy (H_R) and SiO_2, Cl , $\delta^{18}O$ and δD in the separated water at the weirbox and the separation temperature and $\delta^{18}O$ and δD in the condensed vapor at the separator together with the calculated parameters in the Los Azufres geothermal

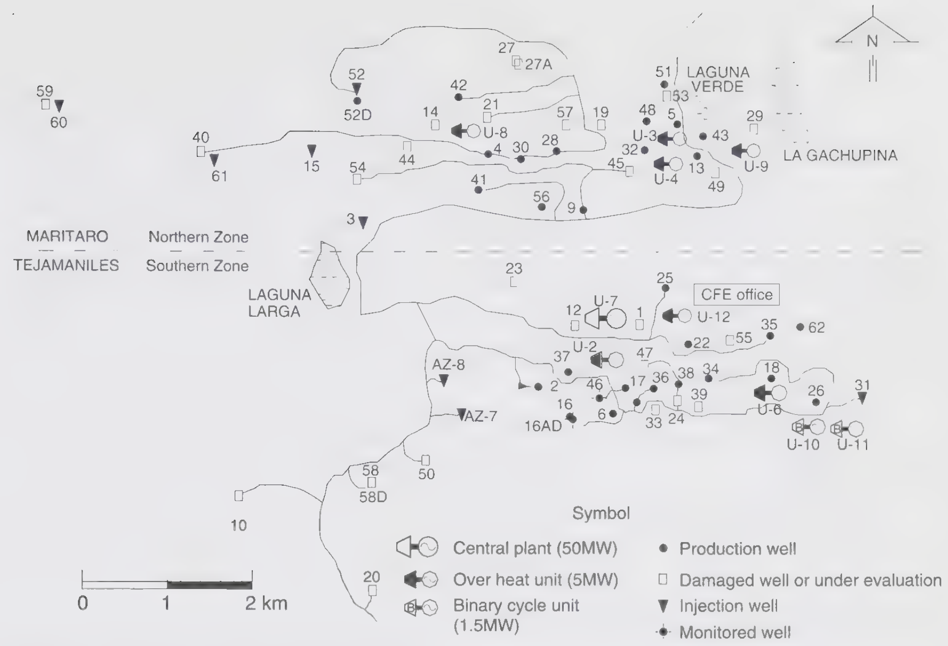

Figure 8. Well location map of Los Azufres geothermal system, Mexico (modified after Verma et al. 2002b).

Table 3. Well data from the Los Azufres geothermal field and estimation of deep reservoir fluid parameters through the quartz geothermometer. The chemical analyses are in ppm, and isotopic data in $^0/_{00}$.

	Analytical data							
		Weirbox (liquid)				Separator (vapor)		
Well	H_R (J/g)	SiO_2	Cl^-	$\delta^{18}O$	δD	T (°C)	$\delta^{18}O$	δD
AZ-5	1912	994	3140	−1.2	−57.6	171	−4.3	−66.1
AZ-9	1754	1154	3930	−0.2	−52.4	176	−4.0	−62.9
AZ-13	1631	890	3070	−0.2	−51.3	190	−3.7	−65.5
AZ-19	1423	952	2495	−1.2	−52.0	178	−5.9	−70.0
AZ-22	1410	1050	4399	−1.4	−59.0	174	−4.3	−75.6
AZ-28	1449	959	2642	−0.4	−53.2	186	−4.7	−67.5
AZ-32	2661	767	2304	2.2	−30.1	178	−3.22	−62.4
AZ-36	1532	773	3035	−0.7	−51.9	178	−4.28	−61.9

	Calculated data in the reservoir							
				Liquid phase			Vapor phase	
	Vapor frac.	T (°C)	SiO_2	Cl^-	$\delta^{18}O$	δD	$\delta^{18}O$	δD
AZ-5	0.42	289	621	1963	−2.83	−65.67	−3.89	−61.97
AZ-9	0.28	302	689	2348	−2.20	−60.60	−3.14	−57.20
AZ-13	0.26	281	581	2005	−1.85	−61.05	−3.04	−57.05
AZ-19	0.11	287	609	1597	−3.16	−61.14	−4.22	−57.34
AZ-22	0.07	295	649	2720	−2.74	−67.35	−3.86	−63.95
AZ-28	0.11	286	603	1660	−2.29	−61.40	−3.35	−57.70
AZ-32	0.95	313	747	2243	−2.17	−63.45	−3.00	−60.65
AZ-36	0.23	269	526	2065	−2.27	−59.16	−3.59	−55.36

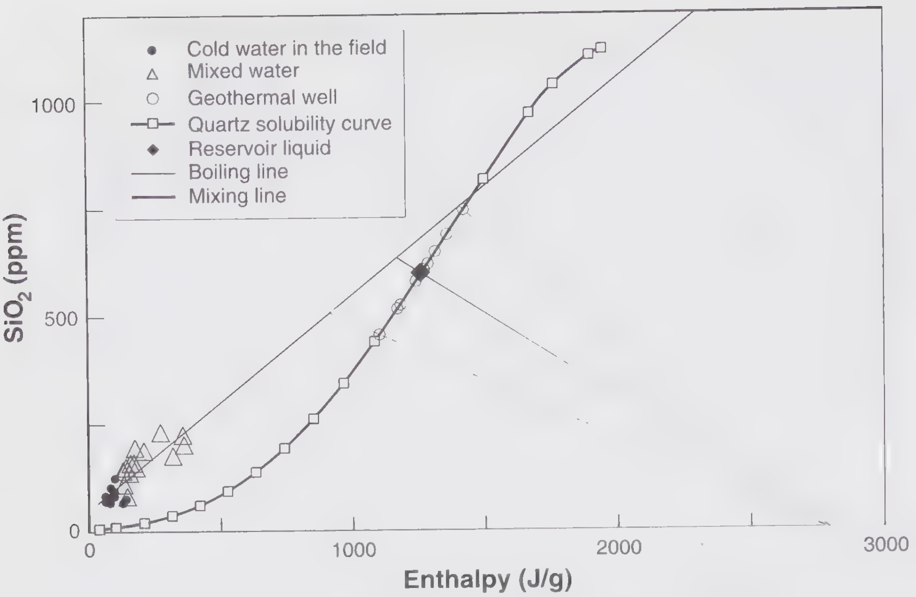

Figure 9. Enthalpy versus SiO_2 mixing model for the Los Azufres geothermal system.

reservoir using the above procedure. The separated waters were corrected first for the lost vapor at the weirbox and then mixed with the condensed vapor at the separator in order to get the deep reservoir parameters through the conservation of mass and energy. The average temperature in the reservoir is ~290°C and the reservoir fluid is in two phases.

The formation of natural manifestations undergoes various processes like boiling, mixing and re-equilibration. Therefore the application of silica geothermometer to natural manifestations is not so simple. There is need to correct the silica concentration for these processes. The boiling and mixing may be handled with reasonable exactitude. On applying directly the silica geothermometer to the natural manifestations may provide sometime reasonable temperature, when the boiling effect is more or less equal to the cold-water dilution. Boiling causes an increase in the silica concentration, while dilution reduces the silica concentration in the mixed water. Sometimes the dilution with cold groundwater could be high enough to limit in getting the deep reservoir characteristics and visa versa. Therefore a mixing model approach is more useful.

Figure 9 shows the silica-enthalpy mixing model in order to understand the formation of natural manifestations in the Los Azufres geothermal field. We use the same classification for the natural manifestations as presented by Ramírez et al. (1988). The mixed-water springs contain a component from the deep reservoir liquid phase. Thus the proportion of cold and geothermal component may be calculated through the mixing model approach. The geothermal well temperatures are within ±20°C, but it creates a wide uncertainty in the calculated geothermal component in the mixed water. Consequently, there should be a wide error in the estimated reservoir temperature through these manifestations.

The behavior of isotopic data together with the expected isotopic values of these mixed-water type springs is shown in Figure 10. It can be observed in the figure that there are only few mixed-water springs in this region. There is one more point to be emphasized that it is rare to find an isotopic equilibrium between the separated water and vapor at the separator. Therefore the mass balance equation is used only to calculate the total discharge isotopic compositions.

Similarly, Figure 11 shows a Cl^- versus enthalpy diagram. Again the chloride concentration in the natural manifestations is relatively low. There are only few springs in the mixed-water composition region. An explanation of this discrepancy is that there are re-equilibration of silica

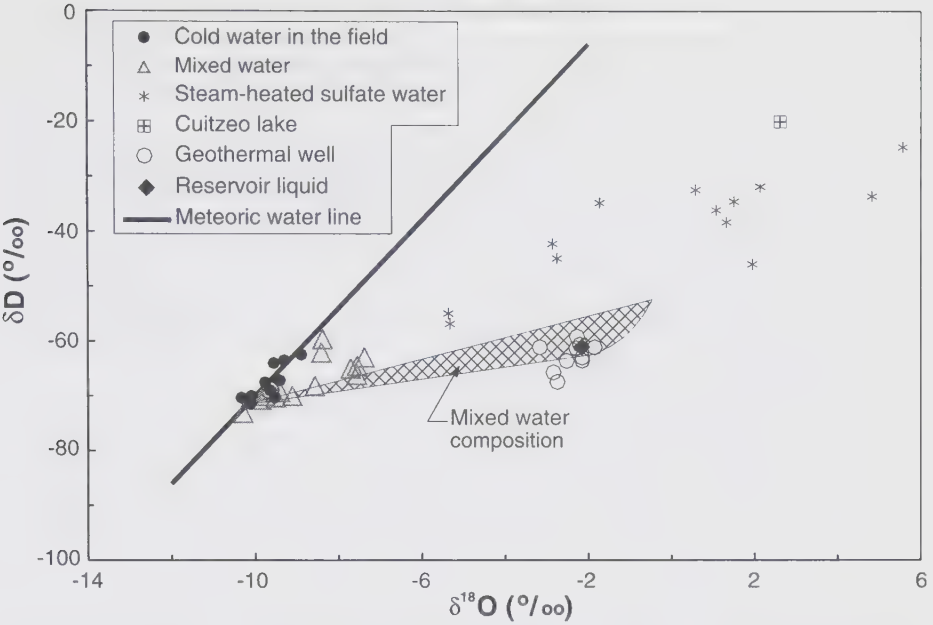

Figure 10. An isotopic relation of different types of water in the Los Azufres geothermal system. The mixed water composition is calculated using the composition of reservoir liquid and cold springs within the field.

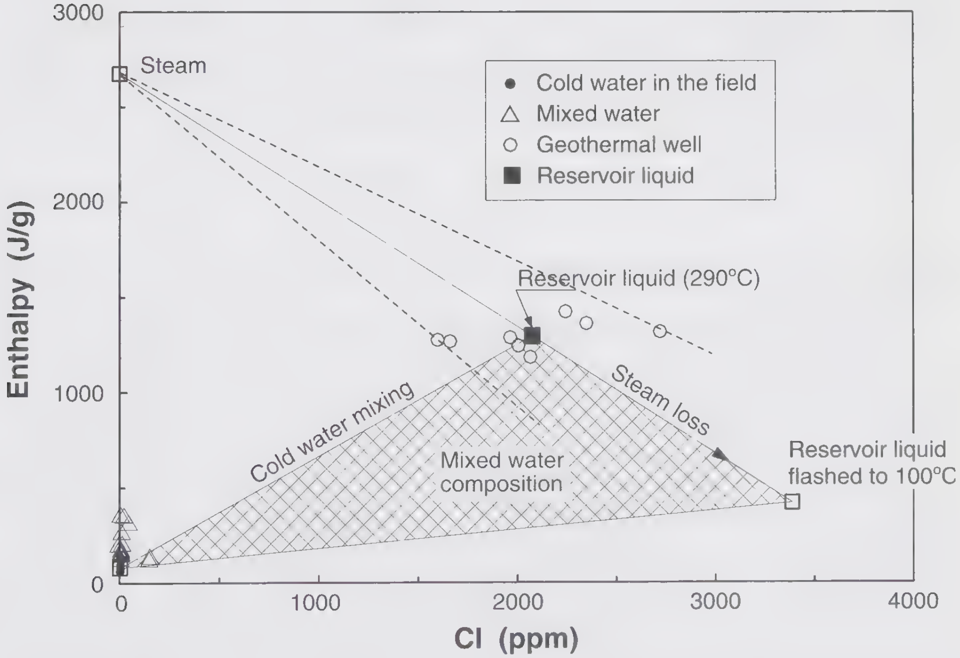

Figure 11. Enthalpy versus Cl⁻ mixing model for the Los Azufres geothermal field. The calculation of mixed water composition is same as in the Figure 10.

during the formation of these mixed springs and they have relative very small geothermal components. Silica has many stable phases at low temperatures. Thus the equilibrium state between aqueous silica and the solid phase depends on the residence time of silica in the water-body. In other words the application of silica geothermometer to natural manifestations has many limitations.

Additionally, the commercial electricity generation in the Los Azufres geothermal field was initiated in 1982. It is well established that the exploitation of a geothermal reservoir reduces its pressure and consequently the contribution of geothermal component to the superficial natural manifestations. The springs were sampled in 1987 (i.e. after five years of exploitation of the reservoir). It is also reasonable that the water component has less possibility to ascend to surface on the reduction of reservoir pressure. Thus there is very little contribution of geothermal water component to natural manifestations in case of Los Azufres geothermal system and the manifestations within the field are disappearing slowly.

In summary, the estimation of deep reservoir parameters of a geothermal system from natural manifestations in the area is only consistent when there is a contribution of liquid geothermal component. Therefore, the existence of such component needs to be proven first with conservative species. Otherwise the application of gas chemistry is more reliable, although there are many limitations in the concepts of gas geochemistry and it is not the subject of present work.

6 H_2O-CO_2 HEATING NUMERICAL SIMULATION IN A GEOTHERMAL RESERVOIR

CO_2 is the second dominated component after water in geothermal systems. Michaelides (1982) and Michaelides & Shafaie (1986) discussed the influence of non-condensable gases and salts on the power production by geothermal systems. They used the distribution of CO_2 between vapor and liquid phases. However, the CO_2 in solution presents in the form of carbonic species and its distribution between vapor and liquid phases also depends on pH. Verma (2002b) develop an algorithm for heating H_2O-CO_2 in a constant volume reaction vessel. The basic chemistry of carbonic system is well documented in textbooks on aquatic chemistry (e.g. Stumm and Morgan 1981). In case of heating H_2O-CO_2, the distribution of CO_2 is governed by the partial pressure of CO_2 in the vapor and liquid phases according to the following equation

$$p_{CO_2} = \frac{[H_2CO_3]}{K_H} = \frac{n_{CO_2(vapor)}RT}{V_{Vapor}} \tag{12}$$

where $n_{CO_2(vapor)}$ is the number of mole of CO_2 in the vapor phase, R is gas constant and T is absolute temperature.

A geothermal reservoir is considered as a vessel of 1000 ml containing different amount of water, CO_2 and alkalinity (NaOH or HCl). The reservoir fluid characteristics are dealt during the heating and extracting a small amount of fluid from the liquid and vapor phases. Let us consider first when the container is filled with 100, 500 or 800 ml of alkaline water (0.1 eq/kg) without and with 20 g of CO_2 at 25°C.

Figure 12 shows the variation of pressure, pH and CO_2 in the vapor phase with temperature in the container. In case of $CO_2 = 0$ g, the pressure is along the saturation curve up to the point when whole water converts to vapor or liquid only. In case of 100 ml of water, there is only vapor above 343°C. In case of 500 and 800 ml of water, there will be only liquid above 364 and 250°C, respectively.

The temperature dependence of pressure in case of 20 g of CO_2 with different amount of alkaline water is also shown in Figure 12a. The pressure is in general first controlled by CO_2, then by water vapor and in the last again by CO_2. In case of 800 g of water, the pressure is always controlled by CO_2. The pressure is much higher than the saturation pressure. It means that there is also need of considering the pressure dependence of equilibrium constants.

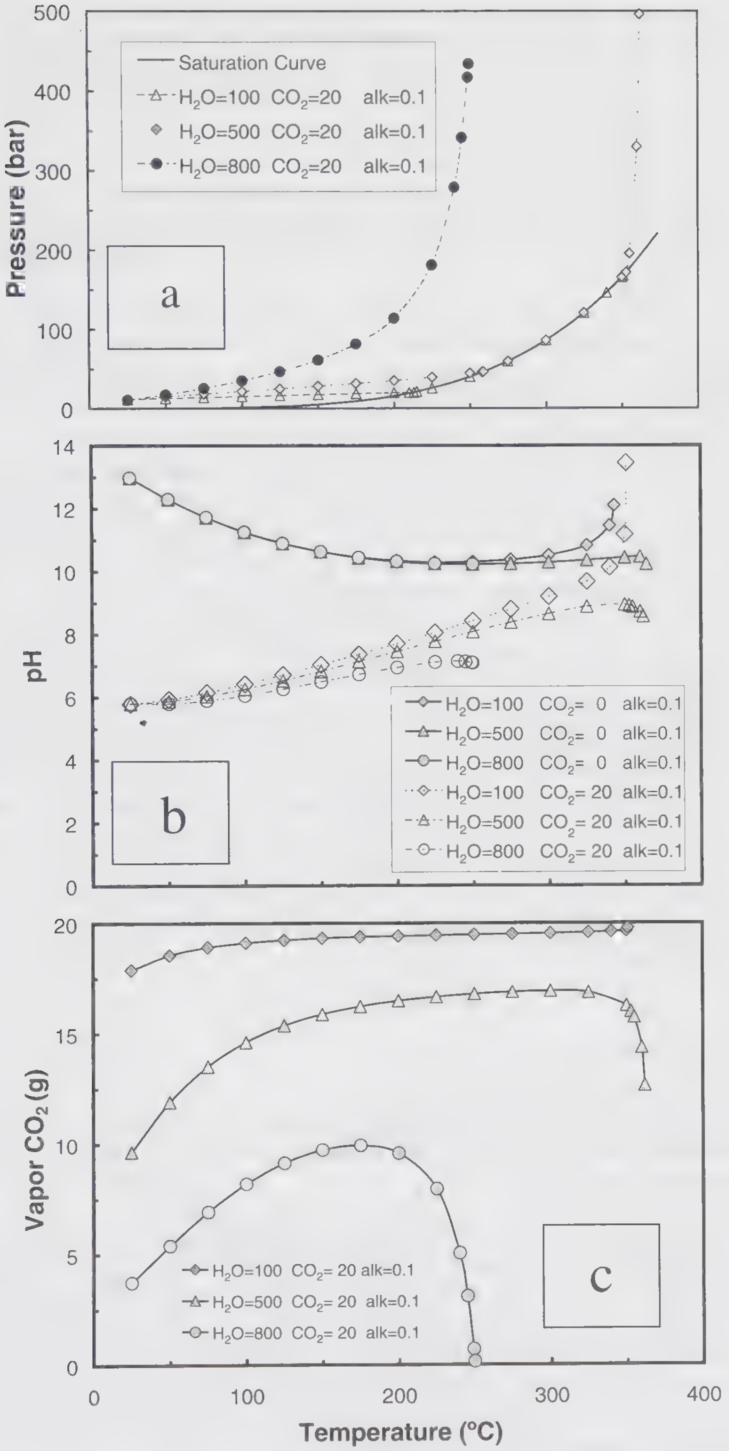

Figure 12. Variation of (a) pressure, (b) pH and (c) amount of CO_2 in vapor phase with temperature in a reaction (1000 ml) with different amount of water (having alkalinity = 0.1 eq/kg) and 20 g of CO_2.

Figure 12b shows the variation of pH with temperature for the cases $CO_2 = 0$ or 20 g. When there is no CO_2 in the container, the pH decreases first on heating, but there is increase in pH at higher temperature for the case of 100 ml water. This is related to concentrating of alkalinity due to conversion of liquid into vapor.

In presence of CO_2 the pH increases with temperature (Figure 12b). This is due to the fact that CO_2 moves to the vapor phase on heating the system. In the case of 100 ml of water there is sudden increase in pH due to concentrating of alkalinity during the conversion of liquid to vapor phase. In the cases of 500 and 800 ml of water, the amount of CO_2 in the vapor phase increases first and then decreases (Figure 12c). It is due to the dissolution of CO_2 in the liquid phase with increase in pressure.

Figure 13 shows the variation of pH and CO_2 in vapor and liquid phases on extracting 5g of vapor or liquid in step from a solution containing 500 g of water and 20 g of CO_2 in the reaction vessel at 300°C. The pH of liquid phase in the container increases in cases of neutral to alkaline solutions, whereas it remains practically constant in case of acidic solution. Additionally, there is larger increase in pH on extracting vapor phase for neutral to alkaline solutions.

Similarly, Figures 13b and 13c show the effect of alkalinity on the remaining CO_2 on extracting vapor or liquid. On extracting liquid, the amount of CO_2 in the vapor phase decreases linearly in case of alkaline fluid whereas increases in case of acidic fluid. Similarly there is increase of CO_2 in the liquid phase in case of alkaline solution, whereas decrease in case of acidic fluid. On extracting vapor, the amount of CO_2 in the vapor and liquid phases decreases exponentially. Thus the variation of gaseous species in the produced geothermal fluid may provide useful information about the characteristics of geothermal reservoir fluid.

The effect of acidic fluid on the damage of geothermal wells has been observed in many geothermal fields. However, there are little efforts to relate the production fluid characteristics with that of the reservoir fluid (Truesdell et al. 1989, Truesdell 1992, Verma et al. 1998). The variation of gaseous species like CO_2 could be useful to identify the geothermal reservoir fluid acidity. Recently, Gherardi et al. (2002) reported the production history of CO_2 in geothermal fluid at Miravalles, Costa Rica. The data are plotted in Figure 14. The behavior is quite complicated. However, there is systematic decrease in case of wells 01 and 12. Knowing the amount of water and vapor produced from the reservoir it is possible to estimate the type of reservoir fluid. However, it is still necessary to incorporate the effect of other gaseous species like H_2S on the reservoir fluid characteristics. We are working on it.

7 CONCLUDING REMARKS

The calculation of physical-chemical parameters of deep geothermal reservoir fluid is based on the conservation of mass, energy (enthalpy) and alkalinity (proton). The contribution of the present work can be summarized as:

- It is not sufficient the knowledge of the distribution coefficient of gaseous species like CO_2, H_2S and NH_3 which exist in aqueous solution in more than one form (e.g. CO_2 appears as H_2CO_3, HCO_3^- and CO_3^{2-}) in order to determine their partition between vapor and liquid phases. Therefore the geochemical calculations are presented here with taking into account pH and total alkalinity of the solution.
- The existing equations for cation-exchange geothermometers are violating fundamental laws of chemical thermodynamics. Therefore the use of quartz geothermometer is more appropriate to estimate the geothermal reservoir temperature.
- A substantial difference was found for the concentration of total CO_2 in water at the separator, calculated from the analytical data of separated water at the weirbox and condensed vapor at the separator. CO_2 is a main component to control the geothermal reservoir pH. Therefore it is

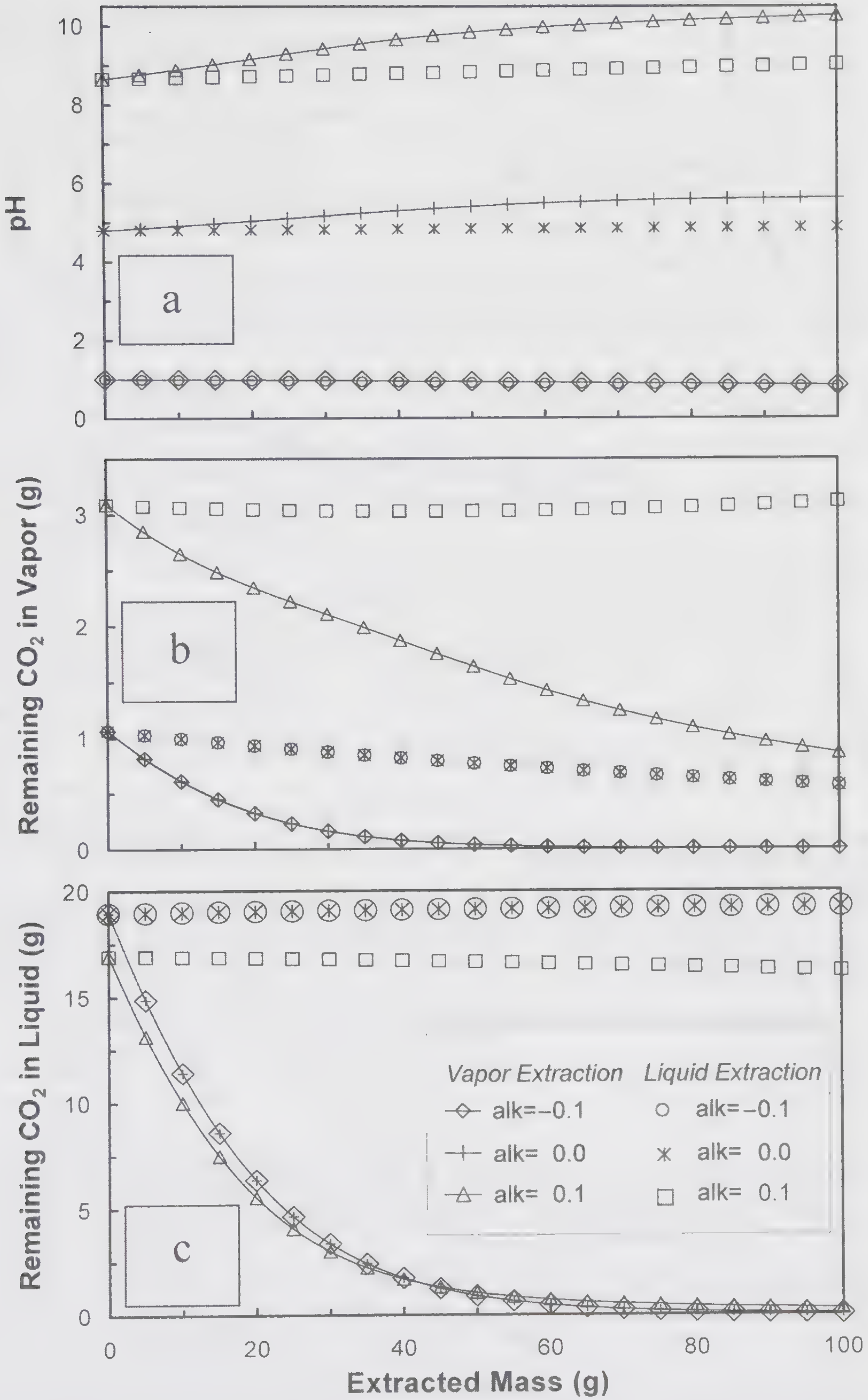

Figure 13. Effect of alkalinity on (a) pH, (b) CO_2 in vapor phase and (c) CO_2 in liquid phases on extracting 5 g of vapor or liquid in step from a reaction vessel of 1000 ml at 300°C containing 500 g of water and 20 g of CO_2 and alkalinity −0.1, 0.0 or 0.1 eq/kg.

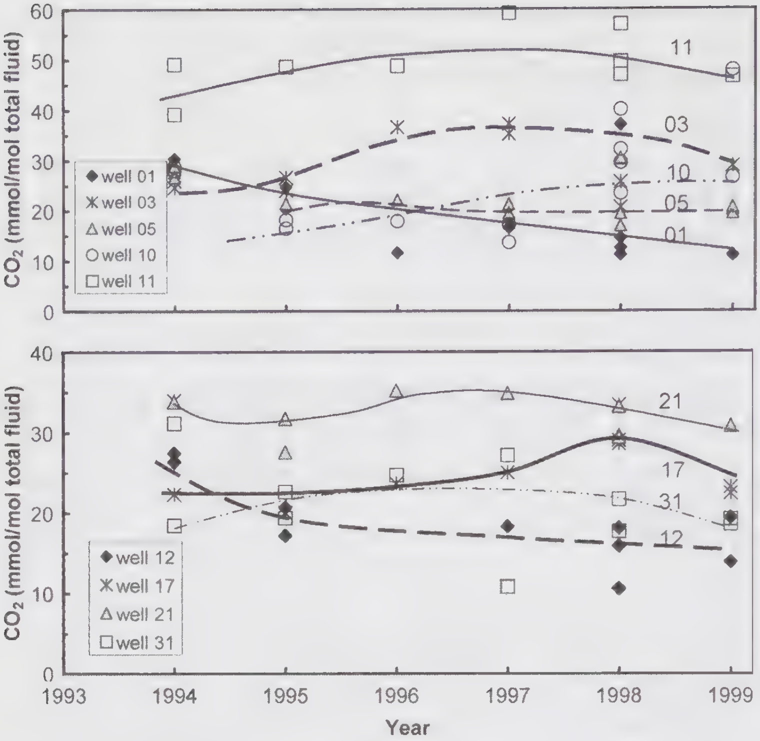

Figure 14. Variation of CO_2 in the Miravalles geothermal field, Costa Rica. The data are taken from Gherardi et al. (2002).

still necessary to improve the quality of analytical data for CO_2 in both vapor and liquid phases through interlaboratory calibrations.

- Natural water systems are not always along the water-vapor saturation curve. It requires creating the temperature and pressure dependent database for equilibrium constants of all the chemical reactions.
- The variation in the concentrations of gaseous species in the geothermal production fluid with time is useful to predict the acid-base characteristics of the fluid in the reservoir.

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Geochemistry of thermal waters and thermal gases

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ABSTRACT: The chemical composition of thermal discharges vary widely due to various physicochemical factors prevailing in the thermal reservoirs and in the environment through which the waters circulate. Common ions and gases present in such discharges are of great help in evaluating any geothermal system. Such evaluation is very important during pre-drilling stages of geothermal energy development projects and assists power project developers, decision making bodies and other administrators in taking the right decision before investing in geothermal related projects.

1 INTRODUCTION

The chemical signatures of thermal waters and gases play an important role in evaluating the reservoir processes and evolution of geothermal systems. This is especially so during the pre-drilling stages of geothermal exploration. The procedure of evaluation of geothermal systems includes collection of samples (fluid and gases) from thermal emergences and interpreting their chemical behaviour. The success of obtaining the right information form such samples depends on the selection of the right sample for interpretation. The procedure is simple and is widely applied to all the explored geothermal provinces of the world. In the present paper chemical characteristics of thermal waters and gases are described and simple methods of evaluating the chemical data are explained. Integrating chemical data with surface geophysical data such as heat flow, geothermal gradient; gravity anomaly of geothermal provinces will provide valuable information for initiating geothermal energy projects.

2 GEOTHERMAL SYSTEMS

Geothermal systems derive its heat either from the high heat fluxes from the crustal rocks due to conduction or due to magmatic bodies at deeper levels due to convection. In places where geothermal gradients are higher than the normal average value of 30°C/km, meteoric waters circulating deep in the earth crust in such areas get heated and give rise to geothermal waters. Areas where the geothermal gradients are found above the normal values are those associated with active continental rifts, rifts associated with volcanism. In such areas the geothermal gradients vary between 60 and 90°C/km and above. Tattapani and Cambay geothermal provinces in India are such areas where the geothermal gradients are as high as 90°C and 70°C/km respectively (Chandrasekharam, 2000).

Table 1. Chemical composition of representative thermal waters of the world.

Location	pH	°C	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Li	Rb	Cs
1 El Tatio/Chile	7.3	x	4340	520	272	0.5	7922	30	46	x	x	x
2 Tokannu/NZ	7.8	x	1710	168	32	0.2	3021	63	2	x	x	x
3 Waitopu/NZ	2.8	x	43	11	27	3.5	32	347	0	x	x	x
4 Waitopu/NZ	2.8	x	406	74	40	7.5	612	666	0	x	x	x
5 Taiwan	2.4	x	5490	900	1470	131	13400	350	0	x	x	x
6 Crater-lake/NZ	1.3	x	740	79	1200	1030	9450	10950	0	x	x	x
7 Wairakei/BW	8.6	x	230	17	12	1.7	2.7	11	680	x	x	x
8 Turkey	9	200	1280	135	2.5	0.2	117	770	1860	x	x	x
9 Carlsbad	7.6	73	1718	104	102	46	617	1662	2100	x	x	x
10 Sulphur bank	6.8	69	1190	23	20	55	644	598	3290	x	x	x
11 Tuwa, India	7.5	62	1012	35	394	5	2020	265	121	x	x	x
12 Guatemala B	8.4	300	1030	210	11	0.01	1700	61	150	8.1	1.9	2
13 Guatemala S	8.7	87	260	37	43	43	170	195	500	0.6	0.08	0.02
14 Mt. Amiata	6.4	51	24	9	859	193	14.6	1245	1943	x	x	x
15 Wairakei B	8.5	240	1170	167	20	0.01	1970	35	5	x	x	x
16 Wairakei S	7.7	99	1220	140	30	4.5	2100	30	30	14.5	2.3	2.1
17 Costa Rica B	7.5	245	1970	238	73	0.02	3300	36	40	5.7	1.05	0.6
18 Costa Rica S	8.5	73	1970	79	22	6.5	2600	120	910	3.4	0.21	0.14

Values in ppm. 1–10: Ellis and Mahon, 1977; 11: Minissale et al., 2002; 12, 13, 15, 16, 17, 18: Giggenbach, 1991; 14: Minissale et al., 1967. B: Bore well; S: Surface spring; x: data not available.

High thermal gradient result due to the presence of high content of radioactive elements in the crustal rocks. This is evident from the high He content (2.1 to 6.9%) recorded in the thermal gases in the above two provinces (Chandrasekharam, 2000; Minissale et al., 2000).

In contrast, most active geothermal systems are hotter than the conductive systems mentioned above and get additional input of heat to drive the convective process through magma bodies. Such geothermal systems occur in areas of active volcanism and tectonism.

The geothermal waters, compared to the groundwaters, differ in their chemical composition because they circulate deep in the earth's crust and have chance to react with the rocks with which they are in contact at high temperatures and sometimes at elevated pressures. Due to temperature dependent reactions, these waters tend to have more amounts of dissolved constituents in them. In volcanic area, such waters have the tendency to incorporate magmatic waters, rich in certain constituents. Volcanic gases rich in Cl when dissolved in thermal waters, the Cl content of such waters becomes abnormally high. Thus, a tag is attached to such waters depending on the amount of dissolved species present in them. For example chloride waters have Cl in excess of HCO_3 and SO_4 (# 1, 2, 5, 11 and 12, Table 1); Sulphate waters have SO_4 in excess of Cl (# 3 and 14, Table 1). The pH of such waters is generally acidic while they reside in the reservoir but vary widely from acidic to alkaline during their ascent. In most geothermal provinces, the meteoric water is the main source recharging the reservoirs. The change in pH is due to mixing of thermal waters with shallow groundwater (dilution) before emergence. Thus most of the thermal waters emerge over the surface are hybrid in character. Other processes, which change the composition of the thermal waters include conductive cooling, boiling and precipitation of secondary phases. For example, Cl tends to increase in the liquid phase during boiling. Exchange of oxygen isotopes between water and rock occurs above 200°C. As mentioned before, such changes sometimes are temperature controlled. After undergoing metamorphic changes the thermal waters emerge on to the surface in the form of bicarbonate, acid-sulphate, dilute chloride and near neutral springs or as dry steam or as fumeroles. Careful examination of their surface manifestation in terms of their chemistry, geological setting and geophysical data, valuable inputs for geothermal energy development projects and for the preparation of blue prints for developing such resources can be obtained. A schematic section

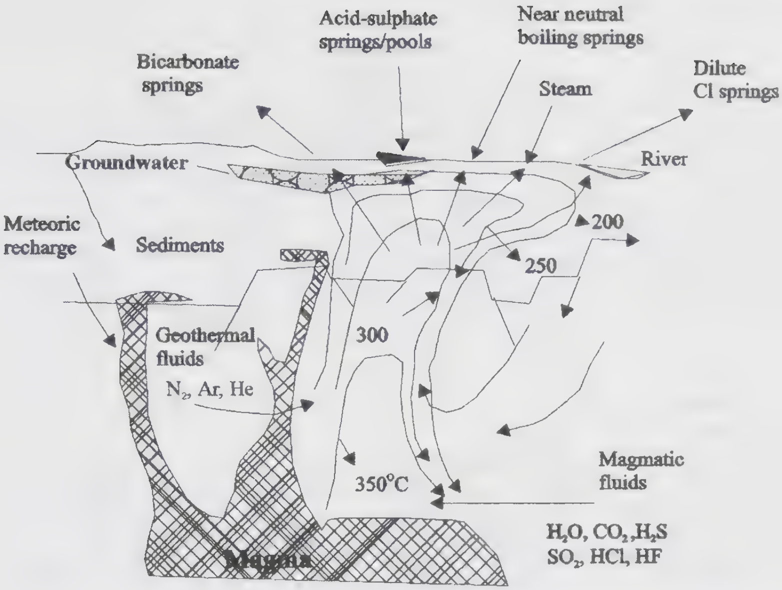

Figure 1. Schematic crosssection of a typical geothermal system (modified after Henley and Ellis, 1983).

of a geothermal system showing compositional variation in thermal waters is shown in figure 1. In order to examine the variation in the chemical components in geothermal waters, chemical analyses of thermal waters from different parts of geothermal provinces are chosen as example and the data are shown in Table 1. It is convenient to discuss the variation in their chemistry by plotting the data on suitable diagrams.

3 CLASSIFICATION OF THERMAL WATERS

3.1 *Chloride rich waters*

In many geothermal provinces over the world, the reservoirs waters are rich in this anion and the waters are generally acidic in nature. They derive their acidity from dissolved gases (e.g. HCl) from magmatic source. Such chloride rich waters represent true composition of the thermal reservoir waters and fall in the shaded area in figure 2. During their ascent to the surface they under go chemical changes due to mixing with near surface groundwaters. The near surface groundwaters have free access to atmospheric CO_2 and thus have higher HCO_3. Mixing of thermal and groundwater results in enrichment of bicarbonate ions in the hybrid waters. Waters sample (# 12) from the bottom hole of a geothermal well from Guatemala and waters sample (# 13) from a thermal spring at the same location, shown in table 1, are plotted in figure 2. Sample # 13 demonstrates the chemical changes that take place in surface thermal springs due to mixing with groundwater. In the absence of mixing surface thermal springs do represent the chemical signature of reservoir waters; like the Tuwa thermal spring waters (# 11, Table 1) which falls within the high chloride- near neutral field in figure 2.

3.2 *Sulphate rich waters*

The Cl/SO_4 ratio in this type of waters is generally very low and such waters are generally found in areas of active volcanism. The SO_4 content in such waters depends on the amount of H_2S present

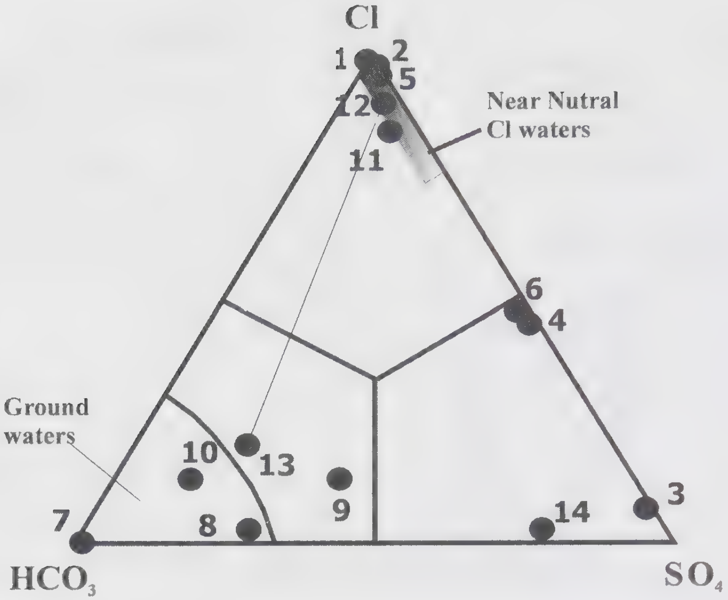

Figure 2. Cl-HCO_3-SO_4 diagram.

in the volcanic gases. Oxidation of H_2S increases SO_4 content in such waters. The sulphate rich waters need not necessarily originate due to condensation process; if the reservoir rocks are of $CaSO_4$ type, such as those reported from Mt. Amiata region (# 14, Table 1) by Minissale et al., (1997), waters originating from such rocks when emerge as springs, with out mixing with the near surface groundwaters, tend to have abnormally high content of SO_4 with SO_4 Cl ratio of about 88. Such waters also plot in the SO_4 field in figure 2.

3.3 *Bicarbonate waters*

These waters form due to mixing of high chloride waters with near surface groundwaters as mentioned above (Figure 2), and also due to condensation of carbon dioxide in near surface waters. CO_2 rich steam heated groundwater will also tend to have high HCO_3 content in them. In low temperature geothermal fields, where water gets heated due to deep long circulation in the crust, such waters are commonly encountered. Depending on the concentration of Na and Ca, such waters tend to be Na-HCO_3 or Ca-HCO_3 in composition. A good example of such type of waters is seen from Central Indian geothermal province (The Tattapani geothermal province: Chandrasekharam and Antu, 1995; Minissale et al., 2000).

The above described classification of thermal waters is an ideal classification. In reality, the composition of the waters changes continuously from the time it leaves the reservoir and ascends to the surface due to various physical processes described above and also due to mixing of waters from different reservoirs. Slow ascending fluids tend to precipitate secondary minerals such as calcite and silica due to decrease in their solubility with decrease in temperature and pressure. Change in the chemical composition due to mixing of waters from different reservoirs has been encountered at Wairakei (T. Seaward, personal discussion, 1999). This is because, with progress in production, the reservoir gets depleted, as a consequence of which the pressure decreases and water with different composition from another aquifer enters the production aquifer thus changing its composition.

4 DISSOLVED CONSTITUENTS IN THERMAL WATERS AND THEIR IMPORTANCE IN GEOTHERMAL RESOURCES DEVELOPMENT

Since the chemical signature of geothermal waters are controlled by the interaction between the rock and the circulating waters, the dissolved constituents like Na, K, Mg, Ca, SO_4, Cl and HCO_3 provide valuable information on the physical conditions prevailing and the chemical processes that occur at depth. Such information, which is not generally available through geological and geophysical methods, is of great help during the pre-drilling stages of geothermal energy resources development. These dissolved constituents in the thermal waters can be grouped into two: (a) chemically inert, non-reactive and (b) chemically reactive groups. The first group is known as the tracers and the second, the geoindicators (Giggenbach, 1991).

4.1 *Trace elements in geothermal waters*

Conservative elements like Cl, Li, B, Rb, Cs are considered as tracers and fall under chemically inert and non-reactive group. These elements are unaffected by the dilution processes at shallower levels or steam loss during ascent and retain their parentage. These elements provide information on the geochemical processes influencing the chemical signature of the thermal waters and their origin. These elements enter the liquid phase during water-rock interaction at deeper depths due to initial dissolution process and then enter the solid phases again when the thermal water and rock attain new chemical equilibrium. The new solid phases, which forms under the new, equilibrium conditions are the secondary minerals, which are commonly encountered along the fluid paths. To attain such new equilibrium conditions the water and the rock should be in contact for a very long period of time. Relative concentrations of Rb, Cs and Li of thermal waters from three deep bore wells and surface springs shown in Table 1 (# 12, 13, 15, 16, 17 and 18) are plotted in the ternary diagram shown in figure 3. Thermal waters in which these elements enter due to initial dissolution fall in the "Rock dissolution" field in figure 3. Initial dissolution takes place when the pH of the reacting waters is very low. The position of deep bore well waters such as # 12, 15 and 17 (Table 1; Figure 3) indicate

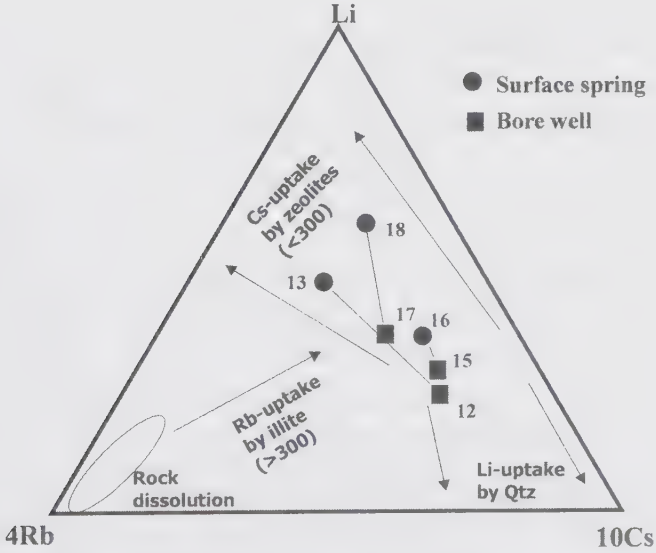

Figure 3. Li-Rb-Cs plots for thermal waters (Data from Table 1).

that these waters have already lost some amount of Rb to minerals like illite and K-feldspar which accommodate Rb in their structure at temperature >300°C. Formation of zeolites at temperature <300°C removes Cs from the thermal waters during its ascent (# 13, 18) thereby shifting the plots away from the Cs apex in figure 3. Similarly precipitation of quartz results in depletion of Li in the waters.

4.2 *Cations in thermal waters*

Na, K, Mg and Ca are known as geo-indicators and belong to the second group. Their entry into the thermal waters depends on temperature dependent reactions with rocks. Concentration of such ions in thermal waters are useful in understanding the temperature dependent chemical reactions that are in operation in the deep reservoirs and hence are quite commonly used to estimate the temperatures of the thermal reservoirs.

4.3 *Cation geothermometers*

Cation geothermometers are widely used to calculate the reservoir temperatures from surface thermal waters. This technique is based on ion exchange reactions with temperature dependent equilibrium constants. An example of such reaction is the exchange of Na and K between co-existing alkali feldspars:

$$\underset{\text{Na-feldspar}}{NaAlSi_3O_8} + K = \underset{\text{K-feldspar}}{KAlSi_3O_8} + Na \tag{1}$$

The equilibrium constant K_{eq} for the above reaction is

$$K_{eq} = [KAlSi_3O_8][Na]/[NaAlSi_3O_8][K] \tag{2}$$

The square brackets indicate activities of the species involved in the reaction. Since the activities of solid are unity, the above reaction can be reduced to:

$$K_{eq} = Na/K \tag{3}$$

Here the concentrations can be expressed in molalities or ppm units.

For reactions involving mono-valent and divalent cations, the reaction can be written as:

$$2.8\ \text{K-feldspar} + 1.6\ \text{water} + Mg^{2+} = 0.8\ \text{K-Mica} + 0.2\ \text{Chloride} + 5.4\ \text{silica} + 2K^{+} \tag{4}$$

For such reactions

$$K_{eq} = K/\sqrt{Mg} \tag{5}$$

Since K_{eq} is a function of temperature, variation of K_{eq} with temperature can be expressed in terms of van't Hoff equation:

$$\text{Log}\ K_{eq} = \Delta H°/2.303\ RT + C \tag{6}$$

Where ΔH° is the enthalpy of the reaction, T temperature in Kelvin, R the gas constant and C is a constant of integration. Between temperatures from 0 to 300°C, the value of ΔH° more or less remains constant. If this is substituted in the Na/K equation above, the relationship defines a straight line. In the above equation, the activities of pure end members are considered (unity). This is always not true because, in natural systems many cations exist in solid solution like Na and Ca in plagioclase and Na, Ca, Mg and K in smectites. Here the activity coefficients of Na bearing phases and Na-Ca silicates are not unity. Besides, there are other minerals which participate in cation exchange reactions involving Na and K like Na and K montmorillonites. For example let us look at the following reaction:

$$Na_{.33}Al_2(Al_{.33}Si_{6.7}O_{10})(OH)_2 + .33K^+ = K_{.33}Al_2(Al_{.33}Si_{3.67}O_{10})(OH)_2 + .33Na \quad (7)$$

In reactions like this, the activities of solids is also unity but the Na/K ratio which results due to exchange involving only montmorillonites at a given temperature is different from that given by Na and K-feldspars. Similarly in certain cases instead of albite sodic clay may be present; assuming the presence of Na-feldspar in such cases is erroneous. In the reaction involving K-feldspar and sodic clay, the Na/K ratio will be controlled by the following reaction:

$$3 \text{ Na-montmorillonite} + 7K^+ + 10 \text{ quartz} = 7 \text{ K-feldspar} + Na + 6H^+ \quad (8)$$

In this case the K_{eq} will be

$$K_{eq} = [Na^+][H^+]^6/[K^+]^7 \quad \text{i.e. } \log K_{eq} = \log [Na/K]/6 \log [K/H] \quad (9)$$

These equations demonstrate that it is difficult to derive a particular Na/K thermometers to estimate the reservoir temperature and because of such inherent problems inconsistencies in Na/K geothermometery arises. The Na/K geothermometer is effective where the temperatures are around 300°C since such reactions respond slowly at lower temperatures.

In the case of Na-K-Ca geothermometer, exchange reactions involving these cations occur between K-feldspar and plagioclases and are quite reliable for temperatures around 200°C. The general reaction involving K-feldspar and plagioclases can be expressed as

$$K^+ + Na_{2/3}Ca_{1/6} \text{ (solid solution)} = (1/6)\, Ca^{+2} + (2/3)Na^+ + K\ (>100°C) \quad (10)$$

$$K^+ + (1/3)Na^+ + Ca_{2/3} \text{ (solid solution)} = (2/3)Ca^{2+} + KNa_{1/3}\ (<100°C) \quad (11)$$

Both the reaction can be combined and expressed as

$$\text{Log } K_{eq} = \log(Na/K) + \beta \log\left(\sqrt{Ca}/Na\right) \quad (12)$$

β takes a value of 1/3 for reactions >100°C and 4/3 for temperatures <100°C. However, in some cases involving hot brines (<100°C), the value of $\log(\sqrt{Ca}/Na)$ becomes negative. In such cases a value of 1/3 is assigned to β. Besides plagioclases, Ca is controlled either by calcite (where calcite precipitates due to steam separation) or by the incorporation of CO_2 by ascending waters, which enhances the pCO_2. Because of such processes Na-K-Ca geothermometer may give inconsistent values (Giggenbach, 1988; Paces, 1975). But it has been found that above 200°C, pCO_2 may not have considerable effect on the Na-K-Ca thermometer, for, the variation in CO_2 at high temperature is systematic and predictable (Fournier, 1991). However, in the case of waters with temperatures between 70 and 200°C, besides CO_2, Mg also plays an important role in controlling the Na-K-Ca geothermometer (Fournier, 1991). Addition of CO_2 causes change in the ionic strength of the solution (due to higher plagioclase dissolution) thereby affecting the Na-K-Ca thermometer. For similar reasons, when Mg concentration in thermal waters is considerably high, Mg correction to the estimated Na-K-Ca thermometer is necessary. The reason is that, at low temperatures, Mg is easily mobilized into the solution from the wall-rock. Equation for calculating "Mg correction (R)" for low temperatures waters (Fournier, 1991) is given below:

$$R = Mg/Mg + 0.61Ca + 0.31K \times 100 \quad (13)$$

When R is between 1.5 and 5 the following correction is necessary

$$\Delta t_{Mg}°C = -1.03 + 59.971 \log R + 145.05(\log R)^2 - 36711(\log R)^2/T - 1.67 \times 10^7 \log R/T^2 \quad (14)$$

and when R is between 5 and 50 the following correction is necessary

$$\Delta t_{Mg}{}^{\circ}C = 10.66 - 4.7145 \log R + 325.87 (\log R)^2 - 1.032 \times 10^5 (\log R)^2/T - 1.968 \times 10^7 \times (\log R)^2/T^2 + 1.605 \times 10^7 (\log R)^3/T^2 \quad (15)$$

Where T is the Na-K-Ca temperature and concentrations are in ppm.

When R is >50, it is assumed that the thermal water is emerging from an aquifer with temperature equal to that of the surface temperature. Where R is less than 50 and the Na-K-Ca temperature is greater than 70°C, then Δt_{Mg}°C should be subtracted from the calculated Na-K-Ca temperature.

In all the above methods of temperature calculations, it is apparent that arriving at meaningful temperature depends on the right choice of the sample. Giggenbach (1991) suggested a graphical method to eliminate all the samples. which are unsuitable for temperature determination, using anion concentrations and pH. Since hydrothermal solutions are chloride rich and near neutral, samples falling in the shaded are in figure 2 are considered the best candidates for calculating reservoir temperatures. Thus, a two step procedure initial elimination of unsuitable samples and final calculation of temperatures, should be adopted to arrive at a meaningful reservoir temperature. Both these steps can be avoided by using Giggenbach's new combined Na-K and K-$\sqrt{Mg}$ geothermometers which are projected graphically by Giggenbach (1988).

4.4 *Na-K and K-$\sqrt{Mg}$ thermometer*

This method, recommended by Giggenbach (1988), is a combination of temperature dependent reactions given in equations 1 and 4 above. The products in these reactions represent full equilibrium phases, which are expected from crustal rocks, which have recrystallized under isochemical conditions. Geothermometers derived based on these two reactions are as follows (Giggenbach, 1988):

$$t^{\circ}C = 1390/1.75 - \log (K/Na) \quad (16)$$

$$t^{\circ}C = 4410/14 (\log K^2/Mg) \quad (17)$$

The rate at which these two reactions respond to varying physical environment during the ascent of the waters is different and hence the temperatures derived from the two equations will also be different. The reaction involving Mg responds faster compared to the reaction involving Na-K. Therefore temperature derived from Mg is always be lower than the Na-K value. Instead of calculating the temperatures, the chemical data of Na, K and Mg of thermal waters can be plotted on the Giggenbach's triangular diagram and the temperatures and status of thermal waters can directly be read from the diagram. Most of the drawbacks associated with ionic species are overcome by this method since it takes into account isocoulombic concentration quotients, which are based on analytical and theoretical information. For a detailed account of the theoretical aspects related to this geothermometers, the reader may refer to the paper by Giggenbach (1988). This diagram of Giggenbach (1988) is shown in figure 4. Basically in this figure, fast equilibrating thermometer (K^2/Mg) is combined with slow equilibrating thermometer (Na/K). The thermal waters presented in table 1 are plotted in figure 4. Thermal waters such as # 3, 4, 7, 9, 10, 13 and 14 (Table 1) have lost their original chemical signature during their ascent to the surface from the reservoir. The best example which confirms this is # 12 and 13. # 12 is a bore well whose measured and estimated temperature agree very well while the same water at the surface (# 13) has recorded reservoir temperature of about 100°C (Fig. 4). Similarly in the case of # 15 and # 16, because of the sensitivity of K^2/Mg thermometer, # 16 has registered lower reservoir temperature while Na/K temperature of both # 15 and # 16 correlate very well. In the case of thermal discharge at Tuwa (# 11), which has not been explored through a test bore well, indicates a reservoir temperature greater than 180°C. This will be a promising site for future development through a detailed investigation. What is apparent from the figure 4 is that temperature estimates made based on

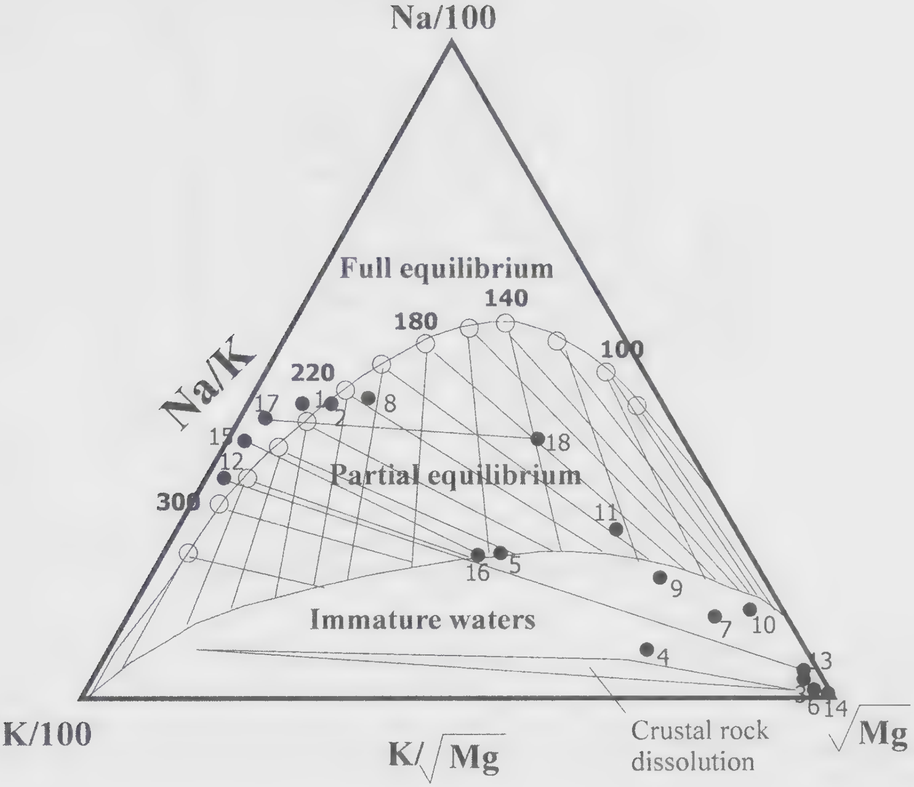

Figure 4. Na/K and K/$\sqrt{Mg}$ Geothermometers (Giggenbach, 1988).

surface discharges only indicate minimum temperature expected in the reservoir. Combining this information with heat flow and geothermal gradient, a good estimate for the reservoir temperature can be made. Thus this diagram provides excellent information on the chemical evolution of the geothermal systems and the equilibrium status of thermal discharges in the reservoir as well as the surface which is very important in any geothermal development projects.

Besides cations so far discussed, silica also plays a major role in thermal waters. Silica solubility in waters is temperature dependent, hence silica minerals (quartz, chalcedony, α and β cristobalite, opal and amorphous silica) provide valuable information on the prevailing reservoir conditions. The solubility of these silica minerals decreases with decreasing temperature below 340°C (Fournier, 1973) as shown in figure 5. But this is always not true since the pH of the fluids also controls the solubility of silica, for, when the fluids are acidic, interaction of the fluids with the wall rocks controls the concentration of silica. However, this problem will not arise if the fluids' pH falls between 5 and 7.5. Steam separation by ascending fluids (assuming no mixing with near surface groundwater) due to conductive or adiabatic cooling, has an effect on the solubility of quartz (Fournier and Rowe, 1966). This is especially true when the temperatures are >120°C. Steam separation increases the concentration of silica in residual fluids, hence calculated temperatures are lower than the actual reservoir temperatures. This problem can be overcome by using silica-enthalpy diagram of Fournier (1991). All these factors should be accounted for before calculating reservoir temperatures using silica thermometer. Based on the solubility of silica minerals shown in figure 4, several silica thermometers for calculating the reservoir temperatures have been proposed by various workers (Fournier and Rowe, 1966, 1977; Fournier and Potter, 1982; Fournier, 1983; Morey et al., 1962). The choice of any individual thermometer in calculating

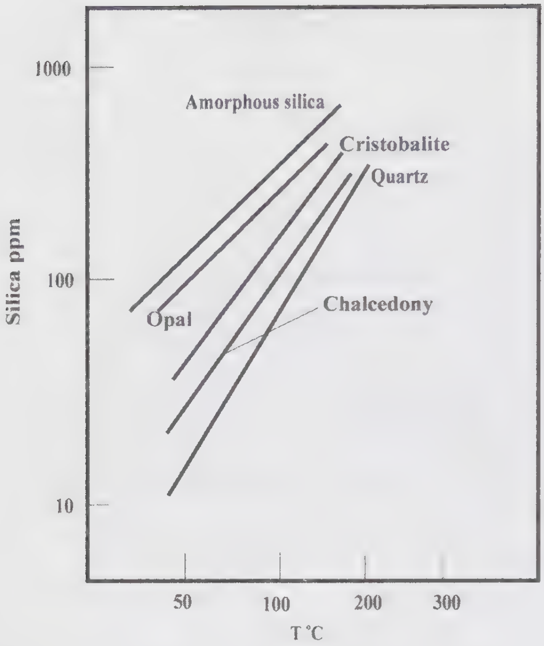

Figure 5. Solubility of Silica.

reservoir temperature depends on knowing which mineral is controlling the concentration of silica in the fluids.

5 CHEMICAL CONSTITUENTS IN THE VAPOUR PHASE

The vapour phase associated with thermal waters contain gases such as H_2, H_2S, CH_4, CO_2, He, N_2, Ar and SO_2. In general, geothermal systems associated with volcanic areas contain H_2, H_2S, CO_2, SO_2 while Ar, N_2 and He predominate in non-volcanic areas. In the case of He, ^4He originates from the crust while ^3He is mantle origin. This division sometimes can not be strictly applied to many geothermal systems, since both volcanic, crustal and atmospheric derived gases mix during the circulation of the thermal fluids. Sometimes, some of the geothermal systems issue "dry gas" which is devoid of thermal fluids. A classic example is the gas vents (CO_2) commonly seen in Larderllo geothermal field (refer to A. Minissale's papers in this volume). So basically the source regions for the gases in thermal waters are meteoric, crust and mantle. The most easily accessible gases from the thermal discharges include Ar, N_2, He and CO_2 and the importance of only these gases is discussed here.

5.1 *Ar, N_2 and He content is gases*

Though the assumption that Ar and He are inert and does not take part in any reactions, this is not so in reality since such reactions are controlled by the prevailing redox conditions and temperature of the reservoir (D'More, 1991). However, it is considered that these two gas species to be chemically inert while N_2 takes part in chemical reaction to form NH_3. Importance of these three gases in understanding the evolution of geothermal systems can be evaluated by plotting the concentrations of these gases in N_2-He-Ar ternary diagram of Giggenbach (1991). In this diagram

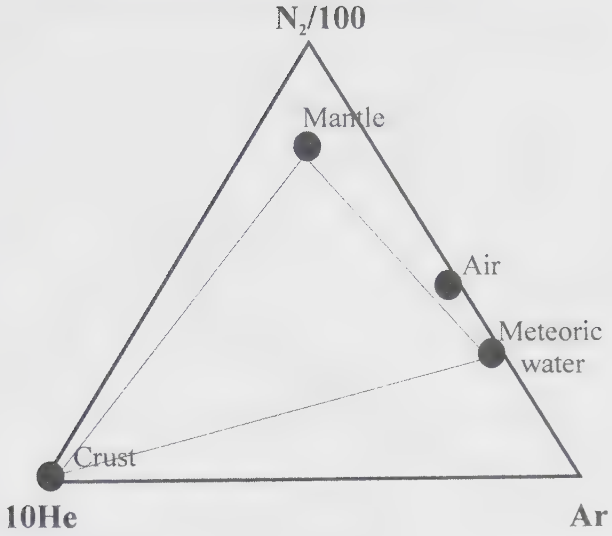

Figure 6. N_2-He-Ar diagram.

(Fig. 6) the three source end members mentioned above are represented which helps in classifying the gases based on their sources. Such classification is very helpful in selecting the gas samples for calculating reservoir temperatures using gas geothermometers. Gases, which have magmatic source, will fall near the N_2 apex with N_2/Ar ratio of about 800 (Giggenbach, 1991). If the member contributing N_2 to the geothermal system is basaltic magma, then this ratio will be <800 while in the case of andesitic magma this ratio will exceed 800. Gases with crustal component are usually rich in He (^{4}He to be very precise) since continental crust is enriched in radioactive elements like U and Th, which produce ^{4}He due to radioactive decay. Such gases will cluster around He corner in figure 6. Since air is rich in Ar, groundwater recharging the thermal reservoirs will be saturated with air and hence contain excess of Ar relative to the other two components. Thermal gases, which contain predominantly air or contaminated with air will cluster around meteoric end member in figure 6. Gases containing mixed components from any two end members will define an array along the respective mixing line. Caution should be exercised while interpreting the gases falling near "mantle" in figure 6. The reason being that N_2 can either be derived from the mantle or can be produced within the crust by organic material. Gas samples clustering around the crustal end member indicate prolonged circulation within the crust before emerging to the surface. If the crust is enriched in radio active elements, such prolonged circulation of thermal waters within the crust enriches them with He (^{4}He). An excellent example can be found in intracratonic thermal fluids from India where the He concentration in the gases associated with thermal discharges vary from 2.13 to 6.89 vol% (Minissale et al., 2000).

Among the gases present in the gaseous phase, H_2 is very sensitive to changes in temperature and redox conditions (Giggenbach, 1980). H_2 can react to for CH_4 and NH_3 depending on the prevailing physico-chemical conditions. Further, this gas enters only the gas phase unlike CO_2 and H_2S, which are more soluble in liquid phase also. Because of such differing solubility characteristics, CO_2 and H_2S based gas geothermometers (Arnorsson and Gunnlaugsson, 1985) met with limited success (Giggenbach, 1991). For this reason Giggenbach (1991) proposed a gas thermometer based on H_2 and Ar content in gases. While H_2 is magmatic in origin, Ar, which is chemically inert is contributed to the geothermal system by the meteoric waters. Further the Ar content in magmatic gases is very similar to groundwater saturated with air (Giggenbach 1987). Both these gases have limited solubility in thermal fluids. Thus these two gases with contrasting

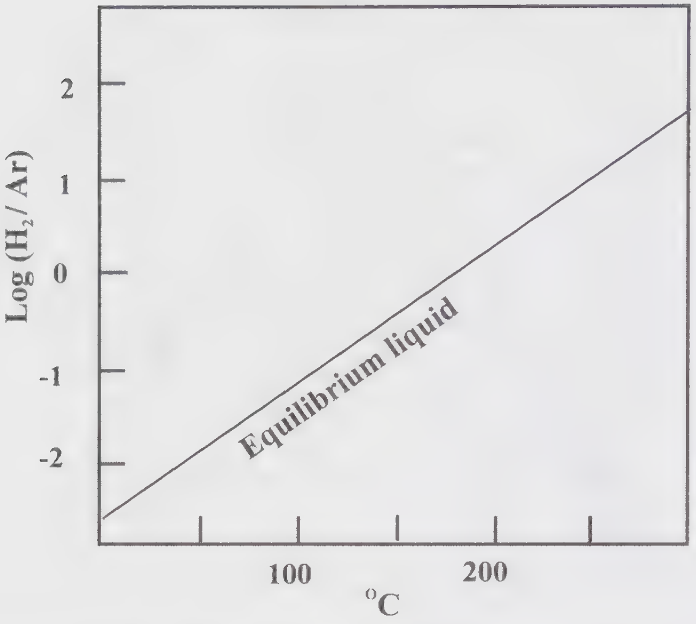

Figure 7. H_2-Ar vs Temperature diagram (modified after Giggenbach, 1991).

behaviour are best suited to calculate the reservoir temperatures of geothermal systems. Giggenbach (1991) has proposed the following equation for calculating the reservoir temperatures:

$$t_{HA} = 70\,(2.5 + L_{HA}) \tag{18}$$

where $L_{HA} = \log(H_2/Ar \text{ mole ratio})$

The temperatures of the reservoir can directly be read using the L_{HA}-t°C diagram proposed by Giggenbach (1991) shown in figure 7.

6 OXYGEN AND HYDROGEN ISOTOPIC RATIO IN GEOTHERMAL WATERS

Craig (1963) has demonstrated that most of the geothermal waters are of meteoric origin and fall on the meteoric water line in the $\delta D‰$ vs $\delta^{18}O‰$ diagram. The ratios of these two isotopes are represented with respect to SMOW (standard mean ocean water) using the follow relationship (Faure, 1986):

$$\delta^{18}O‰ = ({}^{18}O/{}^{16}O_{Sample} - {}^{18}O/{}^{16}O_{Standard}/{}^{18}O/{}^{16}O_{Standard}) \times 1000 \tag{19}$$

$$\delta D‰ = (D/H_{Sample} - D/H_{Standard}/(D/H)_{Standard}) \times 1000 \tag{20}$$

Geothermal liquids, which has only meteoric component, will plot on the "Meteoric water line" of Craig (1963) in figure 8. When magmatic waters rich in $\delta D‰$ and $\delta^{18}O‰$ mixes with geothermal waters, the mixed waters samples plot on the line joining meteoric (X in fig. 8) and magmatic waters. Exchange between the thermal fluids and the rocks with which the fluids are in contact will take place only above 220°C and since D is negligible in common igneous rocks, geothermal fluids interacting with rocks, such as those from wairakei (New Zealand), Larderello (Italy) and Steamboat (USA), show "oxygen shift" parallel to the $\delta^{18}O‰$ axis in figure 8. With increase in reaction temperature this "shift" tend to move towards positive values of $\delta^{18}O‰$ .Thus, depending on the position of the plots of the geothermal fluid temperature environment of

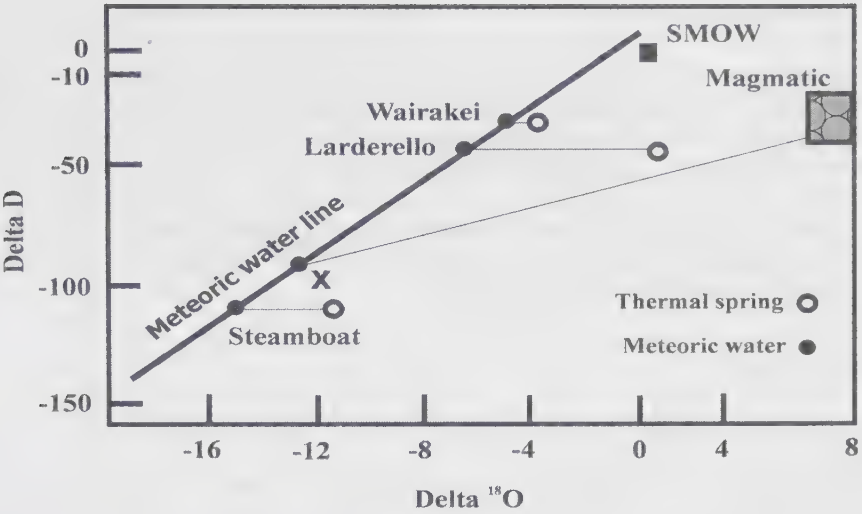

Figure 8. Delta D vs Delta ^{18}O diagram (modified after Nuti, 1991).

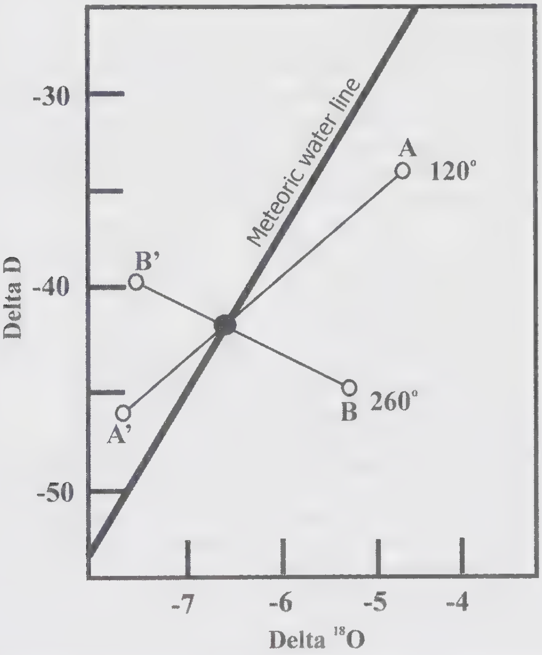

Figure 9. Variation of Hydrogen and Oxygen isotopic composition in boiling water and separated steam (modified after Nuti, 1991).

the fluids can easily be predicted. Since both hydrogen and oxygen can enter the liquid as well as steam phase, their ratios also display variation in the liquid fraction as well as in the steam fraction. It is possible to predict the temperature of the fluids after steam separation at different temperatures using the figure 9 (Nuti, 1991). For example when steam separation takes place at 120°C, the fluid plots at A in figure 9 while the steam plots at A' in this figure.

7 CONCLUSIONS

Chemical characteristics of thermal waters and thermal gases play an important role in decision making during pre-drilling stage of geothermal energy development programme. Basic knowledge in hydrogeochemistry forms an essential tool in any geothermal energy development programme. The above discussed methods provide such simple but significant tools using common ions, elements and isotopes present in thermal waters and thermal gases. These tools help independent power producers, govt. bodies, administrators and funding agencies to take a decision before investing in geothermal energy projects. The degree of confidence depends on the selection of right sample in estimating the reservoir temperatures.

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Environmental aspects of geothermal energy resources utilization

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ABSTRACT: Geothermal energy is often advocated as one of a number of "green", "renewable" alternatives to fossil fuels for the supply of clean energy for the future. Geothermal energy is not without its environmental impacts, however, particularly on air, water, land use and the aesthetic qualities of the landscape in regions with geothermal energy potential. A range of socioeconomic impacts are also important. Geothermal energy is not always renewable, except over very long timescales, and geothermal energy exploitation often takes the form of heat mining with long term implications for site rehabilitation. These environmental factors can be addressed at different stages in the development of geothermal energy resources through environmental impact assessment (EIA) in advance of any development and through the implementation of an environmental management system (EMS) during the operation of a geothermal energy scheme. Approaches to optimizing environmental impacts are also considered.

1 INTRODUCTION

1.1 *Geothermal energy – general features*

Geothermal energy is energy derived from heat from the Earth's interior. This heat can be held in hot water or steam or in the rocks themselves and represents a potentially vast energy resource, estimated by Armstead & Tester (1987) to be more than 300 times the energy held in fossil fuels. Although sometimes included in lists of "renewable" energies, most sources of geothermal energy are non-renewable, at least over human time scales, and the utilization of geothermal energy is sometimes referred to at "heat mining", a useful term that serves as a reminder of the non-renewable nature of these resources. In view of the greatly reduced emissions of CO_2 that are associated with geothermal energy when compared with the use of fossil fuels, geothermal energy is often described as a "clean energy" (Department of Energy, 1994) but there are still environmental impacts to consider in relation to its utilization. Geothermal energy associated with hot water or pressurized steam held in aquifers or with hot dry rocks requires different approaches to its exploitation.

1.2 *Geothermal aquifer systems*

In the case of geothermal aquifer systems, heat can be held as pressurized steam or in hot water in deep aquifers and can be exploited directly by drilling into the aquifer. In "high enthalpy" geothermal systems, such as those of Iceland, New Zealand and California, pressurized steam or superheated water can be used to drive a turbine, either passing the steam directly into the turbine in "direct cycle" systems, or using a heat exchanger in a "binary cycle". In "flash cycle" systems, energy is extracted from hot water by passing it through a low pressure vessel to produce steam to drive the low pressure stages of a turbine. Waste steam from these systems can either be vented directly to the atmosphere (non-condensing systems) or can be condensed prior to reinjection into wells (condensing systems), both of which have potential environmental impacts.

In "low enthalpy" geothermal systems, hot water aquifers at temperatures below boiling point can be used directly by pumping to district heating schemes, for horticultural and agricultural use (Rinehart, 1994) or for industrial purposes or to preheat water for electricity generation. Geothermal district heating schemes have been successfully developed in Southampton, UK (ETSU, 1994), for example, and at Melun, France (Armstead, 1878).

1.3 *Hot dry rock systems*

In hot dry rock (HDR) geothermal systems, heat is extracted from dry rocks rather than aquifers. In this case, water must be introduced into the dry system in order to transfer heat to the surface where it can be used to generate electricity or for space heating or other purposes. The extraction of heat from an HDR geothermal energy resource is essentially non-renewable as the rock is cooled in the process, but HDR resources are extremely large (Armstead & Tester, 1987). Research into HDR systems is currently taking place in Europe, the USA and Japan but none are as yet in production.

1.4 *Geothermal energy in developing countries*

Geothermal energy generally makes a small contribution to the energy needs of the major developed countries but makes a significant contribution in a number of developing countries, including the Philippines, Mexico, Indonesia, El Salvador and Kenya (Reed & Renner, 2002).

The geothermal electric power industry in the USA is the largest in the world, with an electrical generating capacity of over 2100 MW (megawatts of electricity), a little over half of which (1100 MW) is in The Geysers geothermal field in California. Generating capacity in the Philippines is currently around 890 MW and in Mexico is 700 MW; other developed countries with major geothermal capacity include Italy with 545 MW, and New Zealand with 460 MW (Reed & Renner, 2002). Interestingly, in Iceland, which has an overabundance of both hydroelectric and geothermal energy potential, most geothermal energy is used for space heating and hot water rather than electrical generation (Reed & Renner, 2002).

2 ENVIRONMENTAL IMPACT ASSESSMENT FOR GEOTHERMAL ENERGY UTILIZATION

2.1 *Scope of environmental impact assessments*

An Environmental Impact Assessment (EIA) is a formal procedure carried out as part of the planning process prior to any development. Its purpose is to assess the future impact of a proposed development on both the natural and human environments. For large projects with potentially significant environmental impacts, such as a major geothermal energy scheme, the

EIA might be compulsory. For smaller projects, such a geothermal heat pump installations, the EIA might be optional but might be produced in support of a planning application to demonstrate that the environmental impacts have been considered.

The EIA will take into account any plans within the proposed development to address environmental impacts. Thus, the possible creation of water pollution problems, for example, might not be considered problematic if water treatment and monitoring procedures are also part of the plan. Similarly, plans for the restoration and aftercare of abandoned sites would be taken into account in the overall EIA.

The scope of an EIA is necessarily very broad and will vary from project to project. It will include impacts on both the natural environment (in terms of physical, chemical or biological impacts) and the human environment (in terms of economic development, employment, health implications, cultural aspects etc.).

An EIA will address the impacts of both the construction and operational phases of the proposed development. Indeed, the impacts associated with these different phases of the project might be significantly different. An EIA should include, short-, medium- and long-term impacts, local and global impacts, direct, indirect, secondary, cumulative, permanent and temporary, positive and negative effects of the project. Clearly, for a major geothermal energy development, the impacts are likely to be many, with local and global implications for the physical/chemical/biological and human environments.

2.2 *Framework for environmental impact assessment (EIA)*

A framework for EIA is provided by the European Community's Council Directive on the assessment of the effects of certain public and private projects on the environment (85/337/EEC) which states that an EIA *shall identify, describe and assess in an appropriate manner, in the light of each individual case ... the direct and indirect effects of a project on the following factors:*

— *human beings, fauna and flora;*
— *soil, water, air, climate and the landscape;*
— *material assets and the cultural heritage;*
— *the interaction between* [these] *factors* (European Community, 1985).

Geothermal energy schemes are covered by Annex II of the Directive (proposed developments which *may* require EIA following a case-by-case examination or thresholds or criteria set by Member States). Here, there is specific reference to "Deep drillings, in particular: geothermal drilling", "Industrial installations for the production of electricity, steam and hot water" and "Industrial installations for carrying gas, steam and hot water; transmission of electrical energy by overhead cables". "Construction of overhead electrical powerlines with a voltage of 220 kV or more and a length of more than 5 km" is included in Annex I (where EIAs are always required). Annex IV of the Directive provides a detailed list of the information requirements of an EIA, which, for a geothermal energy development, should include the information outlined in Table 1.

3 ENVIRONMENTAL IMPACTS OF GEOTHERMAL ENERGY UTILIZATION

3.1 *Global environmental factors*

With increasing concern about climate change associated with increasing atmospheric CO_2 concentrations that are due, at least in part, to the burning of fossil fuels, geothermal energy,

Table 1. Scope of an EIA: information required under EC Directive 85/337/EEC (based on European Community, 1985).

1. A description of the project itself, including in particular:
   - a description of its physical characteristics and land-use requirements during the construction and operational phases;
   - a description of the main characteristics of the production processes including the nature and quantity of the materials used;
   - an estimate, by type and quantity, of expected residues and emissions (including water, air and soil pollution, noise and vibration, light, heat, radiation, etc.) resulting from the operation of the proposed plant.
2. An outline of the main alternatives studied by the developer and an indication of the main reasons for choosing the proposed scheme, taking into account the environmental effects; here, reference would normally be made to the non-fossil and, if applicable, renewable nature of the energy resources being developed.
3. A description of the aspects of the environment itself that are likely to be significantly affected by the proposed scheme, including the human population, fauna and flora, soil, water, air, micro- and macro-climatic factors, material assets, including the architectural, archaeological and cultural heritage, landscape and the interrelationship between these factors; here, questions relating to the development in an area of outstanding natural beauty or of special scientific interest (common features of geothermal fields) would be addressed. This description should include the direct effects of the proposed scheme and any indirect, secondary, cumulative, short-, medium- and long-term, permanent and temporary, positive and negative effects of the project.
4. A description of the likely significant effects of the proposed project on the environment resulting from:
   - the existence of the project;
   - the use of natural resources;
   - the emission of pollutants, the creation of nuisances and the elimination of waste;

   and a description by the developer of the forecasting methods used to assess the effects on the environment.
5. A description of the measures envisaged to prevent, reduce and where possible offset any significant adverse effects on the environment; here, the planned environmental protection and management methods would be described with special reference to the special problems likely to be encountered at a geothermal energy plant.
6. A non-technical summary of the information provided under the above headings (allowing non-technical decision-makers to reach their conclusion as to whether or not the scheme should go ahead).
7. An indication of any difficulties (such as technical deficiencies or lack of know-how) encountered by the developer in compiling the required information.

along with other "renewable" energy resources, is considered to offer global benefits through the provision of clean energy with low associated CO_2 emissions (International Energy Agency, 1998).

These global benefits are shown in Tables 2 and 3, in which life cycle emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_X) associated with a range of renewable energies and with conventional fossil-fuelled electricity generation, are compared with emissions from geothermal electricity generation. These emissions values are based on life cycle analysis of the different energy sources and include emissions associated not only with energy generation itself but with the construction of plant and manufacture and transport of machinery and components, which can be greater for renewables than the energy expended in producing the plant and machinery for conventional electricity generation because renewables generally harness energy sources that are more "dispersed" or "dilute" (in contrast to the "concentrated" energy represented by, say, coal or oil).

It is clear from these comparisons that geothermal energy offers significant reductions in emissions of CO_2, the main greenhouse gas, and of SO_2 and NO_X, both of which are toxic gases and major contributors to acid rain. These reductions represent the main argument offered in support of the further development of such energy sources. Locally, however, the balance of environmental costs and benefits is sometimes less clear.

Table 2. Life cycle emissions (g/kWh) of key pollutant gases for electricity generated from renewable energy sources (adapted from International Energy Agency, 1998).

	Energy crops (current practice)	Energy crops (future practice)	Hydro (small)	Hydro (large)	Solar (photo-voltaic)	Solar (thermal)	Wind	Geo-thermal
CO_2	17–27	15–18	9	3.6–11.6	98–167	26–38	7–9	79
SO_2	0.07–0.16	0.06–0.08	0.03	0.009–0.024	0.20–0.34	0.13–0.27	0.02–0.09	0.02
NO_X	1.1–2.5	0.35–0.51	0.07	0.003–0.006	0.18–0.30	0.06–0.13	0.02–0.06	0.28

Table 3. Life cycle emissions (g/kWh) of key pollutant gases for electricity generated from fossil fuels and geothermal energy (adapted from International Energy Agency, 1998).

	Coal (best practice)	Coal (FGD and low NO_X)	Oil (best practice)	Gas (CCGT)	Diesel (embedded)	Geothermal
CO_2	955	987	818	430	772	79
SO_2	11.8	1.5	14.2	–	1.6	0.02
NO_X	4.3	2.9	4	0.5	12.3	0.28

CCGT: combined cycle gas turbines; FGD: flue gas desulphurization.

3.2 *Local environmental factors*

Despite the emissions reductions that can be achieved by utilizing geothermal as opposed to conventional (fossil) energy sources, the local environmental impacts can sometimes be significant, especially with regard to air and water pollution, land use, and impacts on the aesthetic qualities of the landscape. The socioeconomic impacts on the local environment must also be considered.

3.2.1 *Air pollution*

Although emissions of CO_2, SO_2 and NO_X are lower for geothermal energy than for conventional fossil fuels, there are still important gaseous emissions associated with geothermal energy utilization. Of particular importance is the emission of hydrogen sulphide, which can represent an odour nuisance at low concentrations but which is toxic at concentrations above 0.001% v/v (Smith, 1991). There are, however, absorption and stripping techniques available for the removal of H_2S gas and there are no emissions at all if binary plant is used.

Other gaseous pollutants include traces of ammonia, hydrogen, nitrogen, methane, radon and the volatile species of boron, arsenic and mercury, though generally in very low concentrations (International Energy Agency, 1998). Silica is also sometimes problematic, as at Wairakei in New Zealand, where forest damage has been attributed to silica deposition (Armstead, 1978).

In addition to gaseous emissions, dust can be associated with the construction of the plant, with drilling and with the clearance of the land for site development. More visible are the plumes of steam which contribute to the overall visual impact of the site during its operation.

3.2.2 *Water pollution*

Both surface waters and groundwaters can be affected by geothermal energy schemes. The most important potential impacts on the water environment are associated with the management and disposal of wastewaters, notably geothermal brines, which are commonly disposed of by reinjection into wells (where they can contaminate groundwaters) or by storage in holding ponds (from which they can leak into surface waters).

Table 4. Metal concentrations of geothermal brines from Imperial Valley, California, compared with maximum admissible concentrations for drinking water.

Metal	Concentration range (ppm[1]) (Mattigod and Page, 1983)	Maximum admissible concentration in drinking water (ppm[2]) (From EC Directive 80/778/EEC (European Community, 1980[3]))
Na	610–58,440	150 (from 1987)
K	70–23,800	12
Ca	9–40,000	100 (guide level)
Mg	<0.05–740	50
Ba	0.15–1100	100 (guide level)
Sr	2.10–448	–
Co	<0.0005–<0.01	0.01[4]
Cd	<0.0005–2	0.005
Cu	<0.1–8	3
Fe	<0.01–2290	0.2
Mn	<0.05–1400	0.05
Ni	<0.01–4	0.05
Pb	<0.5–102	0.05
Zn	<0.01–600	5 (guide level)
B	4–498	1 (guide level)
As	0.025–12	0.05

[1] Presented as $\mu g\ g^{-1}$ by Mattigod & Page (1983).

[2] Presented as $\mu g\ l^{-1}$ in EC Directive 80/778/EEC.

[3] EC Directive 80/778/EEC is being superseded by Directive 98/83/EC (European Community, 1998); the values provided by the new Directive are less comprehensive, however, and these are provided for reference only.

[4] Target value for groundwater set by Netherlands Directorate General for Environmental Protection (1991) for contaminated land remediation.

At the time of writing (May, 2002), EC Directives and other legislation relevant to the environment are available online through the "EUR-Lex: Directory of Community legislation in force" at http://europa.eu.int/eur-lex/en/lif/ind/en_analytical_index_15.html.

Chloride brines of Na and Ca are particularly important as they can have very high concentrations of metals (Mattigod & Page, 1983). Of particular interest here are Fe, Mn, Pb, Zn, Ba and B. Other contaminants can include I, Sb, Li, H_2S, Hg, Rb, bicarbonate, fluoride, silicate and ammonia (Nicholson, 1992). Contamination of shallow groundwater reservoirs can also be caused by drilling fluids and as a result of well casing failure, which might also affect groundwater levels (Hunt & Brown, 1996).

The metals content of geothermal brines from Imperial Valley, California, are shown in Table 4 where they are compared for reference with maximum admissible concentrations recommended for drinking water under the European Community drinking water directive of 1980. The higher metal concentrations observed in the Imperial Valley brines clearly exceed maximum admissible concentrations for drinking water and, therefore, represent a potentially significant environmental hazard.

Geothermal brines can not only contaminate surface and groundwaters but can also affect soils, with implications for agriculture; phytotoxic boron is particularly important in this respect (Mattigod & Page, 1983).

The pollution impacts on the water environment can be mitigated through effluent treatment, the careful storage of waste water and its reinjection into deep (as opposed to shallow) wells and through careful monitoring of the condition of holding ponds and well casing (Hunt & Brown, 1986).

In addition to water quality impacts, the abstraction of geothermal waters can impact on groundwater levels. The most important consequence of this is ground instability and subsidence (considered below), but lowering the water table can also affect local water supplies (International Energy Agency, 1998).

3.2.3 *Solid wastes*

Apart from the general wastes associated with any commercial operation (office and workshop wastes, canteen wastes, general garbage etc.), there are few solid wastes produced during geothermal energy utilization. The main solid waste specific to geothermal energy results from the chemical deposition that takes place within the pipes and vessels of the plant, notably of calcite and silica (Armstead, 1978). These deposits also occur naturally in geothermal areas where they are deposited as travertine and siliceous sinter around hot springs and other geothermal manifestations. The problems caused by these deposits are usually operational as they can cause blocking of pipes and boreholes and can reduce the permeability of the aquifers being developed. Where they have to be removed in order to maintain the operation of plant (as at Wairakei where silica deposition occurs in open channels), the resulting waste is small in volume and is not considered to be a major environmental concern (Armstead & Tester, 1987).

3.2.4 *Land use*

As with any major energy development, a geothermal power plant will require land and that land will either already be in use for another purpose or might be valued as natural environment or might have other proposed uses. There is then an opportunity cost associated with the geothermal development (that is, the land cannot be used for any other purpose during the lifetime of the plant). Land take can be reduced by the use of directional drilling techniques, as advocated by the Sierra Club, a leading environmental organization in the USA, in its conservation policy on geothermal energy, as one of the measures for minimizing surface disturbance in resource production areas (Sierra Club, 1980).

3.2.5 *Aesthetic impacts*

Many geothermal energy resources are located in regions that are considered to be of great natural beauty (as at Rotorua, New Zealand, or the geysers of Iceland) or in National Parks (such as Yellowstone, USA) or in areas considered to be aesthetically valuable. Indeed, may geothermal phenomena (such at geysers and hot springs) are themselves valued as important environmental assets with both intrinsic value as natural phenomena and economic value for tourism. Among possible impacts of the exploitation of geothermal resources is a fall in reservoir pressure which can result in a reduction in the vigour of geysers and other geothermal phenomena and affect their economic value as tourist attractions. This potential loss of aesthetic value has been recognized by the Sierra Club, which noted the need to protect "hot springs, geysers, thermal pools, and other thermal features and their ecological, educational, aesthetic, and recreational values" (Sierra Club, 1980).

As well as the major impacts that a large geothermal station might have on the aesthetic quality of the landscape, local visual impacts from buildings, plant, pipework and plumes of steam might also be considered important, especially by local residents, but this can be reduced by careful screening of the site.

3.2.6 *Other physical impacts*

Among other physical impacts that might be encountered during the utilization of geothermal energy resources are noise, ground instability and heat pollution.

Noise can be associated with the exploration, construction and production phases and can be significant in terms of occupational exposure, requiring workers to be suitably protected. Noise as an environmental impact (along with many of the visual impacts) can be reduced by the screening of the site with earth bunds and/or trees (Hunt & Brown, 1996) and through the adoption of good working practices, such as restricting working hours.

Ground subsidence occurs when geothermal fluids are withdrawn from a reservoir at a rate greater than natural inflow back into the reservoir. This causes compaction of the rock formations at the site which, in turn, leads to surface subsidence, as observed at Wairakei in New Zealand. Ground subsidence can be reduced by reinjecting waste waters into wells to maintain well pressure, though associated risks of groundwater contamination need to be considered when designing the reinjection process. Subsidence might also result from thermal contraction of rocks associated with hot dry rock geothermal utilization (Taylor, 1983).

Because many geothermal resources are located in seismically active zones of the Earth's crust, there are sometimes problems of instability, both in the natural landscape and in association with geothermal energy utilization (DiPippo, 1991). The reinjection of fluids into the ground, for example, can enhance the seismic activity of the area affecting buildings and other structures and allowing seepage of fluids within the system, though this can be minimized by keeping reinjection pressures to a minimum. Landslide hazard might also be a feature of geothermal regions where steep slopes are susceptible to failure, perhaps leading to damage to well heads or pipes resulting in the release of steam and hot fluids. The likelihood of this can be minimized by stabilizing all slopes which may be prone to landslides (DiPippo, 1991).

Heat pollution of air and, particularly, water can represent a significant environmental impact as well as being energy inefficient. The discharge of hot water to rivers can damage aquatic wildlife (as in the Waikato River in Wairakei) and lead to unwanted growth of vegetation (Armstead, 1978). The effects of heat pollution are local, however, and the total amount of heat released in this way is negligible compared with solar radiation and does not in itself represent a significant global environmental problem (Armstead, 1978).

3.2.7 *Rehabilitation of disused sites*

Where geothermal energy resources become exhausted, the rehabilitation of sites becomes necessary and the same approach may be adopted to the management of disused geothermal sites as is employed in the assessment and remediation of land affected by other industrial activities. These aspects are covered by Cairney (1993), Pratt (1993) and others and are beyond the scope of this paper.

3.2.8 *Socioeconomic impacts*

In its overview of the socioeconomic impacts of geothermal energy, the International Energy Agency (1998), as an OECD organization, focused on the employment benefits to OECD members, noting that the investment of US$2.4 trillion (1 trillion = 10^{12}) foreseen by the World Energy Council (1993) on renewable energy resource development as a whole represented a huge business opportunity with significant benefits in terms of employment. It was also noted that, as renewable energy developments are commonly in rural areas, these jobs are often made available in areas with few other employment opportunities (World Energy Council, 1998). This is a particularly important factor in parts of the world where agriculture is in decline (as in the UK, for example) and where alternative uses are being sought for agricultural land.

The tourist potential of geothermal regions and the need to protect geothermal phenomena like geysers has already been noted as a major economic consideration. At Svartsengi geothermal power station in Iceland, geothermal energy utilization has itself been used to the advantage of the tourist industry where geothermal waste waters have been used for the development of the Blue Lagoon, a spa facility developed adjacent to the plant itself (Blue lagoon Ltd., 2000).

The International Energy Agency (1998) also sees the restructuring of energy markets as an important economic impact of renewable energy sources which tend to take the form of many small, dispersed units rather than the large centralized power plants that have characterized the energy markets in recent decades. This is seen as contributing to increased competition and greater flexibility. The ability of local schemes to meet local demands (for heat, for example, in the case of geothermal energy) is also noted (International Energy Agency, 1998).

4 MANAGEMENT OF OPERATIONAL ENVIRONMENTAL IMPACTS

4.1 *Environmental management systems*

4.1.1 *ISO 14001*

During the lifetime of a geothermal energy plant, day to day environmental impacts can be managed through the implementation of an environmental management system (EMS). The international standard for environmental management systems is the International Standards Organization's ISO 14000 series, of which ISO 14001 is the specification with guidance for use (ISO, 1996). ISO 14001 provides a structure for carrying out the following key environmental management activities:

- establishment of an environmental policy;
- evaluation of the environmental effects of the business;
- identification of legislative and regulatory requirements;
- establishment of environmental objectives and targets;
- establishment and maintenance of an environmental management programme to ensure that the objectives and targets are achieved;
- employment of environmental management procedures and documentation;
- monitoring and measurement of operational environmental impacts in the field;
- implementation of operational control measures and preventive and corrective action;
- keeping of environmental management records;
- implementation of environmental management system audits; and
- arrangement of periodic environmental management reviews which provide the mechanism for modification of the EMS in response to changing conditions or the results of environmental audits.

In a formal EMS, control of the environmental impacts of any project is brought within the overall management structure of the organization. For this to be effective, appropriate management structures must be put in place. Equaly important is an understanding of the environment itself and of the way the project impacts upon it. The ISO 14000 approach to EMS has been criticized (e.g. by Krut & Gleckman, 1998) as serving the interests of the company rather than those of the environment but, through the identification of (at least) the legal requirements for environmental protection, which allows the minimum environmental objectives and targets to be set, and regular monitoring of the environmental impacts in the field, an EMS ensures that the operational impacts are kept to within prescribed limits. In this way, an EMS under ISO 14000 will at least enable compliance with legislation.

It is of interest to note that ISO 14001, the standard for environmental management, is closely linked to the quality standard, ISO 9001 (ISO, 2000). If, therefore, an organization is already using the ISO 9000 structure (which is commonly the case in many countries), it is already well prepared to adopt an ISO 14000 environmental management system.

4.1.2 *Eco-Management and audit scheme (EMAS)*

An alternative to the ISO standard is the European Community's Eco-Management and Audit Scheme (EMAS) (European Community, 2001). The main provisions of EMAS are similar to those of ISO 14001 but there is greater emphasis on the publication of the results of environmental reviews and audits.

The purpose of EMAS, for which registration is obtained on a site-specific basis after independent (external) verification, is to help industrial (and local authority) sites to:

- minimize pollution, creating a cleaner and healthier environment;
- operate more efficiently, by minimizing energy and water usage, saving natural resources and reducing waste;
- minimize their production and processing costs, therefore improving profitability and enhancing competitiveness;
- openly report their environmental improvements in an environmental statement, ensuring that the general public are informed of their environmental achievements;
- develop new markets for their products and services from the competitive advantage that positive environmental management can achieve.

To achieve this, EMAS consists of seven core steps:

- formalizing an environmental policy;
- carrying out an environmental review;
- establishing an environmental programme to put the policy into practice;
- managing the programme, including organizing and documenting it, ensuring that responsible staff are trained, and integrating it into the company's existing management structure;
- audits of performance at regular intervals;
- issuing annual public environmental statements linked to the audit process.

There are clearly similarities between the EMAS and ISO 14001 approaches to environmental management and auditing, but they are considered to be different in several respects. EMAS was developed by governments acting through the European Community and thus represents many different interests, while the ISO is considered to be primarily an international industry organization. EMAS requires external verification while ISO 14001 has no external verification requirement and can be certified internally. EMAS requires disclosure of environmental information whereas ISO 14001 leaves this to the discretion of the organization itself. For these reasons, many (like Krut & Gleckman, 1998) favour EMAS as the more rigorous system.

4.2 *Optimization of the environmental impacts of geothermal energy utilization*

The environmental impacts of a geothermal energy scheme can be optimized through the adoption of environmental procedures at different stages in the development of a project.

Environmental questions are addressed in advance of the development of a geothermal scheme through the implementation of an environmental impact assessment (EIA), which addresses a range of questions relating to the impacts of a proposed project on the physical, chemical, biological and human environments. During the operational phase of a geothermal scheme, day to day environmental impacts can be managed through the implementation of an environmental management system (EMS).

The environmental impacts of a geothermal development can also be optimized by paying special attention to the following aspects (International Energy Agency, 1998):

- Site selection: care in choosing a site for a geothermal energy scheme is particularly important if adverse impacts on the natural and human environments are to be avoided. Avoidance, where permitted by geological considerations, of National Parks and areas of outstanding natural beauty, special scientific or archaeological interest or cultural value is particularly important in this respect. Choice of site and possible alternatives is a key consideration in an EIA.
- Environmental costs and benefits: geothermal energy, like some other alternative energy sources (such as wind power) is interesting in that it offers global benefits (through reduced

use of fossil fuels) yet creates environmental impacts that cause concern at a local level. Information is, therefore, a key element of any debate about any proposed geothermal energy scheme, but it is still difficult to present the balance between the local impacts and the global benefits (as is the case for the further development of wind power schemes in the UK).

- Best technology and management practices: selection of technologies to minimize disruption to the natural and human environments is important along with the adoption of sound technical and management practices that are sensitive to environmental concerns and that minimize the adverse impacts of the scheme. A structure for good environmental management is provided by a formal environmental management system (EMS), such as those provided by ISO 14001 and EMAS.
- Public information and local involvement: with increasing environmental awareness among the general population, the involvement of the public through public consultation and the provision of information has become increasingly important in explaining the environmental aspects of any proposed geothermal energy scheme. Here, the importance of the socioeconomic impacts of any proposed project should not be underestimated and a clear understanding of local, regional and national policies relating to energy supply, conservation and planning are essential. The involvement of the local community in proposed schemes has also often helped to improve public acceptability. Other approaches suggested by the International Energy Agency (1998) include providing concrete benefits to the local population through, for example, the payment of rent for land occupied, inclusion of local people as owners of the scheme, offering lower electricity prices, providing local use of waste heat, and maximizing local employment opportunities.

The environmental impacts (physical/chemical/biological and socioeconomic) associated with the development of geothermal energy resources with vary from site to site according to the nature of the scheme itself and of the environment into which it is emplaced, and environmental impact assessments are needed for each proposed scheme in order to identify the specific environmental issues raised by the proposed development.

5 CONCLUSIONS

Geothermal energy offers considerable advantages over conventional fossil fuelled electricity generation through greatly reduced CO_2 emissions (with global implications with regard to climate change) along with lower SO_2 and NO_X emissions (with implications for local air quality and the generation of acid rain). Despite the global environmental benefits that can be claimed for geothermal energy, there may be important local impacts on the atmosphere, notably through the emission of H_2S and other minor gaseous pollutants, and on surface and groundwater, mainly through the disposal of contaminated waste water.

The impacts of geothermal energy utilization can be managed and minimized through their careful consideration as an environmental impact assessment (EIA) prior to site development and through the implementation of an environmental management system (EMS) during the operation of the scheme. Socioeconomic impacts are also important and can be optimized through the involvement of local communities in the development of geothermal resources.

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Economics and financing

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Geothermal energy development covers a huge range of resource technologies as well as a huge temperature range, and a host of alternative conversion technologies including space heating, district heating, industrial process heating and a number of generating options from dry steam to binary. Because of this, it is impossible to provide a guide and definite method of determining the economics of any given project. Each will be differently depending upon the characteristics of the resource and how that resource will be used. It is possible, however, to provide insight into how various characteristics in technology drive project economics, and the authors have tried to cover all of the economic factors that are common to all projects.

Once the economic viability of the project development has been established, it is possible to begin to assemble the necessary financing package. The focus is the identification and analysis of those issues that are critical to obtaining financing in clarity: the basic institutional framework, financing options and risk allocations principles.

1 INTRODUCTION

The factors that must be considered when assessing the viability of a geothermal project vary from project to project, from conversion technology to conversion technology, and especially from electrical generation to direct use. There are, however, a number of factors common to all projects, although actual cost and impact on project economics will be, to a large extent, dependent upon resource characteristics and national or even local political and economic circumstances.

The economic factors that are common to all projects include: provision of fuel, i.e., the geothermal resource; design and construction of the conversion facility and related surface equipment, e.g., the electrical generation plant together with required transformers and transmission lines; the generation of revenue; and, of course, financing. The cost of obtaining the required fuel supply, together with the capital cost of the conversion facility, will determine the amount that must be financed. Revenue generated through the sale of electricity, by-products, thermal energy, or product produced, e.g., vegetables, plants, or flowers from a greenhouse, minus the cost of O&M of the fuel supply and conversion facility, must be sufficient to meet or exceed the requirements of the financing package.

Because financing is such a critical factor in the economics of any project, an entire subchapter is devoted to this subject with the aims of describing the institutional prerequisites for successful financing and development of a geothermal energy project, summarizing the debt and equity structures for such a project, with emphasis on the broad range of structuring options and funding sources, and surveying the key issues in project agreements that should be addressed so that financing can take place. For many new projects, the largest annual operating cost is the cost of capital (Eliasson et al., 1990). In fact, the cost of capital can be as high as 75% of the annual operating expense for a new geothermal district energy project with O&M (15%) and ancillary energy provision (10%) making up the balance.

2 ECONOMIC CONSIDERATIONS

2.1 *Provision of fuel*

For most projects that require a sustained and economically attractive fuel supply, the project sponsor must only contact a supplier and negotiate a long-term supply of natural gas, oil, propane, or coal. To help guarantee low and stable fuel supplies, more and more project sponsors are purchasing gas fields, or oil or coal reserves. For projects that depend upon biomass (wood), fuel can be contracted for from a wood products mill or the mill may even become a partner in the project, providing an even more secure supply. Long-term availability of biomass can be determined from long-term timber holdings within a geographically defined area and/or plans for harvesting as defined by a state or federal land market authority. With municipal solid waste, fuel supply can be assured through local government action requiring that all material be controlled by one authority and delivered to a specific facility for a given time period.

In the case of geothermal resources, however, the fuel cannot be purchased on the open market, legislated into existence, bought from a local utility, or transported over long distances from a remote field.

Whether the steam or hot water is to be provided by the project sponsor, i.e., the steam field and conversion facility are under one ownership, or whether the steam is to be provided by a resource company, the geothermal fuel is only available after extensive exploration, confirmation drilling, and detailed reservoir testing and engineering. Once located, it must be used near the site and must be able to meet the fuel requirements of the project for the lifetime of the project. Even before exploration can begin, however, the project sponsor may incur significant cost, and a number of extremely important legal, institutional, regulatory, and environmental factors must be fully evaluated and their economic impacts considered.

2.1.1 *Obtaining access and regulatory approval*

In order to obtain rights to explore for and develop geothermal resources, access must be obtained through lease or concession from the surface and subsurface owners. In many countries, the state claims rights to all land and to all mineral and water resources. In other countries, land and subsurface rights can be held in private ownership. Unless the geothermal developer has clear title to both surface and subsurface estates, an agreement for access will have to be entered into with the titleholder of these estates. Such access will normally require a yearly lease fee and eventually royalties upon production. In areas where there is significant competitive interest, competitive bidding may be used to select the developer. Competitive bids can be in the form of cash bonuses or royalty percentages. Royalties can be assessed on energy extracted, electrical or thermal energy sales, or even product sales. Whatever the system, it will have an impact upon project economics and should be carefully considered in terms of overall economic impact. In particular, developers of direct use projects, because of the limited rewards that can be expected, must carefully evaluate how royalties will be calculated. In a number of instances, royalties, if assessed, would comprise up to 50% of annual operating cost, making projects uneconomical to pursue.

The second factor that will have an impact on overall project economics is obtaining all regulatory approvals, including the completion of all environmental assessments and the securing of all required permits and licenses, including, if necessary, a water right. Increasing concern for the environment in nearly all countries of the world has resulted in sharply increased cost for preparing the necessary environmental documents. A complete environmental impact statement for any proposed development is now required by federal land management agencies in the United States, and cost for preparation can exceed one million dollars. It is not uncommon to invest up to 40,000–60,000 person-hours in completing all necessary environmental documents and obtaining required licenses and permits for a major electrical generation project. Because so many environmental decisions are now contested, a contingency to cover the legal costs related to appeals must be included in any economic analysis; depending upon the issues and the financial and political power of those appealing a decision, the cost of obtaining necessary approvals can easily double. Because most direct-use projects are more limited in scale and, therefore, in environmental impact, these costs may be only a small fraction of the cost incurred by the proposal of a major power generation project. Even such a reduced cost can, however, be significant in relationship to the scale of the project, and the economic impact should not be underestimated. Unfortunately for the project sponsor, most of the cost related to obtaining access and environmental and regulatory approval must be incurred early in the project, and, in many instances, even before detailed exploration or drilling can begin, and with no clear indication that any of the costs will or can be recovered.

2.1.2 *Exploration*

Once access has been secured and all necessary regulatory approvals have been obtained, the developer may initiate a detailed exploration program, refining whatever data was initially gathered in the reconnaissance or pre-lease phase of the development process and sequentially employing increasingly sophisticated techniques that will lead to the drilling of one or more exploration wells; hopefully these wells will be capable of sustaining a reservoir testing program, and possibly also serving as preliminary discovery and development wells. Reconnaissance, in all likelihood, included such activities as a literature search, temperature gradient measurements in any existing wells, spring and soil sampling and geochemical analysis, geologic reconnaissance mapping, air-photo interpretation, and, possibly, regional geophysical studies. Costs incurred may range from a low of a few thousand dollars to even \$100,000 or more, dependent upon prior work in the area, geological complexity, and, of course, the scale of the proposed project and whether or not the intended use is electrical generation or direct application.

Once the area of principal interest has been selected, the exploration program can be more intensely focused, with the primary objective of siting deep exploration wells. Techniques likely to be employed include detailed geologic mapping, lineament analysis, detailed geochemical analysis, including soil surveys and geochemical analysis of all springs and wells, temperature gradient and/or core drilling, and geophysical surveys, including resistivity, magnetotellurics, gravity, and seismic. Costs increase as the complexity of the techniques and the detail of the surveys become more focused. For large, direct-use projects, costs of \$100,000 or more can be incurred. For projects directed toward electrical generation, the cost of this phase of the work can easily exceed several hundred thousand dollars, and may exceed several million dollars.

The final phase in any geothermal exploration program involves the siting, drilling, and testing of deep exploratory wells, and, subsequently, production and injection wells.

2.1.3 *Well drilling*

Well cost can vary from a low of a tens of thousands of dollars for small, direct-use projects to several million dollars per well for wells required to access high-temperature resources for electricity generation. Success ratios for exploration wells can be expected to exceed 60%; however, the risk of dry holes in the exploration phase remains high and can have a significant economic impact. Even in developed fields, 10 to 20% of the wells drilled will be unsuccessful (Baldi, 1990). Drilling cost is typically 30–50% of the total development cost for an electrical generation project and variations in well yield can influence total development cost by some 25%.

(Steffanson, 1999) Prospective developers must anticipate and prepare for the eventuality that despite an investment ranging from a few hundred thousand dollars to several million dollars in lease fees, environmental studies, licenses and permits, and exploration and drilling activities, an economically viable geothermal reservoir may not be discovered.

If, however, drilling is successful, the reservoir must then be tested to determine its magnitude, productivity, and expected longevity. Only after such testing can a determination be made as to the eventual size and design of the generating facility or direct-use application.

2.1.4 *Well field development*

Well field development for an electricity generation project can last from a few months to several years, depending upon the size and complexity of the project, the speed at which procurement contracts can be let (Koenig, 1995), and the availability of drill rigs. At this stage it also becomes of increasingly critical importance to collect detailed data and to refine the information available on the reservoir. Of course, for most projects this will include both production and injection wells. Many projects experience unnecessary difficulties and delays in financing or in milestone review because of either incomplete or inaccurate data collection, analysis, and/or interpretation (Koenig, 1995). Such difficulties and delays can seriously affect project economics and can have a catastrophic economic impact if delays result in contract forfeiture or if contracts contain a penalty clause tied to milestone completion. Coincidental with well field development will be the construction of well field surface facilities.

Costs associated with both drilling and the construction of well field surface facilities will be affected by the availability of skilled local labor and by geologic and terrain factors. Labor costs can be expected to increase by 8–12% in areas where most of the labor must be brought in or a construction camp erected to provide housing and meals. Terrain and geologic factors can add from 2–5% if special provisions must be made for work on unstable slopes or where extensive cut-and-fill is required for roads, well pads, sumps, etc.

Over half of the total production cost over the lifetime of the project will in fact be expenses associated with the well field. Because of this, it is imperative that wells must be properly maintained and operated to ensure production longevity. But even with proper O&M, many wells will have to be periodically worked over and, for most power generation projects, 50% or more of the wells will likely have to be replaced over the course of the project, adding considerably to the initial well field cost and, of course, to the cost of generating power. For example, if 60% of the wells must be replaced over the economic life of the plant, it would have the effect of increasing the levelized cost of electricity by 15 to 20% (Parker et al., 1985).

For small to medium-sized direct-use projects requiring only one or two production and injection wells, costs will generally be much lower. Because the water chemistry of most geothermal resources that are developed for direct-use applications is of generally higher quality than that available for power production, well life can be expected to be much longer and few, if any, wells will have to be worked over or redrilled during the economic life of the project.

2.2 *Project design and facility construction*

2.2.1 *The power plant*

Just as there are numerous geothermal resources throughout the world exhibiting differing temperatures and chemical characteristics, there are numerous power plant designs. These include direct steam, flashed steam, double flashed steam, and binary cycle, each able to best meet the specific requirements of a particular reservoir. The selection of the most economically viable power conversion technology can only be accomplished through a thorough evaluation of the differing strengths and weaknesses of various technologies relative to the characteristics of the resource and local circumstances, including environmental and regulatory requirements (e.g., requirements for noncondensable gas emission abatement or fluid injection). Terms of the power sales contract can also have a major influence on power plant design. For example, are there premiums paid for availability during certain times of the year or even times of the day, are there advantages to being able to operate in a load-following manner, or is capacity factor of paramount importance? Another major consideration is the manner in which steam is provided; e.g., is the steam field and the power plant under one ownership or is steam purchased from another party? If purchased, the terms of the steam purchase contract can have a profound impact on economics and, thus, on design. For example, if steam is paid for as a percentage of the selling price of electricity, there is little incentive to achieve high steam use efficiency and a strong incentive to minimize capital cost. On the other hand, if steam is purchased on the basis of dollars per kilogram delivered, then achieving highest possible fuel use efficiency becomes extremely important (Bloomquist and Sifford, 1995).

In order to achieve maximum steam use efficiency, some developers have adopted equipment procurement evaluation criteria that penalize offerings for inefficient use of steam and/or electricity at a capitalized rate of X thousand dollars per kilogram of additional steam required and X thousand dollars per kilowatt of parasitic load (Kleinhaus and Prideau, 1985).

2.2.1.1 *Cycle selection*

(1) Direct steam

Although extremely rare in nature, where available, direct steam will result in the lowest power plant cost. The steam is directed from the wellhead, expanded through the turbine, and condensed or, in certain circumstances, exhausted to the atmosphere. If condensed, the condensate can be used for cooling water make-up and/or injected back into the reservoir.

(2) Flash steam

In the case of high-temperature, liquid-dominated resources, a flash steam plant is the most economical choice. The hot water or liquid vapor mixture produced from the wellhead is directed into a separator where the steam is separated from the liquid. The steam is expanded through a turbine and, if condensed, can be used as cooling water or injected, together with the separated brine, back into the reservoir. The brine could, however, be used in another application, such as space or industrial process heating and/or agriculture, in a technique known as cascading.

(3) Double flash steam

A double flashed steam cycle differs from a single flash cycle in that the hot brine is passed through successive separators, each at a subsequently lower pressure. The steam is directed to a dual-entry turbine with each steam flow flowing to a different part of the turbine. The advantage is increased overall cycle efficiency and better utilization of the geothermal resource but at an overall increase in cost. The decision as to whether or not a double flash plant is worth the extra cost and complexity can only be made after a thorough economic evaluation based on the cost of developing and maintaining the fuel supply, or cost of purchasing fuel from a resource company, plant costs, and the value of the electricity to be sold.

(4) Binary

With a binary cycle, the heat from the geothermal brine is used to vaporize a secondary or working fluid that is then expanded through the turbine, condensed through an air condenser, and pumped back to the heat exchanger to be revaporized. Binary cycles can more economically recover power from a low-temperature ($<175°C$) reservoir than can a steam cycle. In addition, binary plants may be more easily sited where environmental concerns are paramount and where either gas emissions or cooling tower plumes need to be avoided. Recent developments in adding spay cooling to air condensers can improve summer efficiency by as much as 25+%, greatly improving the economics of such operations (Sullivan 2001 Personal Communication). The brine can be used in other cascaded applications and/or injected back into the reservoir.

(5) Other design considerations
In addition to temperature, fluid chemistry is extremely important in cycle selection and power plant design. Many high-temperature resources are highly aggressive brines, with high contents of total dissolved solids (TDS), and bring a host of other problems that affect both design and economics.

A number of techniques have been adopted to recover power from problem brines. Design options include the use of a crystalizer reactor clarifier and pH modification technologies.

The use of either technique can add considerably to capital costs as well as to plant O&M cost. If pH modification is used for scale control, corrosion could also become more severe. Of course, metallurgy of system components thus also becomes crucial and can add significant cost to the plant if more exotic materials such as titanium must be specified.

The use of binary cycles in the presence of high TDS or corrosive brines is limited by the fact that tube-and-shell heat exchangers can easily be fouled or suffer rapid deterioration from corrosion.

The availability of cooling water is also an important consideration in plant design. In a condensing direct steam or flashed steam power plant, the condensate is used for cooling water make-up. The plant can thus take advantage of the low wet bulb temperatures that may be present even though the ambient dry bulb may be quite high. A water-cooled cycle capable of approaching the wet bulb temperature presents a significant advantage, as far as overall power generation is concerned, in comparison to a dry cooled binary cycle that approaches the dry bulb instead of the wet bulb (Campbell, 1995). If, however, limited water is available, it may be used to improve the overall efficiency of a dry-cooled binary plant by injecting a fine spray or mist through the air condenser or onto a fibrous material (e.g. fiberglass) that can be used to enclose the sides of the air condenser (Sullivan, 2001, Personal Communication). This could be especially attractive where there is a premium for peak summer power. In an area lacking any source of water for cooling, the optional economic cycle may shift from a binary cycle to a flashed steam cycle (Campbell, 1995). In fact, the terms of the power sales agreement may have a profound influence upon conversion cycle selection, cooling system design, and, eventually, plant operation.

2.2.1.2 *Equipment selection*

(1) Steam cycle
The turbine generator set is the most expensive piece of equipment in a steam cycle power plant. For direct steam and single flashed cycles, a single admission steam turbine is appropriate. In turbines up to approximately 30 MWe, a single flow turbine is usually selected. However, larger turbines generally incorporate double flow, i.e., the steam is introduced into the middle of the turbine and flows in both directions, thus balancing thrust. Single flow turbines generally exhaust out the top, allowing the condenser to be located to the side and at the same elevation as the turbine, thus minimizing cost. With the double flow turbine, the steam exhausts downward, requiring the turbine to be mounted above the condenser. This arrangement increases capital cost, but that cost is more than justified by the increase in turbine efficiency. Other efficiency considerations include the number of turbine stages, blade length, and whether the plant will operate as a base load unit, will be used for load following, or must be dispatchable. If load following is desirable for either resource or contractual considerations, incorporation of partial-arc admission into the turbine design is critical. Partial-arc admission, as the name implies, allows for steam to enter the turbine through only a portion or "partial arc" of blades under certain operating conditions, and to enter the turbine through the full arc of blades during other conditions. Partial-arc admission allows a turbine to be operated at various output levels while maintaining a much higher level of operating efficiency than would be possible if the turbine were controlled through the use of a single throttling valve. In fact, when the plant is operating at the minimum output allowed by the partial-arc arrangement, it will be only 5% less efficient than at full output. This operational flexibility ensures the use of the minimum amount of steam possible for any given

level of output. The use of partial-arc admission also allows for plants to be ramped up very quickly, that is, from minimum output to full output in only a few minutes (Bloomquist, 1990). Partial-arc admission can also provide the ability to significantly increase output from a single machine if higher-pressure steam is available. For example, at one plant at The Geysers each of the turbines produces 40 MWe at 8 bars inlet pressure, while either machine can produce 80 MWe at 11.6 bars. This arrangement has allowed this particular plant to maintain both capacity and availability in the high 90% range (Bloomquist and Sifford, 1995).

Two major categories of condensers are used with steam cycles: the surface condenser and the direct contact condenser. In a surface condenser, the cooling water is circulated through the inside of heat transfer tubes with steam condensing on the outside of the tubes. In contrast, in a direct contact condenser the cooling water is sprayed into the condenser where it directly contacts the steam from the turbine discharge. The primary advantage of the surface condenser is that contamination of the cooling water with constituents of the wellhead steam is avoided – an important factor where hydrogen sulfide abatement is required (Campbell, 1995). The direct contact condenser, however, is less expensive and is less prone to maintenance problems, and would thus be the most economical choice if hydrogen sulfide is not a problem.

The selection of direct contact or surface condenser will also have an impact on pumps and pumping requirements, i.e., parasitic power requirements. In a surface condenser, the condensate from the condenser is collected in a hot well and a condensate pump is required to pump this condensate from a vacuum of about 0.098 bara up to the top of the cooling tower. The other major pumps required for surface condenser operation are the cooling water pumps, located at the base of the cooling tower, and used to circulate cooling water through the tubes of the condenser and back to the cooling tower.

Because the condenser itself is at a vacuum, no pump is required in a direct contact condenser to move cooling water from the cooling tower basin into the condenser. However, a pump is required to pump cooling water and the condensate back into the cooling tower. Because of the usually high content of carbon dioxide and other contaminates in a direct contact condenser, stainless steel pumps are normally specified to resist corrosion.

Noncondensable gases must be removed from the condenser in order to reduce backpressure and optimize steam use efficiency. Noncondensable gas removal, however, results in a significant parasitic load either in terms of steam used in jet ejectors or electricity used to power compression or vacuum pumps. Steam jet ejectors have by far the lowest capital cost but are relatively inefficient in comparison to liquid-ring vacuum pumps or mechanical compression. A commonly used arrangement employs one or two steam jet ejectors in series followed by a liquid-ring vacuum pump, thus taking advantage of the low capital cost of the initial stage with the higher efficiency final stage.

If the noncondensable gas contains concentrations of hydrogen sulfide that require removal, a number of options are available, including liquid reduction-oxidation using an iron chelate solution such as is employed in the Dow Sulferox process, and the Wheelabrator Lo-Cat process. The Stretford process is another option that has been successfully used with geothermal power generation. Inclusion of hydrogen sulfide abatement can increase the capital cost of a steam cycle plant by 10% or more, and will also result in an ongoing increased cost for O&M.

The cooling tower design can also have a major impact on capital cost, O&M, and cycle efficiency. The most commonly used cooling tower designs include cross-flow, cross-flow with high efficiency fills, and counter-flow. The counter-flow tower yields more efficient heat transfer and greater depression of water temperature than the cross-flow design. The high efficiency fill not only increases efficiency at a lower cost than conventional towers, but also the tower can be shorter, thus resulting in a lower parasite load for pumping cooling water to the top of the tower. On the downside, high-efficiency fills have a tendency to become clogged and cooling water chemistry must be carefully controlled. Biocides are generally added to minimize algae and other biological growth, and corrosion inhibitors are added to protect the system

(Campbell, 1995). Although dry cooling towers (see Binary cycle below) can be used with steam systems, efficiency considerations will generally discourage their use.

(2) Binary cycle

Selection of the right working fluid is the most critical design decision in the development of a binary cycle power plant. The selection must achieve a good match between the heating curve of the working fluid and the cooling curve of the geothermal heat source. The cooling curve of liquid brine is a relatively straight line, whereas a two-phase flow of liquid and vapor will give a curve of a different shape. Working fluids used in binary plants fall into two broad categories: light hydrocarbons and freons. The light hydrocarbons include butane, propane, isopentane, isobutane, and even hydrocarbon mixtures designed to find the most efficient match of working fluid to resource. In terms of freons, R11 and R22 have both been successfully used with low-temperature resources.

The light hydrocarbons have the disadvantage of being highly flammable, requiring installation of fire control equipment. The use of R11 has been banned because of its adverse impact on the ozone layer, and R22 will be phased out over the next several years. However, more environmentally friendly replacements are now available, and work is now being directed toward the development of other even more efficient and environmentally acceptable replacements. There is also increasing interest in ammonia as a working fluid and a number of demonstration applications are already planned or on line.

Because the heat content of the geothermal resource is transferred in the binary cycle to the working fluid, the heat exchanger becomes an additional critical equipment component, and can account for a significant capital cost increase over that of a steam cycle plant. The heat exchanger is generally of shell-and-tube design with the geothermal brine pumped through the tubes and the working fluid on the shell side. Because of the heating curve, counter-current flow is desired and achieved by laying out the heat exchangers in series with single-pass flow on both shell-and-tube sides. Material selection is critical to avoid problems of both corrosion and erosion of the heat transfer tubing. For most applications, carbon steel is acceptable if oxygen can be kept out of the system, and has the lowest capital cost. The cost of the heat exchanger can escalate rapidly if stainless steel or even titanium is required. The use of a direct contact heat exchanger would reduce capital cost and limit the problems associated with erosion and corrosion of the heat exchanger tubing. However, problems associated with contamination of the working fluid by corrosive constituents in the brine and noncondensable gases can result in serious problems downstream in the turbine and condenser. Loss of working fluid to the spent brine is less of a problem, but must still be taken into account by including recovery equipment.

Another major cost that is specific to the binary cycle is the number of pumps required and the significant parasitic load they place on the plant. Because the binary cycle operates much more efficiently if brine from a liquid-dominated reservoir can be maintained as a single-phase flow through the heat exchanger, production well pumps are used. Standard production pumps are multistage, vertical turbine pumps driven by a motor at the surface. Downhole pumps could be an attractive and economical alternative, and recent advances could soon result in commercially available downhole pumps. But the high temperature of the geothermal brine has so far limited their applications. Improvements in vertical shaft turbine pumps now make multi-year runs between servicing possible and have significantly improved operational economics and reduced downtime.

The second major requirement for pumps stems from the need to pump the working fluid through the heat exchangers and to the turbine inlet. The pumps are usually multi-stage, vertical canned pumps. Multiple stages are used to achieve the required turbine pressure. In addition to the additional capital cost attributable to the need for production and/or working fluid circulating pumps, pumping requirements result in a parasitic load of 10 to 15% of the power that is generated, a significant reduction in the amount of power that is available for sale.

Power is generated in the binary cycle using either a radial inflow or axial flow turbine. The radial inflow turbine can achieve efficiencies as high as 90% and is usually the preferred option.

Once expanded through the turbine, the working fluid must be condensed before being returned to the heat exchanger in a continuous cycle. To date, a majority of binary cycle plants have employed air-cooled condensers. In the air-cooled condenser, the condensing working fluid is directed through the heat transfer tubes and air forced across the tubes to remove the heat. The air-cooled condenser can be extremely large and expensive both to build and to operate.

A water-cooled system is an alternative and can provide significantly increased efficiency under certain operating conditions. The water-cooled system, however, does have a number of drawbacks. The most critical of these is probably the fact that the binary cycle does not in itself generate a source of cooling water so that an external source of cooling water is required. If an external source can be obtained, an evaluation must be made of capital and operating costs vs. electrical output. The combined cost of the condenser, cooling towers, and cooling water pumps of the water-cooled system will be less than the cost of the air coolers of the air-cooled system. However, the cost of water, chemicals, and disposal of blow-down, coupled with the parasitic load associated with cooling tower pumps and fans, can exceed the cost of operating the air-cooled condenser. Other advantages of the air-cooled option are avoidance of the cooling tower plumes and cooling tower emissions, factors that are often critical to obtaining the necessary permits and meeting regulatory mandates. The best of both systems may be the hybrid based on the use of air coolers but with injection of a water mist into the airflow of the air cooler or the spraying of water onto fibrous metal used to enclose the walls of the cooling tower. This can significantly increase cycle efficiency and output during peak demand periods in a summer peaking area. Testing at a facility in California in 2001 resulted in a 25+% increase in power output (Sullivan, 2001).

(3) Power plant construction

A number of factors related to power plant construction can have a significant influence on project economics, including geologic conditions, terrain, accessibility, labor force, economies of scale, and site or factory assembly of major components.

Geologic conditions and terrain, e.g. slope stability and need for extensive cut-and-fill, can be expected to increase the cost of construction by 2–5%. The need to build or reinforce roads to carry heavy equipment will also be affected by both geologic conditions and terrain factors.

The availability of an adequate and skilled labor force can also impact construction cost. If the site is located in a rural area with little or no skilled construction labor force, most construction personnel will have to be brought to the site and, in fact, depending upon the commuting distance, a construction camp may have to be established to provide living quarters and meals for the workers (Sifford et al., 1985).

Economics of scale will often favor the larger power plant; however, a number of factors can virtually eliminate the initial capital cost advantage and may provide operational characteristics that greatly increase both plant availability and capacity factors. The most important of these are modular design and factory assembly of major components. Modular design will often allow for factory assembly of major components, virtually eliminating most weather-related delays, minimizing the need to upgrade roads to carry extremely heavy pieces of equipment, and helping to ensure more consistent and higher quality workmanship, possible because of the controlled environment where the work is taking place. Modular design may also allow for staged start-up of generation, providing for a revenue stream much earlier than with the larger, site-erected plant, and minimizing interest during construction. For example, a 110-MWe power plant, made up of two 55-MWe turbine generators at The Geysers has a normal construction period of three years. Modular plants of approximately 25 MWe and less can often be on-line within one year of the start of construction with subsequent modular plants coming on-line at 6- to 12-month intervals. The generation of considerable revenue during the construction period more than offsets any advantage that economy of scale may provide. In addition, the ability to bring units on-line sequentially often is a major benefit in being able to better track load growth of the utility.

However, within the size range of most modular constructions, e.g., less than 25 MWe, economy of scale does apply. For example, it would be more cost effective to erect five 5-MWe modules rather than ten 2.5-MWe modules.

2.2.2 *Direct use*

A discussion of project design and facility construction relative to direct-use projects is much more difficult than the previous discussion relating to power generation. A direct use project may be supplying the needs of a greenhouse or aquaculture complex, an industrial facility, or a district energy system supplying multiple commercial, industrial, and even residential customers. (Note: Individual systems to heat and/or cool a single residence or greenhouse, or projects directed toward balneology, will not be considered.)

The three uses mentioned above, however, share a number of design considerations and even some equipment components, all having a bearing on the economics of the project. All are highly dependent upon resource characteristics, including temperature and flow, hydrostatic head, drawdown, and fluid chemistry. The characteristics of the resource will dictate not only the type of project that can be developed, but also the scale of the project and the metallurgy of the components selected. Direct use projects must be located near enough to the resource site to allow for economic transport of the geothermal fluids from the wells. For very large district energy systems, however, this distance may be several tens of kilometers. If the well(s) does not flow artesian, well pumps will be required and, at resource temperatures at which most direct use projects operate, either line shaft or downhole pumps may be used. Because of variations in flow requirements to meet seasonal loads, inclusion of variable speed drives should be considered in order to minimize electrical costs.

Piping from the well(s) to the application site will be dependent upon temperature, pressure, and distance. Insulated pipe may or may not be required, and will depend on distance and whether or not some temperature loss is acceptable. The pipes may be constructed above ground, but local regulations may require burial.

Another major design consideration is whether or not the heating system should be based on meeting the peak heat demand entirely with geothermal or whether the system should rely on a fossil fuel (oil, propane, natural gas, or even coal) boiler for peaking and/or backup. In many instances, a strategy where the geothermal system is designed for "base load only" operation may be the most economical. For both greenhouse applications and district energy systems, designing the geothermal system to meet 50–70% of the peak heating load will still allow the geothermal system to meet 90–95% or more of the annual heating requirement in most climatic zones. This is because a system that is designed to meet peak-heating load only operates a few hours of the year under those conditions. For example, if a district energy system is to meet peak demand solely with geothermal, the number of wells will have to be doubled and the size of the distribution piping increased by approximately 30% to accommodate the requirement for increased flow. Another strong argument for meeting peak demand with a non-geothermal system is the need for back up for both greenhouse applications and for district energy systems. And although back up can be provided through the use of standby wells and back-up generators to run pumps, a fossil fuel system may be the most secure alternative and also the most cost effective. Whether or not to include fossil fuel peaking for an aquaculture or industrial application will depend upon the particular requirements of the application.

In addition to giving careful design consideration to the selection of the most appropriate and economical heating system, similar consideration should also be given to the provision of cooling. For most greenhouse operations, cooling can be provided through a combination of shading and the use of evaporative coolers. However, if a more sophisticated cooling system is required, or there is a need for refrigeration, absorption cooling may be an option worth evaluating. New advances in double and even triple-pass absorption equipment allow for a coefficient of performance (COP) significantly above 1 to be obtained, and even at geothermal resource temperatures as low as 80–100°C, absorption cooling may be the answer to meeting the needs of both greenhouse operators and providers of district energy service.

2.2.2.1 *Equipment selection* Most if not all systems will require the inclusion of a heat exchanger to separate the geothermal fluids from the in-building circulating loop because of the potential for corrosion and scaling associated with most geothermal fluids. Both plate-and-frame and shell-and-tube heat exchangers have been successfully employed in such applications. Despite higher cost, however, a number of factors tend to favor the plate-and-frame exchanger. Approach temperatures across the plate-and-frame exchanger are somewhat better at 3° to 6°C vs. 8° to 11°C for shell-and-tube. Another major consideration in the selection of a plate-and-frame heat exchanger is the ability to easily add plates in order to expand the heat exchanger capacity, and the fact that the exchanger can be easily opened for cleaning. (Note: This is not true for brazed plate-and-frame exchangers.) Materials include various grades of stainless steel and titanium.

Selection of the piping material is especially important in applications that have extremely long pipe runs such as is common to all district energy systems. If the geothermal fluid is to be circulated through the distribution-piping network, material selection and even carrier-pipe wall thickness become crucial decisions. For example, in the case where geothermal fluids are circulated, thin-walled, pre-insulated district heating pipe, so common to most district energy systems in Europe, may not be appropriate. If, however, the heat is transferred to a secondary fluid that is circulated in a closed loop, and where addition of inhibitors is practical, the thin-walled, pre-insulated pipe is probably a logical choice. Other points to consider include the choice between metallic and nonmetallic pipes and whether flexible pipes should be used. Flexible piping is only available in the smaller size ranges, but the decrease in cost associated with its installation may make providing heat to areas with relatively low heat load density economically viable. If nonmetallic piping is selected, care must be taken to ensure that it has an oxygen barrier or that areas served with nonmetallic pipes are separated by a heat exchanger from areas served with metallic pipes. If this is not done, severe corrosion problems may occur in the metallic pipe portions of the system due to oxygen infiltration.

Other system components and design considerations are very application-dependent and beyond the scope of this chapter. The reader is, however, referred to the other chapters of this book and to the Geothermal Direct-Use Engineering and Design Guidebook published by the Oregon Institute of Technology in Klamath Falls, Oregon (see listing at: htpp://geoheat.oit.edu).

2.2.2.2 *Project construction* For greenhouses and aquaculture projects, construction of the geothermal portion of the project is usually a very minor part of the entire project, and consists primarily of wells, pumps, heat exchangers, peaking and/or backup equipment, piping, and controls. However, with a district energy system, the thermal energy transmission and distribution piping system will comprise 60% or more of the total construction budget. District energy systems may include multiple heat exchange and peaking or back-up stations, thermal storage tanks, and extensive control systems. In the majority of district energy applications, the geothermal fluid is most often used to heat a secondary fluid that is circulated to meet customer needs. In some cases, however, the geothermal fluid is circulated directly to each customer, where the heat exchange takes place. The principal cost during construction is related to pipe lines and includes excavation, back filling, and repaving, if necessary. The installation of the piping system can run from an equivalent of $300 US per meter to as high as $9000 US per meter in highly developed urban areas. A major problem for most developers of district energy systems is that the transmission piping must be sized to meet the needs of the system at full build-out although revenue will increase only slowly as the system expands and as the customer base increases. This dilemma is by far the most important economic consideration in determining the feasibility of introducing geothermal district energy service into an existing community. The use of computer models for determining the economic viability of constructing a new district energy system or expanding an already existing system is now available. For one such model see HEATMAP© GEO, which can be found at http://www.energy.wsu.edu/software/heatmap/. In a new community or a new area of a community, much of the cost of constructing the distribution system can be shared with the developers of other utility services, including sewer, water, and electricity.

2.3 *Revenue generation*

For power generation projects, the power sales contract establishes the legal framework for revenue generation. For direct use projects, however, the revenue stream to support the project may well come from the sale of a product, e.g., flowers, plants, or vegetables from a greenhouse project, fish or shellfish from an aquaculture project, value-added service, e.g., dehydration in an industrial process, or thermal energy sales for a district energy project. Considerable interest in so-called co-production is increasing rapidly as a means of improving the economics of geothermal power generation by providing an additional revenue stream. Co-production involves the extraction of valuable by-products for the geothermal brine before reinjection. These by-products may include zinc, manganese, lithium and silica – all with relatively high market value.

2.3.1 *Electrical generation*

Ultimately, the economic viability of a particular power generation project will depend upon its ability to generate revenue, and revenue can only be generated from power sales. Such sales must be equal to or exceed that required to purchase or maintain the fuel supply, to cover debt service related to capital purchases, and to cover operation and maintenance of the facility. The output from the plant, and hence the source of revenue generated, will be highly dependent upon how well the plant is maintained, how it is operated, and the ability to take maximum advantage of incentives to produce at certain times or under certain conditions. For example, a plant selling into a summer peaking service area must be able to provide maximum possible output when a premium is being paid for output.

With the increase in the number of geothermal power plants by private sector developers, O&M has assumed even greater importance. Competition means that margins for profit are slimmer, making O&M costs all the more critical. Because most power sales contracts are output-based, and because geothermal generation costs are predominantly fixed as opposed to variable, the unit cost of geothermal power decreases rapidly as the capacity factor increases, i.e., maximum operation yields maximum return to the owner. For example, as the plant capacity factor increases from 50 to 90%, the levelized cost of producing electricity could be expected to decrease by nearly 50% (Parker et al., 1985).

A number of innovative approaches have been adopted to ensure the highest possible capacity factor and thus maximum revenue to the plant owner. The most common of these is the use of redundant or back-up equipment, including spare wells, cooling water pumps, noncondensable gas removal equipment, and the use of multiple turbine generation sets. The presence of redundant equipment allows for routine or even forced maintenance to be accomplished without taking the plant off line or at least the entire facility off line. The use of multiple modular turbine generators is a prime example of a strategy to achieve maximum capacity factor. In many instances, the steam or brine can be routed from the downed unit to other operating units capable of operating at slightly over design, thus providing the possibility of covering the entire load of the unit that is out of service.

One of the most innovative uses of this philosophy is at the Santa Fe plant in The Geysers geothermal field. Due to Santa Fe's common ownership of the plant and well field, regulatory restrictions, and contractual incentives, it was highly desirable to obtain highest allowable capacity and availability for maximum revenue generation with minimum per unit fuel use and production cost. Maximum capacity was ensured through the use of two two-flow turbines, each capable of producing the maximum regulatory allowable 80 MWe. The use of two turbine generator sets allows for more frequent refurbishing of the turbine blades to maintain performance at or near design value without significant loss of revenue during down time and without the need to maintain two spare rotors. Higher efficiency was also ensured through the selection of a turbine design that incorporated partial arc admission and the capability to slide to 50% overpressure. The use of the partial-arc admission resulted in reduced throttling losses under normal operating conditions (two-turbine operation, each at 40 MWe net output) and improved single turbine operation, i.e., 80 MWe net output. At eight bars throttle pressure at (or near) the first valve point, the larger valve is fully open and the smaller valve is fully closed. Under these operating conditions, each machine produces 40 MWe of net output. When only a single turbine generator is operable, the small valve is operated at 11.6 bars throttle pressure, and one turbine can produce approximately 80 MWe net (McKay and Tucker, 1985). According to the design engineers, Stone and Webster (Personal Communication), the cost of the second turbine generator would be covered by an additional two weeks of operation per year, approximately equal to the time required for routine maintenance (Stone and Webster, Personal Communication). Efficiency is further enhanced through the use of a large, multi-pressure condenser that guarantees a low average condenser pressure, and condenser bypass that allows full steam flow through the condenser of the operating unit, as well as the use of the entire cooling tower so that design back-pressure can be maintained during single turbine operation (McKay and Tucker, 1985). Through such innovative approaches, not only is maximum capacity and potential for revenue generation ensured, but efficient use of steam is also achieved.

Revenue can also be affected by plant availability, dispatchability, and load-following capability. Many power purchase contracts provide incentive payments for: availability, i.e., the ability to generate at certain levels or during certain peak demand periods; dispatchability, i.e., the ability to go off-line or curtail production when the power is unneeded; or load-following capability, i.e., the ability to match power output to the need for power of the receiving utility. Availability, much like plant capacity factor, can be achieved through the highest possible flexibility and reliability in plant operation, and, as with capacity, is often achieved through the use of redundant equipment. However, possibly as important in terms of revenue generation is the ability of the plant to quickly come on-line after a forced outage, after being tripped off-line, or upon request of the utility to curtail production. In many areas, being tripped off-line means shutting in wells to avoid unabated hydrogen sulfide emission and a lengthy restart because major components have to be brought up to temperature slowly. The use of a turbine by-pass and computerized well field control can individually or, ideally, together minimize both these effects and help maximize on-line availability. By being able to route the steam flow past the turbine and directly into the condenser, it is possible to remove the noncondensable gases, and any hydrogen sulfide can be removed and treated in the hydrogen sulfide abatement system. Without the turbine by-pass, the wells would have to be shut in or vented to the atmosphere, and it could take up to several hours to bring the wells and plant back to full production. In its first full year of operation, Santa Fe Geothermal, one of the first plants to use the turbine by-pass, achieved a capacity factor of 98.6% of its 80 MWe operating permit and had an availability of 99.9% (Fesmire, 1985).

Other factors that can affect revenue generation include plant dispatchability and load-following ability. Although the commonly held philosophy is that geothermal power plants, because of the ratio of fixed to variable costs, must operate in a base load manner, utility requirements and/or reservoir concerns may require that the plant be operated in a load-following or dispatchable manner. Reservoir depletion at both The Geysers and Larderello has forced load following, and some utility contracts provide incentives for dispatchability that more than offset any loss of revenue while the plant is operated below design capacity.

A number of plant features, including partial-arc admission, turbine by-pass, and computerized well field operation, all mentioned before, help maximize revenue generation during load-following operation. The Italians have also found that remote operation can play a significant role in meeting the demands of load-following operation while at the same time significantly reducing labor costs, costs that become increasingly important when a plant or plants are operated below design capacity. It is also important to note that availability takes on increasing importance when operated in a load-following mode inasmuch as severe economic penalties may be imposed if the plant is not available when needed.

The direct link between revenue generation, plant availability, and capacity also places greater emphasis on O&M. Plant operation costs and on-line performance are under increasing scrutiny by purchasing utilities, direct electrical service customers, and those who provide financing. Indeed, because investors and financiers are typically more conservative than developers, an experienced, big name company able to provide both O&M has strong appeal to backers, and that appeal translates directly into slightly lower financing costs, which are a major economic consideration. It is extremely important that the O&M provider or in-house staff be retained at an early stage in the development process and provide review and input into plant design, participate in plant construction, start-up, and conduct system checks. The contractor or plant staff should also be capable of and required to perform a post-hoc analysis of all significant events, including root cause analyses for future planning (Independent Power, 1989).

The increase in partnerships developing projects also highlights another O&M trend: affiliates of financiers and/or partners are often highly competent facility operators. A vested interest in plant performance provides a motivating influence to the O&M provider. Such motivation, in turn, provides security to financiers. Other incentives to peak performance, however, do exist. A bonus for good operation, tied with a penalty for not meeting minimum performance requirements, helps ensure optimum performance, guarantees achieving output to match contractual requirements, and generates maximum revenue and profit. But good O&M goes beyond maximizing current profits, to an efficient use of the reservoir in order to prolong life and assure supply. Smart developers also know that a good performance record will be critical to obtaining both future power sales agreements and financing for future plants at attractive rates.

2.3.2 *Co-production*

Co-production, i.e. the production of silica and other marketable products from geothermal brines, is rapidly becoming not only a very viable source of additional revenue for power plant owners, but a key technique for improving power plant economics by reducing operation and maintenance costs. The removal of silica may allow additional geothermal energy extraction in bottoming cycles or additional uses of low-grade heat that are presently prohibited due to problems associated with scaling.

Precipitated silica has a relatively high market value (1–10 US dollars per kilogram) for such uses as waste and odor control, or as an additive in paper, paint and rubber (Borcier, 2002, Personal Communication, Borcier, et al., 2001). Initial estimates from Salton Sea geothermal fields places the market value of extracted silica at 84 million US dollars a year.

Silica removal also opens the door to the downstream extraction of, for example, zinc (ZN), manganese (MN), and lithium (LI), all with relatively high market values. The first commercial facility for the recovery of zinc from geothermal brine was built in the Salton Sea geothermal area of southern California in 2000. The facility is designed to produce 30,000 metric tonnes of 99.99% pure zinc annually at a value of approximately 50 million US dollars (Clutter, 2000).

Silica removal has the additional benefit of helping to minimize reinjection problems and, in one case in California, could allow use of the spent brine as the source of cooling water needed to improve summer power plant performance. Initial studies indicate that power plant efficiency of an air-cooled binary plant could be increased by 25+% through the use of spray cooling (Sullivan 2001, Personal Communication).

2.3.3 *Direct use*

Most large-scale direct use projects tend to fall into three broad categories: provision of district energy; industrial processes, including dehydration; and agriculture, including greenhouses and aquaculture. In all except the provision of district energy, revenue is generated from the sale of a product, such as potted plants from a greenhouse, or from a value-added service rendered, e.g., the drying of onions in a dehydration plant. Ultimately, in both cases, revenue generated and economic viability are totally dependent upon the value and marketability of the end product. Long-term contracts for sale of these products are almost never available. Geothermal may be the most economic form of energy for any given application, and may even provide certain other benefits such as fuel price stability or constant heat, but the economic viability of the project will seldom be driven by the cost of developing and/or operating and maintaining the geothermal source. The geothermal resource developer must therefore not only have a thorough appreciation of the costs involved in developing and operating a geothermal project in an economical manner, but must fully understand what factors ultimately determine the economic viability of the products produced.

With district energy, on the other hand, revenue is generated solely from the sale of thermal energy in the form of either hot water or chilled water. Long-term sales contracts to customers are the norm, and most contracts call for both capacity (fixed) payment and variable payment components. The capacity or fixed portion of the payment is based upon the capital invested, including wells, heat exchangers, thermal storage units, back up or peaking boilers, and the transmission and distribution network. The variable portion of the amount charged relates to O&M, including personal cost, cost for fossil fuels used in the back up and/or peaking boilers, and redrilling of wells. In most systems, charges are based on usage, metered either as flow or thermal demand, i.e., kW/hour. Some systems, however, use a fixed orifice and charges are based upon the orifice size.

Because weather conditions will, to a large extent, determine thermal energy usage by residential and commercial customers, it is extremely important that rates are structured in such a way as to ensure that revenue is always able to cover both fixed and variable costs.

3 FINANCING CONSIDERATIONS

Once a geothermal project has demonstrated technical feasibility and economic viability, it faces a critical test – financeability. Whether a project is financeable depends on such matters as 1) the intent and permanence of legal, structural, and economic reforms; 2) the availability of debt and equity capital; and 3) the risk allocation reflected in project contracts.

The following is an analysis of some of the critical issues to be examined when considering development of a geothermal energy project. The primary focus of this analysis are those issues that most often arise in the context of a proposed geothermal power project. Some of these issues will not be applicable to a direct use or district heating project using geothermal energy. Nevertheless, the basic institutional framework, financing option, and risk allocation principles described below provide a useful benchmark for analysis of geothermal energy projects that do not involve the production of electricity.

3.1 *Institutional framework*

Facilitating private investments in geothermal energy projects requires that governments create a legal environment that is conducive to long-term investment. Such an environment consists not only of governmental restraint in affecting the settled expectations of private investors, but also of explicit governmental authority for the contemplated investment. In this context, some of the basic legal reforms undertaken to facilitate financing of geothermal energy projects may include:

- Empowering a private party to engage in a given "public" activity (e.g., electric generation or supply of thermal energy) together with, or on behalf of, the government.
- Empowering a public entity to select the private party that will perform the activity and empowering the public entity to enter into legally-binding relationships designed to produce a firm, reliable stream of payments to support a project financing.
- Reconciling the financing arrangements for the project with the terms of any applicable public procurement rules.
- Authorizing the private party to have a legal entitlement to payments made by the ultimate consumers of the goods/services to be provided.

Through establishment and implementation of a reform program, governments have also taken a pro-active role in creating an environment conducive to foreign investment in energy sector projects.

In most countries, privately owned geothermal energy projects are new entrants in a market that previously consisted of government-owned electricity or thermal energy suppliers. The encouragement of these new market entrants may also require fundamental constitutional, legislative, and regulatory reforms.

In some countries, private ownership of power generation facilities or thermal energy systems has been prohibited by the constitution. Many countries have instituted constitutional, statutory, and regulatory reforms to authorize private ownership.

Attention often focuses on the need to institute sound economic reforms in utility regulation: cost of service pricing and an end to government subsidies (which results in electricity or thermal energy being priced below the marginal cost of production) are among the most important of these reforms. From a legislative perspective, however, two types of reforms stand out as essential predicates to attracting private capital: a commitment to refrain from upsetting the settled expectations of contracting parties by imposing retroactive and economically burdensome regulations and/or taxes, and a willingness to enable the support of utility or direct customer purchase commitments by authorizing central bank commitments in the form of currency convertibility assurances (where necessary) and liquidity instruments (e.g., letters of credit) to enhance the credit of the utility or direct use purchaser.

Discussed below are seven critical areas where the extent (and certainty) of policy reform is critical to the success of privately owned and financed power plants or thermal energy supply and distribution systems.

3.1.1 *Power procurement approach*

A basic issue that needs to be clarified in most countries is the framework for purchasers to acquire new supplies of electric or thermal energy. Options include the following:

- Sole-source negotiations. The purchaser is free to negotiate with proponents of a proposed project, without the need for formal submission of proposals and ranking.
- Formal competitive bidding. The purchaser establishes criteria for ranking and selection, with bids to be submitted and evaluated (and contracts awarded) on a specified schedule.
- Uniform rates and contracts. A standard rate and master contract is developed, with contracts available for projects meeting prequalification criteria (if any).

Variations of these approaches exist. However, project development has been most difficult in those countries that have shifted approaches with some frequency.

In addition, attention needs to focus on the types of market opportunities that are to be encouraged. The four basic types of market opportunities – electric power sales to a utility under the Build-Operate-Transfer (BOT) or Build-Own-Operate (BOO) models, sales of electric or thermal energy to "end-use" customers, unit repowering, and operations contracts – are discussed below.

3.1.1.1 *Central power plants – the BOT and BOO models* Egypt, Philippines, and Pakistan are among countries that have allowed privately owned entities (with or without government equity participation) to build, own, and operate major power plants to sell electricity to the government-owned electric utility. At the end of a specified term (10 to 20 years, usually), it is contemplated that project ownership will be transferred to the government. Project documentation, including technology transfer agreements, must contemplate the transfer. A critical issue in power contract negotiations is the transfer provisions, which may establish certain performance criteria to be satisfied as of the time of transfer and which may specify liquidated damages for failure to meet those criteria. Some of the variations on the BOT theme include: concession agreements, with transfer at the end of the concession term; no transfer of the facility at the end of a specified term (the Boo model); construction by the government utility and sale to a private owner/operator; and lease by the government utility of a privately constructed and owned plant.

3.1.1.2 *Direct sales* Many countries allow only a limited class of privately owned facilities - those serving the industrial user that owns the facility. Other countries allow a broader category of privately owned facilities, but allow them to sell electricity or thermal energy only to utility wholesalers. In some countries, markets have been liberalized and sales can be made to any purchaser, including industrial and commercial end-users.

3.1.1.3 *Purchase, repowering and refurbishment of existing facilities* In addition to construction of new facilities, many countries are offering to sell existing power generation and transmission and distribution system assets (or thermal energy production and distribution systems) to private investors, including foreign investors. The private purchaser is then enabled or required to repower, refurbish, or expand the existing facilities.

3.1.1.4 *Operator contracts* While not involving private ownership per se, a number of governments have been willing to enter into operation contracts providing the operator with a participation in the outcome of the operations (e.g., in cost savings), with or without a responsibility for hard costs of operation and maintenance. Such contracts may pertain to particular facilities or to entire electric energy or thermal energy systems. There may be accompanying obligations or opportunities to improve performance by investment and refurbishment of the facilities.

3.1.2 *Energy regulation*

In countries that allow privately-owned electric generation facilities or thermal energy systems, an important question that must be addressed is the choice of a regulatory model. While there is no standard model, it is important to establish a transparent regulatory framework, not subject to retroactive changes, that addresses certain basic matters.

3.1.2.1 *Prices* In some countries, the price for sales of electric or thermal energy is a product of conventional, "cost-of-service" regulation. In essence, profits are controlled, and revenues are a product of a cost-plus-reasonable-profit calculation. Countries that have deregulated pricing for sales of electric or thermal energy follow a different approach: the seller can charge the price established through bilateral contracts, spot market sales, or competitive bidding (for long-term sales), or electricity trading transactions. An alternative approach is to establish a standard price for all sellers, with some variation in pricing to reflect differences in fixed and variable costs of certain technologies.

3.1.2.2 *Market entrance* Some countries also require owners of new generating units or thermal energy facilities to obtain licenses or concessions. Significant issues can arise under a license and concession regime, including such matters as grounds for revocation, level of royalty payments or license/concession fees, and restrictions on transfer of shares.

3.1.2.3 *Performance* In many countries, regulations may cover such matters as dispatch, interconnection, metering, and quality of service. These regulations need to address any specific exemptions (or modifications) that need to be given to certain power generation or thermal energy technologies.

In reviewing an existing regulatory framework, or establishing a new regulatory system, it is important to determine whether the regulations meet intended policy goals. For example, if a country desires to encourage the use of renewable technologies using indigenous resources, care must be taken to assure that price and dispatch regulations do not act to prefer technologies using non-renewable resources.

3.1.3 *Privatization*

Privatization, in the classic sense of sale of government-owned utilities to the private sector, is not a necessary and essential prerequisite to success in encouraging new, privately owned electric power generation or thermal energy facilities. Certainly, constitutional and legislative provisions may need to be modified to allow for private ownership of generating facilities or thermal energy systems. But a successful private energy sector program need not wait for completion of a broad privatization program.

The critical issue is the interplay in any country between 1) the introduction of privately owned facilities and 2) the transition, through privatization, from government-owned, integrated electric or thermal energy utilities to a system of public- and privately-owned generation, transmission, and distribution systems. Development and financing of new generation or thermal energy systems is difficult during a transition period, when the identity, let alone credit quality, of the wholesale purchaser is uncertain.

3.1.4 *Environmental regulation*

An important area for governmental action involves legislative and or regulatory initiatives aimed at clarifying the environmental standards to be applied to independent power or thermal energy projects. In some countries, environmental standards are a “moving target”.

Given the inherent complexity of environmental laws, and the many difficulties that will arise in trying to interpret these laws in the absence of a lengthy history of implementation, it is important to determine the prospects for changes in environmental law that would be made applicable to projects in development or operations. At a minimum, attention needs to focus on the power or thermal energy sales contract implications of potential changes in environmental law.

3.1.5 *Commercial and tax laws*

In some countries, fundamental corporate and finance law reform is essential to facilitating private investment in power or thermal energy projects. Preferred forms of business and ownership of particular projects or operations may not be available in a given country. Some countries limit the scope of corporate activities generally, or those of foreign corporations, in ways that may not be acceptable. For example, some statutes may not allow corporate entities to be stockholders in a corporation. Similarly, corporate entities may not be allowed to be partners in a partnership. Certain entities, such as limited partnerships and limited liability corporations, may not exist under local law. Local nationals may be required to hold a part or a majority of the equity.

Tax issues arise in two contexts. First, care must be taken to identify all existing and potential local taxes, to ensure that potential sales rates and pro forma projections adequately account for the array of income, sales, excise, withholding, and import taxes characteristic of most projects. As a related point, attention has to focus on the potential risk of change of tax law. A second block of tax issues relates to the ability to implement tax structures that maximize project profitability. In part, this relates to the question of whether tax payments made to foreign tax authorities are recognized for purposes of home-country taxation of profits from project investment.

3.1.6 *Currency issues*

One potentially daunting issue faced by project developers is the risk associated with the potential unavailability of hard currency to pay for the output of the project. Unfavorable balance of trade conditions in many countries have required government officials to direct their other hard currency reserves to the repayment of long-standing foreign debt and the purchase of basic essentials (e.g., food, medical supplies, and basic manufacturing equipment).

Assuring availability of hard currency is critical to obtaining project financing, which is premised on creditworthy contractual arrangements designed to produce a firm, long-term revenue stream. If project revenues are payable in local currency, or if the country has inadequate access to hard currency, lenders will insist on appropriate credit-supports (e.g., stand-by letters of credit or parent guarantees) to mitigate perceived currency risks. Equally important, a shortage of hard currency may impair the ability of the developer to repatriate profits from the project.

An additional currency issue exists if payment is to be made in local currency. Assuming satisfactory arrangements are made for availability of hard currency, attention must also focus on potential volatility in exchange rates. This is especially important to the extent equity investors and lenders require payment in hard currency, and seek protection against local currency devaluation.

If the purchaser of electric or thermal energy prefers to pay in local currency, two related considerations arise:

- Is there a central bank commitment to making available hard currency reserves to facilitate currency conversion (or to offer inconvertibility insurance)?
- What are the consequences of changes in exchange rates?

As discussed below (Contracts and risk allocation), contractual approaches exist by which governments can provide meaningful assurance on currency issues.

3.1.7 *Guarantees of payment*

In the international context, a key issue is the practical ability of a utility purchaser of electric or thermal energy to make full payments on a timely basis. In some countries, the issue focuses on the question of availability of payment backstops, guarantees or supplemental measures that alleviate concerns about reliability of payment.

Central bank support of the payment obligation of a utility may have to be reconciled with existing constitutional and International Monetary Fund (IMF) restrictions. For example, countries with constitutional barriers on pledging of credit for private purposes may not be able to offer central bank guarantees of utility payment obligations, or, even if offered, those guarantees may cease to have legal effect if the utility is privatized. Similarly, IMF limitations on central bank borrowing or allocation of hard currency from export earnings (for purposes other than debt service) may present similar difficulties.

3.2 *Financing approaches and sources*

Geothermal energy production continues to advance in industrialized and emerging economy countries. While a variety of factors have increased the demand for new geothermal energy facilities, the relative success of a project relates to the practical availability to the project sponsors of the wide range of financing approaches, project structures, and funding sources that can be used.

One question often asked is why a particular financing approach is used for a given project. As a practical matter, a project sponsor will access those capital sources that will result in the lowest possible overall cost of capital. In some instances, such as projects involving market or technology risks, debt capital may not be available at attractive terms. Thus, the choice of project structure and capital sources will reflect an ongoing examination of the attractiveness of the project to debt and equity sources.

In a similar vein, there is no constant differential in overall costs of capital between differing financing options. Certain rule of thumb principles, of course, exist. "All-equity" financed projects in most cases will have a higher cost of capital than 100% debt-financed projects; however, an "all-equity" financing may be necessary when debt capital is unavailable (or, if available, is priced – due to financial market conditions, risk uncertainties, or otherwise – at a level too high for a project sponsor). Debt and equity capital usually has a higher cost when raised at the early development stage as compared with funds available when construction is ready to commence. Likewise, debt and equity capital will have a lower cost when a project has a favorable operating history.

3.2.1 *Traditional corporate or sovereign debt*

Through the early 1980s, power supply and thermal energy projects were financed through traditional debt financing techniques. For example, investor-owned utilities financed new power projects through a combination of newly issued corporate securities and first mortgage debt.

Government-owned electric or thermal energy utilities financed construction and operation through two vehicles. In some countries, the government-owned utility or an authorized authority issued debt that was either guaranteed by the issuing authority or secured by the revenues of the project owner (with a related obligation to charge rate payers at rates sufficient to pay the debt). In most countries, the debt (which in turn may have been borrowed from the World Bank) was backstopped by a sovereign (i.e., country) guarantee of repayment.

These traditional sources of financing improvements in the electric or thermal energy sector are not generally available to meet the full need for financing of new projects. In the power sector, one reason for the change in financing sources is the sheer magnitude of capital requirements for new projects. A government-owned utility may not have sufficient net worth to support a corporate credit financing. Another is that the borrowing capacity of the developing countries is substantially exhausted. A third is that the World Bank, which has financed or subsidized much of the electric sector of the developing world, has made a deliberate decision to greatly reduce its government-to-government lending, while promoting private sector investment in electric power generation or thermal energy technologies that are environmentally sensitive.

3.2.2 *Export credit and trade assistance*

In the past decade, project owners have increasingly focused on the availability of "tied assistance" financing in making decisions on equipment suppliers and construction contractors. The export credit agencies of Canada, France, Germany, Italy, Japan, Spain, Denmark, Sweden, and the U.S.A. have been active (in varying degrees) in offering subsidized debt financing for projects that use equipment fabricated in their country or construction contractors located in their country. In addition, specialized trade agencies, such as the U.S. Trade and Development Agency (TDA), offer financing for some of the costs of developing a project. TDA makes funds available for projects that potentially will use U.S. goods and services (and where there is the existence of competition from non-U.S. companies that are receiving financing assistance from their home country).

3.2.3 *Project finance*

The term "project finance" is generally used to refer to the arrangement of debt and equity for the construction of a particular facility in a capital-intensive industry in which the lenders look chiefly to revenues generated by the facility – rather than the general assets of the developer of the facility – to cover the repayment of the debt, and rely on the assets of the facility as collateral to secure payment of the debt. Thus, in simplest terms, project financing is essentially corporate financing secured substantially by revenue-producing contracts, rather than the credit of the developer.

In addition to the financial strength of the project itself, external credit support may be provided by the participants in the project, such as the developers, the construction contractor, the purchaser of the electric or thermal energy, or others who may benefit through the sale of equipment to the project. This indirect support may take the form of completion agreements, contracts to purchase the output, and so forth. While the objective of the project developers may be to have nonrecourse financing (i.e., nonrecourse to the general credit of the developers), that objective must be reconciled with the requirements of the lenders. Ultimately, most project financings are not truly nonrecourse throughout all phases of the project.

There are various risks in financing a project. Project financing involves identifying and evaluating these risks and allocating them appropriately. Risks can be allocated to the project developer, to another participant in the project, or to the lender. All of the parties that might be willing to accept a specific risk will have a limit as to the degree of risk they will be willing to accept and their price for doing so. In making an informed judgment on risks to be accepted, a lender attempts to understand each risk thoroughly. Specific ratios or standards that might be applied to a given category of risk may be unacceptable if they do not give proper weight to the interrelationship with other risks.

Typically, project financing is used by entities that want to achieve any or all of the following objectives: 1) elimination of, or limitation on, the recourse nature of the financing of the facility; 2) off-balance sheet treatment of debt financing; and 3) leveraging debt so that existing equity need not be diluted. Each of these objectives is briefly discussed below.

3.2.3.1 *Nonrecourse financing* The objective of project developers to eliminate the recourse nature of a financing is often an important one. Classic nonrecourse project financing provides a structure that removes the developer from any obligation to stand behind the project debt if the revenues of the project are insufficient to cover principal and interest payments on the underlying debt. The nonrecourse nature of a project financing insulates other projects and assets owned by the developer from the liabilities associated with any particular project. A typical nonrecourse loan includes a provision providing generally as follows:

"Notwithstanding any other provisions of the loan documents, there shall be no recourse against the borrower or any affiliate of the borrower nor any of their respective stockholders, agents, officers, directors or employees for any liability to the lender arising in connection with any breach or default under this loan agreement except to reach project security, and the lender shall look solely to the project security in enforcing rights and obligations under and in connection with the loan documents."

Occasionally, the terms "nonrecourse" and "limited recourse" are used interchangeably. It is important to note, however, that typically a project financing is with recourse to the developer, to a limited extent, since the developer remains liable for fraudulent representation and warranties made in connection with the financing.

3.2.3.2 *Off-balance sheet treatment of project debt* A second objective of some project financings is the off-balance sheet treatment of the nonrecourse project debt, which generally is available where the project entity is not controlled by the project promoter. The balance sheet liabilities of a project entity that is controlled more than 50% by the project promoter is consolidated on a line-by-line basis with the balance sheet liabilities of the project promoter. If this control test is not satisfied, the project promoter reflects its interest in the project entity as a line item on its balance sheet on an "equity" or "cost" accounting basis.

It should be noted that since the bankruptcy of Enron Corp. in November 2001, the structuring techniques utilized by the financial community and the rules applied by accounting profession are the focus of greater scrutiny. As a result, the market's view on the range and acceptability of off-balance sheet financing approaches is in a relative state of flux.

3.2.3.3 *Non-dilution of existing equity to finance the project* The third, and perhaps most significant, objective of project finance is to enable the developer to finance a project using highly leveraged debt. Typically, the leverage percentage is between 70 and 90%. Developers thereby obtain needed financing for a project without diluting existing equity.

The percentage of the equity contribution varies from transaction to transaction, and is influenced by many factors, including whether project participants have provided subordinated debt to the project.

3.2.4 *Financing sources – multilateral and bilateral agencies*

A variety of international and country-specific agencies provide assistance to individuals and entities pursuing power development or thermal energy projects. Among its many functions, an international agency or organization may provide direct loans or grants, help an enterprise to pursue adequate financing, and insure investments against commercial and non-commercial risks.

Several types of financing assistance and investment insurance programs are available through bilateral, multilateral (e.g., the Multilateral Investment Guarantee Agency and the International Finance Corporation), regional (e.g., the Inter-American Development Bank), export credit, and trade assistance agencies.

3.2.5 *Financing sources – commercial banks*

Commercial banks have also been lenders in private power project and thermal energy system financings. They have served as construction and take-out (e.g., permanent financing) lenders, and, less frequently, as lenders for resource evaluation and development projects (those funds most typically are provided by the project sponsors). Commercial bank willingness to finance projects in a specific country are a product of traditional project finance analysis, coupled with evaluation of lending risks in a specific country.

Financing for energy facilities typically is provided in two tranches (with, perhaps, an additional tranche available to finance resource development). The initial tranche comprises the financing necessary to construct the facility; the second and final tranche comprises the permanent financing for the facility. The construction financing is intended to fund development of the project on a relatively short-term basis. The construction lender extends this financing with the intention of being repaid in full out of the proceeds of the permanent loan at such time as the construction of the facility is completed and commercial operation commences.

The construction lender typically will loan the project developer the full amount of funds necessary to construct the project. In contrast, the permanent lender generally will be willing to loan the developer only a portion of the funds required to repay the construction lender, and will require that the balance of such funds be provided by the developer in the form of equity. To the extent that the developer itself lacks or is unwilling to invest the requisite amount of equity, it will have to be obtained from institutional or other sources. Construction lenders require that a stipulated amount of equity be firmly committed by a creditworthy equity source or subordinated lender prior to closing the construction loan.

Projects have generally relied on two forms of funding options from creditors: 1) fixed rate loans by insurance and finance companies with prepayment penalties; and 2) floating rate loans by banks at rates based on spreads over the prime rate, the London Interbank Offered Rate (LIBOR), or other established rates. Banks generally are more flexible in their lending practices and documentation provisions than insurance and finance companies, and floating interest rates generally are lower than fixed interest rates. Accordingly, the trend has been toward bank borrowings, at least during the construction period when sensitivity to rates is usually less. As increased levels of bank reserve and capital adequacy charges drive up rates available from banks, however, projects have been attracted to the commercial paper market.

Subordinated debt also serves a role in the project finance marketplace. Subordinated (or high yield) debt issues have helped the project financing market by allowing capital to be raised from funding sources with a larger appetite for credit risk of a type that used to be apportioned totally to equity owners, such as:

- Inability to provide security or liens to the creditors in a project financing.
- Accepting specific risks in a project such as refinancing, fuel, or operating risk.
- Providing part of the returns of the vendors and suppliers through the subordinated claims instead of cash payment.
- Lowering equity funding requirements.

Notwithstanding the benefits of subordinated debt, the presence of more than one class of creditors will complicate the transaction substantially.

3.2.6 *Funding sources – equity*

Private power or thermal energy projects need a substantial amount of equity. Equity investment can come from energy companies, institutional investors, such as specialized funds and insurance companies, and members of the project consortium.

Participants in project-financing transactions must be knowledgeable about the legal and business consequences of selecting a particular type of entity to own the project. The type of ownership entity selected impacts the overall project finance structure and the drafting and negotiation of project finance documentation, as well as the regulatory permitting process. For example, permits granted to a developer and later transferred to a partnership in which the developer is a partner may no longer be valid in some jurisdictions. Also by example, a contract that does not contain a full assignment clause may preclude a later transfer to a limited partnership organized as a means for the needed equity contribution. Factors that may be significant in determining the equity structure for a project financing include 1) the permissible ratio of equity to debt, 2) tax considerations affecting the project participants, and 3) concern with management of the project.

3.2.7 *Funding sources – public capital*

A number of international power or thermal energy projects have accessed the public capital markets to raise debt or equity capital. In a typical structure, the project company intends to issue securities in the capital markets in the United States, Europe, or Asia. In some countries, there may be active interest in the local stock markets for flotation of shares in the project company.

3.3 *Contracts and risk allocation*

The ability to obtain commercial agreements that support available financing options is the key to project development. And, for most developers, project financing will be the financing technique of first choice. The relationship of contracts to a project financing is straightforward the ability of the project to produce revenues is the basis of most project financings. Consequently, participants in a project financing must pay particular attention to the contracts negotiated by the project developer. Each of the underlying contracts necessary to construct and operate a project must be sufficient to support the financing structure.

The project contracts are the means by which risk allocation is memorialized in a form acceptable to lenders and equity investors. The basic risks that arise in investment in power generation or thermal energy production projects differ during the three stages of project investment: development, construction, and operation.

3.3.1 *Project risks*

During the development stage, the following risk factors pertain:

- Market risk the need for power or thermal energy (and applicable price) may change before a purchaser can be identified that will commit to a long-term contract. Similarly, the relative price advantage of a given project over alternative sources of thermal or electric energy may change over time.
- Regulatory changes - anticipated regulatory approvals may be denied, or applicable energy and environmental laws may change without grandfathering provisions, rendering the project site unusable or the project concept/structure meaningless.
- Unforeseen price increases or delay – often due to changes in market profile or interest rates, project economics can be altered in a manner that renders the project uneconomic. While other risks may pertain, these factors most often are the reason for project failure and a related write-off of investment.

At the construction phase, the potential for additional cost exposure, or incurrence of project losses, is a product of four events (as well as the continued potential occurrence of adverse regulatory or market changes, as described above).

- Cost overruns – whether due to change in law, unexpected site conditions, or contractor or equipment supplier error, construction costs can increase in a manner that jeopardizes project economics.
- Construction delays – either due to force majeure or contractor/supplier error, a project can fail to meet scheduled completion dates, requiring increased payment of interest during construction during periods of incurrence of operating losses due to minimal receipt of project revenues.
- Substandard performance – even if construction deadlines are satisfied, the completed project may not produce electricity or be able to supply thermal energy at the expected unit availability, may not produce power at the expected level of unit capacity, or may face output shortfalls due to inadequate flow or quantity of geothermal fluids.
- Finance cost increases – in a period of volatile interest rates, project debt costs (if unhedged) may fluctuate to a point that interest payments exceed projected levels.

These construction period risks can leave a project owner with the unpalatable choice of making substantial equity contributions (or loaning needed additional funds) or abandoning an uneconomic project.

At the stage of project operation, in addition to regulatory and market changes, substandard operations may jeopardize project investment. Whether due to force majeure, operator fault, or equipment failure, the power plant or thermal energy system may operate at insufficient levels of output or substandard availability. During the operation period, the project may also face risks similar to those applicable in the prior periods. Any of these adverse events could affect project economics, resulting in the same potential choice between additional infusion of capital or write-off of project investment.

3.3.2 *Risk mitigation*

At the development stage, the critical risk mitigation technique essentially relates to a combination of project selection and "off-ramp" techniques and cost controls on project expenditures. Even the best-conceived project concept may be rendered unattractive by changes in power or thermal energy markets or regulatory climate. For that reason, companies have developed exit strategies that allow for cessation of development funding in the event of project failure or unexpected project delays.

Cost controls also are a critical risk management strategy during the development period. Among other techniques, a company may require potential equipment suppliers or constructors to bear their own preliminary design costs. In addition, a joint venture partner may be required to share development costs. Because of the potential lengthy period for project development, these cost control strategies are common.

Risk mitigation techniques during the construction and operating periods essentially relate to the choice of finance strategy. As described above, project financing, as well as the related contracting approaches, have become an essential feature of energy industry risk management strategies.

Certain unique risks presented by energy project investment are mitigated through a combination of agreements with the energy purchaser, foreign government, insurance providers, and lenders. For example, change of law risks are mitigated through a combination of insurance packages, contract price adjustment provisions, and government obligations. Set forth below is a discussion of four main blocks of risk mitigation agreements: currency arrangements, governmental support obligations, power or thermal energy sales agreement provisions, and insurance packages.

3.3.2.1 *Currency arrangements* The available methods for managing currency risks can be characterized by the extent of necessary government involvement. If the government is willing to allocate sufficient funds in advance, one approach is for the foreign government to obtain an irrevocable standby letter of credit from a money center bank that will ensure payment of utility contractual obligations over the term of the financing. Similarly, a government can simply provide a sovereign guarantee of project debt. In most cases, however, governments are either unwilling or unable to dedicate hard currency reserves, or to provide direct debt guarantees. For example, arrangements with the IMF, World Bank, or other lenders could be jeopardized by the conventional approaches described above.

Another approach historically used involves currency "swap" arrangements and block fund transfers. These vehicles facilitate the availability of hard currency without the necessity for government involvement. They are most often used when companies in need of local currency or registered capital are matched, through traders, with companies needing dollars or other hard currency. This approach often amounts to trading currency in the "spot" market, however, which may be of limited assistance in a project financing.

Finally, a combination of barter and countertrade vehicles may be utilized where the government wishes to facilitate project financing while minimizing its credit exposure. Under this approach, the government agrees to make available sufficient quantities of commodity stocks that it owns or controls (e.g., sugar, cocoa) for the purpose of generating hard currency in the international markets. The project sponsor arranges for "forward sales" of such commodities to "counterparties" who will pay for the commodities in hard currency. The payments of the counterparty are deposited in a trust and then allocated to debt service, project expense distributions, payments to project sponsors, and other reimbursements as provided for in the basic contract arrangements for the project.

The need for government assurances may vary from country to country and depend on the economic cycle. Examples, such as Argentina's economic crisis in 2002 highlight the potential complexity of problems that may arise.

3.3.2.2 *Government support obligations* Government support arrangements take three forms. First, as discussed in Section 9.3.1 (Institutional framework), economic and structural reforms are put in place to facilitate private investment in the energy sector. Similarly, as discussed below, steps are taken to enhance the ability of the utility to pay for power or thermal energy deliveries. Finally, agreements are executed that delineate the extent of governmental assistance and define obligations in the event of change of law or force majeure.

Government support may be needed if the purchaser is not creditworthy in its own right. For electric generation projects, an essential feature in the success of those projects that have closed financing arrangements has been the creation of enforceable contractual commitments by the utility to provide liquidity instruments (such as letters of credit) and funding of payment reserve contingencies, all designed to assure lenders that funds will be available to the developer to pay debt service in all but the most catastrophic of situations. Often, these arrangements have been backstopped by standby payment commitments from regional or national government banks.

For power projects, a related series of approaches to facilitate purchaser creditworthiness is based on the fact that one of the reasons some foreign utilities may be deemed to have less than investment-grade credit is that prior government policies have caused these utilities to sell electric energy at below the marginal cost of generation and transmission. However, the decision of a government to subsidize service to one segment of the customer base of the utility does not mean the entire customer base is incapable of paying for services priced at or above production costs. In other words, if part of the customer base of the utility is comprised of large, reliable, creditworthy customers, the electric energy sales contract can be structured to channel payments from such customers to private developers. A variation on this approach is for electricity to be sold directly to end users who are creditworthy purchasers.

The contract entered into between the host government and the project sponsor is typically referred to as the "Implementation", "Cooperation", or "Coordination" agreement. Traditionally, this document has been used to memorialize transfer arrangements (after lenders and equity have received their anticipated return on investment) for BOT projects, to confirm that the plant, equipment and spare parts of the project will not be subject to governmental import controls or excessive duties or tariffs, to ensure the availability of foreign exchange and provide protection against devaluation, to specify tax treatment, and to acknowledge rules governing employment of domestic and foreign nationals.

In the context of currency risk mitigation, government participation has taken at least two forms. In the case of countries that lack readily convertible currencies, the Implementation Agreement has been used to memorialize the commitment of the government to make forward sales of state-owned or controlled commodities (e.g., sugar cane) or to pledge revenues from utility sales to industrial customers for payment pursuant to the energy sales agreement. Where the host country is willing to provide credit support in the form of a liquidity commitment (e.g., letter of credit), the Implementation Agreement may also serve to establish the government's obligation to issue such instruments through the central bank or other financial institution.

Other provisions of the Implementation Agreement accomplish the following purposes:

- Grant a concession to use natural resources (unless covered by a separate concession agreement).
- Clarify and confirm legal authority to engage in the generation, transmission, or distribution of electricity or thermal energy.

  Acknowledge authority to do business (including confirmation of legality of ownership vehicle and restrictions, if any, on change of ownership or control).
- Memorialize authority to sell electricity or thermal energy (including right to obtain water supplies for power generation) and to use energy resources (if the energy input is owned or controlled by the government).
- Guarantee performance of government-owned water and back-up energy suppliers, if any.
- Guarantee the payment obligations of government-owned purchasing utilities (or acknowledge back-up support arrangements such as escrowed funds and letters of credit).
- Identify required governmental approvals and mandate governmental support in expeditious processing of permits.
- Specify consequences of change in law and sustained force majeure periods (e.g., tariff adjustments or government obligation to buy the facilities at a price that retires debt and provides return of equity).
- Provide protection against uninsurable force majeure events, such as war, insurrection, terrorism, general strikes, and natural events as to which a country may be especially vulnerable (e.g., floods and cyclones).
- Delineate tax and customs status (with acknowledgment of specific effects of change in law).
- Specify procedures for resolution of disputes when government agencies have competing interest (an occasional problem when the interests of a government-owned energy purchaser differ from that of the government entity that owns or controls the geothermal resources).
- Establish procedures governing availability of foreign exchange, convertibility protection, and exchange risk coverage.
- Clarify immigration procedures.
- Provide a covenant against expropriation and assurance of no discriminatory action.
- Removal of foreign ownership limits.

These covenants are often requested by sponsored power projects. Although not every project will have an Implementation Agreement, project sponsors, investors, and lenders will seek assurances that these matters are covered in binding agreements or applicable laws.

3.3.2.3 *Energy sales agreement provision* In power project financings of energy facilities, the power sales or thermal energy sales agreement represents the primary source of revenue for the project. Unless the sponsor and its funding sources are willing to bear market risks, the agreement must obligate the energy purchaser to purchase enough power or thermal energy from the project to support the project debt. A firm commitment at a specified revenue level or levels, not subject to material changes or offsets, is the classic technique to mitigate market risks. A commitment to take if delivered, subject at most to very narrow maintenance and emergency exceptions, is a preferable approach.

The key contract terms and mitigation approaches are identified below:

- Term. It is important that the contract have a term that is sufficient to support the financing. The term also must fit with the schedule of projected construction and operation.
- Prices. The basic goal of the energy sales agreement is to establish a firm commitment to purchase power or thermal energy, at a specified revenue level or levels, and without the possibility of material changes or offsets. The absence of a firm price for the output of the project could lead to instability of the revenue flow. Pricing may take the form of a capacity charge (sufficient to cover fixed costs) and an energy component (to cover variable costs).
- Conditions. Conditions precedent to the obligation to the purchaser to purchase the energy output should be minimized.
- Termination. The grounds for termination should be narrow in scope. The energy sales agreement should give a successor party the right to continue performance in the event of a bankruptcy.
- Force majeure. The ability of the purchaser to terminate or modify the energy sales agreement in the event of governmental action should be eliminated, and the obligation to continue capacity payments (at a level sufficient to cover debt service) should be clarified during force majeure periods.
- Government jurisdiction. The energy sales contract should not contemplate continuing governmental review of the contract.
- Operations. The energy sales contract should contemplate the details of interconnection requirements and charges, design and construction requirements, equipment and metering, and continuation of service if an outage occurs.
- Additional capital or operating costs. Energy sales agreements must be examined for potential imposition of additional capital or operating costs. Of course, other contract provisions may also provide risk mitigation objectives. In the international market, a preferred, but less common approach, is to obtain such clauses as price adjustment provisions that adjust the energy sales rate to accommodate changes in project economics due to changes in environmental laws.
- Currency mix. Rates may be payable in a basket of currency that reflects the mix of currencies in which the project's obligation (e.g., operations, debt service, profit) are payable.
- Currency fluctuation. The rate may be subject to change to reflect changes in exchange rates.
- Change of law. To the extent changes in law (e.g., tax laws or environmental rules) require construction of additional facilities or incurrence of increased expenses, the rate may be subject to adjustment.
- Disputes. The experiences of corporate investors caught up in Argentina's economic crisis in 2002 demonstrate that it is important for investors to nominate an appropriate forum for international arbitration. Project sponsors will need to weigh the comparative benefits of alternative fora for dispute resolution.

As discussed above, related matters may be covered in the Implementation Agreement.

3.3.2.4 *Insurance packages* Many techniques exist to deal with overall country risks. The underlying concerns include political instability, war, terrorism, unknown legal requirements, change of law, currency convertibility, and unknown conditions for performing the work.

As discussed above, certain of these risks can be dealt with contractually. In many foreign projects, the Implementation Agreement incorporates the government's granting of certain protection and assurances. Certain risks, however, cannot be adequately covered by contracts with other parties. A primary example is casualty losses. The primary means of addressing these risks is through insurance. For example, all-risks insurance and business-interruption insurance are the principal protection against casualty losses and attendant loss of revenues.

In the international context, political risk insurance is available from a limited number of sources to offset certain risks. The basic risks covered are expropriation, currency inconvertibility, and breach of contract by governmental bodies.

In the wake of the September 11, 2001, terrorist attacks in New York City and Washington, D.C., terrorism insurance has become a subject of renewed importance, not just in relation to projects located in the U.S., but on a worldwide basis. Whereas terrorism was once included in general casualty insurance policies, the heavy losses suffered by the insurance industry as a result of the September 11 attacks has led to the creation of terrorism insurance as a separate, and often expensive, policy which financiers frequently require project sponsors to obtain. The cost and availability of terrorism insurance has therefore become an additional factor to be considered in relation to project budgets and financing.

3.3.3 *Other project agreements*

Consummation of the project financing of a power plant or thermal energy system requires that the developer obtain all permits necessary for the construction of the project, and that all of the contractual arrangements relating to development of the project be negotiated and executed. The purpose of obtaining the permits and entering into the agreements is to ensure the project lender that it may advance funds to the project with a high degree of confidence that the project will be successfully developed and implemented. A brief description of site selection, permitting, and construction issues is set forth below.

3.3.3.1 *Site selection and permitting* Among the most fundamental aspects of any project financing are those involving site selection and permitting. Lenders typically are unwilling to fund project construction unless they are assured that the developer had definitive control of the project site and has in hand all permits necessary to initiate construction of the project. A key permitting consideration for power supply projects, of course, is receipt of sufficient rights to obtain, transport, and use fuel for power generation. The developer may establish its control over the site either by acquiring the site directly, or entering into a long-term lease. Whichever alternative is selected, the lender will require appropriate evidence of ownership, title insurance, and appropriate mortgages or other security arrangements granting the lender a first lien security position with respect to all real property comprising the project.

When power facilities or thermal energy systems are built in industrial areas, environmentally related issues frequently arise in connection with the site acquisition process. Lenders will require appropriate assurances that by lending to the project, they will not incur any liability under applicable environmental laws, either by virtue of their security interest in the real property comprising the facility or as a result of any foreclosure on that interest. It is now routine for lenders to condition the availability of their financing on the availability of a satisfactory environmental audit of the project site. Such audits are commonly provided by firms specializing in environmental analysis.

Lenders also will not finance project construction unless all permits necessary to begin operation of the project have been obtained, or evidence exists that they can be obtained prior to operation. The permits required would include air quality permits, waste disposal permits, and water discharge permits. In addition, all required regulatory filings for power or thermal energy sales must be in place.

3.3.3.2 *Construction contract* Certain provisions of the construction contract are important in energy project development. Key provisions of construction contracts that need to mesh with the energy sales contract include the following:

- Fixed price. The contractor may agree to perform to construct the facility for a fixed price, which must apply regardless of the actual price of construction.

- Completion date. The contract may establish the date by which construction of the project is to be completed. The contractor typically is subject to penalties in respect of a failure to complete the project in a timely fashion in amounts sufficient to pay the additional interest on the construction debt resulting from the failure of timely completion. In addition, contractors may be entitled to bonus payments for early completion of the project.
- Project acceptance. The construction contract normally establishes a set of operating standards that must be satisfied by the project before it will be subject to acceptance by the developer. If the project does not meet the contractually-established performance standards, the contractor usually is required to pay damages to the developer and lender in amounts intended to compensate them for the increased construction cost and/or lost energy sales revenues resulting from the failure of the facility to operate at the specified performance levels.
- Warranties. The contract should provide performance warranties on workmanship, engineering, and mechanical parts providing for replacement of defective parts and repair of defective work for a specified time-typically two years-at no cost to the developer.
- Bonding. Bonding may not be required of very large and financially strong construction companies. All other construction companies, however, typically are required to post payment and performance bonds for the full amount of the construction contract, which are payable to the developer and lender in the event of default by the contractor.
- Insurance. Risk of loss pending completion of construction typically is placed on the contractor, which must insure the project in amounts equal to the full replacement cost of the facility. The contractor also must provide appropriate liability insurance for the construction.
- Retainage. Construction contracts generally provide for payment of the contractor in a series of installments coming due as construction milestones are achieved. Ordinarily, however, the contractor will not be paid a certain portion of each milestone payment until final satisfactory completion of the project. The amount of the retainage is typically from 5–10% of each construction draw.

3.3.3.3 *Enforceability* In the end, contracts are only as good as their enforceability. It cannot be taken for granted that laws of the host government will assure that contractual provisions are enforceable. Some questions relate to formal legal rights, such as the ability to perfect security in revenues in accounts or revenues subsequently realized. Other legal issues may relate to issues of when ownership interests vest. There may also be issues as to whether a "foreign" lender may enjoy security interests in a collateral package.

Legal steps can be taken to improve the position of a developer. For example, choice of law clauses, international arbitration procedures, and waivers of sovereign immunity are critical. But the ultimate protection is a well-conceived project, one that will make economic sense over time, and one with the proper mix of local support (including local partners) to best ensure long-term viability.

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SELF-ASSESSMENT QUESTIONS

1. What are the primary factors affecting project economics common to all forms of geothermal development, whether power production or direct use applications?
2. The fuel for a geothermal facility (i.e., the geothermal resource) is similar to oil, gas, and biomass in terms of its availability and cost. True or false?
3. Explain the similarities or differences between the fuel for a geothermal project and fuels such as coal, gas, oil, and biomass.
4. Why are productivity and longevity of the geothermal reservoir so critical to obtaining project financing?
5. Explain why detailed data collection and accurate data analysis and interpretation are so important.
6. What are the primary factors that result in significantly higher capital cost for a binary plant vs. a steam cycle plant?
7. Why do binary plants have significantly higher parasitic loads than steam cycle plants?
8. Why does the power sales contract play such an important role in influencing power plant design?

9. Name one mechanism that can be used in the equipment procurement process to ensure steam use efficiency.
10. What is partial-arc admission and how does it contribute to plant operating efficiency?
11. The design of the cooling tower is simply a matter of personal preference and has no impact on cost or operation. True or false?
12. In a steam cycle plant, a turbine by-pass plays a significant role in environmental compliance but plays no role in plant availability. True or false? Explain your answer.
13. Many direct use geothermal projects depend totally on geothermal to meet thermal demand. What effect on economics would meeting peak demand with a fossil fuel-fired boiler have and what other reasons can you give for considering this approach?
14. What technology allows geothermal resources to be used to provide cooling?
15. From which sources does revenue generation come from in 1) electric generation, and 2) two direct use applications?
16. What factors are critical to ensuring that a generating plant produces maximum revenue?
17. Why are operation and maintenance important not only to revenue generation, but also to the obtaining of financing?
18. Geothermal power plants are generally considered to be base load units. However, certain factors may make load following or even operating in a dispatchable mode necessary or economically attractive. What are these factors and what design consideration should be taken into consideration to ensure maximum operation flexibility and fuel-use efficiency?
19. Why is revenue potential for such direct use applications as greenhouses or industrial processing almost entirely independent of the viability of the geothermal system?
20. Because thermal sales from a district energy application are very weather-dependent, what contractual provision ensures that revenues will equal or exceed the cost of providing service?
21. When should cascading be considered and what impact can it have upon project economics?
22. Explain why policy reform may be critical to the success of governmental efforts to encourage private sector development of geothermal facilities.
23. What is a BOT project?
24. Under what circumstances may "payment backstops" be necessary?
25. How does "project financing" differ from conventional means used to finance energy projects?
26. What are examples of market risk, and at what stages of project development can they arise?
27. What is an Implementation Agreement?
28. How do Energy Sales Agreements serve to mitigate market risks?

ANSWERS

1. The primary factors include a) fuel supply, b) design and construction, c) revenue generation, and d) financing.
2. False
3. Geothermal "fuel" is available only after extensive exploration and development drilling. It cannot be transported over long distances, cannot be purchased on the open market, or legislated into existence.
4. The ability to generate revenue to cover financial obligations is totally dependent upon an adequate fuel supply over the economic life of the project.
5. Detailed and accurate data are critical to making decisions concerning project design, operation and maintenance, and documentation to potential financiers that the project will be able to meet its financial obligations over the economic life of the project.
6. The heat exchangers, air-cooled condensers, well pumps, and circulating pumps.
7. Because of the need to pump the geothermal fluids under pressure through the heat exchanger, and the need to pump the working fluid through the heat exchanger and to the turbine.

8. The power sales contract establishes terms of payment including all incentives and/or penalties.
9. The use of procurement evaluation criteria that penalize offering for inefficient use of steam.
10. Partial-arc admission refers to a turbine design that allows for steam to enter the turbine through differing portions of the turbine blade sets and allows for the turbine to be operated at various steam pressure levels and at different outputs.
11. False.
12. False. The turbine bypass also allows the plant to come back on-line more quickly after a forced outage.
13. The use of a fossil fuel-fired boiler to meet peak demand could dramatically reduce the number of wells that would be required, as well as allow for the use of smaller diameter piping. Other benefits would include a secure back up and the ability to meet temperature requirements in excess of that available from geothermal.
14. Absorption chiller.
15. 1) The sale of electricity and, possibly, thermal energy from cascade users. 2) Thermal sales, product sales (e.g., flowers or plants from a greenhouse), and value-added service (e.g., vegetable dehydration).
16. Ability to meet the conditions of the power sales contract including flexibility of operation, a high level of availability, and sound operation and maintenance procedures and practices.
17. Financiers look very closely at the operation and maintenance team because of the critical role sound operation and maintenance practices have upon the capacity and availability of a facility, and, hence, the potential of a facility to generate revenue over the economic life of the project.
18. Both contractual provisions of the power sales contract and/or reservoir concerns can provide incentives for operating in a load-following or dispatchable mode. Design consideration includes use of redundant equipment, use of a turbine bypass, partial-arc admission, computerized well field operation, and remote operation.
19. Revenue generation for these projects is dependent upon the sale of a product (e.g., vegetables) or providing a value-added service (e.g., lumber drying).
20. Thermal sales contracts should contain both capacity and variable-cost provisions. The capacity portion of the bill should be sufficient to cover debt service where other costs such as O&M and fuel make up the variable-cost portion of the bill.
21. Cascading should always be considered and can often serve as a secondary source of revenue generation.
22. The country may not have yet in place laws and regulations that are conducive to long-term investment in the energy sector.
23. A build-operate-transfer project.
24. A payment backstop, such as a letter of credit or central bank guarantee, may be necessary if the energy purchaser cannot provide meaningful assurances of its practical ability to make timely payments for delivered electricity.
25. Unlike sovereign-guaranteed financing (where the government guarantees debt payment) and corporate finance (where the sponsor pledges its corporate assets as security for the loan), the lender in a project financing looks solely to the revenues to be produced from the project being financed, and the underlying contracts and physical assets, as security for repayment.
26. Market risk can exist due to changes in the near-term and long-term need for energy of the energy purchaser. Market risk can also arise from changes in the prices a purchaser is willing (or able) to offer to suppliers from new facilities. Market risk can exist at the development, construction, and operation stages.
27. An Implementation Agreement is a contract by which the government makes certain commitments to a project sponsor in order to facilitate project development, financing, construction, and operation.
28. An Energy Sales Agreement serves to mitigate market risks by establishing the contract term, purchase price, and sales quantity.

Geothermal Energy Resources for Developing Countries, Chandrasekharam & Bundschuh (eds)
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Resources and policy of geothermal energy in Central America

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ABSTRACT: During the next decades Central American electricity demand is expected to increase at an annual rate of about 6% due to a growing population and expanding economies. This will require the development of more reliable and environmentally sound electrical systems. However, the region is becoming more and more dependent on imported fossil fuels and on hydroelectric projects highly susceptible to climate events. Little or no consideration is given to the abundant and much more reliable indigenous and environmentally friendly geothermal energy resources. Thus, in 2002, electricity production in the region is dominated by hydroelectric generation (50%), followed by thermal (41%) and geothermal (7%). Opportunities as well as hurdles to the exploitation of geothermal energy for a sustainable economic and social development are discussed within the framework of the ongoing deregulation of national and regional electricity markets. Physical, economical and political limitations, potential markets, economic and social and environmental benefits of geothermal resource development are analysed and compared against those of conventional and other renewable energy sources that are being used in the region for electricity generation.

1 INTRODUCTION

The decade of the 1990s brought peace and significant economic growth to the Central American region (Table 1). Actual problems, which face the Central American countries are: account deficits, dependence on multilateral aid, high debt burdens, slow movement on economic and land reforms, financial sector problems, relatively high oil prices and correspondingly high import bills as well as low prices of agricultural products and hence low export bills.

Table 1. Demographic and economic indicators for the Central American countries.

	Guatemala	Honduras	El Salvador	Nicaragua	Costa Rica	Panama	Total
Population (million) July 1999e[1]	12.336	5.997	5.839	4.717	3.674	2.229	34.729
population (million) July 2001e[2]	12.974	6.406	6.237	4.918	3.773	2.846	37.154
Real GDP in current prices (2001)							
Total (billion US$) 2001[3]	18.7	6.1	13.9	2.5	16.7	10.2	68.1
Per capita (US$) 2001[3]	1512	872	2087	486	4266	3463	1833
Growth (%) 2001e[4]	2.0	2.5	1.5	2.0	0.3	0.7	1.3
Inflation rate (%) 2001e[4]	9.8	9.0	3.0	5.8	11	0.7	7.1
GDP – PPP (Purchasing Power Parity)[2]							
Total (billion US$) 2000e	46.2	17	24	13.1	25	16.6	141.9
Per capita (US$) 2000e	3700	2700	4000	2700	6700	6000	3819
Real growth rate (%) 2000e	3	5	2.5	5	3	2.5	3.3
Inflation rate (Consumer Price Index, CPI) (%) 2000[2]	6	11	2.5	11	11	1.8	4.6
Electrification (% of population)	56	50	65	52	80	67	59
Total electricity production 2000 (GWh/year)	5348	3547	3327	2265	6935	6691	28,090
Electricity demand growth rate forecast 2000 2020 (%/year)	8	7 to 10	4.1 to 7.35	6	4.8 to 6.1	6	∅ 6
Estimated economic available geothermal potential (MW)[4]	3320	990	2210	3340	2900	450	13,210
Installed geothermal capacity 2002 (MW)	29	0	161	70	143	0	403

[1]Central Intelligence Agency 2000, [2]Central Intelligence Agency 2001, [3]IMF 2002, [4]advanced technology potential: Gawell et al. 1999; e – estimated.

A further economic and social sustainable development requires regional integration towards common stable markets, which would improve future confidence in the economic, social and political stability of the region and which would attract international private sector investors. The national and regional development requires the substitution of oil and natural gas imports for power generation by nationally available energy resources. New markets, like environmental services and tourism, must be developed and strengthened. This is especially true about the tourism sector which, for example, in the case of Costa Rica has become the principal industry of the country, and opens many possibilities for further market development in the entire region. A precondition for the development of that sector is the protection of the environment to preserve the rain forests and their important biodiversity, which are the main attractions for the tourists. Therefore, the development of different renewable energy resources in a well-balanced mix, as part of a sustainable development program, will not be only a possibility but a necessity.

Growing population, expanding economies and new markets, will all contribute to an increase in electricity demand at an annual rate of about 6% through the next decades. This will require the development of more reliable and environmentally sound electrical systems to reduce power blackouts and rationing of electricity, both very common in some of the countries. Additionally, the integration of the electricity systems to develop a regional wholesale market is required. The large investments required for this purpose call for a partnership between the public and private sectors. Private investments in the region's electricity system vary from country to country, and in general have been on the increase.

Central America is an excellent candidate for geothermal power development. Its location in the so-called "Ring of Fire", the geological active region around the Pacific Ocean, makes it an optimal region for high-enthalpy geothermal resources. Gawell et al. (1999) estimates that the maximum electrical generating capacity of the region is about 8.8 GW using today's technology, and about 13.2 GW capacity using "enhanced technology" for power generation. The high-temperature geothermal areas are found in the narrow band roughly parallel to the Pacific coast, which is marked by the occurrence of numerous volcanoes (Fig. 1). With the exception of Belize

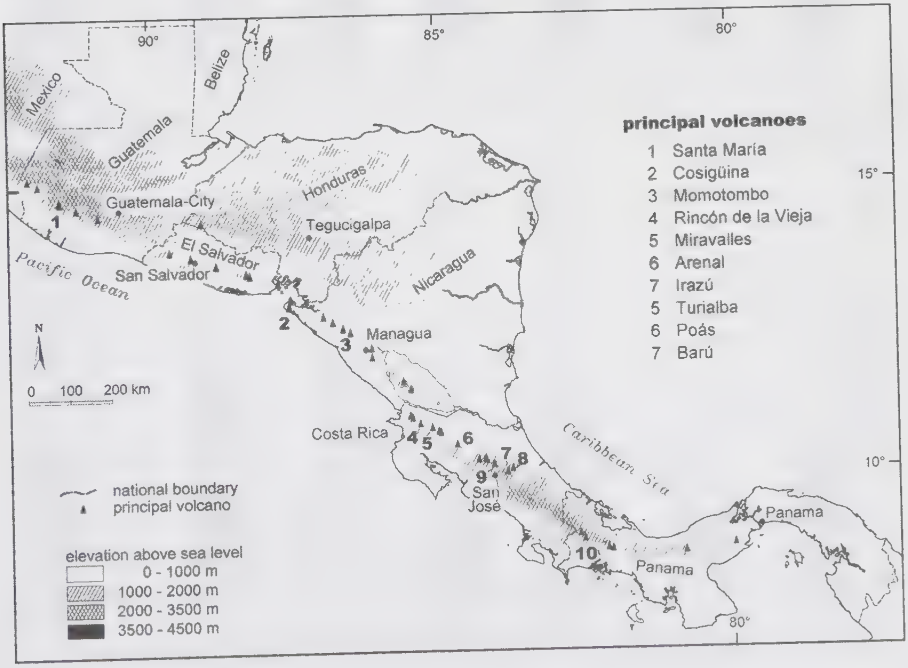


Figure 1. The Central American region and its principal volcanoes.

and Panama, all other energy sources, which are presently used for electricity generation, could theoretically be substituted by geothermal energy. Both of these countries have little or no geothermal energy resources, but transmission lines could be used to transfer geothermally generated electricity from other parts of Central America.

At present, the sustainable development of the region's huge geothermal energy resources, both for power generation and direct use, is far from complete. In 2002, fifty percent of Central American electricity was produced by hydroelectric projects, followed by thermal (41%) and geothermal (7%); the energy mix (i.e., installed capacity and electrical generation) is shown in Figure 2. Based on the experiences from the 1980s droughts, which affected the security of supply, the share of thermoelectric generation was increased during the last decade. This was done in spite of a lack of significant oil and gas fields in the region: Guatemala, is the only country with oil resources. All fossil fuels must be imported, mostly from Mexico and Venezuela.

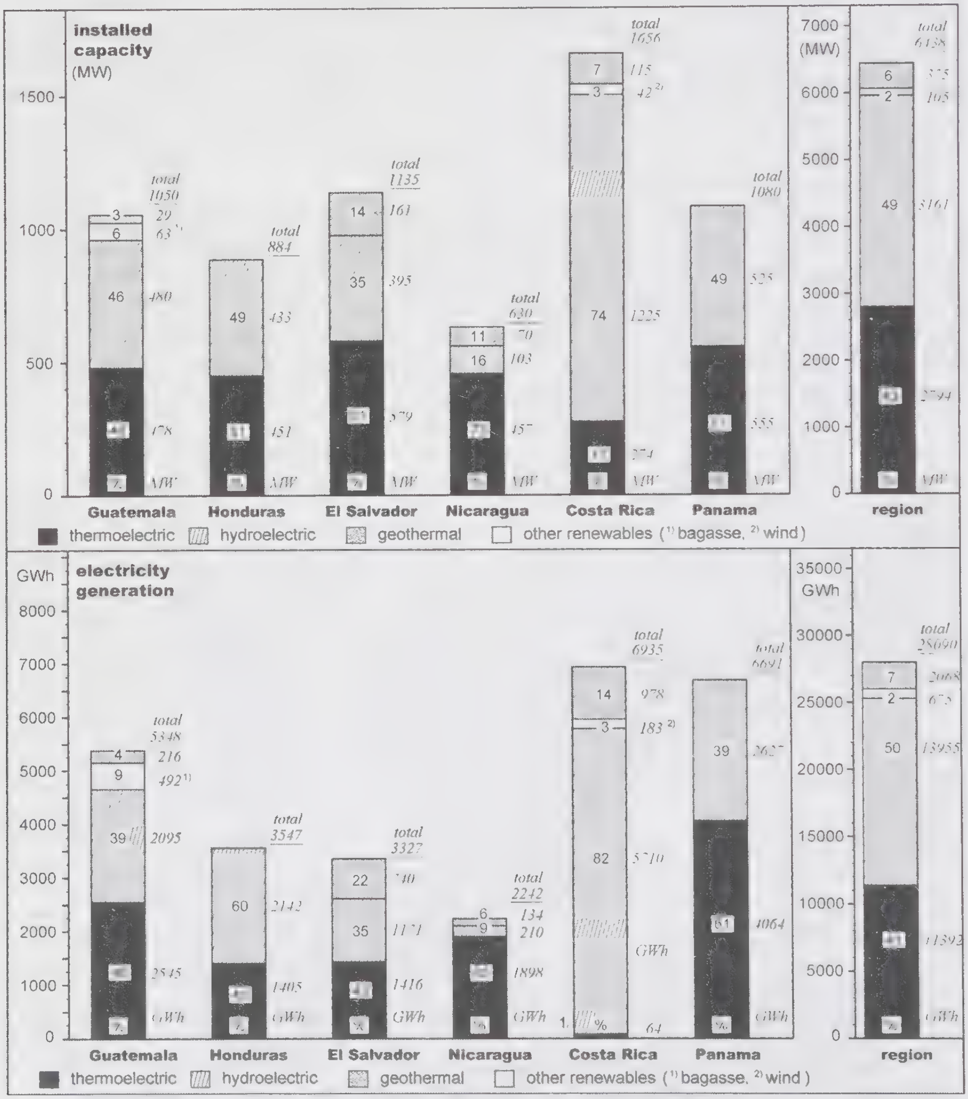


Figure 2. Sources of installed capacity and electricity production in 2000.

Instead of accelerating the development of indigenous, renewable energy resources, El Salvador, Honduras and Nicaragua have become more dependent on imported fossil fuels to supply their growing electricity demand. On the other hand, Guatemala is focusing on a large increase of hydroelectric power production, and Costa Rica is depending on an over-developed hydroelectric power program. This makes both of these countries very vulnerable to droughts and other natural phenomena. Geothermal energy, an alternative to hydropower, which is not dependent on climatic events, has yet to receive the attention it deserves.

The purpose of this chapter is to analyse the possibilities, opportunities, obstacles and needs of promoting environmentally friendly geothermal energy for a sustainable economic and social development of the Central American region. Physical, economical and political limitations, potential markets, and economic, social and environmental benefits of geothermal resources shall be discussed and compared with other conventional and renewable energy sources used in the region for electricity production at the present time. These issues are addressed in the frame of ongoing regionalisation, deregulation and related increase of private sector participation, while taking into consideration the national demand and energy plans of the different countries. Therefore, not only large-scale power generation, but also rural electrification based on small geothermal plants and direct-use opportunities will be discussed.

The characteristics of the Central American countries are presented using a regional approach, rather than by single country updates. Thereby, the countries (with the exception of Belize) will be referred to as the "Central American region" or the "region". This approach takes into account the ongoing liberalisation and restructuring of national energy markets and the activities to implement a regional electricity market.

2 GEOTHERMAL POTENTIAL AND ACTUAL USE

The Central American countries have huge economical accessible geothermal reserves of at least 6820 MW (today's technology potential, Gawell et al. 1999) (Fig. 3). National estimates are more

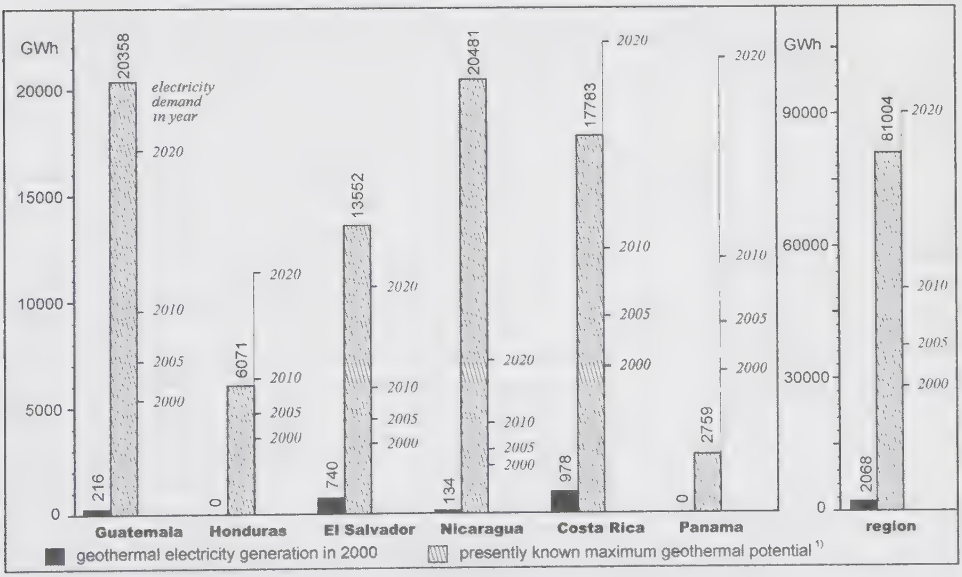


Figure 3. Central America. Geothermal electricity generation and power demand in the year 2000 compared to future demand forecasts and estimated maximum geothermal potentials: [1]Geothermal potentials are calculated from estimates from Gawell et al. (1999) and a plant capacity factor of 0.7.

conservative (Guatemala and Costa Rica about 1000 MW each, El Salvador 600 MW). The estimate of Gawell et al. corresponds to a geothermal electricity production of 42,000 GWh/year, and is equivalent to the burning of 3.7 million tons of fuel oil/year or 7.1×10^{12} m^3/year of natural gas. This potential geothermal generation is about 2 times higher than the power consumption of the region, which was 28,090 GWh/year in 2000. Considering an energy demand growth rate of 6% per year, these reserves would be able to cover the power demand of the region for the next two decades solely. The future introduction of the binary fluid technique, which makes geothermal resources of lower enthalpy suitable for power production, would double this potential. Additionally it must be considered that the aforementioned geothermal potential comprises only the actual known geothermal reserves, whereas the real regional reserves are expected to be even higher.

3 ECONOMIC, ENVIRONMENTAL AND SOCIAL BENEFITS OF GEOTHERMAL ENERGY DEVELOPMENT FOR CENTRAL AMERICA

3.1 *The economic asset value of geothermal energy*

Geothermal power plants use indigenous renewable energy resources, whereas almost all fossil fuels consumed in Central America must be imported, although Guatemala produces some oil. The development of the region's geothermal resources could help reduce the growing trade deficit and external debts. Both will become bigger as the demand for electricity continues to increase, unless the energy mix for electricity production (presently about 41% based on fossil fuels) is changed towards indigenous energy resources.

To estimate the economic asset value of geothermal in the region, the presently known geothermal energy reserves are calculated in terms of fuel oil and natural gas equivalents. Table 2 illustrates the importance of geothermal energy as a national and regional energy resource.

Table 2. Central American geothermal energy reserves and their economic value.

	Guatemala	Honduras	El Salvador	Nicaragua	Costa Rica	Panama	Total
Economic available geothermal capacity[1] (MW)	3320	990	2210	3340	2900	450	13,210
Potential geothermal production[2] (GWh/year)	20,358	6071	13,552	20,481	17,783	2759	81,004
Fuel oil equivalent (10^6 tons/year)[3]	1.79	0.53	1.19	1.80	1.56	0.24	7.11
Natural gas equivalen (10^9 m^3/year)[3]	2.10	0.63	1.40	2.11	1.83	0.28	8.35
Asset value (10^6 US$/year)[4]	196	59	131	198	172	27	781
Asset value per capita (US$/year)[5]	15.1	9.1	21.0	40.2	45.5	9.4	21.0
Asset value as percentage of GDP	1.05	0.96	0.94	7.9	1.03	0.26	1.15

[1] Maximum advanced technology potential (Gawell et al. 1999); [2] based on a plant capacity factor of 0.7; [3] fossil fuel heat value 11.4 MWh/t fossil fuel; natural gas 9.7×10^{-3} MWh/m^3 natural gas (Organisation of American States 2001); [4] based on a fuel oil price of 110 US$/ton; [5] based on 2001 population and GDP numbers given in Table 1.

Using a fuel oil price of 110 US$/ton, the annual economic asset value of Central American geothermal reserves is about 1.2% of the region's Gross Domestic Product (GDP). This value will increase with the price of fossil fuels.

The important economic benefits of geothermal energy development can be shown for the case of Nicaragua, the poorest country of the region. Nicaragua spends about US$ 95,000,000 per year to import oil for electricity generation, which amounts to about 4% of its GDP (73% of the installed capacity corresponds to thermal plants). Geothermal power plants could rapidly displace all thermal plants and improve the country's foreign trade balance. The development of Nicaragua's geothermal resources would not only solve its energy supply problems, but would also allow the export of electricity to the rest of Central America. This option would benefit from the construction of the Central American electrical interconnection line (SIEPAC). Another example is Guatemala, the only country in the region with oil reserves. Guatemala could replace its thermal plants with geothermal units and export the locally produced oil, or use it to refine transportation fuel, to improve its foreign trade balance.

3.2 *Environmental and social economic benefits through emission reduction*

Geothermal is a clean energy source, which could significantly contribute to the reduction of greenhouse and other gas emissions by replacing fossil fuels. The emissions of CO_2, sulphur oxides (SO_x) and nitrogen oxides (NO_x) from a geothermal plant, are less than 2% of the emission from an oil-fuelled power plant (UNFCCC 1997). On average, a geothermal plant emits 0.893 kg CO_2/MWh, whereas an oil-based plant, 723 kg CO_2/MWh (diesel fuel emission factor; UNFCCC 1997). For SO_x these values are 0.16 kg/MWh (geothermal) and 4.99 kg/MWh (oil fuelled plant; UNFCCC 1997).

To determine the economic value and importance of this reduction for the Central American countries, the present and future emissions of thermal power plants were estimated. The forecasts are based on the national energy plans, and where these are not available, predictions are made assuming an annual growth rate, no change of the source mix and the same technologies as presently used. The results for the 2000–2020 period are given in Figure 4. The figure clearly shows the exponential growth in gas releases. Under the assumption that CO_2 emissions in the region will increase at an annual rate of 6%, they will raise from the present (about) 10 million tons to 30 million tons in 2020 and 96 million tons in 2040.

Figure 4 also indicates the geothermal potential of all the countries in the region, clearly showing that fossil fuels used for power production could be completely substituted. One should remember that forecasts of electricity demand growth are quite reliable, but that uncertainties associated with the regional projects like the planned Central American SIEPAC electricity interconnection and long-distance gas pipelines, may significantly change the type of fuels used by the different countries and the region.

The planned El Hoyo-Monte Galán geothermal development in Nicaragua illustrates the potential reduction in CO_2 emissions. During the 38 year lifetime of the project (annual generation: 520,000 MWh), carbon dioxide releases to the atmosphere would be reduced by 14 million tons when compared to fossil fuel fired plant of similar capacity (UNFCCC 1997).

Environmental and social economic benefits are derived from the substitution of fossil fuels with clean energy sources. The burning of fossil fuels releases large amounts of CO_2, SO_2 and NO_x gases and solid particles into the atmosphere. Reductions of such emissions have a monetary value. Average environmental benefits, defined as CO_2 emission reduction costs, vary between US$ 5 and 10 per ton of CO_2; social benefits are defined by the reduction of SO_2 and NO_x emissions. On the basis of the forecasts given in Figure 4, in the year 2020 the region may reduce its CO_2 emissions by 65 million tons if geothermal units substitute thermal plants. This results in direct financial benefits (not including ancillary benefits) of US$ 325 million or 0.35% of the region's GDP. The 2020 GDP is calculated from the 2002 GDP (Table 1) assuming an average annual GDP growth rate of 1.3% and a CO_2 allowance cost of US$ 5 per ton.

3.3 *Comparison of impacts and natural vulnerability of hydropower and geothermal projects*

3.3.1 *Climate related risks, environmental and social impacts*

A number of Central American countries, especially Guatemala and Costa Rica, plan to build large hydroelectric projects in spite of some uncertainties regarding the future of hydropower in the region (Table 3). There are concerns over the viability of these projects in areas prone to heavy

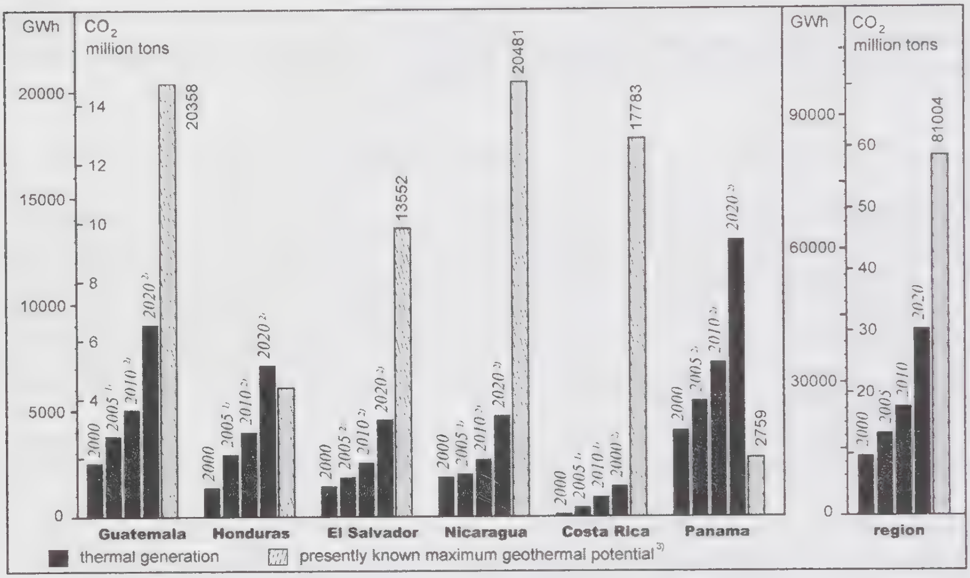


Figure 4. Present and future thermal electricity production and corresponding CO_2 emissions. [1]Based on the energy plans of the individual countries, [2]based on a 6% annual growth in power demand and generation, and assuming that the energy mix will remain constant, [3]maximum advanced geothermal technology potential (Gawell et al. 1999).

Table 3. Comparison of potential impacts and risks associated with hydroelectric and geothermal power projects.

	Large hydroelectric projects	Geothermal projects
Critical construction components	Dam, lake	Wellfield, power plant
Vulnerability, risks	Seismic, dam failure, landslides, high climate dependency	Volcanic and seismo-tectonic
Designed project lifetime	About 40 years, but possible up to 100 years (or more)	25–40 years or more (under sustainable exploitation)
Environmental and social impacts	Microclimate change (evaporation), large extension, visual impact (positive/negative), flooding of agricultural or natural sensitive areas, relocation of local population	Microclimate change (heat emission into atmosphere), air quality change (H_2S, CO_2, steam emissions into atmosphere), visual impact, small extension (positive)

rain and flooding. For example, after two weeks of rainfall and flooding, 100,000 persons had to be evacuated from areas downstream of the El Cajón, Honduras, hydroelectric project in September 1999. On the other hand, period of droughts or low and variable rainfalls can greatly reduce hydroelectric outputs and send power prices higher during times of peak demand. This calls into question the reliability of hydropower as a continuous, baseload energy source.

The susceptibility of these projects to climatic events is one of the dangers of relying too much on hydropower to supply the electricity needs of a country or region; El Cajón generates 60% of Honduras' electricity and Honduras has suffered from electricity rationing in recent years.

In El Salvador, hurricane Mitch caused a landslide that hit a two-phase pipeline between two wells in Berlín geothermal field, and the pipeline took the hit without breaking. The greatest damage in the country was to lands downstream from a hydro power plant, and there was risk that the power plant and dam would suffer some damage during the maximum water flow, although in the end the structured held together well.

Considering these facts, Central America's energy sector should reduce instead of increase its vulnerability to climate-related phenomena and natural disasters, like Hurricane Mitch that struck the region in October 1998. This calls for promotion of geothermal energy, which is more reliable and would lead to a well-balanced renewable energy mix between hydroelectric and geothermal sources.

The building of hydroelectric dams has been criticised because of negative effects on the environment and local populations. Therefore, consideration of environmental and social impacts in the evaluation and planning of hydroelectric projects becomes increasingly important. This is especially true for large hydroelectric projects, which may require the displacement of local populations and the flooding of agricultural areas, forests and other ecologically sensitive lands. The latter tends to affect surface and subsurface water flow regimes and quality, and may create or increase water-borne diseases.

The lakes formed behind the dams contribute positively to the development of tourism and irrigation systems, create new employment and contribute to develop the infrastructure of remote areas. However, sedimentation in those lakes is a problem that may significantly reduce the lifetime of hydroelectric projects.

Compared to large hydroelectric projects, geothermal projects have much less environmental and social impacts and generally are not affected by hurricanes, droughts, flooding and heavy rains. Additionally, geothermal installations occupy much less land than hydroelectric projects. Because geothermal is a more constant and reliable energy source than hydropower, it can be used optimally to supply base-load. Geothermal power has traditionally been used for base-load operation only, as modulation would require throttling wells in real time or venting off steam into the atmosphere. Modulation of geothermal plants in order to follow a load curve would require more research into the types of valves that could be used to throttle two-phase flow and be controlled remotely.

It should be noted that the use of geothermal energy is not without possible environmental and social impacts. The extraction of deep thermal fluids, which often are highly mineralised, may affect soils and shallow aquifers if they are not properly handled at the surface. This impact is minimised by re-injecting the cooled waste geothermal waters back into reservoir at depth. Re-injection may produce micro-earthquakes, but recharges the reservoir and reduces ground subsidence. Emissions from geothermal plants are low compared to those of conventional fossil-fuel fired plants, but might locally change the air quality and produce acid rain. However, the air-monitoring program at the Miravalles (Costa Rica) geothermal field shows that this effect is negligible.

In some areas, the development of geothermal resources may require special considerations. Many high-enthalpy sites are in volcanic zones that may include natural parks and other protected areas of interest to tourists. This is especially true in Costa Rica, where these areas cover about 25% of the country (i.e., nearly its entire main mountain range which includes volcanoes of geothermal interest). The Rincón de la Vieja and Tenorio volcanoes are two examples. The first is the most promising site for geothermal exploration in Costa Rica with most of its geothermal resources located within a national park. Therefore ICE, the national electrical utility, has decided to restrict its exploration and possible geothermal exploitation activities to areas directly at the boundaries of the national park, a less likely successful target.

The following example shall show that the conflict between national park and geothermal plants can be solved. In Japan, Sumikawa geothermal field is located within a national park. This power plant was built with very strict environmental controls: wellpads are minimal in size, and surrounded by woods, the swath cut through the forest for pipelines is minimal, pipelines are camouflaged to blend in with the background vegetation, the power house was architecturally designed to look like a mountain chalet, the substation is very small, the H_2S emissions are strictly controlled, the drilling mud is carried away by truck to eliminate the use of mud sumps. It is actually worth a visit from a Central America delegation, it is so impressive. However, the cost is very high, by our standards, although everything in Japan is incredibly expensive. They do talk about US$ 4000/kW in Japan, even for power plants like the ones in Central America, because their drilling costs are ridiculously high, they pay about twice as much for Japanese power plant components as Central American countries do, and their safety and environmental control measures are so strict. Central America can try to adapt some ideas of this Japanese example, but still needs to try to keep the costs down.

Another concern is the visual impact of geothermal surface installations, especially the network of pipelines and roads. This is of special importance in the case of high-enthalpy areas located in sensitive natural areas of tourist interest. On the other hand, geothermal developments outside volcanic regions, especially those of lower temperature, might be near urban areas. In all cases the visual impact of geothermal activities can be significantly reduced by taking appropriate mitigating measures.

3.3.2 *Volcanic and seismic hazards*

Because of the high growth in energy demand in Central America, i.e., on the average 6% per year, new plants are installed and the risk of volcanic and seismic events affecting the region's energy projects increases. Many Central American geothermal areas are located in zones of active volcanism and seismicity. There is no complete compendium of the region's historic and prehistoric volcanic and seismic activity (Fig. 5). Only during the last two decades (especially in the past few years) geological and neotectonic investigations have provided information on past violent geologic events. Several studies and reviews, including evaluations of historic records, allowed to develop a relative crude picture of the Holocene (the last 11,000 years) geological history of Central America.

The 1100-km long Quaternary volcanic range of Central America extends from the Mexico-Guatemala border to central Costa Rica. It comprises 40 major volcanic centres (large andesitic shield volcanoes, composite volcanoes, and twin stratovolcanoes), with a 175-km gap between the Turrialba (Costa Rica) and Barú (Panama) volcanoes. These centres are regularly spaced along narrow discrete lineaments. The close spacing of approximately 26 km provides one of the world's highest densities of active volcanic centres along a convergent plate margin (Carr & Stoiber 1988). In Central America there are 57 historically active volcanoes that had over 400 eruptions since 1500 A.D. Volcanoes that have been dormant for quite some time are often the most dangerous ones. The great explosions of Cosigüina (Nicaragua) in 1835, Santa María (Guatemala) in 1902, and Arenal (Costa Rica) in 1968, all took place at volcanoes that had no historic record of eruptions (Fig. 1). In addition, only few volcanoes have been carefully studied or are being monitored. In fact, from about 70 stratovolcanoes, only 17 have the minimum volcanic monitoring systems in place (Alvarado et al. 1999).

Although the probability that a volcanic eruption will affect a given geothermal plant during its less than 100 year lifetime is very low, volcanic hazards must be adequately evaluated. The possibility of hydrothermal explosions within the geothermal fields should also be studied. Thus,

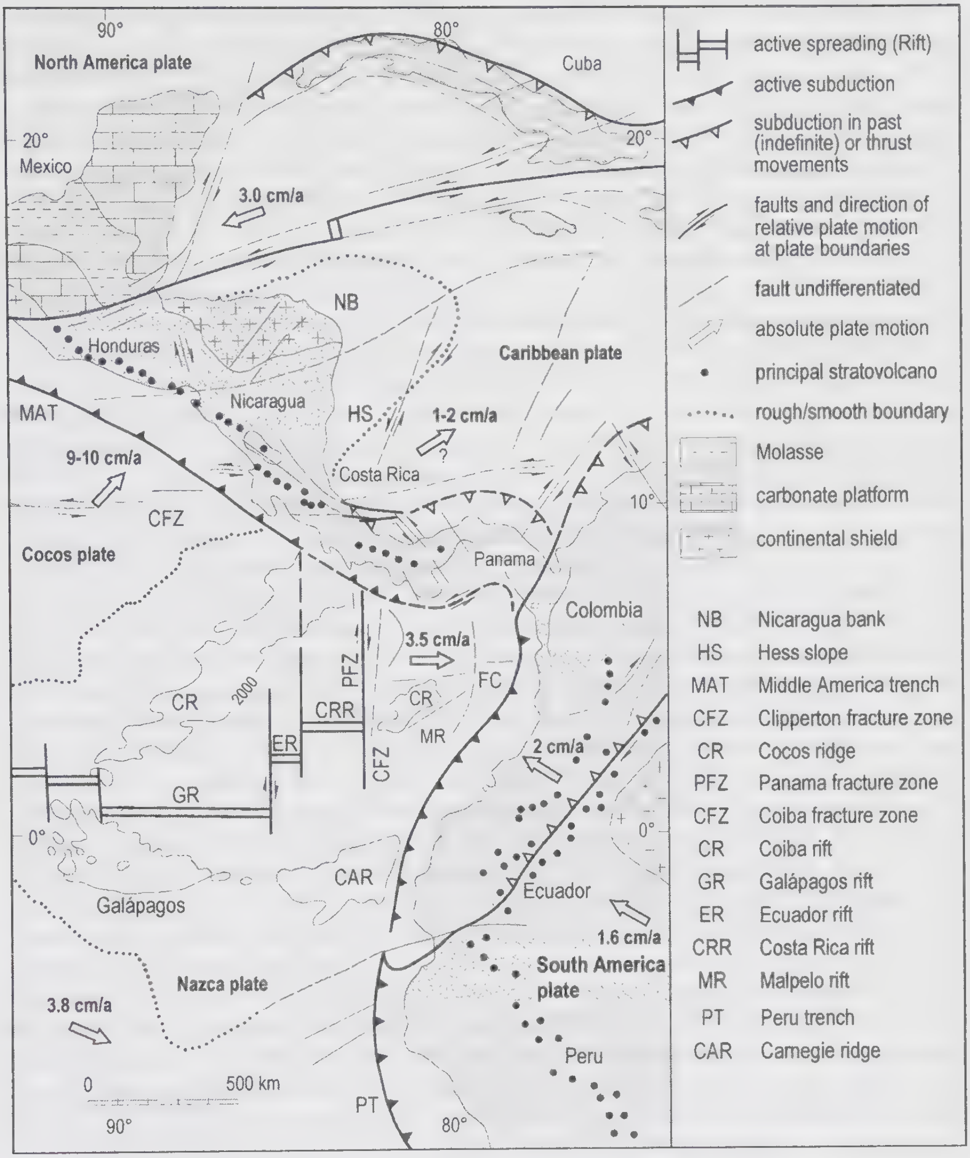


Figure 5. Geotectonic map of Middle America and the Caribbean.

detailed tephrastratigraphic investigations, mapping and geochronological dating of volcanic deposits, and the preparation of volcanic hazard maps assuming different scenarios, should be part of the studies made during the pre-feasibility and/or feasibility stages of a geothermal project.

With respect to earthquake related hazards, the probability of seismic events is similar for geothermal and hydroelectric projects. Dams are usually constructed in tectonic valleys or gorges, while many geothermal projects are located in very active volcano-tectonic areas. Even if the probability of a seismic event is similar, the social and economic consequences for geothermal and hydroelectric projects are quite different. The downstream flooding caused by a dam failure may cause high losses in life and property, whereas those associated with the collapse of a geothermal plant are expected to be much smaller.

The magnitude 7.6 earthquake of January 13, 2001 in El Salvador produced only minimal damage in the geothermal plants. The only damage reported in the geothermal power plants was that a cable broke in Berlín that connected two transformers, and a perimeter wall around Ahuachapán power plant cracked in some places. Thermal and hydro plants also reported minimal damage, but some substations and transmission lines suffered severe damage during the earthquake. This indicates that geothermal power plants can be built at least as sturdy as any other plant, and the risks of catastrophic damage from natural phenomena are no greater than for hydro or thermal plants.

There are geologic evidences of continuous seismic activity in the Central American region. Detailed seismological and neotectonic studies of the area began during the last 2 3 decades. The installation of permanent local networks is helping to locate and study earthquake events, and discover new active faults. The development of empirical attenuation relations made it possible to correlate earthquakes and estimate seismic hazards (White & Harlow 1993, Climent et al. 1994, Montero 1999). Several recent studies examined the spatial, temporal, and magnitude distribution of larger upper-crustal Central American earthquakes that occurred since 1500 (Montero 1999, Peraldo & Montero 1999).

Different characteristics in the seismicity, focal mechanism, and neotectonic environment allowed to define different seismo-tectonic regions in the area. The larger earthquakes are related to: 1) the subduction of the Cocos Plate under the Caribbean Plate, 2) the triple-point plate limits (e.g. Polochic-Motagua and Panama fractures zones), 3) local, less frequent shallow crustal earthquakes, 4) intra-Cocos Plate seismicity, and 5) large volcanic quakes ($4.5 < M < 7.0$).

Forecasting the occurrence and maximum magnitude of earthquakes is one of the most difficult problems in seismic hazard assessment for geothermal and other projects. In some cases, estimations using seismic catalogues are too limited because they do not consider a long enough time period. The application of paleo-seismologic criteria, as well as a combination of probabilistic and deterministic seismic hazard studies, is strongly recommended.

To determine if an active fault exists at the site of a future geothermal powerhouse, at least two exploration trenches are needed. If such fault is found, the plant will have to be moved at least hundred meters away from the fault trace. In any case, it is important to study the local soil conditions below and around the site of a powerhouse.

The potential of induced seismicity caused by geothermal operations should also be considered. Therefore at least 3–5 years before the start of the project, it is necessary to install a closely spaced local network of seismic stations to measure background activity.

Also, if stratigraphic studies suggest the existence of a thick compressive geologic layer in the geothermal area, the early installation of a geodetic network will be necessary to obtain baseline data and to monitor possible future ground subsidence. If it occurs, changes in the reservoir management plan might have to made (e.g., changing fluid production and injection patterns).

3.4 *AIJ/CDM opportunities through emission reduction*

Practically in Central America, geothermal energy projects are not considered as opportunities for AIJ (Activities Implemented Jointly) or CDM (Clean Development Mechanism) projects. This can be explained mainly by a lack of information and awareness. There are several relatively small AIJ/CDM projects on renewable energy related to hydropower and wind energy. Only Nicaragua applied for a geothermal AIJ project (i.e., El Hoyo-Monte Galán geothermal field); it was approved but had to be cancelled (see below).

In the case of Costa Rica, a wrong understanding of the issues behind AIJ/CDM projects ruined a good opportunity. President Figures (1994–98) made the commitment that Costa Rica would eliminate fossil fuel as a source for electricity generation by the year 2001. This commitment was used to establish a baseline for GHG emission and meant that starting in 2001 the GHG baseline emission would be zero and no future reduction could be achieved and credited to AIJ CDM projects. According to Costa Rica's Office of Joint Implementation OCIC, the president's statement was not a commitment to a national baseline (Boscolo et al. 2000). However, all official AIJ estimates of carbon emissions reductions from energy projects use baselines with a rapid decrease of non-renewable energy sources for electricity generation, hence reducing future AIJ CDM opportunities in Costa Rica (Boscolo et al. 2000).

This unreasonable exclusion of geothermal projects from CDM/AIJ project opportunities must be changed. Efforts should be made to improve among political leaders, governmental decision makers, UNFCC focal points, NGO's and private sector leaders an understanding of CDM with respect to geothermal.

On the other hand, the failure of the Hoyo-Monte Galán geothermal AIJ (UNFCCC 1997) project was due to a series of political, institutional and financial problems. The geothermal prospect is located within the Marrabios Range, the active volcanic chain in Nicaragua, about 65 km northwest of the capital Managua (Figs 1 and 5). In December 1995, the Instituto Nicaragüense de Energía (INE), the country's energy regulatory entity granted an exploration lease in the El Hoyo-Monte Galán geothermal area to Trans-Pacific Geothermal Corporation (TGC). The company would perform geoscientific investigations to determine the commercial viability of generating geothermal electricity. These studies included geologic mapping, water and gas chemistry, geophysics (MT and AMT) and energy capacity calculations.

The economical feasible potential for the Hoyo-Monte Galán concession area was estimated to be between 150 and 200 MW. In 1998, before the end of the concession, TGC requested a two-year extension from INE because it could not obtain a Power Purchase Agreement (PPA) from ENEL, the Nicaraguan national utility. In the meantime, INE urged TGC to show evidence of sufficient financial support to continue with the activities required in the next stage of the project, i.e., the exploitation phase. Accordingly, TGC presented INE a letter of intent of partnership from Calpine Corporation.

By the end of year 2000, TGC still was not able to sign a PPA with ENEL. The utility had already begun its privatisation process and the Inter-American Development Bank (IDB) recommended ENEL not to sign any long-term PPA. By that time, Calpine had ended its agreement with TGC. In spite of all these inconveniences, INE approved an extension of the concession period for another year. Since then, the last extension has expired and by law, INE cannot grant a new one to TGC.

These experiences from Costa Rica and Nicaragua demonstrate the urgent need to raise the awareness among politicians, government officials, NGOs and private sector leaders of the importance of geothermal development to the region. These decision makers should also get a better understanding of CDM projects involving geothermal energy resources because of the resulting opportunities and benefits.

3.5 *Other benefits associated with geothermal*

In the next decades, the Central-American countries face a difficult environmental challenge. Sustainable development policies are required to reduce or even stop the ongoing deforestation, loss of biodiversity and general land degradation.

Geothermal can contribute significantly to these sustainable policies and at the same time, reduce air and water pollution. In addition it will help decrease the use of firewood to cook meals, thus contributing to the region's conservation efforts. Proleña (1995) estimates that in Honduras alone seven million cubic meters of firewood are chopped every year. Precious hardwoods, mangroves and pine and oaks are cut to obtain firewood. Such damaging practice is very common throughout Central America.

Even though there are numerous areas of hot springs in the region they are mainly used for washing, bathing and swimming by the local population. Guatemala is the only Central American

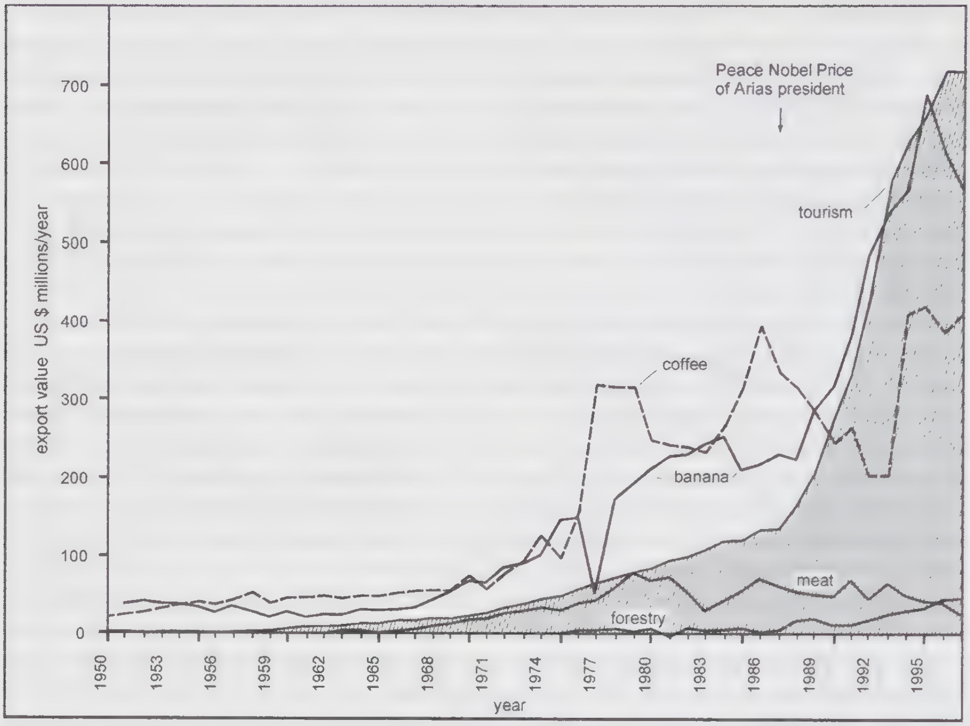


Figure 6. Value of Costa Rican exports compared to that of the tourist industry sector (modified after Gámez 2001).

country with successful commercial direct-use projects (curing concrete blocks and fruit dehydration; Lund & Freeston, 2000).

Even though the region is showing an explosive increase in tourism, especially in Costa Rica (Fig. 6), the commercial development of the numerous hot springs (Fig. 7) in form of thermal baths has been minimal. In the future, this could change as eco-tourism becomes even more popular than today. Establishing thermal spas in the region would create got investment opportunities, especially for the private hotel industry.

In the example of Costa Rica, which was worldwide recognised and discovered as a peaceful vacation country as consequence of the worldwide boom of eco-tourism in the late 1980s and reinforced by the Peace Nobel Price award to Arias president on December 10, 1987 for his efforts to stop the civil war in the neighbour country Nicaragua. The volcanic areas of Costa Rica have become a major destination for environmentally conscious tourists from throughout the world. Millions have visited the country's rain forests and volcanoes (Sigurdsson & Lópes Gautier, 2000). Almost 420,000 tourists (67% are Costa Rican) visit the volcanoes every year; Poás volcano is the most popular followed by the Irazú. The tourists should not only be interested in nature and ecology, but also should enjoy relaxing in hot springs and taking mud baths. However and in spite of being universally revered for their soothing, therapeutic qualities and cleansing characteristics, most of the thermal springs associated with these volcanic areas have yet to be developed.

3.6 *Cost assessment*

Under present market conditions, the development of renewable energy resources can only take place if they are cost-competitive. In Central America, geothermal has to compete against fossil

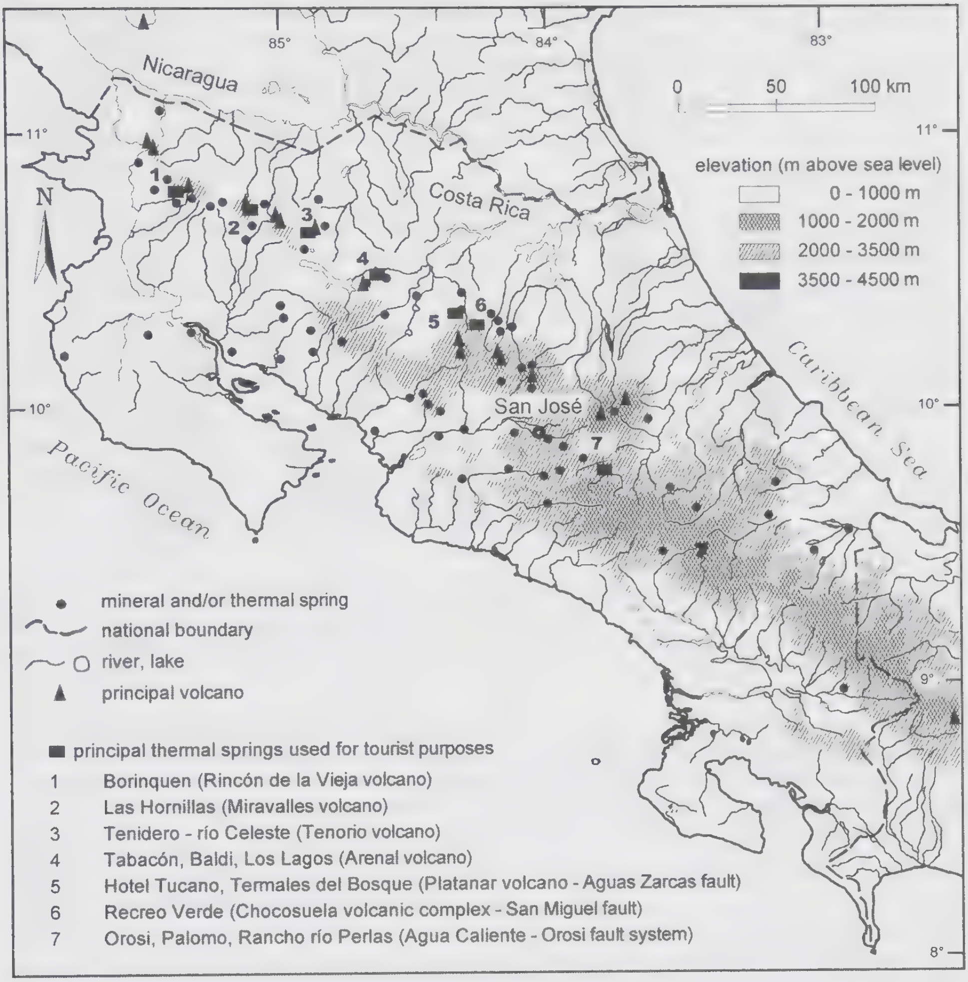


Figure 7. Location of mineral and thermal springs in Costa Rica.

fuels and hydropower, which at the present time are used to generate about 41% and 50%, respectively, of the electricity of the region.

In general in Central America, the present costs per kilowatt (kW) installed are similar for geothermal and hydro, but by 2010, the installation costs for geothermal plants will be about half of those of a hydroelectric project (Energy Information Agency 2000; Fig. 8). In addition, geothermal plants have a much higher capacity factor (around 0.87 or more) than hydroelectric plants (about 0.55, but often lower). In Central America, the overall cost of the electricity produced by geothermal plants is lower than that from hydroelectric plants and will become much cheaper in the future (Fig. 8).

The cost of installing fossil-fueled power plants is lower than that of geothermal and hydroelectric plants. It depends on the type of fuel being burned and the size of the plant; it varies between 300 and 900 US$/kW. By 2010, the installation costs for geothermal plants will be significantly reduced (Fig. 8).

In respect to the fossil fuel energy costs which is about 0.05 US$/kWh, fossil fuel plants are similar to hydropower plants and more expensive than geothermal plants.

Comparing geothermal energy with other renewable sources, solar energy will not become economically competitive during the next decade. Wind energy has lower installation costs, and

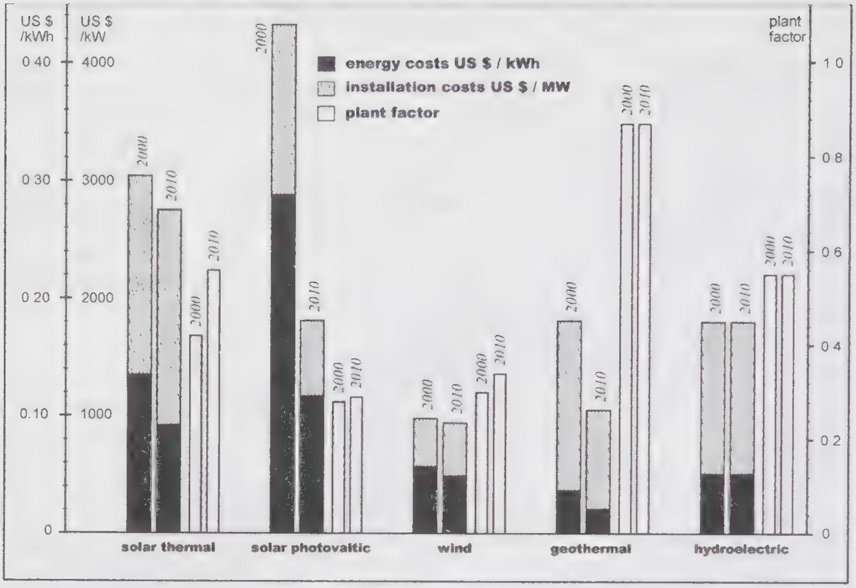


Figure 8. Comparison of installation costs, electricity costs and plant factors for different renewable energy sources for the years 2000 and 2010 (source: Energy Information Agency 2000; Instituto Costarricense de Electricidad 2001; costs for hydropower are based on Costa Rican conditions).

Table 4. Costs of installation and electricity generation for Central American power plants that use renewable energy sources – comparison by source.

Projects by energy source country/examples	Capacity (MW)	Life time (yrs)	Installation cost	
			Total (million US$)	US$/kW
Wind energy				
CR Plantas Eólicas S.A. (1999)[1 2]	20	15	27–30[3]	1350–1500
CR Aeroenergía S.A. (1997)[1 2]	6.4	21	8.85	1382
CR Tierras Morenas[1 2]	20	14	31.5	1575
HN Honduras (16 km S Tegucigalpa)[1 2]	60	n.a.	32	
Hydropower				
CR Don Julia S.A. (1998)[1]	16	n.a.	32	2000
GT Zacapa[1]	50	20	36	720
GT Guatemala 2[1]	14	15	25	1785
Geothermal energy				
CR Miravalles I (1994)	55	25	219.5	3981
CR Miravalles II (1998)	55	25	166.5	3027
NI El Hoyo (2003)[4]	75	35	160	2133
NI Momotombo (1989/93)	2 × 35	25	84	1200

CR: Costa Rica; GU: Guatemala; HO: Honduras; NI: Nicaragua: [1]from EIC 2000: [2]from Dutschke & Michaelowa 2000; [3]no exact number can be given due to confidentiality; [4]project recently cancelled; n.a.: data not available.

the cost of the electricity it generates is similar to that of hydropower. However, for both of these energies the corresponding costs are higher than those for geothermal.

The costs for some Central American renewable energy projects are shown in Table 4. For hydropower and geothermal plants, the values given in the table are in general agreement with those of Figure 8, but show the project-dependent variability of installation costs. The costs for the wind power plants in Costa Rica exceed those given in Figure 8 by 30 to 60%.

A disadvantage of wind energy projects is their short lifetime, about 15 years, which is less than half that of geothermal and hydropower plants. Also one should keep in mind, that the capacity factors for wind projects are very low (around 0.3; Fig. 8) compared to other power plants, especially geothermal.

The case of Miravalles (Costa Rica) illustrates the economic viability of geothermal projects. Between 1994 and 2000, the sale of electricity generated by Miravalles Unit 1 amounted to US$ 188.96 million (Moya & Fernández 2001). Based on these numbers, the initial investment of US$ 248.8 million will be returned during 2004. This example shows that investment costs for a geothermal plant, not considering other costs as capital interests and devaluation, can be returned in about 10 years. Considering, that the capital costs for the Miravalles Unit 1, were about US$ 4500 per kW installed, and that they are about half as much in 2002 and expected to be about a quarter in 2010, the time of investment return will be correspondingly decreased.

Summarizing, geothermal has a number of advantages over fossil fuels and other renewable energies, and should be the energy source of choice for the Central American region.

4 GEOTHERMAL ENERGY IN THE FRAMEWORK OF DEREGULATED ELECTRICITY MARKETS

4.1 *Overview*

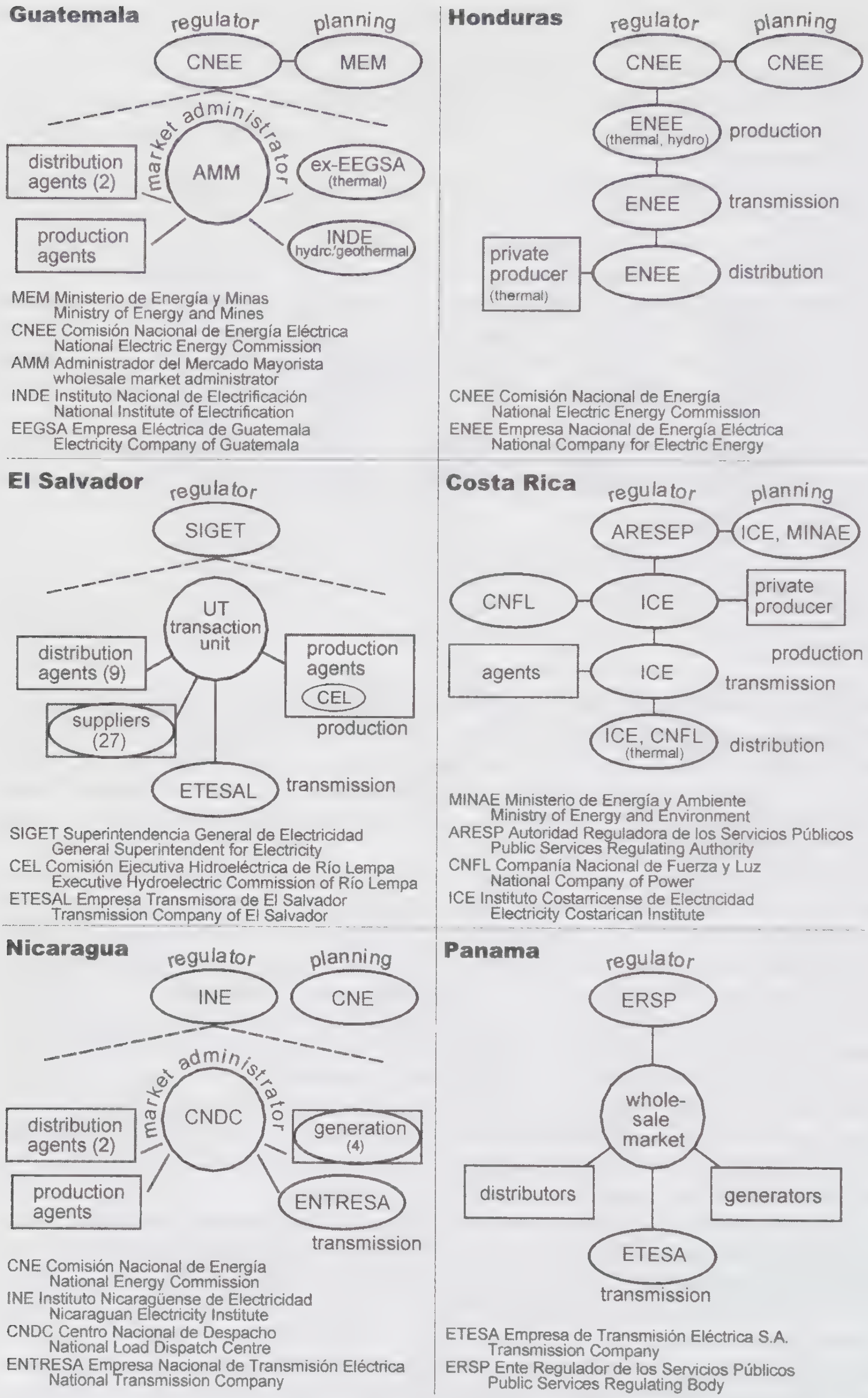
The future opportunities for the use of geothermal energy resources must be seen in the framework of the energy markets of the individual countries and the region as a whole. At the present time, the Central American countries are working to introduce more competition to get greater economic efficiencies in their electricity sectors, and to attract local and foreign private investments. This is needed due to the scarcity of government funds and the high (about 6%) annual growth in energy demand in the region.

To reach those goals, the Central American countries reformed their national energy laws and regulations; implementation varies from country to country (Fig. 9, Table 5). The former state-owned monopolies have been broken up and partly privatised. The electricity markets are in the process of deregulation by privatising, upgrading and expanding power generation, transmission and distribution sectors. The progress of deregulation varies significantly across the region. While the national energy markets of Panama, El Salvador, Nicaragua and Guatemala have already been quite liberalised, those of Costa Rica and Honduras maintain a monopolistic structure with only limited opportunities for private sector participation.

Deregulation of the Central American electricity market requires massive investments by the private sector and multilateral institutions like the Inter-American Development Bank (IDB); at least US$ 7300 million before 2006. However, the introduction of competition in wholesale electricity markets benefits consumers by decreasing electricity prices.

Deregulation of the national electric sectors will have mixed impacts on geothermal projects. They will be affected by transition period instabilities, and by the changing competitive environment. Both tend to increase private investors' risks. One of the advantages of deregulation is the reduction of the hazard of political uncertainties.

Deregulation will provide a huge opportunity to promote the use of geothermal and other clean energy resources. On the other hand, it requires special attention from governments and corresponding tax benefits or other incentives to promote and support private investments in renewable energy projects. This will allow the gradual replacement of polluting fossil fuels that degrade the environment with cleaner energy sources.



MEM Ministerio de Energía y Minas
Ministry of Energy and Mines
CNEE Comisión Nacional de Energía Eléctrica
National Electric Energy Commission
AMM Administrador del Mercado Mayorista
wholesale market administrator
INDE Instituto Nacional de Electrificación
National Institute of Electrification
EEGSA Empresa Eléctrica de Guatemala
Electricity Company of Guatemala

CNEE Comisión Nacional de Energía
National Electric Energy Commission
ENEE Empresa Nacional de Energía Eléctrica
National Company for Electric Energy

SIGET Superintendencia General de Electricidad
General Superintendent for Electricity
CEL Comisión Ejecutiva Hidroeléctrica de Río Lempa
Executive Hydroelectric Commission of Río Lempa
ETESAL Empresa Transmisora de El Salvador
Transmission Company of El Salvador

MINAE Ministerio de Energía y Ambiente
Ministry of Energy and Environment
ARESP Autoridad Reguladora de los Servicios Públicos
Public Services Regulating Authority
CNFL Compania Nacional de Fuerza y Luz
National Company of Power
ICE Instituto Costarricense de Electricidad
Electricity Costarican Institute

CNE Comisión Nacional de Energía
National Energy Commission
INE Instituto Nicaragüense de Electricidad
Nicaraguan Electricity Institute
CNDC Centro Nacional de Despacho
National Load Dispatch Centre
ENTRESA Empresa Nacional de Transmisión Eléctrica
National Transmission Company

ETESA Empresa de Transmisión Eléctrica S.A.
Transmission Company
ERSP Ente Regulador de los Servicios Públicos
Public Services Regulating Body

Figure 9. Structure of national energy markets in the Central American Countries: rectangles = private, circles and ellipses = public entities.

Table 5. Opportunities and restrictions for private sector participation in Central American electricity markets.

	Panama	Costa Rica	El Salvador	Guatemala	Honduras	Nicaragua
Generation	+	+[1]	+	+	+	+
Transmission	–	–	+	–	–	–
Distribution	+	–	+	+	–	+

+ Open to private investors, – state monopoly; [1]Private participation very limited.

4.2 *Guatemala*

In the past, two government monopolies, the Empresa Eléctrica de Guatemala (EEGSA) and the Instituto Nacional de Electrificación (INDE), controlled Guatemala's electricity sector and made only few investments. In the years 1997–98 EEGSA was privatised and a wholesale electricity market was established. At the present time, the two electricity distribution companies of INDE are in the process of being privatised, but the Guatemalan Government plans to retain INDE's transmission and distribution facilities. In July 1998, an 80% share of the urban power distributor, EEGSA, was sold for US$ 520 million, to Spain's Iberdrola Energía, in partnership with Electricidad de Portugal, and TECO Power. EEGSA distributes 70% of Guatemala's power to 510,000 consumers in greater Guatemala City. Iberdrola plans to invest US$ 100 million and to compete in the region's deregulated energy market. Rural power authority INDE, with about 580,000 users and generating 30% of the nation's power, was sold to Spain's Unión Fenosa, for US$ 101 million in December 1998. These privatisation activities offer the private sector investment opportunities in at least six hydroelectric projects with capacities varying between 13.5 and 440 MW, and four geothermal projects with capacities between 5 and 50 MW.

The electricity wholesale market of Guatemala comprises the trading of blocks of energy or standby capacity according to contracts. According to the General Electricity Law, the wholesale market agents include generators with a capacity of over 10 MW, transporters with connected capacity of over 10 MW, distributors with at least 20,000 customers, and marketers trading energy blocks over 10 MW. The electricity wholesale market is freely accessible, prices are competitive, and spot prices are not regulated. A coordination of operations with generators, international grids, and transporters shall be established to minimize operations cost.

4.3 *Honduras*

In 1994, Honduras' energy sector began to change. The government encouraged the participation of the private sector in the electricity generation and distribution markets. However, this only has occurred for thermal and small cogeneration plants.

Since 1998, Honduras has approved legislation to facilitate private sector participation in sustainable energy projects. A July 2000 IMF mission to Honduras insisted that the country's entire power sector be privatised and deregulated. Deregulation could encourage private generators and facilitate interconnections between Honduras and other Central American nations. The Unidad de Transacciones (UT), created by the Framework Law, shall manage the Honduran electricity wholesale (fixed and spot) market.

Private power producers currently generate about 29% of the country's total power. ENEE, the vertically integrated government electric power company, provides electricity to 98% of the end-users (400,000 customers). ENEE's portfolio consists of four hydroelectric plants and ten thermoelectric plants (five are operated by the private sector). Under the Framework Law, ENEE's generation, transmission, and distribution sectors are to be separated and its distribution assets privatised. Besides the ENEE privatisation, there investment or commercial opportunities for the private sector in five hydroelectric projects ranging from 79.6 to 713.2 MW, and six geothermal projects with a minimum capacity of 20 MW.

To date (2002), 21 Power Purchase Agreements (PPA) have been signed by ENEE, 17 correspond to hydroelectric projects whose capacity range from 0.17 to 50 MW, and four correspond to biomass cogeneration plants with capacities that vary from 0.5 to 12 MW.

4.4 *El Salvador*

El Salvador's state-owned vertically integrated monopoly, the Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL) was broken up into several components, some were privatised, and some remain under government control. Since 1996, the country's electricity distribution system was divided into five companies, and then sold separately to private investors. A high-voltage system (115 kV and higher) operator was created (the Unidad de Transacciones, or UT) as a CEL spin-off, and is now owned by distributors, transmitters, generators, and end users, with no single group in control. The thermal generation assets were separated into two different companies and sold to private investors. Finally, the transmission grid and geothermal generation assets were separated from CEL into subsidiary companies, still owned by CEL. The last component, the hydroelectric generation assets, is still an integral part of CEL. The Superintendencia General de Electricidad y Telecomunicaciones (SIGET) is the regulatory body that oversees the electricity market, and the Dirección General de Electricidad (DGE), an office of the Ministry of the Economy, sets electricity policy.

Experiences: Privatisation of energy assets is the recent trend in El Salvador. In 1998, U.S.-based AES, Houston Industries, PPL, EMEL of Chile, and Electricidad de Caracas of Venezuela won a 75% stake in four distribution companies with 900,000 customers, with bids totaling US$ 585 million. AES has since consolidated its position and now controls all companies with 79% of the distribution assets, except for DELSUR, which is controlled jointly by EMEL and PPL. CEL does not plan to privatise its hydroelectric generating assets, but recently concluded a process to select a strategic partner to explore and develop two geothermal resources in exchange for minority participation in the geothermal company, Geotérmica Salvadoreña (GESAL). The selected partner was Enel Green Power, of Italy, with a bid of 8.5% of GESAL's shares in exchange for the resource evaluation. Enel would obtain additional shares for a development stage. Additionally, Orpower 7, a subsidiary of Ormat Group of Israel, obtained concessions to install 50 MW power plants in each of the San Vicente and Chinameca fields. In November 2000, Duke Energy International announced that it had completed work on a US$ 75 million, 100 MW expansion of the Acajutla power plant, which serves wholesale power markets in El Salvador and Guatemala.

Since the electricity market in El Salvador is open, new geothermal projects must compete with other sources of electricity without the benefit of government incentives. As the alternative to geothermal is imported fuel and due to the technical complications in bringing cheap fuel to El Salvador, geothermal is considered a competitive option.

El Salvador's electricity wholesale market is composed of two parts: the contracts market, which accounts for about 80% of the energy transactions, and the spot market (Mercado Regulador del Sistema, or MRS), which accounts for the rest of the energy sales. The contracts market consists of bilateral agreements between operators to buy and sell power at an unregulated price. Data on the energy and power amounts of these transactions (not prices) are disclosed to the UT, and dispatch is ensured except in cases of congestion or other technical problems. For the MRS, the UT takes price bids for each hour and dispatch is done on a lowest-price order. The marginal generator sets the MRS price, which is paid to all generators who participate in the MRS at that hour. The monthly average MRS price is translated to a tariff, which varies monthly, and is the maximum price at which the distribution company can sell to an end user. However, these users can contract directly with their distribution company or an energy trader to obtain the best price in the contracts market.

4.5 *Nicaragua*

The legislation for privatising the National Electricity Company (ENEL) was approved by the local Congress in March 1998. Due to the impact of Hurricane Mitch, the process was delayed until October 2000, when the first phase of ENEL's privatisation was completed. Thereby, 95% of ENEL's distribution network was bought by Spain's Union Fenosa for US$ 115 million (the Northern and Southern Distribution Companies). The two power-generating companies GECSA and GEOSA, which belong to ENEL, could not be sold on October 2000 due to lack of qualifying offers. ENEL plans to retain its transmission company as state property. The future of 26 small and isolated power plants is yet unclear. The Inter-American Development Bank (IDB) gave two concessional loans to support the restructuring process of the national electricity sector.

4.6 *Costa Rica*

A first attempt to privatise the energy sector of Costa Rica, the state-power monopoly energy company ICE (Instituto Costarricense de Electricidad), followed a mandate from President Rodríguez, who in October 1998 presented a proposal to liberalise the country's power generation market by opening it to private investment. The aim of the proposal was not to privatise ICE, but to reorganize it into a profit-based company. In March 2000, the Legislative Assembly held in first debate a corresponding "Law to Transform Costa Rican Electrical Institute". This bill known as "Energy Combo" was comprised of three components. The first was to break up ICE by separating it in two companies, one in charge of the electricity system (ICELEC) and the other of telecommunications (ICETEL). Following that separation, both state-owned monopolized markets would be opened to private national and foreign investments and competition. Independent private power producer sales obligations to ICE were foreseen for a five-year transition period, after which full competition would be introduced. At that time, private companies could market power directly to local end-users, in competition with ICE, as well as to customers in other Central American countries. ICE would retain its monopoly in distribution. This plan of the "Energy Combo" was opposed by the majority of the Costa Rican people, and resulted in strikes and demonstrations in March 2000.

4.7 *Panama*

There is increased competition in Panama's growing energy market. In 1998, the state-owned electricity company, Instituto de Recursos Hidráulicos y Electrificación (IRHE), was broken up into four generating and three distribution companies, and sold for a total of US$ 603 million. U.S.-based Coastal Corporation and Canada's Hydro-Quebec International paid US$ 118.1 million for a 49% share in the Fortuna hydroelectric plant; it corresponds to about one-third of the country's total installed capacity (the Panamanian government owns the remaining 49% of the project). Houston-based Enron Caribe III bought 51% of the Bahía Las Minas power station for US$ 91.72 million, while U.S.-based AES bought a 49% stake of the Chiriquí and Bayano generators. AES will also build a new hydroelectric plant for an estimated US$ 200 million. There are currently eight electricity generators and three distributors operating in Panama. Foreign company involvement in the Panamanian electricity sector includes U.S.-based Coastal, AES, Enron, Illinova, and Noresco, Canada's Hydro Quebec, and Spain's Union Fenosa. Transmission remains in the hands of the government through the publicly-owned company ETESA. Also in 1998, a regulatory body was created, the Ente Regulador.

5 REGIONALISATION OF NATIONAL ELECTRICITY MARKETS – OPPORTUNITIES AND OBSTACLES FOR GEOTHERMAL ENERGY PROMOTION

Currently, the Central American regional electricity system is fragmented by national boundaries. The electricity markets of the regions require more integration, which soon is going to be achieved by the Central American Electric Interconnection System (SIEPAC) and a number of natural gas pipelines.

In November 2001, the US$ 240 million financing plan for SIEPAC was approved by the Interamerican Development Bank (IDB), including US$ 70 million from the government of Spain, which are administered by IDB. Additionally the Central American countries provided US$ 106 million. This project includes the construction of 1830 km, of 230 kV power transmission lines connecting Costa Rica, El Salvador, Honduras, Guatemala, Nicaragua, and Panama. SIEPAC could be completed by 2006. It will allow large-scale electricity transfer within the region, develop the first regional electricity grid, and be the base to establish a regional Central American wholesale market. This will overcome the poor quality of the old and unreliable interconnections between the participating countries. With respect to regionalisation, two new institutions will be established: the Regional Electric Interconnection Commission (CRIE) which will be regulating the regional wholesale market, and the Regional Operating Agency (EOR) which will be the system's operator and administrator of regional power transactions. The six participating utilities are Instituto Costarricense de Electricidad ICE (Costa Rica), Comisión Ejecutiva Hidroeléctrica del Río Lempa CEL (El Salvador), Instituto Nacional de Electrificación INDE (Guatemala), Empresa Nacional de Energía Eléctrica ENEE (Honduras), Empresa Nicaragüense de Electricidad ENEL (Nicaragua) and the Empresa de Transmisión Eléctrica S.A. ETESA (Panama). These utilities will transfer the loan obtained for the project to the Empresa Propietaria de la Línea (EPL). This company will be the owner of the SIEPAC grid and will allow private investments. IDB will also support the development of legal, regulatory and technical rules needed to create an optimal regional electricity market. The new system will alleviate periodic power shortages, reduce operating costs, optimise the regional use of geothermal and hydroelectric power, create a competitive market in the region, and attract private (foreign and local) investments.

SIEPAC, undoubtedly, will be a good opportunity for the private sector to invest in the development of geothermal resources in Central America. The existence of a legal framework governing the wholesale electricity market in the region will increase private investors' confidence in stable "rules of the game". With regards to economy of scale, large geothermal projects could be developed in each country. About 30 million people live in Central America. For private investors the region's combined market is much more attractive than that of individual countries. Since the regional electricity market is designed to be open, geothermal operators will have to compete against other generation technologies in every one of the countries.

The disadvantage of SIEPAC for geothermal energy is that particular countries may import cheap electricity from other countries in the region. From a strictly market point of view, importing power may be the lowest-cost option for a given user or distributor. In fact, the differences in local legislation from one country to another may make it attractive to trade energy across country borders even in cases where it is not the best-cost option. For example, the Guatemalan spot market includes only energy costs, whereas the Salvadoran MRS includes energy, capacity, transmission, regulatory, and operation costs, etc., all in a single price. This makes it attractive to buy energy from the Guatemalan spot market (where all capacity payments and regulatory and transmission costs are excluded), and sell into the Salvadoran MRS at a significant profit. Work needs to be done to make legislation more uniform throughout the region. However, if all externalities are taken into account, geothermal is probably one of the most competitive energy options in Central America. A regional policy to take into account externalities in prices would be a significant step in promoting geothermal energy and other clean energy sources.

Compared to state-owned monopolies, regional and national wholesale markets have advantages and disadvantages for the promotion of geothermal energy. In the past, geothermal developments in El Salvador, Nicaragua, and Costa Rica originally came from investments made directly by state-owned monopolies as part of the long-term expansion plans of each country. Financial backing was typically from the IDB or World Bank. This model, although effective in promoting several projects, like Ahuachapán, Berlín, Momotombo, and Miravalles, depends on long-term government commitments, and each country's capacity to assume debt. The wholesale market model gives access to much vaster (and faster) sources of finance. However in the short-term, competition is against fossil fuel plant options that may be less economical in plant lifetime, but more attractive to investors because of short-term financial considerations (low initial capital costs for fossil fuel plants). In these markets, the future of geothermal will depend on its ability to deliver cost-competitive power in the medium and long terms.

In addition to SIEPAC, two more regional projects must be considered: (1) Guatemala and Mexico have agreed to build by 2004 a natural gas pipeline from southern Mexico to Guatemala. The gas would be used both for industrial purposes and electricity generation. The pipeline could eventually be extended to the Honduran and Salvadoran borders, and possibly to Nicaragua and Costa Rica as well, as part of a wider Central American gas pipeline network; and (2) In 1999, Colombian natural gas producers proposed to build a gas pipeline into Central America. The Colombian pipeline would initially extend from Cartagena to Colon, Panama, where it would supply a planned thermal power plant; more pipelines and distribution systems could grow with demand. Eventually it might reach into other countries and possibly meet the Mexican pipeline in Guatemala. The installation of these pipelines will significantly influence the type of energy that will be used for power generation in the future. These projects will encourage the use of natural gas, making geothermal energy less attractive.

6 RESTRICTIONS TO PRIVATE SECTOR PARTICIPATION IN GEOTHERMAL DEVELOPMENT

6.1 *Legal aspects; electricity and geothermal laws*

In the Central American region no special geothermal laws exist. Only Nicaragua has prepared a draft of such law. Geothermal energy issues are generally regulated by mining, water and general electricity laws.

To improve competition, efficiency and investments through private sector participation as related to the deregulation of national electricity markets, the electricity and corresponding laws of the different countries refer to for private sector participation in electricity production, transmission and distribution. The way and extent of this possible participation varies between countries.

In Costa Rica, the Authorization of Autonomous or Parallel Electric Generation Act, No. 7200 of September 1990 regulates private electricity generation. In Guatemala, the General Electricity Law of 1996 and corresponding regulations issued in 1997 govern power generation and distribution. The regulatory and control body is the Comisión Nacional de Energía Eléctrica (CNEE). The Guatemalan Ministry of Energy and Mining (MEM) grants permits for power generation and distribution.

In Honduras, the Gabinete Energético (Energy Bureau), formulated in 1994 the Electric Subsector Framework Law (Ley Marco del Subsector Eléctrico) which regulates the generation and distribution of electricity, and defines and formulates electricity policy. The Law also establishes the Comisión Nacional de Energía Eléctrica (National Energy Commission) whose task is to supervise and implement the law.

In El Salvador, the electricity law (Ley General de Electricidad; LGE) was passed in 1996 to create an open and competitive electricity market. It provides all generators and users with open access to the transmission grid with a predefined transmission charge, defines methodologies to obtain concessions for the use of indigenous natural resources in electricity generation, and sets rules for system and market operation and contracts. Another relevant legislation is the Ley de Creación de la Superintendencia General de Electricidad y Telecomunicaciones (SIGET), which created that body and defined its operations.

Starting in 1998, Honduras has approved legislation to facilitate private renewable energy promoters participation in the field of electrical generation, giving these projects some specials provisions, such as an incentive base on the energy price, and tax and import duty exemptions.

The Nicaraguan Government is interested in promoting private investment in all energy sector activities and establishing the legal basis for privatisation. In 1998, the Electricity Industry Law (Ley de la Industria Eléctrica) and the Organic Law of the Nicaraguan Institute of Energy (Instituto Nicaragüense de Energía INE) were approved. According to the electricity law, the state electricity monopoly, the National Energy Company (ENEL), must be broken up into several power generation, transmission and distribution companies. The rules and regulations of the electricity sector are developed and enforced by the INE's Energy Policy Council. The electricity law establishes that privatisation of the generation, distribution, and commercialisation activities should occur two years after its enactment. It also establishes regulations for electrical generation, distribution and commercialisation activities, and for import and export of electricity. The National Energy Commission (Comisión Nacional de Energía; CNE) is in charge of energy sector policy and planning, managing of rural electrification, funding, and formulation of rules and criteria for new energy sector investments. According to the electricity law, the electricity sector has to.

- Provide quality, continuity and security in electrical service.
- Minimise the cost of electrical service, based on the efficient use of energy resources.
- Promote an effective competition and attract private capital.
- Further the efficient use of electricity.
- Provide electrical service following environmental protection, and industrial and personnel safety regulations.

The law exempts from import duties all imported machinery, materials and equipment used exclusively in the generation, transmission and distribution of electrical energy for public use. A recently approved tributary law, called "Justicia Tributaria", stipulates that any investor will begin paying income tax only after recovering his capital investment, and be able to repatriate profits without any foreign exchange limitations. Environmental regulations on exploration and exploitation of natural resources will have to be strictly followed.

Nicaragua is the only country in the region that has drafted a geothermal law. To exploit the renewable geothermal resources rationally and efficiently, the state has to preserve the resource, balancing the interests of the investors with those of the nation. Taking this into account, INE, through its geothermal department, prepared draft geothermal legislation for submission to the Nicaragua's National Assembly. The main principles behind the proposed law are:

- Geothermal resources belong to the Nation.
- INE is the state agency in charge of formulating, promoting and regulating the policies, strategies, supervision and control of geothermal exploration and development activities.
- The activities related to the exploration and development of geothermal resources are of national interest.
- The rational development of geothermal resources is declared of public interest for all legal purposes.
- The state may grant geothermal exploration and development leases.

6.2 *Power generation*

Power generation is open, without restrictions, to private companies in Panama, Guatemala, Honduras, El Salvador, and Nicaragua.

In Guatemala, hydroelectric plants with more than 5 MW capacity require special authorization from MEM, which can be granted for a maximum of 50 years. In Honduras, private power generators must sell power exclusively to the Empresa Nacional de Energía Eléctrica (ENEE).

In El Salvador, the General Electricity Law provides open access to the private sector in all types of generation. According to the Salvadoran constitution, hydraulic and geothermal resources belong to the state, but can be exploited by private companies once they obtain concessions through a public tender procedure defined in the LGE and administered by SIGET. Concessions are permanent and transferable, and subject to public offerings administered by SIGET. Companies interested in concessions must present written requests to SIGET. Currently, all thermal generation is in private hands. Two geothermal power plants are majority owned by Geotérmica Salvadoreña (GESAL), a CEL subsidiary, but have private partners, while all hydro generation is owned by CEL. Two other geothermal fields, San Vicente and Chinameca, have been given in concession to a private investor, and are in the evaluation phase. Some thermal generators, e.g. Duke Energy El Salvador and Nejapa Power, have power purchase agreements with CEL, which expire by 2003. Additionally, private companies import about 9% of the electrical power needs from Guatemala.

In Nicaragua, the electricity law allows private power plants to produce and sell electricity to any buyer; power generation licences are granted by INE. However, private producers are not allowed to distribute electricity.

In Costa Rica, private power production is strongly limited and controlled. Private generation is regulated by the Act No. 7200. The National Electricity Service (SNE) is the regulatory agency in charge of granting concessions of up to 20 years for environmentally friendly electricity production. Concessions to a given company are limited to a total plant capacity of 20 MW. Concessions can be transferred after approval by the SNE. In the first version of the law, Costa Rican nationals must hold at least 65% of project equity. To improve foreign investments this number was reduced to 35% in 1995. Power plants of more than 2 MW capacity require an environmental impact study and a permit from the Ministry of Energy and Environment (MINAE). Private electricity generation is limited to 15% of the country's total, and is excluded from public bidding needs. An additional 15% can be bought by ICE by applying public bidding regulations; in that case, the maximum total capacity of a company is increased to 50 MW. Incentives to promote the generation of environmentally friendly electricity are given by issuing special credits through national banks and import duty exemptions which allow free import of equipment into Costa Rica.

6.3 *Power transmission*

Presently, Nicaragua is the only Central American country that allows private power transmission, as stated in the 1998 electricity law. In El Salvador the high-voltage transmission grid is owned and maintained by Empresa Transmisora de El Salvador (ETESAL), a wholly owned CEL subsidiary. However, there are no legal limitations for a private investor seeking to invest in the expansion of the grid. The Unidad de Transacciones (UT) is in charge of the transmission system; all expansions of the grid must submit operational control to the UT.

6.4 *Power distribution*

Power distribution is open to the private sector in Panama, El Salvador, Guatemala, and Nicaragua. Whereas in Panama and in El Salvador private participation is unlimited, in Guatemala's MEM issues permits that establish areas of distribution on a non-exclusive basis and are limited to 50-year periods. In Nicaragua, private power distributors must by law allow connection to their systems by any economic agent or consumer. With the exception of isolated rural areas, these distributors are not permitted to generate electricity. The government-operated National Dispatch Centre allows distributors to buy electricity based on lowest marginal generation cost. In Costa Rica, private power distribution is not permitted. In Honduras the opening of power distribution to private companies is planned under the Framework Law; distribution assets are to be privatised. In El Salvador, in accordance with the LGE, CEL spun off into five separate companies and sold its distribution assets. Today, about 79% of the country's distribution is owned by AES Corporation (U.S.A.), the rest by EMEL (Chile) and PPL Corporation (U.S.A.).

7 GEOTHERMAL ENERGY IN THE FRAMEWORK OF NATIONAL ENERGY DEMAND AND EXPANSION PLANS

According to a 1998 study by the Inter-American Development Bank (IDB), Central America's annual growth rate will be between 6 and 9%. As a result of deregulation and privatisation, coherent national energy plans do not exist. In addition and due to present trend toward regional planning and the proposed natural gas pipelines, forecasting future use of different energy sources in individual countries is difficult. This is especially true for countries where the privatisation process is most advanced as in El Salvador, Guatemala and Nicaragua.

In Costa Rica, geography and the abundant rainfall have permitted the construction of several large (and small) hydroelectric projects. The total electricity production in the country was 6718 GWh in 2001 (Fig. 10). The main energy source for electrical generation was hydropower (84.6%), followed by geothermal (12.2%), and wind (2.7%). Thermal plants, which are used predominantly for peak load, produced the balance (i.e., 0.5%). Approximately 80% of the Costa Rican population have access to electricity. According to ICE's estimates, the country power sector needs investments of about US 3000 million by 2011, to satisfy the demand which is forecasted to grow at an annual rate of 4.8 to 6.1% during the 2000–2020 period. Costa Rica's National Energy Plan calls for the installation of 29 new power plants, predominantly hydroelectric projects, resulting in an extremely high dependence on hydropower. According to ICE's plans, Costa Rica will maintain its present energy mix for the next 15 years or so.

At the end of 2001, El Salvador's installed generating capacity connected to the high-voltage grid was 1117.6 MW (395.8 MW hydroelectric; 161.2 MW geothermal; 560.6 MW thermoelectric). During that year, 3973 GWh were generated (47.8% thermal, 29.5% hydro and 22.7% geothermal). CEL estimated that electricity demand in El Salvador would grow in the next 15 years at an average annual rate of 4.1% to 7.35%. Since deregulation, no organization has produced a national energy plan, but historic data can be obtained from SIGET, UT, and DGE. Figure 10 shows the historic and future development of installed capacity and electricity production. The forecasts are based on the assumption that there will be no significant changes of the relation between the different energy sources in the future. However, most electricity plants publicly announced by private companies are thermoelectric installations to be built in El Salvador or neighbouring countries to generated power for export to El Salvador. This is mainly due to short-term financial reasons than fundamental economics, and may cause an increase in the price of power in El Salvador in the near future.

In 2002, the installed capacity in Nicaragua totalled 653 MW (15.8% hydroelectric; 70.4% thermoelectric; 13.8% geothermal). The total electricity generated in 2001 amounted to 2522 GWh (81.5%; 7.9% hydroelectric; 7.9% geothermal). Because during the 1980's and most of the 1990s, no significant investments were made in the energy sector, presently only 52% of the population have access to electricity. Overall the country lacks adequate electrical power generation capacity. INE estimated a 6% per annum growth in electricity demand over the next two decades. To satisfy this demand and increase electricity generation capacity to 1179 MW, at

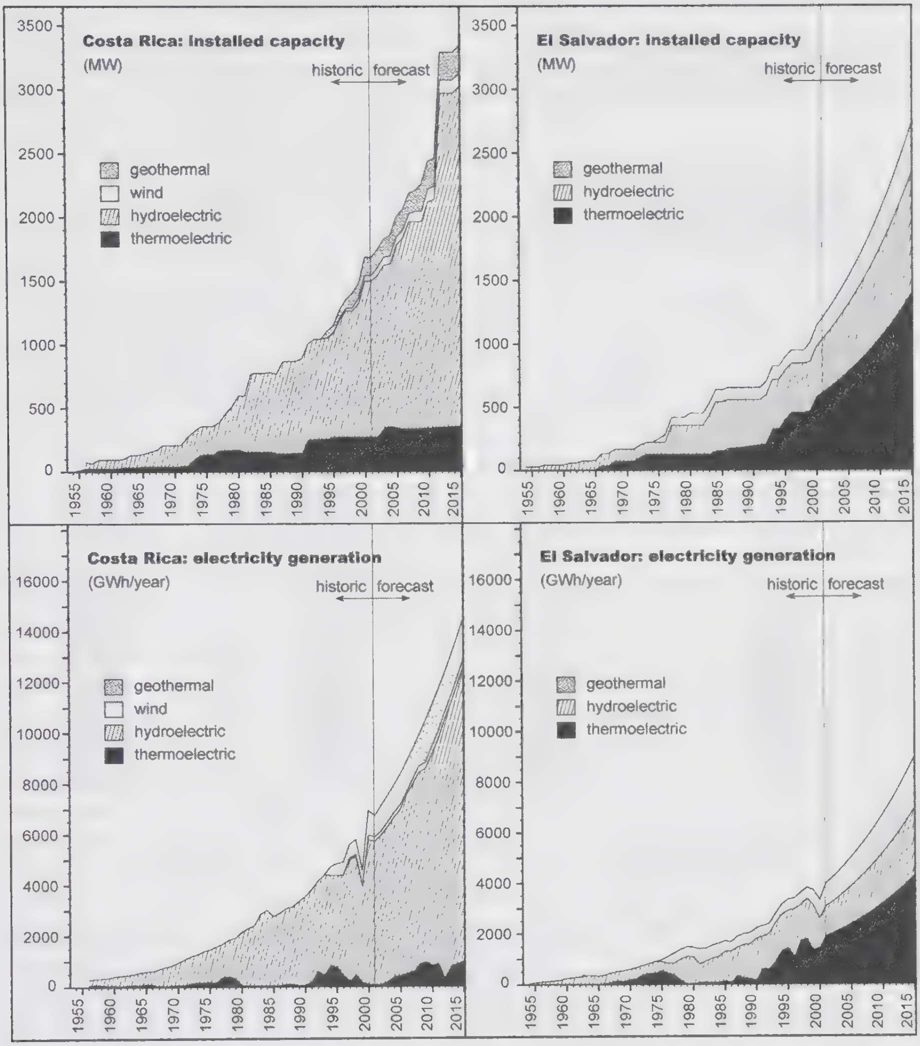


Figure 10. Historical and forecasted growth of installed capacity and electrical generation in Costa Rica and El Salvador, by source. Forecasts for El Salvador were obtained assuming an average 6% annual growth in demand; those for Nicaragua are based on data from the national energy plans developed by the National Energy Commission (Comisión Nacional de Energía 2001).

least US$ 1800 million need to be invested. A 1998 IDB loan is being used to promote the development of renewable generation projects in areas not connected to the national grid. In late 1998 work began on a 232-MW geothermal plant in western Nicaragua, with backing from Germany, the United States, and Russia. Spain's Iberdrola is developing a 22-MW, US$ 25 million wind power project south of Managua. A Geothermal Master Expansion Plan for the country's power generation system was developed by the National Energy Commission.

By 2005 Nicaragua's installed capacity will increase from 653 MW to 725 MW, reducing thermoelectric by 14 MW, and increasing geothermal by 86 MW (Comisión Nacional de Energía 2001). This will significantly increase the contribution of geothermal to the power mix (i.e., from 14 to 24%, in terms of installed capacity). In addition a 15-MW biomass power plant will be installed. For the period 2006–2010, Nicaragua has developed a number of scenarios for future

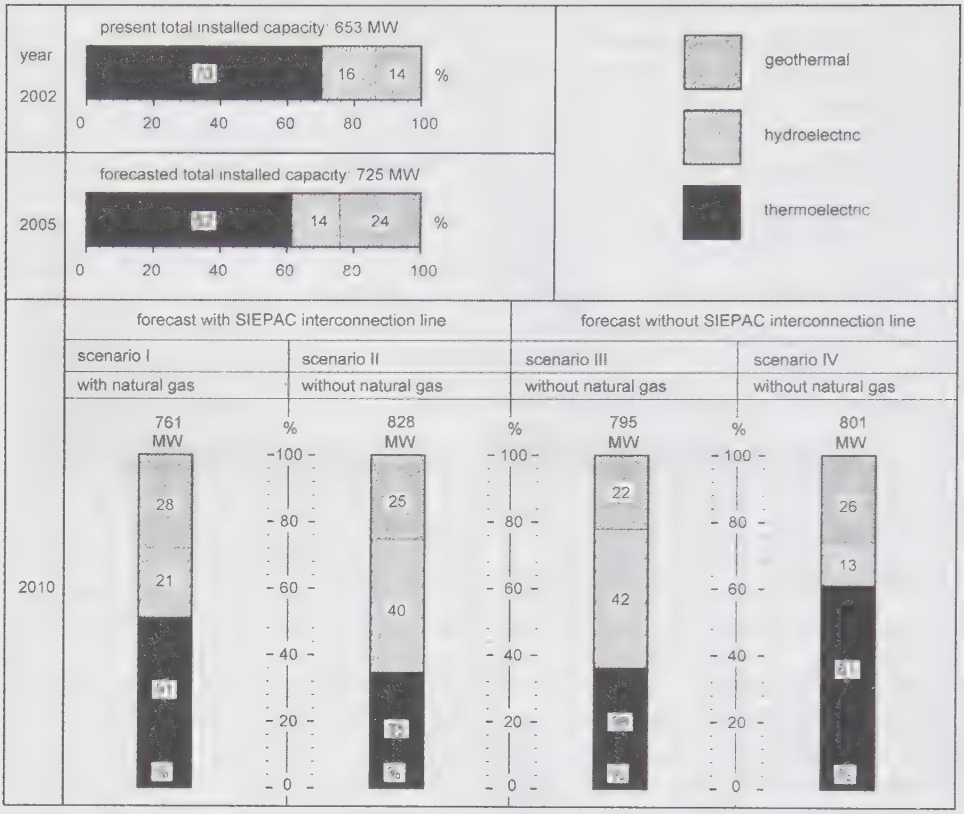


Figure 11. Nicaragua – Installed capacity (2002) and energy expansion plans by source (based on data from the Comisión Nacional de Energía 2001).

energy projects assuming the use of different energy sources. The amount and type of sources that will be used depend primarily on the execution of two projects, the construction of the SIEPAC electricity interconnection line and the natural gas pipelines projects from Guatemala or Colombia/Panama (Fig. 11). With the SIEPAC project (scenarios I and II) and without it (scenarios III and IV), the contribution of geothermal to the country's total installed capacity will be quite similar (i.e., in the 22–28% range). However, the percentages of installed capacity will markedly change for thermoelectric and hydroelectric projects (Fig. 11). The most sustainable energy solutions are scenarios II (with SIEPAC) and scenario III (without SIEPAC), which would increase renewable energy (i.e., geothermal plus hydro) capacity from 30% in 2002 and 38% in 2005 to about 65% in 2010. On the other hand, scenarios I and IV would increase sustainable energy capacity only to 49 and 39%, respectively.

In 2002, Guatemala had an installed electric power capacity of 1231 MW (48.7% thermoelectric; 46.8% hydroelectric; 5.1% biomass; 2.4% geothermal). The amount generated in 2001 was 2545 GW (48.5% thermoelectric; 40.3% hydroelectric; 7.8% biomass; 3.4% geothermal). The projected annual growth rate is 8% up to the year 2020. The government plans significant capacity increases and private investment in the electricity sector which suffers from the effects of periodic droughts that reduce hydroelectric output and send prices higher during peak demand periods. Guatemala also plans to increase electrification efforts, only 56% of the population has access to the electrical grid. It plans to install 12 hydroelectric, one geothermal plant, and two 120-MW thermal plants. This would make Guatemala even more dependent on hydropower whose availability is strongly affected by climate events.

In 2001, Honduras' electricity consumption reached nearly 4300 GWh, which had been increasing at an average annual rate of 7% to 10%. Hurricane Mitch (August 1998) was a devastating blow to the economy and caused a temporary reduction in energy demand. The growth in demand returned to its earlier trend as soon as the large consumers of electricity recovered from the disaster (i.e., by the year 2001, the growth rate was 8%).

Honduras has an install electrical generating capacity of 987.8 MW. Hydropower contribution is 44%, most of it coming from the 300-MW Francisco Morazán (El Cajón) project. One percent of the capacity corresponds to cogeneration based on biomass, the rest (55%) to traditional thermal plants (private companies own 52% of these plants). Until 1993, more than 90% of electricity generated in the country came from hydropower projects. However, economical and financial problems of the national utility prevented the expansion of the country's hydroelectric installed capacity. To keep up with the growth in demand, and taking into consideration that in December 2001 only the 57% of the population had access to electricity, Honduras needs to develop strategies to increase its electrical capacity and output using all available resources. Geothermal could contribute significantly to those plans if adequate policies are established.

Honduras' electricity consumption annual growth rate is 14%; demand was approximately 600 MW before Hurricane Mitch. The total installed power generating capacity is 720 MW (60% hydroelectric; 40% thermoelectric). Currently, more than 30% of the Honduran population lacks access to electricity. In addition to the extensive damage caused by Hurricane Mitch, a fire took the El Cajón hydroelectric plant off line in February 1999, thus reducing Honduran generating capacity by 300 MW, or 40% of the total. Thermal plants and electricity imports filled the power generation gap while repairs took place.

Electricity generation accounts for most of Panama's domestic energy production, with hydroelectric generation alone accounting for 75% of the country's total energy production. Electricity demand is expected to grow significantly in the coming years, and new projects are planned to help meet the demand. Since the break-up of IRHE, the Panama City area has faced a power shortage. To deal with this, Panama has turned to the private sector, namely Minova Generating of Germany, in partnership with U.S.-based Noresco and Wartsila, for a 60-MW, fast track power supply project. In March 2001, a construction contract for the Esti hydroelectric project was awarded to Sweden's Skanska. The 120-MW plant is scheduled for completion in November 2003. Other possible hydroelectric projects include Río Cocle del Norte (18 MW), Río Indio (25 MW), and Indio-Gatán (10 MW). In June 2000, neighbouring Colombia's Senate approved a bill allowing natural gas exports, which previously had been banned. This paves the way for the possible construction of a gas pipeline from offshore Colombian gas fields directly into Panama.

In May 2000, the IDB approved its first project in Panama. The bank will loan US$ 59.8 million to IGC/ERI Pan Am Thermal Generating Limited (PATG) for the construction and operation of a 96-MW, US$ 92-million thermal electric plant near Panama City. Construction of AES's US$ 200-million, 132-MW Esti hydroelectric project in Panama's Chiriqui province began in August 2000. Esti is made up of two hydroelectric plants, Guasquitas and Canjilones, on the Chiriqui River. By September 2002, ETESA is expected to ask for bids for the construction of a US$ 144-million transmission line to connect the Esti project to the national electrical grid. According to existing plans, the emphasis on hydroelectric projects and thermal power plants will not change in Panama during the next two decades.

8 GEOTHERMAL RURAL ELECTRIFICATION AND DIRECT USE OF GEOTHERMAL ENERGY

In spite of Central America's huge potential for direct uses of lower temperature geothermal resources, practically there are no developments of this type in the region. Currently, direct uses are mostly restricted to tourism and bathing purposes. Only in Guatemala, geothermal heat is used commercially for drying agricultural products and for other industrial purposes.

Additionally, geothermal energy can be used in rural electrification by installing small (less than 5 MW) power plants that could help improve the development of the region. These smaller plants would be an economic alternative to the costly extension of national grids. They could also improve rural micro- or mini-grids, which classically are based on small generators that burn diesel, a fuel that is expensive and sometimes not available due to a lack of an appropriate infrastructure, especially roads that are impassable during rainy seasons. Both, the promotion of direct use and rural electrification based on geothermal resources, require the implementation of pilot projects to help popularise these opportunities.

In Guatemala, geothermal energy is used at the Amatitlán geothermal field (Fig. 12) in two industrial plants. The first is the Bloteca plant that produces construction blocks. Since 1998, the

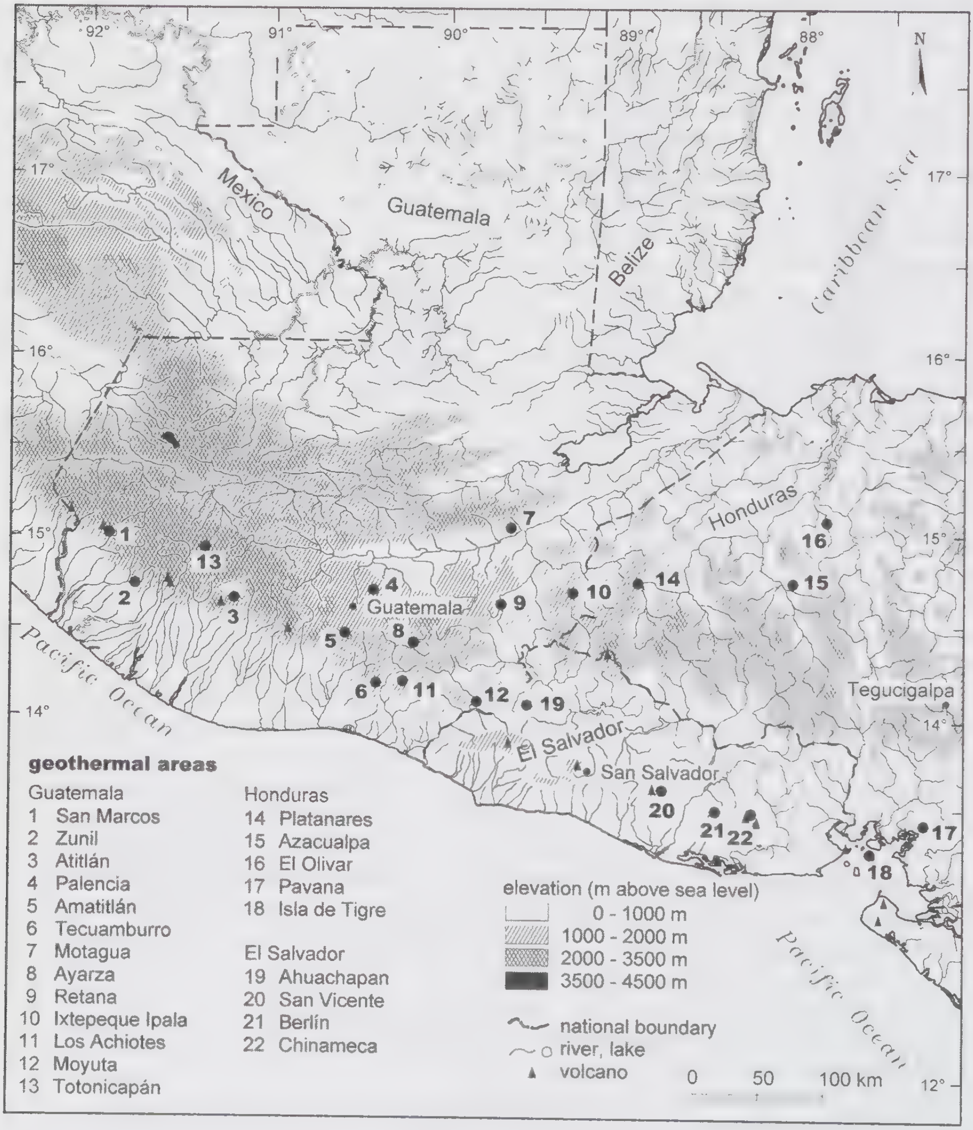


Figure 12. Geothermal areas of interest in Guatemala, El Salvador and West-Honduras.

plant has used geothermal energy in the form of steam to cure its concrete products. The installed capacity is 1.60 MW and the annual energy use is 40.4 TJ corresponding to 11.2 MWh per year (plant capacity factor 0.77). Replacing diesel fuel with geothermal energy saves US$ 24,000 per month. The second industrial operation using geothermal energy directly, is the Agroindustrias La Laguna fruit dehydration plant. Initially it was a demonstration pilot project, but later it became a commercial enterprise. A downhole heat exchanger with an estimated installed capacity of 0.5 MW (12.1 TJ/year or 3.4 GWh/year) is used. During the development of the project, the owners decided to introduce a green product, called Eco-Fruit, to the local market. It was a great success showing that consumers prefer products produced by clean technologies, e.g., drying fruit using geothermal energy.

At the present time, Nicaragua has no direct use geothermal projects. INE with support from the European Union and the United Nations Economic Commission for Latin America and the Caribbean (ECLAC), had planned a geothermal rural electrification and direct application pilot project in Cosigüina and Ometepe Island (Fig. 13). It would have been a pilot project to demonstrate the possibility and importance of using low- to medium-enthalpy geothermal fluids as an economic and environmentally sound way to improve the standard of living of rural populations. It would evaluate the application of those fluids for drying grains, fish farming, and heating greenhouses (Fig. 13). The projects were located in those particular areas because of the importance of their agricultural and tourist activities. Unfortunately, the ECLAC's project "Direct Use and Rural Electrification" failed. INE could not carry out needed investigations in Ometepe and Chinandega.

Geothermal electricity generation in rural and isolated zones reduces their dependence on oil and diesel fuels, which often must be transported over long distances, and sometimes over environmentally sensitive areas like Lake Nicaragua (Fig. 13). Currently fuel is shipped to Ometepe and other islands in that lake to supply diesel generators. A spill could harm the unique fauna of Lake Nicaragua.

CNE, Nicaragua's national entity responsible for rural electrification, is in charge of studies prioritising the use of the geothermal resources in rural areas. On the other hand, private developers could exploit these resources for direct uses as well.

9 LIMITING BARRIERS AND FUTURE NEEDS TO PROMOTE GEOTHERMAL ENERGY

With the exception of Belize and Panama, all Central American countries could use geothermal energy to satisfy large part of their present and future electricity needs. In addition, geothermal energy has a huge potential to be used in direct application and for rural electrification projects. Both market opportunities have yet to be developed in the region. To use geothermal resources for electricity generation, the countries must create or improve policies on sustainable renewable energies and must integrate geothermal energy in their development plans and not consider it only from a purely market point of view.

In the framework of deregulation of the national and regional electricity markets, Central American governments should use the restructuring process as an opportunity to promote geothermal energy and other clean energy sources. This would improve the economic and sustainable development of the countries and the region by considering all ancillary benefits, including the social development of the region.

The true potential of renewable energy sources could only be successfully harnessed to satisfy an increasing percentage of the fast growing energy demand, if Governments prepare the institutional and regulatory frameworks that would help overcome the present economical and financial obstacles associated with geothermal projects. To attract foreign private investments in geothermal energy projects and in public electricity institutions as well as to obtain the required international loans, regulations, laws and market instruments must be developed. Clean energy

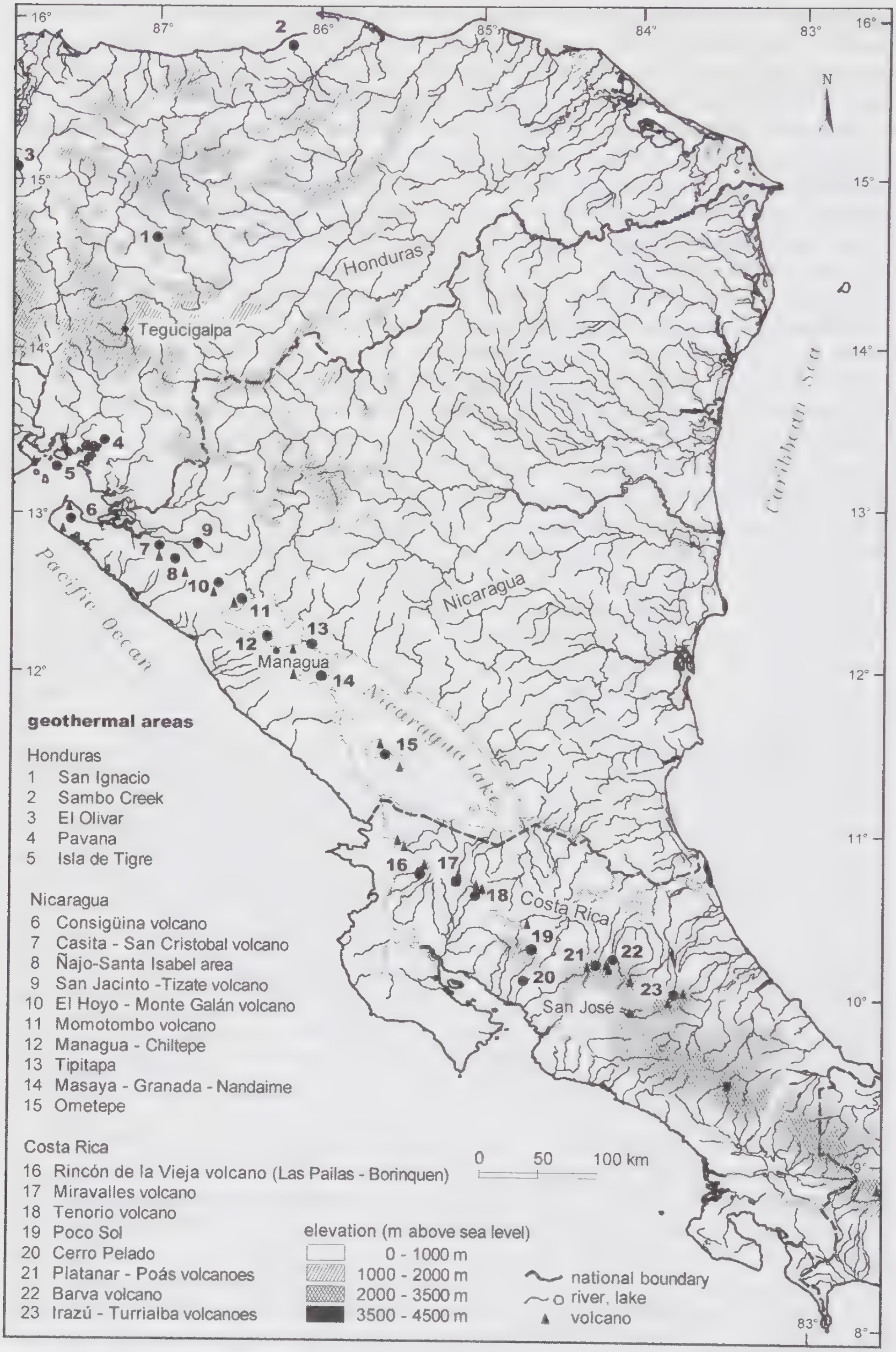


Figure 13. Geothermal areas of interest in Honduras, Nicaragua and Costa Rica. For details from Costa Rica geothermal fields see Moya et al. (this book).

projects may be promoted by tax incentives, subsidies and investment guarantees. On the other hand, investments in environmentally unsound projects must be made unattractive through special taxes, like taxes on fossil fuels, including use taxes and higher import taxes. Costa Rica has done so by implementing the 5% Fossil Fuel Tax Forestry Law #7575.

Only such incentives will avoid that low fossil fuel prices result in public and private investments in fossil fuel plants and become an obstacle for sustainable, renewable energy development. This is because without incentives, investors will select projects with the highest benefits from the purely market-economic value.

In the case of renewables, especially geothermal, private sector participation is very important due to the high costs and risks of exploration and the high initial costs to develop a geothermal field.

Additionally capacity building and popularisation of geothermal energy will be required to create awareness and acceptance of geothermal energy by politicians and decision makers. In addition, there is need for institutional strengthening, human resources formation and to consider geothermal projects as AIJ/CDM opportunities since they lower electricity generation costs (an important incentive for private investors).

Because of new and improved technologies the costs associated with geothermal projects is declining and will continue to do so. Potential private investors must learn from the experiences of other geothermal regions where private participation is more widespread (e.g., in USA and Asia).

To improve their development in an economic and social sustainable way, Central American countries should increase the use of their indigenous geothermal resources.

Costa Rica which already uses predominantly renewable energy resources to generate electricity and which has the most sustainable energy policy of the region. The country is recommended to substitute their few thermal plants and to reduce its over-dependence on hydropower with its seasonal weather related problems. During the next decades Costa Rica will favour a larger geothermal energy development; the electricity energy mix will tend towards a 1:1 relationship between hydropower and geothermal energy. Unfortunately El Salvador, Panama, Nicaragua and Honduras are planning to satisfy most of their future electricity demand using fossil fuels. On the other hand, for the same purpose Guatemala is expanding its hydroelectric sector.

We strongly recommend the Central American countries to integrate renewable energy sources in their future electricity development plans and to implement sustainable energy policies that provide incentives to all renewables sources, including geothermal.

10 GEOTHERMAL AREAS

In this chapter the geothermal areas of Guatemala, Honduras, El Salvador, Nicaragua, and Panama. Costa Rica's areas of geothermal interest are separately treated in this book in the chapter of Moya et al.

10.1 *Guatemala*

Research in geothermal resources in Guatemala started in 1972. The studies were funded by the National Institute for Electrification (Instituto Nacional de Electrificación, INDE), and supported by the International Development Bank (IDB), the Organization of Petroleum Export Countries (OPEC), the Latin-American Energy Organization (OLADE), the United Nations ROCAP/AID programme, the European Community (EC), the Japan International Cooperation Agency (JICA), and the International Atomic Energy Agency (IAEA).

The first studied area was Moyuta (Fig. 12), where surface geothermal manifestations indicated high probability of locating a high-enthalpy geothermal reservoir for electricity generation. In

1975, two commercial exploratory wells were drilled and unfortunately temperature reversal was encountered in these wells.

As consequence of these negative results, further research was focused on the Zunil and later on the Amatitlán geothermal field (Fig. 12). With the financial support of the Latin-American Energy Organization (OLADE) in 1981 the National Institute for Electrification (INDE) and the French Geological Survey (BRGM) carried out national inventory of the country's geothermal resources. This study found 13 geothermal areas (Fig. 12) located along the volcanic chain, which crosses the country from East to West, from the El Salvadoran border to the Mexico border. In addition to this areas around San Marcos, and Tecuamburro were also identified to belong to the group of the most promising geothermal areas. These sites are followed by in decreasing order of importance by Los Achiotes in Santa Rosa province, Moyuta in Jutiapa province and Ixtepeque-Ipala in Chiquimula province. In a third category the geothermal areas Palencia, Retana, Ayarza, Atitlán and Motagua were classified. In 1993, with the technical cooperation of the International Atomic Energy Agency (IAEA), the Totonicapán geothermal area was identified as the most promising area to be explored on a priority level.

In the following paragraphs an overview on the pre-feasibility and feasibility studies undertaken in the above areas (Fig. 12) and in other areas where commercial slim hole drilling were carried out are given.

10.1.1 *Moyuta geothermal area*

The Moyuta geothermal area is located to the West in Jutiapa province (Fig. 12, location 12). In 1972 the INDE started investigation in Moyuta covering an area of about 1000 km^2. In 1974 an area of 330 km^2 was delimited to carry out studies at prefeasibility level, and in 1975 INDE contracted ELC-Electroconsult company to evaluate and to complement the previous studies (ELC-Electroconsult 1977). As a result of these investigations and drilling of 12 slim holes, an area of 10 km^2 was selected to drill two commercial wells (INDE 1 and 2). Logging results indicated maximum temperatures of around 114°C, which are too low for electricity production. As a consequence, in March 1976 the exploration activities in the Moyuta area were suspended and further studies were concentrated on the Zunil geothermal field. In 1990, the INDE in cooperation with the Los Alamos National Laboratory (U.S.A.) re-evaluated the Moyuta geothermal system. This new study concluded that there are alternative sites in the Moyuta area to drill new exploratory wells with a high probability to discover a commercially exploitable geothermal resource to generate electricity.

10.1.2 *Zunil geothermal area*

The Zunil geothermal area is located in Zunil municipality, Quetzaltenango province (Fig. 12, location 2). First reconnaissance studies were performed between 1973 and 1977, with the technical cooperation of the Japanese government. From 1977 onwards, the INDE studied an area of approximately 310 km^2 with the objective of bringing the project to the prefeasibility level, drilling finally 18 slim holes. According to the results obtained in the preliminary feasibility study, in 1979 a 4 km^2 area was selected as the most promising area for further studies at feasibility level. This area was named Zunil I and the surroundings area Zunil II.

ZUNIL I: In 1980 and 1981 previous to signing a contract with ELC-Electroconsult to carry out the feasibility study for the field and the power plant, using its own funds, the INDE drilled six deep exploratory wells, of which four were productive. In 1982 the feasibility report of the field potential was released. This report confirms the existence of a 15 MW geothermal potential, which allows the installation of a power plant with a 20 years lifetime, and suggested drilling three more wells to sustain steam flow. However, these studies were not conclusive regarding the field capacity. In the following period, the INDE obtained a loan from the Interamerican Development Bank (IDB) to build the Zunil I geothermal plant, and in 1988 INDE signed a contract with the Company Morrison Knudsen-MKFerguson to perform complementary studies, plant design and supervision. Additional studies, based on geochemical results demonstrated that there exists a deeper geothermal reservoir. Based on these positive results, in 1991/92 three successful directional wells with depths between 1500 and 2000 meters were drilled. The power output of the first was over 12 MW, those of all three wells was about 24 MW. As part of modernisation process and to promote the private sector participation in electric power generation, in 1992 the INDE decided to renounce the IDB loan, which was designated to buy electromechanical equipment and invited private companies to construct and to operate a geothermal power and to sell the generated electricity to INDE on the basis of a Power Purchase Agreement (PPA). With this purpose a bid process was made and at the end of 1993 INDE signed a contract with the company Orzunil I de Electricidad Limitada. According to the contract, Orzunil I promised to install and operate during 25 years a 24 MW power plant and INDE will provide the steam required for the plant operation. This power plant starts its production on October 1, 1999.

ZUNIL II: Prefeasibility studies in Zunil II area, covered around 150 km^2 and started in 1989 with IDB financial funds and West Japan Engineering Co as consulting company. This company made a re-evaluation of the previous field data and selected a 16 km^2 area located two kilometres East of Zunil I as the most promising area to carry out detailed studies. Three slim holes were drilled during the study; one of them was productive, producing 35 tons of dry steam per hour, which confirms that there is a suitable geothermal reservoir. Prefeasibility studies ended in 1992, concluding that there is a commercially exploitable resource with a minimum capacity of 50 MW.

10.1.3 *Amatitlán geothermal area*

The Amatitlán geothermal area is located about 24 km South of Guatemala City (Fig. 12, location 5). First investigations were executed with the support of the Government of Japan in 1972 and by the INDE from 1977 onwards. The studies were interrupted in 1979 when the focus was drawn on the Zunil geothermal site. Studies up to the prefeasibility level were continued in 1980 covering an area of approximately 170 km^2. As part of this prefeasibility study, 10 slim holes were drilled. In 1985 the International Atomic Energy Agency (IAEA) contracted the consultant Werner Giggenbach to study the chemical and isotopic composition of the waters and gases from springs and fumaroles of Amatitlán lake and of the San Marcos and Zunil geothermal fields. This first hydrogeochemical model of the Amatitlán geothermal system indicates that the caldera zones are the discharge area of the system, where geothermal fluids ascend from the reservoir through faults and fractures.

Using loans of the IDB and the OPEC (through OLADE), prefeasibility studies were carried out with ELC-Electroconsult as consulting company. Since the existence of a commercial geothermal resource was confirmed, this company recommended continuing with the feasibility studies. In 1991, West Japan Engineering Co. was given the contract with IDB funds to perform the feasibility studies, and to drill four deep exploratory wells within the area of the calderas (West Jec 1995). These activities were finished successfully in March 1995, confirming the availability of 12 MW using wells AMF-1 and AMF-2 for exploitation and well AMF-3 for re-injection. With the purpose of exploiting the available geothermal resource in this area, in the middle of 1997, INDE approved the consultant service “Evaluation of the field under production and exploitation of the existing wells”. The contract included the installation of a backpressure power plant with 5 MW capacity, which should produce from November 1998 onwards through three years, 35 GWh/year ending that contract in November 2001. In parallel, INDE requested the Japanese government (through JICA) for a non-reimbursable cooperation support, to evaluate the extension of the Amatitlán field, including drilling of one or two deep commercial exploratory wells, with a schedule to be developed during 30 months and a donation of approximately US$ 8 million. This project was considered as high priority work by the Secretariat of Planning and Programming of the Presidency (SEGEPLAN) through the Minister of Energy and Mines (MEM) and on May 18, 1998 the “Scope of Works” was signed between MEM, INDE and JICA. To date complementary studies have been completed and the two wells were drilled. The evaluation of these wells resulted in a total production capacity of 7 MW. With the results obtained from the studies and the drilling operations, JICA presented in March 2002 its final report on the feasibility study, which shows that the reservoir has an initial capacity of 50 MW during 25 years. This fact reduces the exploitation risk to a minimum and makes the Amatitlán geothermal field a good opportunity for private investors. Either on their own, or with the INDE as a counterpart, the private sector may invest in the installation of modular type plants and exploit the total capacity of the field for electricity generation.

10.1.4 *San Marcos geothermal area*

After the regional geothermal study, which was performed by OLADE in 1981, the INDE made preliminary investigations in the San Marcos geothermal area, covering about 85 km^2. (Fig. 12, location 1). On the base of this study, in 1993, INDE signed an agreement for technical and financial cooperation with the European Community (€ 620,000) to define the prefeasibility of San Marcos field. The studies started in September 1993 and the final report was presented in December 1997. The results confirm high reservoir temperatures, suitable for its exploitation to produce electricity with an estimated capacity of 24 MW (Roldán 1997).

10.1.5 *Tecuamburro geothermal area*

The Tecuamburro geothermal area is located in Santa Rosa province at the flanks of the volcano with the same name (Fig. 12, location 6). In this area, from 1988 onwards prefeasibility studies were carried out in collaboration with the Los Alamos National Laboratory (U.S.A.), and with financing through the United Nations ROCAP/AID programme. On the base of geological, geochemical and geophysical studies, an 800 m deep slim hole was drilled, obtaining a maximum underground temperature of 235°C (Goff et al. 1992). The capacity of the field was estimated to be 50 MW (Janik et al. 1992).

10.1.6 *Totonicapán geothermal area*

In the Totonicapán geothermal area (Fig. 12, location 3) preliminary studies started with the aid of the International Atomic Energy Agency (IAEA) based on the Technical and Financial Cooperation Agreement GUA/08/011 signed with INDE through the General Directorate for Nuclear Energy of the Minister of Energy and Mines. In 1996 the first geochemical field work was conducted and in March 1997 samples for isotopic analyses were collected. The samples were analysed by IAEA in Vienna, and preliminary geochemical evaluation was made with the collaboration of an expert from the IAEA (Arnorsson 1997). In the same year preliminary geological study was carried out, and in 1998 gravimetric and magnetometic studies were conducted.

10.2 *El Salvador*

The substantial changes in El Salvador's electricity legislation in the past few years will permanently modify the concept of geothermal developments and power generation in general in the country. Prices per kWh are now set by forces of supply and demand, rather than by executive decree. Several new organizations have been created to control and regulate the power market, which is becoming a very strong and dynamic player in the national economy. Geothermal must compete – and is doing so – with other energy sources without any preferential treatment from the government.

Some of the regional energy projects will further have an impact on geothermal, as they bring more competition on line, some expected by mid 2002. There are projects underway to interconnect all of Central America and construct one large market, and plans to build a gas pipeline from Mexico to El Salvador, or from Colombia to Panama. All of these projects would have an impact on the local electricity market.

In total, the Ahuachapán and Berlín geothermal fields (Fig. 12) accounted for 22.9% of the electricity injected into the Salvadoran wholesale market in 2001, making El Salvador the most geothermal energy dependent country in the world to cover its electricity demand (SIGET 2001). This figure may increase in the following years, as the new power plants in San Vicente and Chinameca are built, and as Berlín and Ahuachapán are further developed (Fig. 12).

10.2.1 *Ahuachapán geothermal area*

Early exploration work started in Ahuachapán in the late 1960s and culminated with the first geothermal electricity generation in Central America in 1975 (Fig. 12, location 19). The Ahuachapán geothermal field was overworked in the early 1980s, when the transmission lines from hydroelectric projects from the North of the country were routinely attacked by guerrilla groups and geothermal energy from the peaceful Western end of the country had to supply the deficit. Furthermore, waste brine was not re-injected, but was dumped via an 80-km-long canal into the ocean. As consequence, the reservoir pressure dropped rapidly, and the power output was cut back from 95 MW in 1981 to just 48 MW in 1994. In fact, in 1981 Ahuachapán produced 41% of the electricity consumed in the country, a figure that still stands as a record. The US$ 50 million "Ahuachapán Stabilization and Rehabilitation Project" was devised to simultaneously stop further pressure drop and to increase power output by carrying out several key project components: (a) drilling 10 new production wells in the South of the production area, closer to the heat source and the recharge area, (b) building a pipeline to inject brine into existing wells in the 7 km far Chipilapa area, which is hydraulically connected to the Ahuachapán reservoir, (c) constructing the gathering system from the new wells to the power plant and to injection wells, and (d) refurbishing some of the electrical and mechanical equipment in the power plant. As new wells have been added and the re-injection has started to work, the power output is now about 62 MW and stable, and the reservoir pressure has essentially stabilized at 1994 levels. Some of the new wells drilled to the far South of the field have shown calcite scaling problems, so the exploitation schemes are being adjusted. Currently, about 75% of the brines are re-injected in the Chipilapa area via a 6 km long pipeline, and the remaining 25% are still being dumped into the ocean. The new environmental regulations require that all the brine be reinjected, so major work is still in progress in Ahuachapán.

10.2.2 *Berlín geothermal area*

Feasibility studies to erect a condensing power plant in the Berlín field (Fig. 12, location 21) were carried out in the early 1980s, but were abandoned when the armed conflicts with the guerrilla made working there too dangerous. The idea was renewed in the early 1990s, and a 10 MW backpressure facility was installed in 1992. After the government obtained financing from the Interamerican Development Bank in 1994 to upgrade the national electricity system, a new 56 MW (2 × 28 MW) condensing facility was installed on July 10, 1999 in the Berlín geothermal field. Reservoir depth is between 1950 m and 2300 m, and the highest measured temperatures are 305°C. Project components were: (a) erection of a 56 MW condensing power plant (2 × 28 MW modular units), (b) drilling of 18 new production and injection wells, complete with access roads, (c) erection of a 7 km long 115 kV transmission line, (d) erection of 16 km of pipelines for the gathering system, and (e) construction of a 24-person camp for workers who will reside on-site. The new power plant is currently operating above nominal capacity. Because field capacity estimates range from 100 MW to 150 MW, feasibility studies are being carried out to determine the possibility of installing a third condensing unit at the same site.

10.2.3 *San Vincente and Chinameca geothermal fields*

In August 2000, concessions were awarded to Orpower 7, a subsidiary of Ormat Industries Inc., to exploit the San Vicente and Chinameca geothermal fields (Fig. 12, locations 20 and 22). Orpower 7 has committed to erect a 50 MW power plant on each field, if the resource is deemed to sustain that capacity.

10.3 *Honduras*

In Honduras, the geothermal resources have been evaluated by the national electricity company (Empresa Nacional de Energía Eléctrica, ENEE), mainly for electricity production purposes with emphasis on medium size projects to be connected to the national grid.

During the regional programmes promoted and financed by United Nations and USAID, which were carried out in the 1970 and 1980, a geothermal resources inventory of the central and western part of the country was carried out and six main geothermal areas were identified (Figs 11 and 12). Hydrogeochemical studies of these sites were performed out by Los Alamos National Laboratory. The same institution carried out a prefeasibility study with exploratory drillings of Platanares geothermal area, which is considered to be the most promising geothermal resource of Honduras.

As a result of the modest geothermal potentials identified during these studies and due to the fact that Honduras does not yet count on any geothermal plant in operation, the investigation entered a lethargic period. The only effort to continue with the investigations has been made by the ENEE, which tried to obtain financing to continue with the studies and to promote the development of the potential geothermal sites identified.

Actually Trans-Pacific Geothermal Corporation (TGC) from U.S.A., is interested in developing the Platanares geothermal project on the base of a Power Purchase Agreements (PPA) with ENEE. By the end of 2001, TGC started inquiring about the proceedings required by law to obtain the permissions, which will allow them to study and develop the Platanares site.

To succeed in promoting private developments of geothermal projects, Honduras needs to update the inventory of the geothermal resources and to determine the economical and environmental viability of the sites with the highest geothermal potentials. The state owned company ENEE is in the process of privatisation, therefore, it does not have plans to build any new plants, but will continue planning and promoting the development of renewable energy projects.

During 2001, ENEE participated of the Regional Geothermal Project for Central America with the technical and financial support of the International Atomic Energy Agency (IAEA). A geochemical investigation of Pavana site was carried out. The results confirmed the temperature of 150°C determined by Los Alamos National Laboratory in 1987. At present, the ENEE continues with the geochemical investigation in the South of Honduras.

10.4 *Nicaragua*

Due to its location within the volcanic zone of Marrabios range along the Pacific Coast, Nicaragua is a country endowed with a large geothermal potential of about 3340 MW (advanced technology potential, Gawell et al. 1999). Geoscientific investigations started at the end of 1960, prioritising the Momotombo and San Jacinto-Tizate geothermal fields (Fig. 12). These studies reached their maximum apogee after 1973, when the oil crisis strongly affected Nicaragua's foreign trade balance. The commercial exploitation of Momotombo started in 1983, when the first geothermal electric unit of 35 MW capacity was put in to operation. The second unit of 35 MW capacity was installed in 1989. In 1993, drilling of a number of deep exploratory wells started to further demonstrate the existence of geothermal resources, which are suitable to be exploited commercially for electricity generation. All over the country these geothermal investigations identified 10 areas of interest (Fig. 12).

Nicaragua developed a geothermal master plan, which includes systematic studies of the geothermal resources, starting in August 1999. The main objective of this master plan is to re-evaluate and to classify the geothermal resources of the country in terms of their electricity generation potential, and to plan the follow-up exploration and development phases. Additionally the master plan is a planning instrument, which offers a solid base to establish optimal lease limits and

Table 6. Geothermal exploration concessions.

Concession	Area (km^2)	Concessionaire
El Hoyo-Monte Galán	89	TGC (expired)
San Jacinto-Tizate	90	San Jacinto Power
Ñajo-Santa Isabel	100	SAI
Momotombo	9	ORMAT
Casita	128	TRITON

concession conditions for the private sector participation. It will also be a document describing and promoting the development of Nicaragua's geothermal areas. The studies in each area include:

- General description and geographic limits.
- Description of available scientific data.
- Additional geoscientific investigations.
- Data synthesis and re-interpretation.
- Development of a preliminary geothermal model.
- Preliminary evaluation of the resource in terms of electrical power.
- Evaluation of environmental impacts.
- Specification of studies needed to reach the feasibility stage.
- Estimation of the costs to reach the feasibility stage.

The Nicaraguan government has released 5 areas for geothermal exploration, realizing that the private sector could be an important factor in the development of the natural resources of the country, particularly of geothermal energy resources (Table 6).

10.4.1 *El Hoyo-Monte Galán geothermal area*

In December 1995, the Instituto Nicaragüense de Energía (INE) granted an exploration lease to Trans-Pacific Geothermal Corporation (TGC) in the El Hoyo-Monte Galán geothermal area to determine the possibility of installing a 50–150 MW power plant using geothermal fluids (Fig. 13, location 10). From January 1996 to February 1997, TGC carried out studies comprising geological mapping, geochemistry, gas- and fluid chemistry, interpretation of aerial photographs and satellite images, microseismic studies, magnetic reconnaissance, and other geophysical studies, which allowed to identify various anomalies indicating a large geothermal resource characterized by shallow seismicity, fumaroles, surface fractures and high subsurface temperatures. Four areas to drill a number of small diameter wells were identified. These are the upper regions of the El Hoyo and Picacho volcanoes, the area Northeast-East of El Hoyo volcano, the Cerro Colorado, and the Monte-Galán caldera fracture systems. Based on volumetric calculations and an integrated analysis of geoscientific data, TGC estimated an economical feasible potential between 150 and 200 MW within its leased area.

10.4.2 *El Ñajo-Santa Isabel geothermal area*

In August 1997, INE granted a 100 km^2 exploration lease in the El Ñajo-Santa Isabel geothermal area (Fig. 13, location 8) to the Unocal Geotérmica Nicaragua company, a subsidiary of Unocal Geothermal International. The objective of the lease is to demonstrate the commercial viability of the area on the basis of geoscientific studies and deep exploration wells. Unocal carried out the following activities during the last quarter of 1997: geological mapping, geochemical studies, geophysical surveys, and satellite image interpretation. On August 19, 1999 Unocal Geotérmica Nicaragua decided to relinquish the El Ñajo-Santa Isabel exploration concession; therefore Sai Geothermal Inc. created a subsidiary Sai Geotérmica Nicaragua S.A. in order to follow the surface surveys and investigations made by Unocal on account of which Sai Geotérmica Nicaragua applied for a geothermal exploration concession on the same El Ñajo-Santa Isabel area. This concession was granted from the Nicaraguan government in December 1999. Sai Geotérmica Nicaragua intends to build a 60 MW geothermal power plant.

10.4.3 *El Casita geothermal area*

The company Black Hawk Mining Inc. has established a subsidiary in Nicaragua, Triton Energía S.A. to develop electrical energy projects from renewable natural resources. On August 1999 Triton Energy obtained an exploration concession from INE, within an area of 90 km^2 called El Bonete, located near of Telica, Santa Clara and Casita volcanoes (Fig. 13, location 7). Tritón Energía's objective was to carry out geocientific investigations near the El Limón Mine, as well as to obtain access rights from property owners in the district, that enable it to develop its own geothermal field in order to build a 10 MW geothermal electric plant to supply its energy needs. Early exploration results of the pre-feasibility study in this area confirmed the existence of a heat anomaly. However the geochemistry and geophysical surveys demonstrated that the heat source is located South-East of the original concession area. Therefore Triton Energía S.A. has requested a new geothermal exploration concession area to follow the surface survey and investigations on the shoulders of El Casita volcano close to the former concession of El Bonete area. This new area is called El Casita and will cover 128 km^2. INE granted this new area to Triton Energy on January 30, 2001. Due to the slide and mudflows, which occurred at El Casita Volcano caused by heavy rains from the hurricane Mitch in October 1998, and which killed over 2000 people, Triton Energía S.A. must take into consideration environmental and geologic hazard concerns when planning the development of this geothermal project.

10.4.4 *Momotombo geothermal area*

The Momotombo geothermal area, located at the foot of the namesake volcano (Fig. 13, location 11), was identified and studied starting in the late 1960s. The first four wells were drilled in the early 1970s, culminating with the installation of a 35 MW unit in 1983. Six years later, a second unit of 35 MW capacity went on line. Due to the overexploitation of the field and a total lack of reinjection during the 1980s, the power declined with time, amounting only about 20 MW in 2002. In March 1999, Ormat International Inc. won a 15-year BOT contract to exploit the Momotombo geothermal field. The objective of the contract signed with ENEL (Empresa Nacional de Electricidad), the national electrical utility was to improve the electricity output from the system and try to reach the total installed capacity of the power plant (70 MW). Because of insufficient geothermal steam, the plant was generating only 12 MW in early 1999. Ormat began its Momotombo operations in June 1999. The company's plan to increase geothermal fluid production was centred on repairing and cleaning of the existing wells, to drill new wells (OM-51 to OM-54), and to inject more fluids back into the geothermal reservoir. Since mid-2000 Ormat has completed three new wells and the drilling of a fourth one is underway (Table 7). The

Table 7. Characteristics of the wells at the Momotombo geothermal field.

Well	Depth (m)	Maximum temperature (°C)	Capacity
OM-51	2375	230	Non productive
OM-52	2839	307.5	Non productive
OM-53	2053	286.6	Commercial
OM-54	1831	252.6	In construction
MT-2	490	202.5	
MT-13	1829	262.8	
MT-14	671	184.6	

well OM-51 was a non-productive well, which reached a total depth of 2375 m and had at its bottom a temperature of about 230°C. The well OM-52 was also non-productive, its bottom hole depth and temperature were 2839 m and 307.5°C, respectively. The well OM-53 was a good well and its steam production is expected to raise the output of the plant to 36 MW; the well is 2053 m deep and its bottom hole temperature is 286.6°C. The drilling of OM-54 began in mid-December 2001; in mid-February 2002 it had reached a depth of about 1200 m. To date, mineral scales in eight production and four injection wells have been cleaned using mechanical methods and chemical scale-inhibition systems have been installed in those wells. At present, 80% of the waste fluids are being re-injected. To improve the understanding of the behaviour of the geothermal reservoir and wells, an interference test between wells MT-2, MT-13 and MT-14 was performed and the conceptual model of the geothermal systems has been updated. Ormat's strategy is giving good results; power output reached 28 MW in February 2002.

10.4.5 *San Jacinto-Tizate geothermal area*

In May 1993, the Nicaraguan-Russian consortium Intergeoterm received from the INE the right to explore the San Jacinto-Tizate geothermal area (Fig. 13, location 9). Between 1993 and 1995, Intergeoterm drilled seven wells with depths that varied between 724 and 2335 m (Table 8). The last well (SJ-7) could not be finished due to financial problems. The measured down hole temperatures range between 264 and 289°C. Wells tests indicated that cumulative capacity of the wells SJ-4, SJ-5 and SJ-6 is about 25 ME (Table 8). San Jacinto Power a joint venture enterprise received from INE an exploitation lease in order to continue the development activities at San Jacinto-Tizate.

10.5 *Panama*

Panama's location along the Quaternary volcanic belt continues to attract geothermal exploration interest (Fig. 14). Panama has been studied for its geothermal potential since the mid-1970s.

The Institute of Hydraulic Resources and Electrification (Instituto de Recursos Hidráulicos y Electrificación, IRHE), which is the former governmental electricity institution published several nationwide hydrologic inventory reports of the main hot springs areas as potential geothermal areas (Fig. 14). These studies include detailed information on the hot springs whose maximum temperature is 72°C, and chemical analysis. It is important to notice that the main springs are located on the southern, more accessible side of the continental surface water divide between Pacific Ocean and Caribbean Sea. Till now, it is speculated that undiscovered geothermal manifestations may exist in the uninhabited jungle north of this divide and existence of geothermal resources were reported by people living in the country.

The Barú-Colorado volcanic complex (known at the beginning as the Cerro Pando prospect) was the first prospect selected for detailed geothermal exploration. Here, six gradient wells with

Table 8. Characteristics of the wells at San Jacinto-Tizate geothermal field.

Well	Depth (m)	Maximum temperature (°C)	Capacity MW
SJ-1	2322	188	No production
SJ-2	1471	97	Impermeable
SJ-3	1876	265	Non commercial
SJ-4	724	267	About 17
SJ-5	2335	289	About 5
SJ-6	1877	264	About 3
SJ-7	1260	–	–

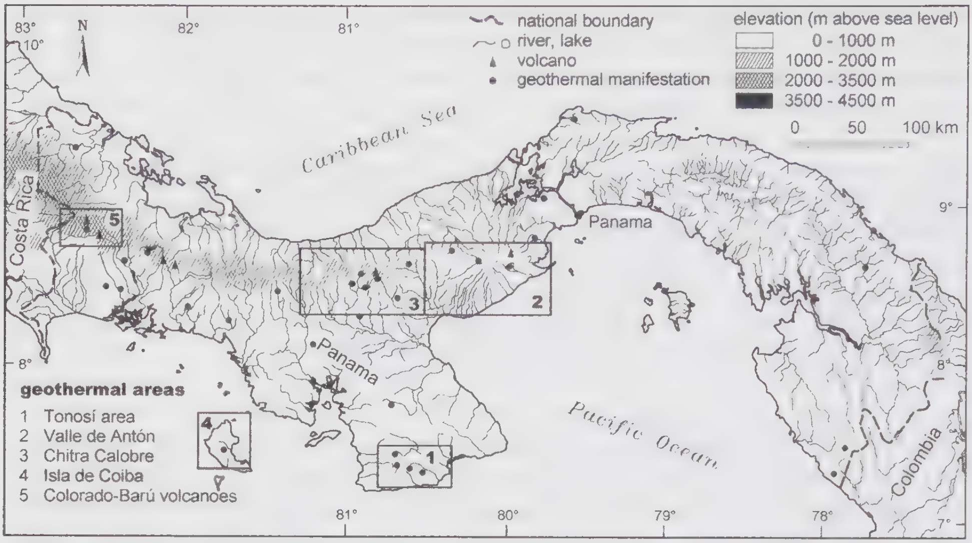


Figure 14. Geothermal areas of interest in Panama.

depths between 100 and 949 m were drilled between 1976 and 1977. The moderate results showed generally temperature gradients of less than 90°C/km. These studies were followed by a programme comprising geological mapping, geochemical sampling and analysis, and a geophysical survey. After reviewing all data acquired nationwide, the United Nations concluded in 1978 that there was low potential for high-enthalpy resources in Panama.

During the 1980s the exploration proceeded under a joint venture between IRHE, the Latin American Energy Organization (OLADE) and the Interamerican Development Bank (IDB). The IRHE was designated by the Panamanian government to be responsible for geothermal exploration and to evaluate previous work. Geological and geochemical studies were performed at each prospect known in the country (Fig. 14) and geophysical studies were extended to the Chitra-Calobre and El Valle de Antón regions, heading to a future plan, to drill a 1000 m deep slim hole to test El Valle de Antón geothermal site. So far, the Panamanian political crisis at the end of the 1980s stopped all geothermal activities in the country including the bid of the geothermal slim hole at the El Valle de Antón geothermal area.

It was until 1995, when IRHE restarted its geothermal programme with the purpose, to drill a well of 1500–2000 m depth at El Valle de Antón site. The IRHE was assisted by a joint venture between two geothermal companies, the West JEC from Japan and GeothermEx from the U.S.A. The aim was to drill this well to obtain direct information from the el Valle de Antón area and to evaluate its geothermal potential. The IRHE prepared all infrastructure needed to make the well (geothermal drilling platform, small dam for water, road access, etc.) plus all requirements that involved this task, like the environmental impact study, which was required by the governmental authorities.

At the same time, the IRHE was restructured to become a private company. This process divided the institution into eight companies, (three generating, four distribution and one transmission company), and from now on the geothermal activity was the responsibility of the transmission company called Electricity Transmission Company (Empresa de Transmisión Eléctrica S.A., ETESA). The ETESA took over the former roll of IRHE to drill the deep well at El Valle de Antón site. All environmental permits were approved and the bid for the drilling was made. ETESA was constructing a cement curtain of 70 m depth around the place where the drilling platform was going to be installed to prevent the contamination of the shallow aquifers. With the arrival of the new government in 1999, all work performed at El Valle de Antón site was suspended claiming environmental risk by the national environmental authorities (Autoridad Nacional del Ambiente, ANAM), and revoked the permit, which was already given by the same institution. Since the new authorities decided to move to another geothermal prospect in Panama, at El Valle de Antón all geothermal activities were stopped. El Valle de Antón area is still considered as one of the best prospects of Panama, but it will have to wait for future government decisions to finish its exploration and to know its geothermal potential.

In 2000, with the support of the International Atomic Energy Agency (IAEA), ETESA started a new campaign to re-evaluate the geothermal sites in Panama but the new exploration programme was designed for a period of three years in the areas of Barú-Colorado, Chitra-Calobre and Tonosí (Fig. 14). The idea was to use new isotopes techniques to improve the understanding of the low- to medium-enthalpy prospects for future development. Thereby the ETESA performed a completely new exploration of the Barú-Colorado area, reviewing all information available, since there were still a lot of doubts regarding the previous conclusions. After reviewing the available information, in 2001 ETESA started with a field campaign for geological verification, geochemical sampling (water and gas samples for chemical and isotopes analysis) and the preparation of the field to carry out a geophysical survey for 280 gravity and magnetic stations, and 28 MT stations. Unfortunately ETESA decided not to continue with that programme. So again the geothermal activity suffered another knockdown. The lack of ETESA authorities in continuing the exploration deviated funds addressed to this project to other activities, which were more important for the company, hence stopping the geothermal programme in Panama once more.

10.5.1 *El Valle de Antón geothermal area*

El Valle de Antón geothermal area is located about 80 km westwards of Panama City at the Pacific side of continental water divide (Fig. 14, location 2). It is characterized by a complex Quaternary volcanic structure, which is underlied by the Tertiary volcanic basement of the Panamanian mountain chain.

The volcanic eruption history at El Valle de Antón is very complex. Confirmed by radiometric dating, it is assumed that the volcanic activity started about 1.5 to 2 m.y. ago. During its initial phase, the activity was dominated by effusive production of lava and pyroclastic flows indicating plinian explosive eruptions. This initial phase is followed by two volcanic edifice failures leaving behind two calderas, La Mesa caldera and El Valle Caldera (Fig. 15). The older one, the La Mesa caldera, is actually an elevated plain with a smooth terrain contour situated about 300 m above El Valle caldera and cut by this younger caldera. The El Valle caldera is well marked by a morphological depression with walls of up to 200 m height.

Following the formation of El Valle caldera about 1 m.y. ago the eruptions of three volcanic domes (Pajita, Gaital and Carocoral) started inside the caldera. The last two eruptions could be identified: (1) a very explosive phase, known as Río Mar eruption (the name is given since that material from this activity was found at Río Mar beach 28 km away) coming from Gaital dome about 45,000 years ago, and (2) an eruption from a place about 1 km Northeast of El Valle de Antón known as Mata Ahogado eruption, whose age is about 35,000 years. The geological setting of El Valle de Antón gave a good probability of the possible existence of a geothermal reservoir, which encouraged the authorities to investigate and to prepare a plan for a more detailed exploration.

Hydrochemical sampling and analysis was performed for main ions and isotopes; sampling for mercury was done in a soil survey, and gases from thermal springs were analysed. The results concluded that thermal spring waters were of chloride-hydrogencarbonate type with high contents of sodium. The geochemical temperature using several geothermometers indicated reservoir temperatures between 140 and 180°C. Since all investigated waters show a high grade of dilution by shallow waters, the determined reservoir temperatures were questioned. The mercury soil analysis survey showed abnormal values in two regions of the caldera. One of the anomalies

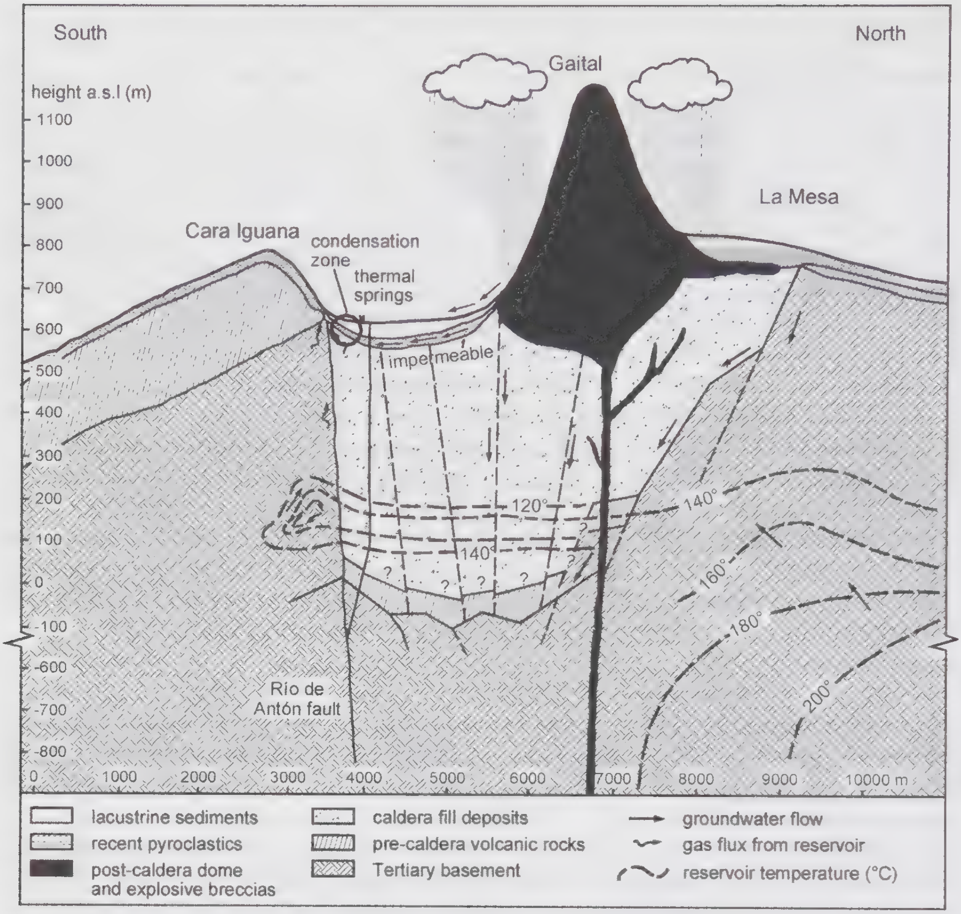


Figure 15. Geological and gravimetric interpretation of El Valle de Antón geothermal field.

is related to the Río Antón fault at the South of the caldera, whereas the anomaly to the northeast of the same in direction to Mata Ahogado town could not yet be explained.

Geophysical studies were carried out at El Valle de Antón including an electrical resistivity survey (SEV), gravimetric and magnetic studies. The results of these investigations helped to define well the structure of the caldera but raised uncertainties about the geothermal reservoir location. The reservoir could be located at the bottom of the caldera, from where geothermal fluids and gases try to reach the Earth's surface through the Río de Antón fault. Both SEV and magnetic survey results support this hypothesis. Another hypothesis is based on the strong anomalies, which were found to the northeast of El Valle de Antón caldera (Mata Ahogado area), which indicate the possible existence of a geothermal reservoir in that direction. Due to lack of sufficient information this hypothesis could not be proved. Depending on the results of the slim hole, which was planned to be drilled at El Valle de Antón, another geophysical survey was recommended for the Mata Ahogado zone including more gravity and magnetic stations plus some MT surveys around the area to analyse this potential geothermal prospect.

10.5.2 *Barú-Colorado geothermal area*

The geothermal investigations at Barú-Colorado region (Fig. 14, location 5; Fig. 16) started in the 1970s and were interrupted in the middle of the 1980s. During this period several

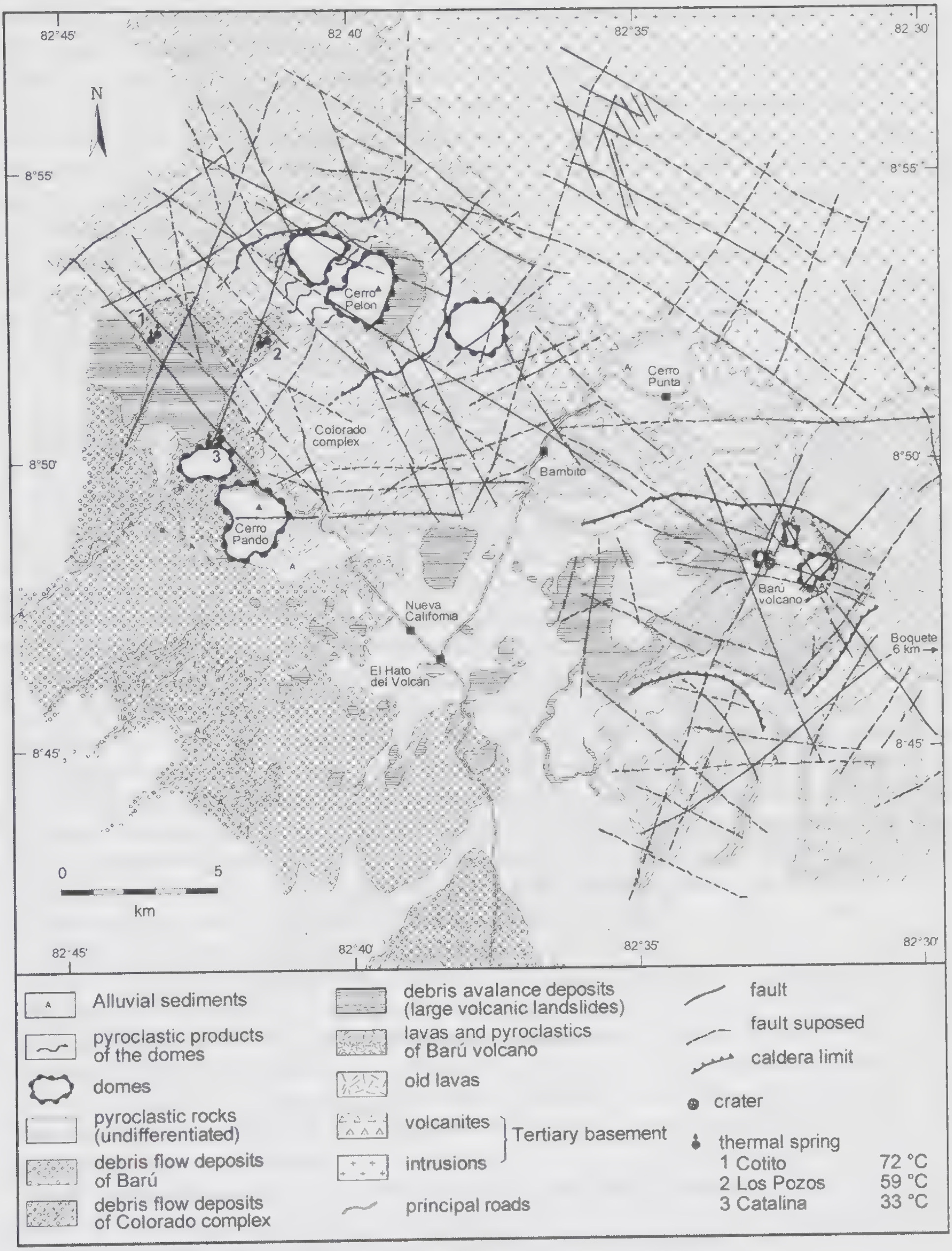


Figure 16. Simplified geovolcanological map of the Barú-Colarado geothermal area.

geovolcanological, geochemical and geophysical investigations were carried out, and six shallow slim holes were drilled in the Colorado area, resulting in different interpretations and conclusions.

The first studies from the 1970s indicated the presence of a possibly high-enthalpy geothermal reservoir with temperatures around 180 to 220°C, whose position could not be located with the investigations performed up to that time. However these uncertainties opened in the 1980s a new investigation programme to improve these results.

The new investigations in 1984 used the methods recommended by the Latin-American Energy Organisation (Organización Latinoamericana de Energía, OLADE), which suggest the following criteria for the presence of a promising geothermal site: (1) a heat source young enough, (2) a zone of permeable rock capable to store a geothermal reservoir of commercial proportions, and (3) an impermeable covering layer, which prevents the dissipation of heat to the surface. With these criteria, new geovolcanological and geochemical investigations were carried out, and a geophysical survey was planned in the area between the volcanic edifices of Barú and Colorado.

The geovolcanological studies demonstrated that the Barú volcano had activities from periods greater than 1 m.y. (oldest rock dated 1.32 Ma). The most recent eruptions, pumice flows on the western flank of Barú volcano, were dated to 700–800 years B.P. This findings divided the volcano's activity in two main phases, an older one with ages over 0.5 m.y., and a younger one with ages below 0.5 m.y.

The Colorado area is considered as a sequence of effusive and explosives products, which is affected by one or several volcanic edifice failures, leaving back a horse-shaped large caldera, which is open to the Southwest. The volcanic activity of the Colorado complex was dated to range from 1.66 Ma to 0.52 Ma. The Tertiary basement in this region seems to be of fragmentary origin (volcanic breccia), which leads to the assumption that it is not susceptible to develop secondary permeability, concluding that it is not permeable. Additionally, the basement was considered to be shallow. Both facts give few probabilities that it is able to store a confined aquifer big and hot enough to develop a geothermal field for electricity generation. However, in the South of Colorado centre, the investigations delimited a tectonically caused lava sunk, which is crossed by an E-W fault dipping 70° S. This finding raised the possibility that enough amount of this rock material may be accumulated in the underground, which is explained by the morphological inclination coming from pre-volcanic activity, that could be covered by the first Barú lavas (eruptions which burned the clay soils already developed over the Colorado lavas). The volume is estimated to be of the order of 1.5–2 km^3. This was considered to be a positive aspect of the geothermal exploration and gave together with the outcrops of the basement of lavic composition at the localities of Bambito and Cerro Punta area expectations to find a possible geothermal reservoir in the area of El Hato del Volcán located between the volcanic centres of Barú and Colorado.

The initial campaign of geochemical investigations, which were carried out in the 1970s showed that the thermal springs from Los Pozos and Cotito were of chloride origin with high content of sodium and with a pH-value close to neutral (6.5). The water temperatures reached 72°C at Cotito, 59°C at Los Pozos, and 33°C at Catalina spring (Fig. 16). A geochemical model using the results of chemical analysis suggest that water from the deep geothermal reservoir with an initial temperature around 180°C mixes on its way up to the surface with meteoric water. In contrast, shallow drilling holes did not find high temperatures below the ground (Catalina 5 drilled in 1977 at a depth of about 500 m got a temperature of 70–80°C but Catalina 6 drilled at 1000 m got temperature of 110–120°C). Consequently it was concluded that the possibility to find high reservoir temperatures is low and possible reservoir temperature were estimated to be around 70 to 80°C. These conclusions are in contrast to the relative high spring water temperatures.

Also the isotopic investigations lead to controversial conclusions. Stable isotopes of hydrogen and oxygen suggested that reservoir water could be recharged from a point of higher altitude than the meteoric water of the zone ($-7.3‰\ \delta^{18}O$ and $-48‰\ \delta^{2}H$) and then experienced a shift to $-2.5‰\ \delta^{18}O$ due to the water-rock interactions. Although this hypothesis was already discarded by Bath & Williamson (1983), other consultants keep it as possibility.

Another interpretation of the isotopic data has been attempted indicating that the water from the geothermal reservoir has obtained its isotopic composition due to evaporation process fractioning through steam loss, so that the remaining liquid became enriched in heavy isotopes. Slopes between 3 and 5 in the $\delta^{2}H$ and $\delta^{18}O$ diagram suggest fractionating of steam from the liquid phase due to evaporation. On the other hand, values around $-7.3‰$ of $\delta^{18}O$ found for meteoric waters at other areas of lower altitudes in Panama suggested that water from a reservoir could come from levels of lower altitude than the area of Barú (1000 m lower). This indicated that the recharged zone could be in a remote place of lower altitude than the discharge. So there was the suggestion that the groundwater recharge for the Barú-Colorado area is located at a lower altitude than El Hato del Volcán town and that this water travel deep into the reservoir and discharges at higher altitudes like found the case in mentioned springs. These controversy interpretations from the past by some authors call for further studies of the Barú-Colorado geothermal prospect.

The initial geophysical studies, which were carried out in the middle of the 1970s in the zone close to the main thermal springs (Cotito and Catalina) showed a typical volcanic structure where three layers could be appreciated.

- The upper 20 to 30 m thick layer had values greater than 20 Ωm, which were associated to unaltered volcanic rocks saturated with meteoric water.
- A conductive 160 to 650 m thick layer with resistivities between 2 and 10 Ωm probably associated to saturate volcanic breccias with geothermal chloride-rich fluids.
- The lower and non-conductive layer seemed to be associated with a rock of prophylitic formation with chlorite and epidote alterations at depth. This layer was found below a depth of 200 m in the area of Los Pozos and Cotito and below a depth of about 700 m at Catalina.

On the other hand, resistivity values below 10 Ωm extends to about one kilometre to the North of the thermal springs to an apparent depth of 400 m. Values under 20 Ωm were also found to the North and South of the thermal springs at an apparent depth of 500 m.

From this it may be concluded that low resitivities values are open to the North and West (no survey performed) suggesting that the altered and hot fluid zone could extend to deeper level in those directions. These results concluded the need to execute additional studies and to evolve, with the help of new geovolcanological and geochemical studies, a hydrogeological model for the area.

In 1985 it was concluded that the probable zone that may store a geothermal reservoir could be located between the two eruptions centre of Barú and Colorado. But this hypothesis leaves an uncertainty of the extension of the impermeable zone in both directions horizontal and vertical, which prevents the influx of cold fluids into the reservoir. However, the absence of thermal manifestations in this zone suggested the existence of an impermeable zone that prevents the discharge of thermal fluids at the Earth's surface.

These former conclusions (1985) promoted a new – not yet performed - geophysical campaign (gravimetry and electric resistivity) at a 15 km long stretch about 4 to 5 km to NW of Cerro Punta and SW of Nueva California, as well as around the thermal manifestation of Cotito and Los Pozos. The purpose of this new programme is to define the depth and grade of rock fracturing at bedrock level, to determine possible water circulation due to tectonic movements associated to faults (ENE–WSW) and to define the geometry, depth and existences of resistivities anomalies that can be found inside the lava formation of Colorado.

Additionally, the investigations will also be covering the zone of thermal manifestation of Los Pozos. The purpose of this was to verify the shape and depth of the bedrock and to compare the new data with the logs of previous drilling holes done in the area; because former investigation suggested the existence of a conductive layer above the basement.

These conclusions were not very clear at all. After the Mt. Saint Helen's eruption, the panel in charge of the programme concluded that the Colorado caldera was not originated by emptiness of the magmatic chamber. It was caused mainly by volcanic debris avalanche of one of the upper side of the caldera giving it the horseshoe shape. This kind of caldera can also give rise to domes within it, as is the case of Colorado caldera. This caused that the entire geothermal programme to be transferred and concentrated to other companies in this region from OLADE in 1985.

The former IRHE, institution in charge to develop these studies in Panama, was not so convinced with the above decision and continued with additional investigations. All those consultants who investigated this area emphasized that the geophysical programme should be concluded and those models elaborated by Mt. Saint Helen's eruptions should not be adopted by Barú-Colorado. These statements raised doubts about the final conclusions interpreted for Barú-Colorado by IRHE personnel.

So far, with the help of International Atomic Energy Association (IAEA), in 2001 ETESA has got a budget to review all geovulcanological studies performed in the past, to sample all thermal manifestation, creeks, and rivers influenced by geothermal activity of the past and to carry out a geophysical programme planned earlier with the help of Instituto Costarricense de Electricidad (ICE).

In 2001 the geovolcanological review of these new investigations has been completed at cabinet as well as in the field. The main conclusions found are that there are no evidence on surface outcrops, which indicate the breccia composition of the basement. Only cores from previous drillings cut volcanic breccias at depths between 20 m and 220 m in the zones of Cotito and Los Pozos followed by andesitic lavas of the Colorado complex. As the zone has been affected intensively by tectonic movement, it is not to clear if the bedrock is of breccia or lava in composition. Due to the outcrops found at Bambito and Cerro Punta, it seems to be of lava formation. Only at Boquete, the existence of volcanic breccias was verified to be part of the basement composition. However, some outcrops of this area showed that the bedrock had lavic composition too. This questioned the hypothesis, whether the whole the area was of breccia composition. This lava composition of the basement in this zone was not reported in previous studies (1984–85).

Similarly, between 1988 and 1994, different consultants have coincided that the drilling cores, which had cut the volcanic breccia are of Quaternary and not of Tertiary age, as previously assumed, raising new doubts. If this is true, the bedrock could be deeper, giving us a better scenario from the geothermal point of view.

The new interpretation indicates, that the temperatures measured at the slim holes ranging from 70 to 120°C are associated with radial heat outflows coming from a deep reservoir of unknown location, possibly between the two volcanic centres of Barú and Colorado.

A temperature inversion, which is explained by lateral outflow from the main reservoir was found at the first 100 m depth of holes N° 4 and 5 from Catalina and Cotito respectively, followed by a normal conductive temperature gradient down to 306 m and 580 m respectively. So far, there are many investigations done in the area, but all of them did not allow developing a model to help understand the geothermal situation at Barú-Colorado.

In 2002, ETESA is expecting to clear up the yet existing uncertainties and based on anew water sampling campaign, isotopic studies and geophysical investigations and to develop a geothermal model.

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Development of the geothermal energy in Costa Rica

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ABSTRACT: The first evaluations of the geothermal resources of Costa Rica were performed around 1966. Preliminary exploratory studies of the geothermal areas were carried out in 1975. ICE obtained the first Interamerican Development Bank (IDB) loan in 1977 to fund the drilling of the first three wells at Miravalles (since June 1979 to May 1980). Between 1989 and 1991 a national geothermal reconnaissance study was carried out, which indicated that the possible total geothermal potential of Costa Rica was about 900 MWe. The commissioning of the first geothermal plant at Miravalles geothermal field took place in 1994. The actual (year 2002) installed capacity at Miravalles is 142.5 MWe, but with the commissioning of Unit 5, a 15.5 MWe binary plant (scheduled for March 2004), the installed capacity will increase to 158 MWe. The contribution of different energy sources to the electricity that the country generated in years 2000 and 2001 are compared to the production of geothermal energy in those years. Between 1994 and 2001 the installed capacity at the field grew from 55 to 142.5 MW (2.6 times more), while generation rose from 341 to 986.3 GWh (2.9 times more).

1 INTRODUCTION

Costa Rica is located in the southern part of the Central American isthmus, between Nicaragua and Panama. The country extends over an area of approximately 51,000 km^2 and has a population of about four million people. Early in the seventies, Costa Rica satisfied its electricity needs using hydro (70%) and thermal (30%) energy sources. The continuous rise in oil prices, especially during the 1973 crisis, motivated the authorities of the national utility, the "Instituto Costarricense de Electricidad (ICE)", to study the possibility of using other energy sources for the generation of electricity, including geothermal energy.

ICE has made a great effort to meet the national energy demand. The contribution of the hydro, thermal, wind and geothermal energies has provided the required energy to cover the national demand. The development and contribution of geothermal energy in the country is described in the following sections.

2 COSTA RICAN GEOTHERMAL DEVELOPMENT

The first evaluations of the geothermal resources of Costa Rica were done around 1966. Preliminary exploratory studies of the geothermal areas in the "Cordillera Volcánica de Guanacaste" were carried out in 1975. One of the recommendations of these studies was to investigate in more detail the areas on the slopes of the Rincón de la Vieja, Miravalles and Tenorio volcanoes. Thus, ICE began to collect geologic, hydrologic and geochemical data over a more than 500 km^2 region

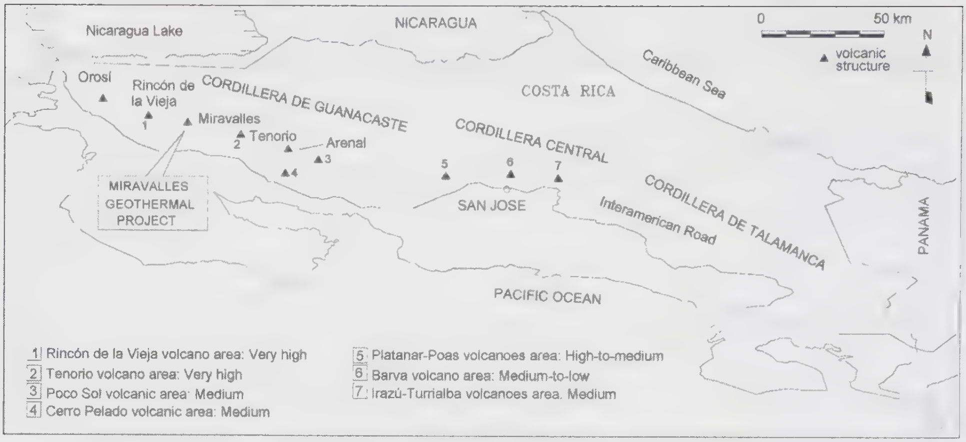


Figure 1. Location of geothermal areas and their ranking in Costa Rica.

located between the volcanoes and the Interamerican Highway ("Carretera Interamericana"; Fig. 1).

The first technical report, a set of pre-feasibility studies on the possibility of exploiting the geothermal resources within the area mentioned above for electricity generation, was presented in September 1976. The positive outcome of this work allowed ICE to continue its applications for loans from the Interamerican Development Bank (IDB), which were needed to initiate the development of the Miravalles geothermal field.

To finance the successive phases of geothermal activities, from exploration to exploitation, Costa Rica decided to use its own funds as well as loans from the IDB. Following this policy, ICE obtained the first IDB loan in 1977 to fund the drilling of the first three wells at Miravalles, which was carried out between June 1979 and May 1980. Based on the steam produced by these three successful wells, sufficient to generate around 15 MWe, the existence of a commercial-size geothermal system was inferred. It was proposed to extend over an area of about 15 km^2 on the southwestern slope of Miravalles volcano, north-northeast of the small town of La Fortuna (Fig. 2).

During 1984–86 six additional production and injection wells were drilled at Miravalles. Based on the well data gathered, the feasibility and environmental impact reports for the first geothermal unit in the country were prepared in 1986–87. In 1987 ICE obtained a new IDB loan to cover the cost of: (1) 20 additional wells, (2) consultant services to prepare the feasibility report for future units, (3) power plant equipment, (4) power house construction, (5) pipelines to transport geothermal fluids at the surface, (6) sub-station equipment, and (7) an electrical transmission line from the field to the main national line at Liberia (approximately 50 km away).

Between 1989 and 1991, ICE, using its own funds and funds from the Italian government, carried out a national geothermal reconnaissance study which was managed by the United Nations Development Program (UNDP). The final report issued in November 1991, entitled "Evaluación del Potencial Geotérmico de Costa Rica", ranked the various areas of geothermal interest in the country, and indicated that the possible total geothermal potential of Costa Rica was about 900 MWe.

3 GEOLOGICAL FRAMEWORK

The geological history of southern Central America is dominated by the growth of a Cenozoic magmatic arc that is superimposed on a Jurassic-Eocene ophiolite basement that consists of

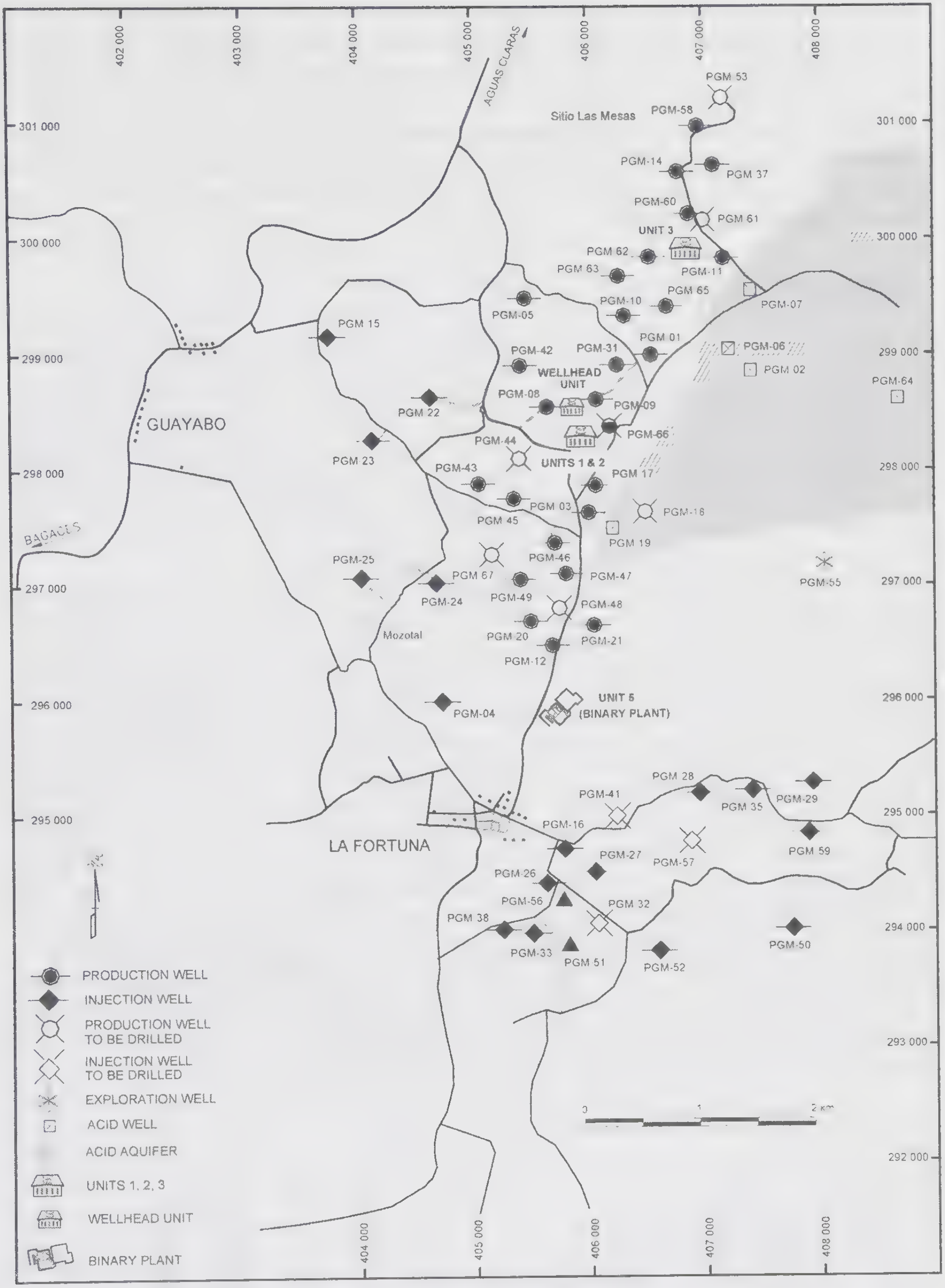


Figure 2. Map of the Miravalles geothermal field.

basalts and volcanic-sedimentary units. Costa Rica is tectonically complex because four plates interplay: Cocos, Caribbean, Nazca, and the Panama block. The Costa Rican Volcanic Front is associated with the northeastwards subduction of the Cocos plate beneath the Caribbean plate with a well-defined Benioff zone with a maximum depth of seismicity at 200 km and a subduction velocity of 9–10 cm/year with an angle of 60 to 70° (Alvarado et al. 1999, Montero 1999).

There are four mountain ranges in Costa Rica, known as Guanacaste, Tilarán, Central and Talamanca ranges. The Guanacaste range is a chain of andesitic Quaternary stratovolcanoes trending NW-SE. It is composed mainly of pyroclastic (fallout, surge, and flow) rocks, lava flows, and fluvio-lacustrine deposits that have formed gently sloping plateaus on both sides of the range. The area is under constant regional stress due to the subduction of the Cocos Plate under the Caribbean Plate, and also due to the regional uplift of the volcanic arc. The interaction between the two plates has created a complex system of faults with northwest, northeast and north as the predominant trends.

4 MIRAVALLES GEOTHERMAL FIELD

Miravalles, the most important Costa Rican geothermal area, is located on the southwestern slope of the Miravalles volcano. The Miravalles volcano, a stratovolcanic complex rising 2028 m a.s.l., is part of the Guanacaste range. This volcanic massif (Latitude 10°47′ N, Longitude 85°10′ W) was built after the formation of the Guayabo Caldera, a nested caldera through at least three phases of collapse and rebuilding between 1.6 and 0.6 Ma. Lava flows are andesitic to basaltic-andesitic with normal potassium contents. Six eruptive centres can be recognized; they are aligned NE-SW and show a clear SW migration. The volcano has no record of historic eruptive activity, but there are many hot springs and fumaroles on its southwestern slopes.

The present field extends over an area of more than 21 km^2; about 16 km^2 are dedicated to production and 5 km^2 to injection. The temperature of the water-dominated geothermal reservoir is about 240°C. Fifty-two geothermal wells have been drilled to date (Fig. 2). They include observation, production and injection wells; their depths range from 900 to 3000 m. Individual wells produce enough steam to generate between 3 and 12 MWe; injection wells accept between 70 and 450 kg/s of waste geothermal fluids. According to the drillings, there are at least 2000 m of lava flows, tuffs, pyroclastic flows, debris avalanche, debris flows, and lake deposits inside the caldera.

Commercial production of electricity using geothermal steam began in Costa Rica (i.e. at Miravalles) in early 1994, when Unit 1, a 55-MW single-flash plant, was commissioned. The following year, ICE completed the installation of a 5-MW wellhead unit. Then, two temporary 5-MW wellhead units came on line as part of an agreement between ICE and the "Comisión Federal de Electricidad of Mexico (CFE)". In January and August 1998, the two temporary wellhead units were disassembled and returned to CFE. Unit 2, the second 55-MW plant, started production in August 1998. Finally in March 2000, Unit 3, a 27.5-MW single-flash private plant, started delivering electricity to the national grid "Sistema Nacional Interconectado", increasing the total installed capacity at Miravalles to 142.5 MWe. The history of the growth of capacity at the field is given in Figure 3. The location of the power plants is shown in Figure 2.

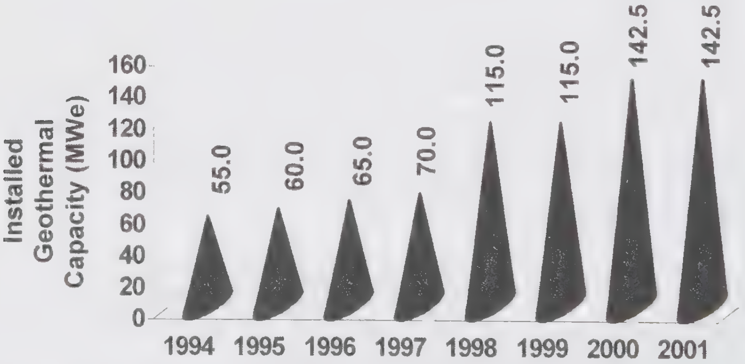


Figure 3. Costa Rica installed geothermal power capacity: 1994–2001.

The commissioning of Unit 5, a 15.5 MWe binary plant (see location on Fig. 2), is scheduled for March 2004. This plant will extract additional energy from waste fluids that are injected back into the geothermal field at the present time.

Steam for Units 1–3 and the wellhead unit are separated from the hot water at seven separation stations. Generally, two or three production wells send their two-phase fluids to each of these stations. Separation stations 1, 2 and 3 supply mainly steam for Unit 1, separation stations 4, 5 and 6 feed Unit 2 and separation station 7 sends its steam to Unit 3.

Figure 4 shows the cumulative production of total, liquid and steam masses from the geothermal field. All of these masses increased linearly from March 1994 up to May 1998. When Units 2 and 3 started production the slope of the curves became steeper, but the increases were still nearly linear over those periods (from April 1998 to March 2000 and from April 2000 to May 2002). By May 2002, the accumulated production was approximately 49.5 million tons of steam, 235.7 million tons of liquid and 285.3 million tons of total mass.

Figure 5 shows the rate of mass extraction from the Miravalles Geothermal Field since production began until May 2002. The steam production rate increased gradually from May 1994 (350 thousand tons/month) to August 2000 (820 thousand tons/month). From September 2000 to February 2001, the production of steam decreased due to maintenance of Units 1, 2 and 3 and also due to a lack of demand to supply the maximum capacity of the units to the

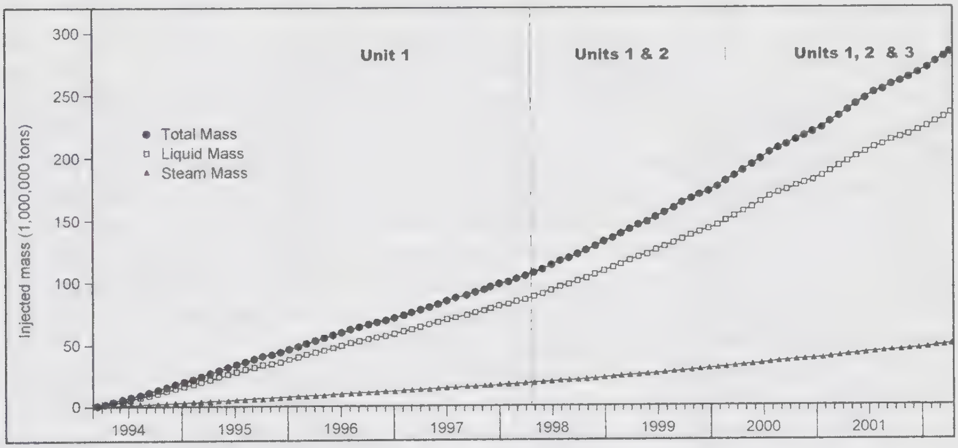


Figure 4. Cumulative fluid mass at the Miravalles geothermal field.

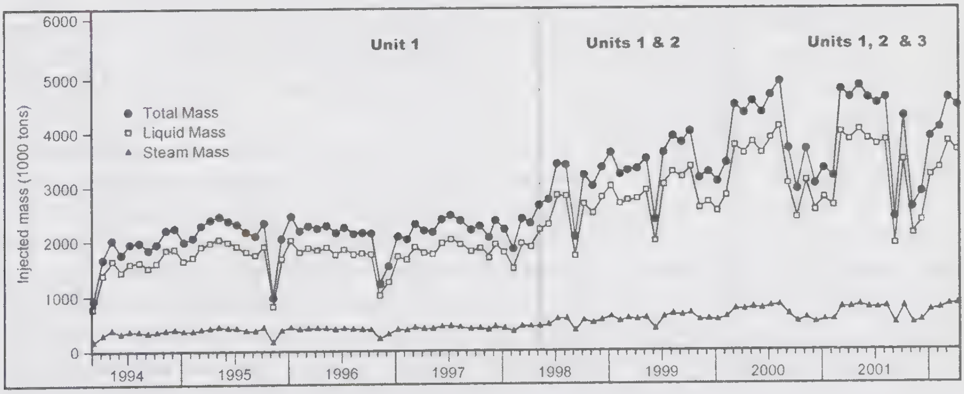


Figure 5. Mass produced from the miravalles geothermal field.

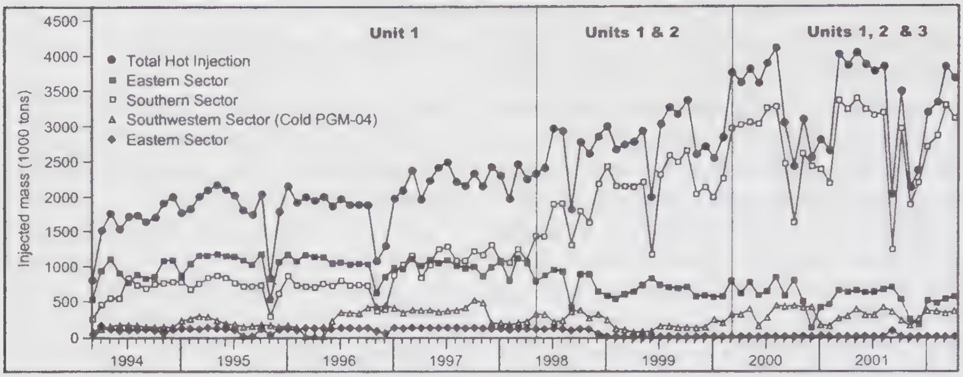


Figure 6. Mass injected into different sectors of the Miravalles geothermal field.

National Energy Control Centre. Since this period, steam production has stabilized at about 775 thousand tons/month, again with exception of maintenance periods, during September, November and December of 2001. Liquid mass and total mass extraction have basically reflected the steam production: there was an increase from March 1994 (1 million tons/month) to May 1995 (2.5 million tons/month); they then fluctuated within a narrow band (1.7 to 2.5 million tons/month) until April 1998. Thereafter, the total mass extraction rate increased from 3.4 to 4.9 million tons/month and the liquid mass rate also increased from 2.9 to 4.1 million tons/month until August 2000. From March 2001 to August 2001, total mass extraction stabilized at around 4.6 million tons/month and liquid mass extraction stabilized at around 3.9 million tons/month. Since the maintenance periods during September, November and December of 2001, the total mass and liquid mass extraction rates have reached stabilized values of 4.6 and 3.8 million tons/month.

Figure 4 and 5 also show the time when commissioning of the three Units (1, 2 and 3) took place. The total steam flow to the power plants is about 300 kg/s and the residual (waste) geothermal water sent to the injection wells is around 1350 kg/s and is distributed in four sectors, that is, the northern, southern, eastern and western sectors (Fig. 6).

The reservoir fluids from the Miravalles Geothermal Field have been classified as Sodium-Chloride waters, with a pH around 5.7 and silica content of 430 ppm (at reservoir conditions): they have a trend of carbonate scaling within the wellbores (Moya & Sánchez 2002). Production wells at the Miravalles Geothermal Field showed a high potential for calcite deposition even before exploitation of the field began. The degree of calcite saturation (log Q/K) was evaluated for each production well using the Watch computer program (Bjarnason 1994) and it was found that the pre-flashed reservoir fluids with a neutral pH are below saturation levels. Arnórsson (1989) discussed two mechanisms by which calcium carbonate minerals can be formed from geothermal fluids. The first process occurs through hydrolysis, and the second one takes place through boiling (Moya & Yock 2001).

In Miravalles, the second process of calcite precipitation (boiling) is the mechanism that affects the output of the production wells; this is supported by the fact that calcite deposition has occurred on the downhole capillary tubing near the flashing zone. As the hot brine rises towards the surface in a production well, equilibrium is reached between the pressure in the wellbore and boiling point of the brine, causing flashing inside the well. When flashing occurs as the deep fluids are ascending to the wellhead, the fluid tends to become supersaturated with calcite and hence there is a high potential for calcite to be deposited (Moya & Yock 2001).

In order to maintain fluid production (i.e. avoid, or significantly, reduce scaling) each production well is equipped with a calcium carbonate scale inhibition system (Fig. 7). At present, there are 22 continuously operating inhibition systems at Miravalles.

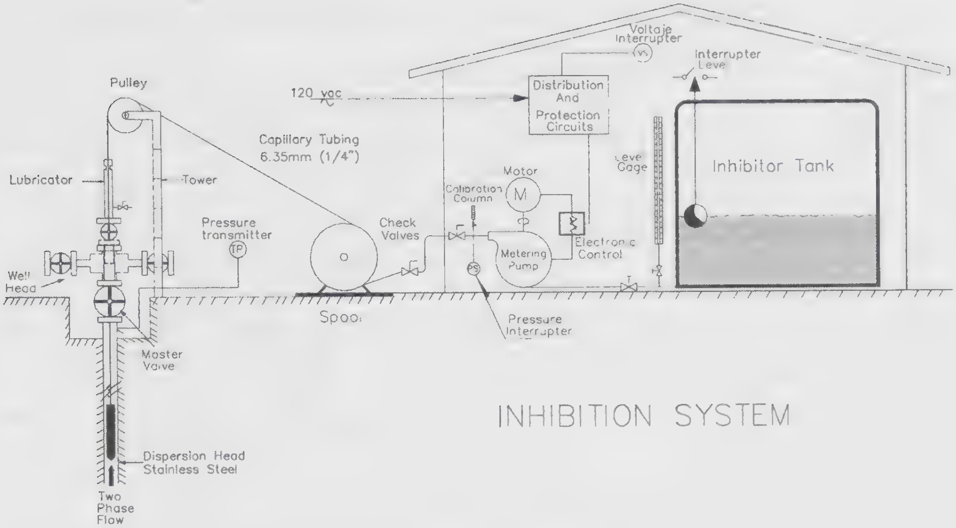


Figure 7. Miravalles geothermal field. Scale inhibition system.

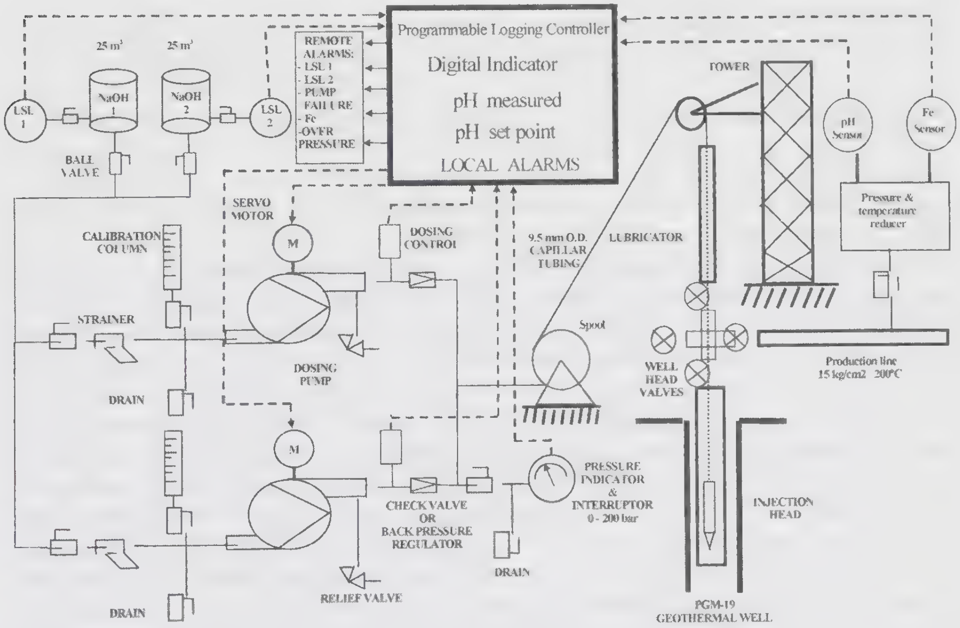


Figure 8. Miravalles geothermal field. Fluid neutralization system.

From the 52 drilled wells to date, five wells (PGM-02, PGM-06, PGM-07, PGM-19 and PGM-64) have produced acidic fluids with a pH between 2.3 and 3.2. The five wells mentioned before are localized in the northeastern part of the field, which suggests the possible existence of an acid reservoir of some extent (Fig. 2). With exception of well PGM-64, the wells have been preliminary tested, in order to study the possibility of incorporating them in commercial operation, utilizing a neutralization system at depth (Fig. 8). To this date, only two acid wells

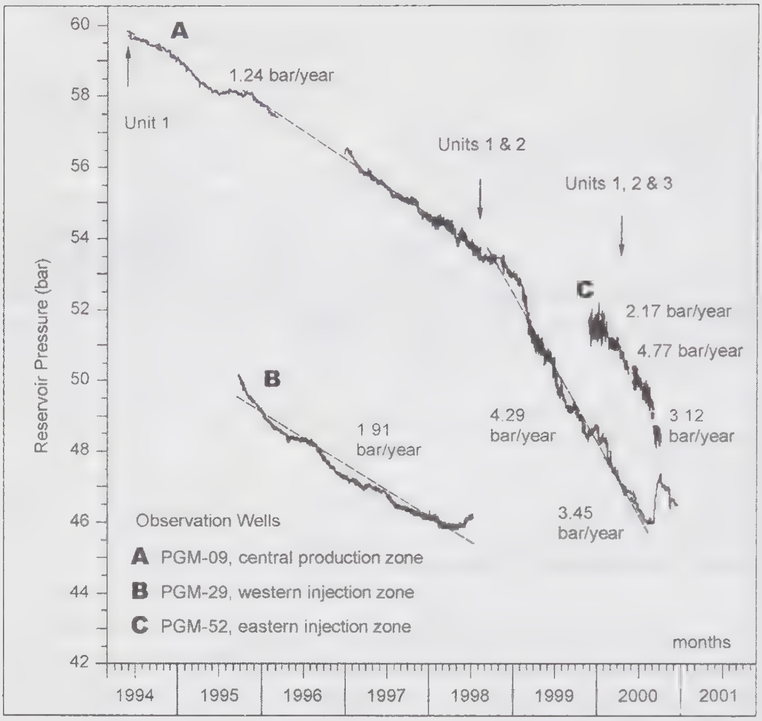


Figure 9. Miravalles geothermal field. Reservoir pressure decline measured in three observation wells.

PGM-19 (since February 2000) and PGM-07 (since October 2001) have been incorporated in production utilizing the neutralization system (Moya & Sanchez 2002).

The neutralization process consists of adding a solution of sodium hydroxide to the geothermal fluid, which neutralizes the H^+ acidic groups, thus raising the pH. The injection of sodium hydroxide (NaOH) must be continuous and it has to be done at an adequate depth within the well, to protect the casings and all surface equipment against corrosion.

The design of the acidic fluid neutralization system is basically a modification of the calcium carbonate inhibition system used at the Miravalles Field since 1994 (Sánchez 1995b; Moya & Yock 2001) and it is conditioned to the chemical and productive particularities of each well.

Figure 9 shows the pressure decline in three observation wells located in different parts of the field. Wells PGM-09, PGM-52 and PGM-29 are in the centre (production), south-western (injection) and south-eastern (injection) areas of the system, respectively. The behavior of the extraction rate curves (Fig. 9) matches quite well with the increases in generation, as the different new generation units have been commissioned. The present rate of reservoir pressure decline (approximately 3.45 bar/year; Fig. 9) agrees with the results of numerical modelling studies performed in 2001.

During the second half of this year (2002), a new exploratory well will be drilled east of the present exploitation area (well PGM-55; Fig. 2) where geological data suggest the existence of a commercial resource, perhaps an extension of the geothermal reservoir presently under exploitation.

In March 2004, after the binary plant (Unit 5) comes on line, the total installed capacity at Miravalles will reach 158 MWe. Based on data and results of eight years of commercial exploitation, as well as numerical modelling studies, ICE has decided to wait to build additional flash units in the known 21 km^2 geothermal area. Only if a separate reservoir is found east of the present production zone, might new plants be installed at this field.

5 CHEMICAL AND THERMODYNAMIC CHANGES WITH TIME

Several parameters have been monitored at each production well to evaluate the evolution of the reservoir over the eight years of its exploitation. These parameters are chloride concentration, magnesium content, enthalpy, measured downhole temperature, Na/K ratio (Fournier geothermometer), silica content (Fournier and Potter geothermometer) and Cl/B ratio (Yock 1998).

There have been three different production scenarios during the period of exploitation. From March 1994 to August 1998 steam was supplied to one condensing power plant and two back-pressure power plants to produce approximately 65 MWe. From August 1998 to March 2000 the steam production was sent to the two condensing power plants (Units 1 and 2) and one back-pressure power plant, generating about 120 MWe. Finally, from March 2000 to June 2002 steam was supplied to three condensing power plants to produce about 138 MWe.

During the first period 12 production wells (PGM-11, PGM-05, PGM-10, PGM-01, PGM-31, PGM-17, PGM-03, PGM-45, PGM-46, PGM-20, PGM-12 and PGM-21) and 6 injection wells (PGM-02, PGM-22, PGM-24, PGM-16, PGM-26 and PGM-04) were used. In the second period, 4 production wells (PGM-42, PGM-08, PGM-43 and PGM-49) and 3 injection wells (PGM-28, PGM-51 and PGM-56) were added. For the last period, 3 more production wells (PGM-14, PGM-60, PGM-62) were utilized; there was no need for additional injection wells (Fig. 2).

Parameters such as chloride concentration and enthalpy have been used to characterize variations in the behavior of the different geothermal wells during the eight years of exploitation. Contour maps of both parameters have been prepared to investigate the evolution of the Miravailes geothermal field in space and time. Chloride contents have been measured weekly since exploitation of the reservoir began. These data have been used to prepare the chloride contour maps described in this section.

Enthalpy data have been obtained from the well production curves, which have been measured once or twice per year since 1994. These data were used to prepare the enthalpy contour maps, which are also described in this section. The 1994 chloride content contour map (Fig. 10a) and the 1994 enthalpy contour map (Fig. 10b) show the initial state of these parameters. These data were obtained two or three months after the commissioning of Unit 1 (55 MWe).

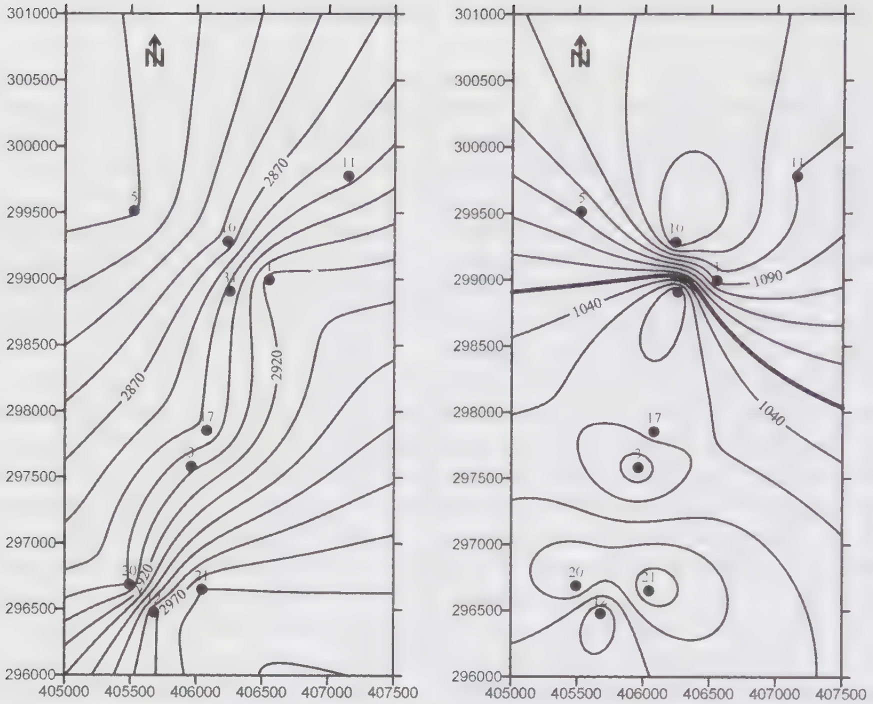
In Figure 10a, it can be seen that the chloride concentration is very similar for all the wells. Lower values are found at the northern wells PGM-05, PGM-11 and PGM-10, the last having the lowest value of the three (2864 ppm). Wells located in the central and southern parts of the geothermal field present higher concentrations (2900 ppm). Well PGM-21 shows the highest chloride content (2980 ppm) of all the wells.

Figure 10b shows enthalpy values as of 1994. Higher enthalpies (in excess of 1050 kJ/kg) are present in the northern part of the field. The contour of 1050 kJ/kg has been highlighted in all the enthalpy maps for comparison purposes. The well with higher enthalpy value (above 1100 kJ/kg) is PGM-10. Of the wells located in the southern part of the field, PGM-20 and PGM-21 show the lowest enthalpy values (less than 1000 kJ/kg).

Figures 10c and 10d show chloride concentration and enthalpy as of 1998; that is, four years after Unit 1 came online and immediately after the commissioning of Unit 2 (55 MWe).

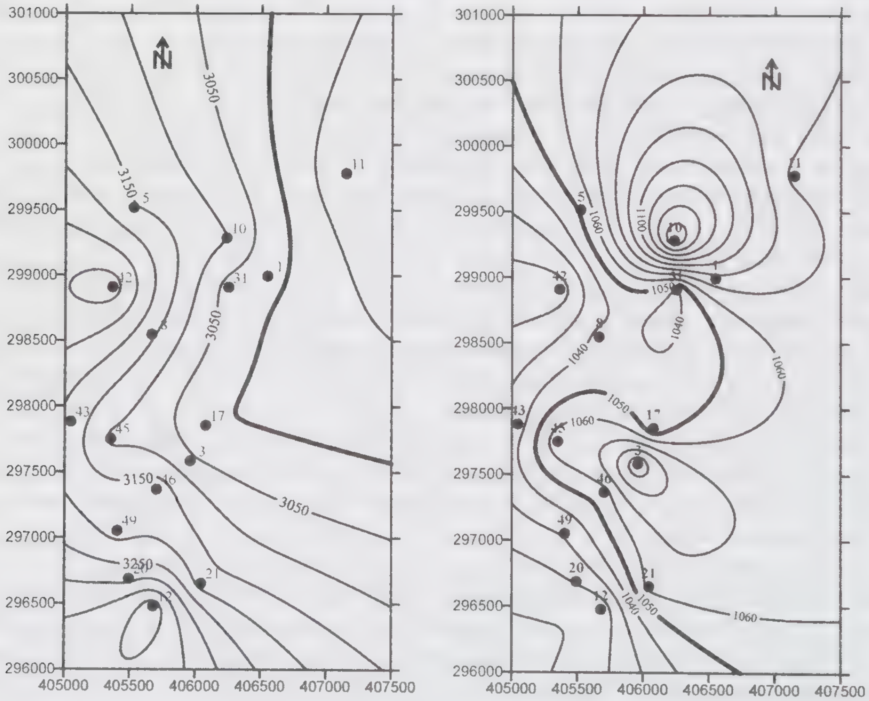
The contour line of 3000 ppm has been enhanced in order to follow the changes in chloride in the production zone of the field. The 3000 ppm contour does not appear in Figure 10a because the collected data all have lower values.

In contrast, in Figure 10c well PGM-11 is the only well with chloride levels below 3000 ppm. Probably many of the chloride contents have been increased by flashing in the reservoir or by the return of injected fluids. In the western zone, two possible entries of injected fluid can be identified. The northern inflow is associated with injection in well PGM-22 (which receives fluid from Satellite 1) and is probably affecting wells PGM-05, PGM-08 and PGM-42 (see Fig. 2). The southern inflow is probably related to injection in well PGM-24 (which receives fluid from Satellite 2) and also to the influence of fluids injected in the southern part of the field



a. 1994 Chloride content contour map.

b. 1994 Enthalpy contour map.



c. 1998 Chloride content contour map.

d. 1998 Enthalpy contour map.

Figure 10. Chloride content and enthalpy contour maps.

(from Satellite 3). The southern entry is believed to be affecting wells PGM-12, PGM-20 and PGM-49 (see Fig. 2).

When Figure 10d is compared with Figure 10b, it is observed that the 1050 kJ/kg contour line shows a major change in position. This is related to an increase in enthalpy in several of the wells, as a consequence of massive extraction of fluid. The same two entries shown in Figure 10c are also present in Figure 10d. In this case, they indicate the entrance of fluids of lower enthalpy, which suggests that the injected fluid, at a temperature of about 165°C, is returning to the production zone. Even though the injected fluids may have caused enthalpy declines in some of the nearby wells, it is not believed that the effect is severe enough to warrant reducing or eliminating the injection that is taking place in wells PGM-22 and PGM-24.

Figures 11a and 11b were prepared using the data collected up to March 2000, which is when Unit 3 (27.5 MWe) came online. Units 1 and 2 were online together for a year and a half prior the commissioning of Unit 3.

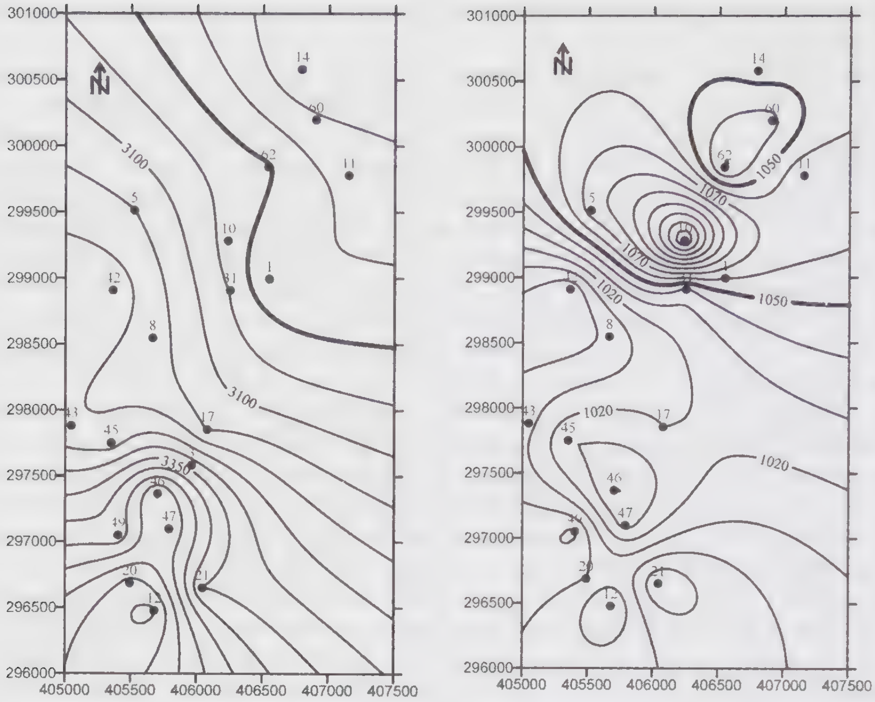
When Figure 11a is compared with Figure 10c, it can be seen that the 3000 ppm contour indicates a decrease in chloride content, probably due to declining chloride concentrations in wells PGM-01 and PGM-31. In Figure 11a, three possible inflows with high chloride contents can be observed. The first (on the north-western side) is also seen in Figure 10c, but Figure 11a indicates that the amount of injected fluid is less than is indicated by Figure 10c. This might be related to the associated normal decrease of the liquid phase of all the wells, mainly as a consequence of their productions, and also to a decrease in the amount of fluid injected into well PGM-22, because the liquid from PGM-05 has not been injected in PGM-22 since Unit 2 came online. The two-phase fluids from well PGM-05 were transferred to Satellite 4, so that the liquid from PGM-05 is now injected into well PGM-28 (in the southern part of the field; Fig. 2). Another reason for the decrease in the rate of injection in the northern zone is that not only wells PGM-05 and PGM-45 were producing in 1998 (Fig. 10c), but also wells PGM-08, PGM-42 and PGM-43 (when Unit 2 came online, Fig. 11a), which might have modified the fluid distribution within the reservoir.

The entry on the southwestern side is also observed in Figure 11a. However, it is less distinct than in Figure 10c, due to the influence of massive injection of fluids in the southern part of the field. In addition, the rate of injection in well PGM-24 decreased because the liquid from well PGM-46 was transferred to Satellite 6 (Unit 2), and well PGM-03 decreased its liquid phase contribution.

The third inflow observed in Figure 11a has the highest chloride content, and seems to originate from fluid injection in the south of the field. The rate of injection in this zone has increased considerably, from 310 kg/s (Fig. 10c) to 1300 kg/s (Fig. 11a).

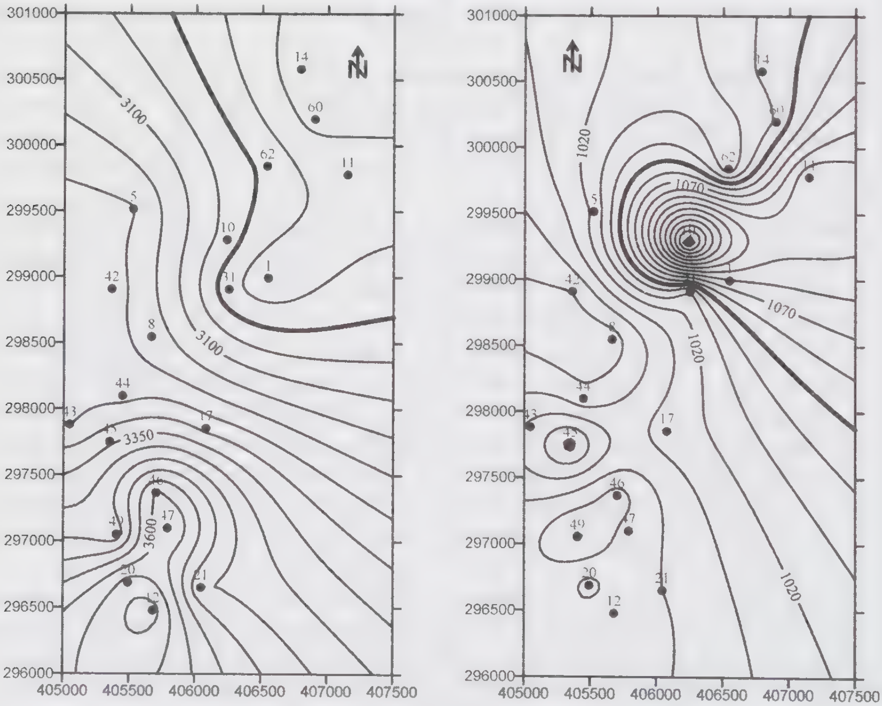
The 1050 kJ/kg contour line in Figure 11b shows a major change in the northern and southern parts of the field. The change in the northern part is associated with the incorporation of wells PGM-14, PGM-60 and PGM-62, which were needed to supply Unit 3 (27.5 MWe). The change in the southern part is related to enthalpy decreases in wells PGM-21 and PGM-46. Although PGM-47 came on line, this well did not help increase the overall enthalpy values in the southern zone because its enthalpy is just 1018 kJ/kg. The decrease in enthalpy in well PGM-21 seems to be associated with the injected fluids in the southern part of the field. The vicinity of well PGM-03 remains the zone where the higher enthalpy values are found, whereas the zone near well PGM-10 is less distinct.

Figures 11c and 11d represent reservoir conditions after one year and four months of continuous operation of the three units. As shown in Figure 11c, the 3000 ppm contour line changes southward, mainly as a consequence of increasing chloride concentrations in the wells located in the southern part of the production zone (PGM-12, PGM-17, PGM-20, PGM-21, PGM-45 and PGM-47). At the same time, the chloride contents in some wells located in the northern part of the production zone (PGM-01, PGM-05, PGM-10 and PGM-11) have remained constant. The wells that supply Unit 3 (PGM-14, PGM-60 and PGM-62) show a trend of increasing chloride,



a. 2000 Chloride content contour map.

b. 2000 Enthalpy contour map.



c. 2001 Chloride content contour map.

d. 2001 Enthalpy contour map.

Figure 11. Chloride content and enthalpy contour maps.

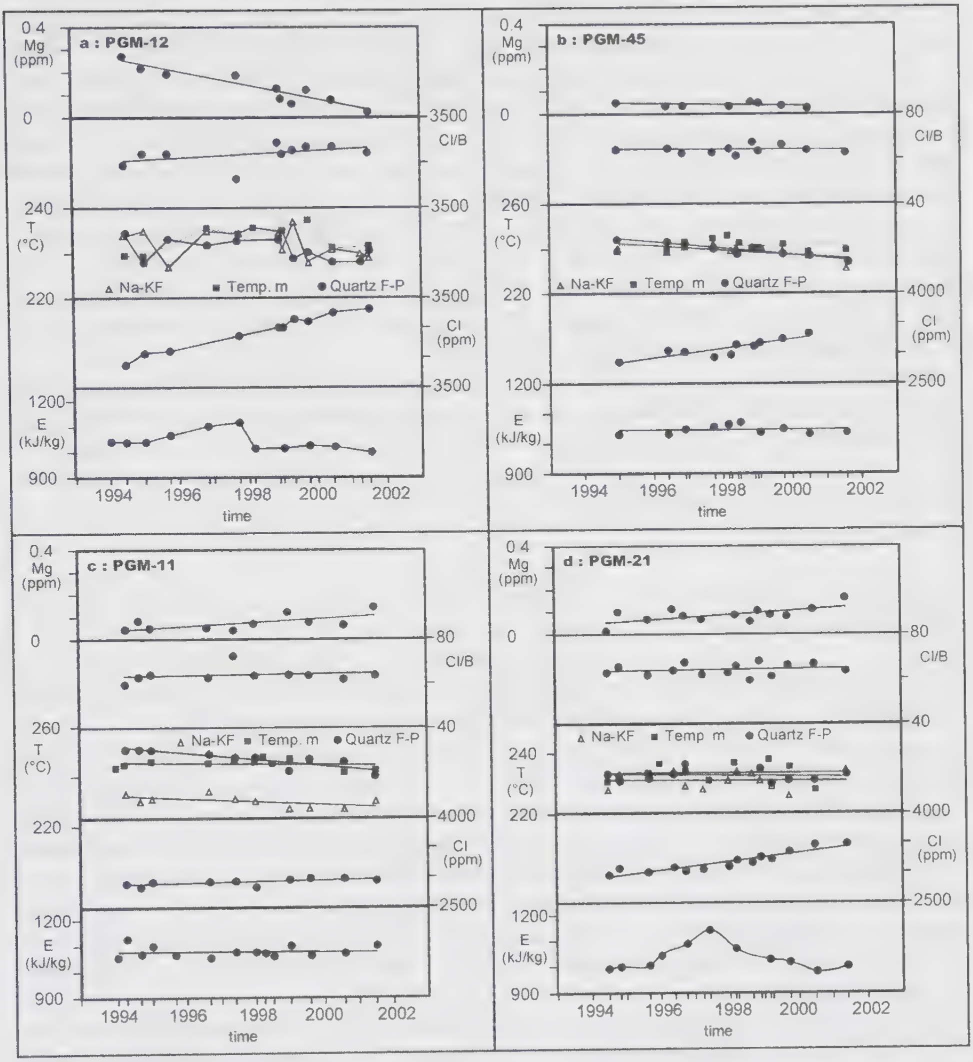


Figure 12. Parameters of the wells PGM-12, PGM-45, PGM-11, and PGM-21.

which is normal during the first months of production. In Figure 11c, it is hard to identify clearly the northwestern inflow, which is well defined in Figures 10c and 11a.

Figure 11d is similar to Figure 11b. The principal difference is that in wells PGM-10 and PGM-05 the enthalpy values have tended to increase, but in the majority of the wells the enthalpy has decreased. Wells such as PGM-21, PGM-42, and PGM-49 show enthalpy values below 1000 kJ/kg, while enthalpies at wells such as PGM-11 and PGM-45 have remained constant.

In Figure 12a the variation of the monitored parameters for well PGM-12 can be observed. This well is located in the southern part of the production zone, and it has been used to supply Unit 1. PGM-12 shows one of the largest variations in chloride concentration (758 ppm). During the first four years of production the enthalpy of this well gradually increased to 1107 kJ/kg; it then decreased to 1012 kJ/kg in early 1998, and has been constant since then. PGM-12 and PGM-46 are the only wells that have shown an initial magnesium concentration that is slightly higher than the reservoir average concentration (0.2 ppm vs. 0.05 ppm). During the last three years, the magnesium concentration in these wells has stabilized at about 0.07 ppm.

The monitored parameters of well PGM-45 are shown in Figure 12b. This well is located in the centre of the field and has been utilized to feed Unit 2. Most of the parameters have remained constant over time, except for the chloride content, which has increased by 348 ppm since August 1996. Well PGM-17 behaves similarly to well PGM-45; in this case, the increase in the chloride concentration has been 393 ppm since June 1995.

In Figure 12c the monitored parameters of well PGM-11 can be observed. This well is located in the northern part of the production zone and it was used to supply Unit 1 until February 2000. Since March 2000 the well has been used to supply steam to Unit 3. Even though PGM-11 has been producing since 1994, its parameters have remained constant. The behavior of well PGM-11 is similar to that of wells PGM-01 and PGM-31.

The monitored parameters of well PGM-21 are shown in Figure 12d. PGM-21 is located in the southern part of the production zone and it has been used to supply Unit 1 since 1994. The enthalpy began to rise until it reached 1142 kJ/kg by the middle of 1997; it then decreased to 979 kJ/kg. The chloride concentration increased by 137 ppm in the three years up to June 1997, then stayed constant for the following nine months. It then increased by 332 ppm during the last three and a half years.

6 RESERVOIR MODELLING

ICE contracted GeothermEx, Inc. (the consulting company for Unit 2) to perform numerical modelling of the reservoir behavior. The modelling effort consisted of simulating the initial state of the reservoir and matching historical production data. The model was then used to predict reservoir behavior under various future production and injection scenarios (ICE GeothermEx, Inc. 1998). At that time, neither flowing enthalpy nor flowing temperature trends could be used reliably to calibrate the model. Since the Miravalles numerical model was not fully calibrated, the results from the forecast runs could be considered only as a general indication of the reservoir behavior under differencing production and injection scenarios. Generally, the model results indicated that the fluid enthalpy should remain stable and that the pressure drop should range between 0.73 to 1 bar/year, depending on the scenario under consideration, over a 25-year period (ICE-GeothermEx 1998).

Once again, ICE contracted the services of GeothermEx Inc. to incorporate the newly collected data into the numerical model of the Miravalles field, in order to predict the reservoir behavior under the current and future production and injection scenarios. The final results of this study were available in March 2002.

The updated three-dimensional model was developed using the TOUGH2 simulation program and included a "double porosity" formulation. Production enthalpies, production chloride concentrations and downhole pressures from observation wells were available for calibrating the model by trend matching. A second water component was incorporated in the model to represent chloride concentrations, which proved to be valuable for calibration because of the high quality of the chloride data and the reliability of chloride as a tracer of injected water. Good pressure and chloride trend matches were achieved in most cases during the calibration stage. Detailed matching of the production enthalpies was not attempted, because the relatively low accuracy of the measurements obscured subtle changes in enthalpy, but a reasonable agreement between calculated and measured enthalpies was reached (Pham et al. 2002).

Many Miravalles wells are producing fluid that was previously injected. Production enthalpies have not declined significantly so far, because the returning fluid has been adequately heated by the reservoir rock, but the model has shown that, under the current scheme of production and injection, reservoir temperatures will decline in the production wells located closest to the injection areas. There will also be additional pressure declines during the next 25 years. A series of forecasts were made with the updated model, using a trial-and-error process, to investigate the best means of mitigating predicted enthalpy and pressure declines. The total pressure decline will range from 7.5 bars for wells close to injection wells to 10 bars for wells located in the main production zone. Furthermore, the model suggests that shifting a portion (up to 300 kg s) of the injected fluid from the southern injectors to the western injectors, will provide additional pressure support to all the production wells in the field (Pham et al. 2002). At present, ICE has taken action to implement the distribution of the injected fluid into the reservoir in order to improve the reservoir behavior.

The results of the trend matching showed that the model successfully simulated the behavior of the reservoir under the historical conditions of production and injection. Pressures derived from water levels and downhole measurements were well matched. Excellent matches to measured chloride data were achieved for the majority of the production wells. Thus, the model was adequately calibrated for use in forecasting future reservoir behavior under various production and injection scenarios (Pham et al. 2002).

7 RECENT EXPLORATION ACTIVITIES

The most studied geothermal systems in the country, besides Miravalles, are those associated with Rincón de la Vieja, Tenorio and Poco Sol volcanic structures. Pre-feasibility studies have already been concluded for Rincón de la Vieja and Tenorio.

7.1 *Tenorio geothermal area*

Tenorio (1916 m a.s.l.) is a dormant stratovolcanic complex with many cones, domes, phreatomagmatic craters and a volcanic graben. The early activity (Lower Pleistocene cone) created important volcano-tectonic collapse features, which are related to a shallow magmatic system that has given rise to an attractive thermal anomaly. The zone, where the exploratory wells have been located, is within a Pleistocene volcanic caldera, characterized by the existence of important geophysical anomalies that are associated with the largest geochemical manifestations in the area. The start of the feasibility-stage work for this project suffered a delay due to the creation of a national park, which included a significant part of the area of geothermal potential already identified in the pre-feasibility studies. It was not until mid-1999 that, having completed the Environmental Impact report and having obtained the work permits from the "Ministerio de Ambiente y Energía" (Ministry of Environment and Energy), the construction of the drilling pads and the drilling of the first of the four programmed wells could begin.

In 1999–2000, two exploratory wells were drilled at Tenorio (1345 m and 2472 m deep). The results were disappointing since they only revealed zones of low temperatures (up to 160°C) and low injectivity indexes (up to 0.5 l/s/bar).

7.2 *Las Pailas – Borinquen geothermal areas*

The geothermal area known as Borinquen-Pailas is found in the extreme northwest of the Guanacaste volcanic range, where zones that have been the subject of geothermal investigations are located along the southern flank of the Rincón de la Vieja volcano. The principal zone of interest covers an area of approximately 10 km by 20 km, aligned along the axis of the cordillera. Much of the area of identified geothermal potential in these studies was incorporated into the newly formed "Parque Nacional Rincón de la Vieja" (Rincón de la Vieja National Park).

As a result, it became necessary to reassess the pre-feasibility according to these new prevailing land-use restrictions, and so an updated pre-feasibility study was completed during the second half of 1999. Based on the results of the updated study, two areas, Borinquen and Las Pailas, have been proposed as being the most promising for drilling exploratory wells and carrying out feasibility studies. In both cases, environmental impact studies must be completed and the appropriate permits obtained from the Ministry of Environment and Energy before any activity associated with the drilling of exploratory wells is begun. During the second half of the year 2000, ICE obtained the permits needed to carry out a feasibility study of the Las Pailas geothermal area, including the drilling of exploration wells, from the Ministry of Environment and Energy. ICE also reached agreements with the local landowners for building roads and drilling sites on their properties. The subsurface geology, structural features and volcanological evolution on the Borinquen-Pailas area have been reported in very good detail by (Barahona et al. 2001). Petrological studies was carried out by Kempter et al. (1996). A 15-km long, 4 to 5 nested-caldera rim, the Alcántaro caldera, collapsed at the Pliocene-Pleistocene boundary, as a result of several pyroclastic flows. Subsequently, a large lake (at least 96 km^2) filled the volcanotectonic depression, followed by the extrusion of 6 domes and, finally, by the growth of the Rincón de la Vieja volcano (1895 m a.s.l., 400 km^2; 250 km^3) in the Middle Pleistocene, and it is still active, having produced phreatomagmatic to phreatic eruptions in recent centuries (Barahona et al. 2001).

In January 2001, as part of a feasibility project, a deep exploratory well program was begun at the Las Pailas geothermal zone on the southern slope of the Rincón de la Vieja volcano. A total of six wells are going to be drilled during the first phase of this project. Preliminary measurements indicate (in the wells already drilled) a temperature close to 240°C, some parameters of the wells in the area are shown in Table 1.

It is expected that the feasibility study at Las Pailas will be finished by the middle of the year 2003.

7.3 *Poco Sol geothermal area*

The Poco Sol area (380–800 m a.s.l.) is characterized as a liquid dominant high-temperature geothermal field, whose temperature has been measured directly ($T > 151°C$, using a Hg thermometer) and indirectly ($T = 224°C$, with a Na-K geothermometer). The hydrogeologic–geothermal conceptual model proposes a recharge area on the andesitic volcanic cones located on the Monteverde reservation, whose high permeabilities permit infiltration, percolation and recharge of deep aquifers within the basaltic basement; where they are heated up to a geothermal reservoir temperature of 224°C by a cooling dacitic Quaternary magma chamber. This geothermal reservoir, within the Aguacate Group, has shown good permeabilities in the existing drillholes for the Peñas Blancas hydroelectric project. Chlorite-sodium geothermal waters ascend via the caldera faults and the Peñas Blancas Fault, which emerge along the Peñas Blancas River.

Table 1. Well parameters at Las Pailas geothermal zone.

Well no.	Depth (m)	Max. T (°C)	Inj. index (l/s/bar)	W.T. (m)	Enthalpy (kg/kJ)	Flow (kg/s)	Est. output (MWe)
PGP-01	1418	244	8.3	459	1140	98.3	8.9
PGP-02	1764	N.A.	<1.4	435	N.A.	N.A.	N.A.
PGP-03	1767	245	4.7	457	1130	34	3.1
PGP-04	1418*	–	–	–	–	–	–

* = Partial depth, the well is being drilled (June 2002); Inj. Index = Injectivity Index; W.T = Depth of water table; Est. Output = Estimated Output; N.A. = Not available.

below 380 m a.s.l. The extension of the geothermal reservoir, as it is inferred by the geologic structures and the geochemical indicators, comprises an area of 23.4 km^2, and an assessed geothermoelectric potential of 186 MW; which makes of the Poco Sol Geothermal Field one of the most promising geothermal prospects in Costa Rica (see Vargas 2002).

8 THE IMPORTANCE OF GEOTHERMAL ELECTRICITY GENERATION FOR COSTA RICA

The Table 2 shows the contribution of different energy sources for the electricity that the country generated in the year 2000. Most of the installed capacity corresponds to hydro (1213.5 MWe) and smaller amounts to fossil fuels (229.0 MWe; bunker and diesel), geothermal (142.0 MWe; all at Miravalles) and wind (46.2 MWe). On the other hand, the amount of electricity generated in the country during that year was: 5690.6 GWh (Hydro), 64.4 GWh (Thermal), 976.5 GWh (Geothermal) and 182.7 GWh (Wind).

Therefore, the total installed capacity in the year 2000 was 1630.7 MWe and the total electricity generated was 6914.2 GWh. A similar panorama occurred in year 2001, the values for this year can be seen in Table 3. The percentages of installed capacity and electricity generated are basically the same and therefore, the plant load factors (for each type of energy) are also very similar.

Concurrently with the growth in installed capacity at Miravalles (Fig. 3) there was an even more important increase in the amount of electricity generated (Fig. 13). Between 1994 and 2001 the installed capacity at the field grew from 55 to 142.5 MW (2.6 times more), while generation rose from 341 to 986.3 GWh (2.9 times more).

The high availability of geothermal plants is illustrated by the numbers given in Tables 2 and 3. Even though the installed capacity at Miravalles is only 8.7 – 8.5 percent of the country's total,

Table 2. Costa Rica electrical system (year 2000).

Energy source	*Installed capacity (MW)	Installed capacity (Percent)	Electricity generated (GWh)	Electricity generated (Percent)	Plant load factors (Percent)
Hydro	1213.5	74.5	5690.6	82.3	53.5
Thermal	229.0	14.0	64.4	0.9	3.2
Geothermal	142.0	8.7	976.5	14.1	78.5
Wind	46.2	2.8	182.7	2.7	45.1
Total	1630.7	100.0	6914.2	100.0	—

*Installed capacity (MW) = Installed capacity (MW) authorized by ICE.

Table 3. Costa Rica electrical system (year 2001).

Energy source	*Installed capacity (MW)	Installed capacity (Percent)	Electricity generated (GWh)	Electricity generated (Percent)	Plant load factors (Percent)
Hydro	1229.5	74.2	5658.2	81.7	52.5
Thermal	240.0	14.5	100.0	1.4	4.8
Geothermal	141.4	8.5	986.3	14.2	79.6
Wind	46.2	2.8	185.5	2.7	45.8
Total	1657.1	100.0	6930.0	100.0	—

*Installed capacity (MW) = Installed capacity (MW) authorized by ICE.

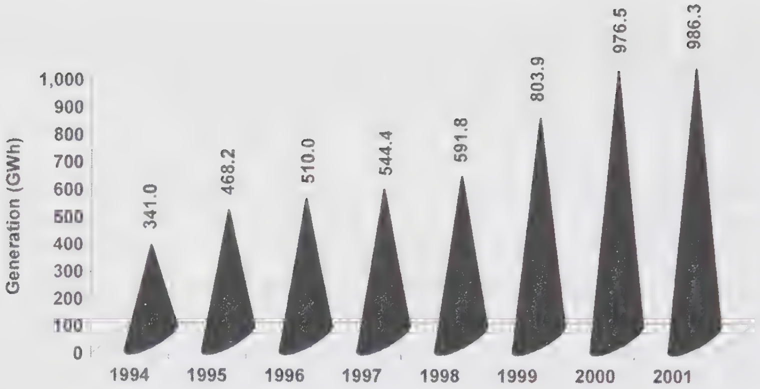


Figure 13. Costa Rica geothermal energy generation: 1994–2001.

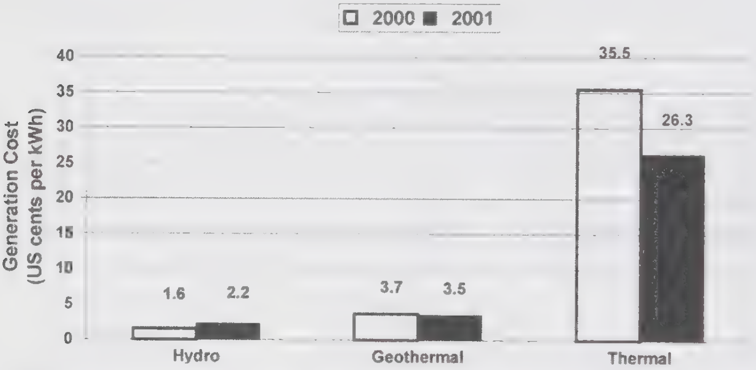


Figure 14. Electricity generation costs for different energy sources.

it produced slightly more than 14 percent of the electricity generated in Costa Rica for the years 2000 and 2001, with a load factor of 78.5-79.6%, which happens to be the highest plant load factor from all the types of energy sources produced in the country.

The cost of the electricity produced by ICE for the three types of energy (hydro, geothermal and thermal) in these two years (2000 and 2001) are shown in Figure 14. Hydro continues to be the cheapest source of energy for electricity production in Costa Rica. The cost associated with geothermal is higher, but much lower than that for the thermal plants. The low load factor of the oil-burning plants they are only used during relatively few peak load periods – makes them very expensive to operate.

9 CONCLUSIONS

In the mid-1960s, the first evaluations of the geothermal resources of Costa Rica were carried out. Preliminary exploratory studies of the geothermal areas were performed in 1975. The first three geothermal wells were drilled at the Miravalles Geothermal Field during 1979 80. The geothermal plants were commissioned in 1994 (Unit 1, 55 MWe), in 1995 (Wellhead unit, 5 MWe), in 1998 (Unit 2, 55 MWe) and in 2000 (Unit 3, 27.5 MWe).

Both, the calcium carbonate inhibition system and the neutralization system have been successfully implemented at Miravalles field. At present (June 2002), there are 22 continuously operating inhibition systems as well as 2 neutralization systems.

Wells PGM-01, PGM-11, PGM-17 and PGM-31 are the most chemically and physically stable boreholes (until June 2001). Most of the wells show a tendency toward increased reservoir chloride content. The largest increase (773 ppm) appears in well PGM-20.

The northern inflow shows a tendency to lessen; the chloride concentration in PGM-05 has decreased since April 1998 and in PGM-42 since December 1999.

Injected fluids are present in the western and southern parts of the production zone. In the southern production zone, the enthalpies measured in July 2001 have decreased with respect to the measured enthalpies in 1998 (see Figs 10d and 11d).

Tracer tests should be carried out in the southern part of the field to establish the origin of the injected fluids.

The commissioning of Units 2 and 3 can be identified as an increase of the mass extraction rates since May 1998 (see Figs 4 and 5).

The total pressure decline will range from 7.5 bars for wells close to injection wells to 10 bars for wells located in the main production zone. It was found that, by shifting a portion of the injection from wells located in the southern part of the field to wells in the western sector, the pressure and temperature decline rates could be greatly reduced. ICE is making this improvement.

Even though the installed capacity at Miravalles is only 8.7 – 8.5 percent of the country's total, it produced slightly more than 14 percent of the electricity generated in Costa Rica, with a load factor of 78.5–79.6%, which happens to be the highest plant load factor from all the types of energy sources produced in the country. In fact, between 1994 and 2001 the installed capacity at the Miravalles field grew from 55 to 142.5 MWe (2.6 times more), while generation rose from 341 to 986.3 GWh (2.9 times more).

Based on the success at Miravalles, ICE has and is exploring other geothermal zones of the country. Presently (June 2002), wells drilled in "Las Pailas" geothermal zone, indicate temperatures around 240°C, enthalpy values close to 1135 kg/kJ and total flows between 35–100 kg/s. Currently, 12 MWe have been found (PGP-01 and PGP-03), two wells have not been tested yet (PGP-02 and PGM-04). Two more geothermal wells are planned to be drilled in this geothermal zone.

The contribution of geothermal energy to the national electrical system has been of great benefit to Costa Rica, not only because of the low unit cost of the electricity generated (i.e., significantly cheaper than thermal), but also due to the high availability and reliability (i.e., production not affected by droughts) and indigenous nature of the resource (i.e., it has reduced the country's dependence on foreign sources of energy). Therefore, ICE plans to continue to develop this clean and renewable energy source in Costa Rica.

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Geothermal development in Mexico

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ABSTRACT: The total installed capacity for electricity generation from geothermal resources in Mexico comprises 853 MWe: 720 MWe at Cerro Prieto, 88 MWe at Los Azufres, 35 MWe at Los Humeros and 10 MWe at Las Tres Vírgenes. The sedimentary basin of Cerro Prieto in NW-Mexico has been exploited for almost 30 years, indicating the existence of regional recharge into the geothermal reservoir. The Los Azufres reservoir, located within the Transmexican Volcanic Belt, is subdivided into a liquid and vapor dominated southern and northern production zone, respectively. Fluid boiling during ascent has formed a convective two-phase system between 1200 and 2400 m a.s.l. A production period of almost 20 (Los Azufres) to 30 years (Cerro Prieto) reflects the renewable character of both reservoirs. The upper part of the andesitic reservoir at Los Humeros is recently under exploitation, whereas the presence of acidic fluid has limited the exploitation of the lower, high temperature (>400°C) part of the reservoir.

1 INTRODUCTION

The origin of geothermal fluids, the influence of surface recharge by meteoric water and/or regional aquifer systems, as well as the hydraulic behavior of the deep fluids is still unknown in many geothermal systems on a global scale. As most of the Mexican geothermal fields are located in semi-arid (Los Humeros) to arid (Cerro Prieto, Las Tres Vírgenes) climatic regions, missing recent recharge to the reservoirs by recent meteoric water could indicate the non-renewable character of these energetic resources. However, a period of almost 30 years of geothermal production in Cerro Prieto reflects the renewable character of the reservoir system. Hydrological balances between natural recharge and artificial exploitation, as well as permanent observations of: a) the production history and, b) temporal and lateral changes in the chemical and isotopic behavior of the geothermal fluids must be performed in order to forecast the future potential of the geothermal production process.

Geothermal exploration in Mexico initiated in early 1950's. The first pilot power plant with 57 kWe was installed in the Pathé geothermal field in the state of Hidalgo, NW of Mexico City (Fig. 1). On the discovery of the huge geothermal reservoir at Cerro Prieto, Baja California, efforts for geothermal development were concentrated to the Cerro Prieto geothermal field. Up to present, 853 megawatts (MWe) are installed in the Mexican fields of Cerro Prieto (720 MWe), Los Azufres (88 MWe) and Los Humeros (35 MWe) and Las Tres Vírgenes (10 MWe), including an amplification of 100 MW in Cerro Prieto IV (in 2000) and the installation of 10 MW in Las Tres Vírgenes (in 2001) (Quijano & Gutiérrez 2000). The expansion work for 100 MWe at Los Azufres and 50 MWe at Los Humeros are in progress. In total, 5619 gigawatts-hour (GWh) were produced in 1999, with an annual average capacity factor of 86%. In 1999, geothermal electricity generation

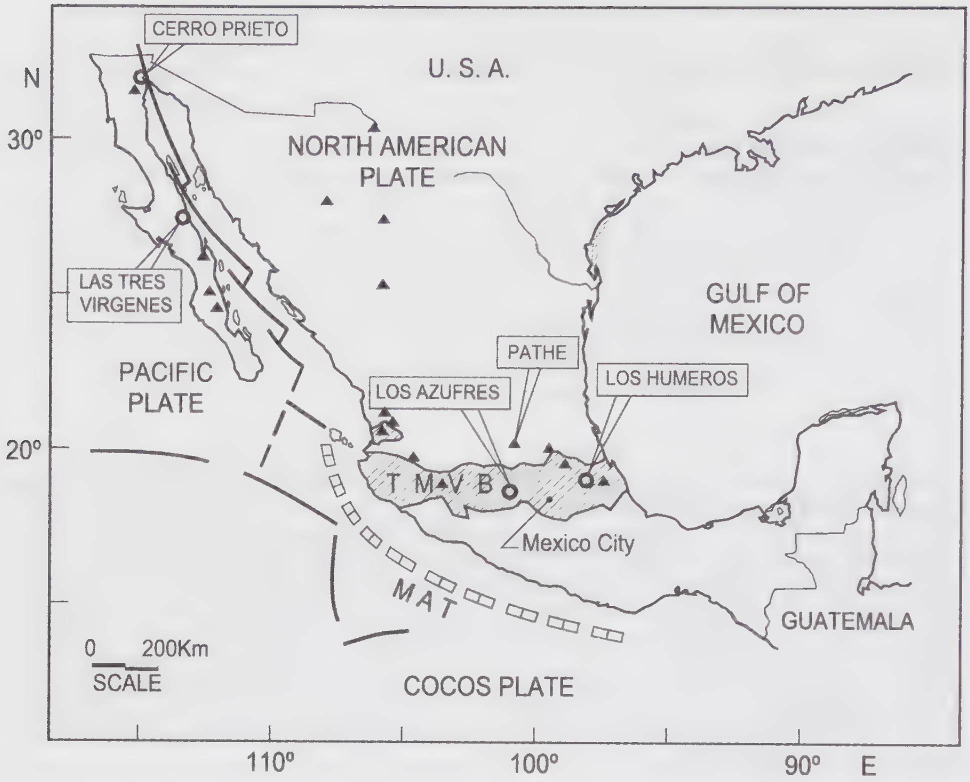

Figure 1. Location of the active (open circles) and potential (filled triangles) geothermal fields in Mexico, mostly located within the Transmexican Volcanic Belt (TMVB).

comprised 3.2% of the total electricity production of Mexico. A total of 1380 sites with thermal characteristics, distributed over 27 states, are identified in Mexico (Torres et al., 1993). The most important zones with geothermal potential are shown in Figure 1 (filled triangles).

This chapter presents the recent development of the geothermal energy in Mexico with its principal use for the electrical sector. Besides the historical development of reservoir exploitation, most recent conceptual models of flow migration within the deep reservoirs are shown.

2 CONCEPTUAL MODELS

2.1 *Los Azufres geothermal field*

2.1.1 *Reservoir development – previous studies*

The geothermal field of Los Azufres is enclosed within the W-E oriented Transmexican Volcanic Belt (TMVB), located in the central part of Mexico, about 220 km NW of Mexico City (Fig. 1). Actually, Los Azufres is the second largest exploited geothermal field of Mexico with an installed capacity of 88 MWe for electricity generation (Torres-Rodríguez & Flores-Armenta 2000), which will be increased in short future by an additional 100 MWe (Quijano & Gutiérrez 2000). 67 wells have been constructed in an area of more than 60 km^2 of extension. Of these wells, 33 are producers, 6 injectors, 16 exploratory and 10 need repair (Flores-Armenta et al. 1998). 626 t/h of separate water, produced in the fields, is condensed and reinjection into the reservoir through 6 injection wells (Torres-Rodríguez & Flores-Armenta 1998).

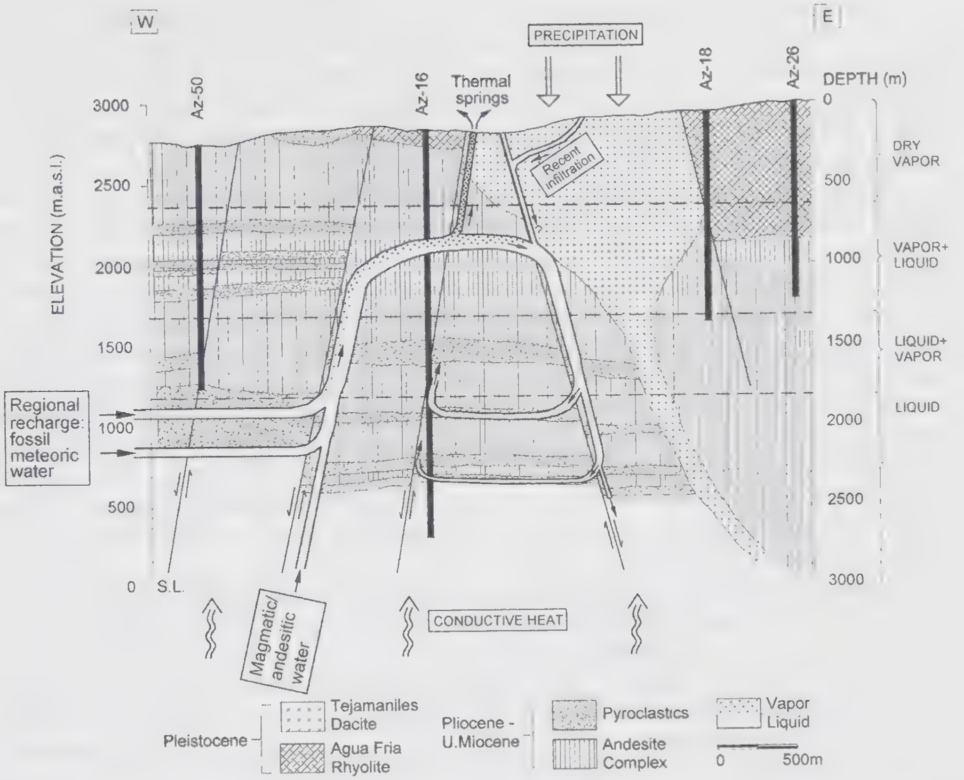

Figure 2. Conceptual hydrogeological model of the Los Azufres geothermal reservoir (geological information modified after González et al. 2000a).

During the initial phase of exploration of the Los Azufres reservoir, the petrological and tectonic studies were carried out by Demant et al. (1975), Electroconsul (1976), Garfías & González (1978), Camacho (1979), Aumento & Gutiérrez (1980), De la Cruz et al. (1982), and Gutiérrez & Aumento (1982), which were published mainly in internal reports of the "Comisión Federal de Electricidad" (CFE). The subsurface geology, structural features and hydrothermal mineralogy on the Los Azufres area have been reported by Dobson & Mahood (1985), Huitrón & Franco (1986), Garduño & López (1986), Cathelineau et al. (1985, 1987), Garduño (1988), González & González (1988), Razo et al. (1989), López (1991), Ferrarri et al. (1991), Viggiano (1991) and González et al. (2000a). Geochemical-hydrogeological and hydrodynamic studies on liquids and gases were performed by Cedillo et al. (1981), Nieva et al. (1983, 1986, 1987), Verma et al. (1989), Suárez et al. (1990, 1997), Tabaco et al. (1991), Torres-Alvarado (1996), Birkle (1998), Birkle et al. (1997, 2001a, 2001b), González et al. (2000a,b), and Barragán et al. (in press).

2.1.2 *Reservoir structure*

The geothermal reservoir is formed by a fractured, 2700 m thick interstratification of Upper Miocene to Pliocene lava flows of andesitic to basaltic composition (Dobson & Mahood 1985), forming the main geothermal aquifer. Up to 1000 m thick of silicic sequences (rhyolitic to dacitic) of Pleistocene age seal the geothermal aquifer from the surface, allowing the geothermal system to pressurize (Fig. 2).

Drilling core analysis provided an effective porosity 11.9% in the upper section and 2.9% in the lower section of the andesitic reservoir with an estimated effective total porosity of 6.3% for the Los Azufres reservoir (Contreras et al. 1984, 1988, Suárez 1991). Permeability values for different core samples from the wells Az-19, Az-5 and Az-9 range between 0.041 and 2.224 mD (millidarcy)(Contreras et al. 1984), therefore secondary permeability is assumed to represent the principal transport medium for geothermal fluids. Despite low permeability characteristics, E-W trending normal faults (Garduño 1988) and microfractures define probably the circulation of deep groundwater.

A mixture of geothermal fluid and vapor is extracted from an andesitic reservoir from a depth between 350 and 2500 m. Based on the fluid composition, the Los Azufres geothermal field can be subdivided in two principal zones: a liquid dominated reservoir in the northern part (Marítaro) and a vapor dominated reservoir in the southern Tejamaniles zones (Nieva et al. 1986) with reservoir temperature around 290°C and 300°C, based on geothermometers and borehole measurements, respectively (Verma et al. 1989). Nieva et al. (1986) demonstrated the existence of a hot liquid system (330°C) at a depth of 3500 m. Concentrations of non-volatiles in the liquid phase increasing with depth and volatiles show an inverse pattern, indicating a process of upward flow and partial condensation of steam in the reservoir (Nieva et al. 1987). During ascend, the boiling of fluid is forming a two-phase system in a depth between 1200 and 2400 m a.s.l.: a liquid dominated system between 1200 and 1700 m a.s.l. and a vapor-dominated system between 1700 and 2400 m a.s.l.. The section above 2400 m a.s.l. is characterized by a superheated system of dry vapor (Iglesias & Arellano 1988) (Fig. 2).

Hydrothermal alteration processes under low temperature conditions (170°C) caused argillitization of the shallow reservoir zone (depth < 500 m) with smectite, zeolite, calcite and chlorite as the principal mineral assemblage (González et al. 2000a). Boiling conditions in the vapor-rich zone at a depth between 1200 and 1500 m are indicated by maximum ice melting temperatures of -0.7 to -4°C and salinities of 6.4 wt%. The hydrothermal mineral assemblage of chlorite, calcite, quartz, zeolite, anhydrite, albite, sphene, pyrite, hematite and illite reflect temperature and pressure conditions of 250°C and 150 bar, respectively (González et al. 2000a). Below 1500 m, epidote, amphibole, prehnite and garnet indicate temperatures above 250°C and pressure conditions between 150 and 200 bars.

2.1.3 *Origin of reservoir fluids*

An average annual pressure drop of 0.71 bar and 0.33 bar in the northern and southern production zones, respectively, (Torres-Rodríguez & Flores-Armenta 1998), as well as temporal isotopic and temperature variations in the Tejamaniles zone (Barragán et al., in press) caused concerns about the future potential of the deep reservoir, initiating chemical and isotopic studies to interpret origin and hydraulic behavior of the fluids. Based on isotopic and chemical information of natural manifestations and drilled wells, Giggenbach & Quijano (1981) postulated the lack of direct infiltration of local meteoric water into the paleo-water reservoir. On the other hand, the intermediate isotopic composition ($\delta^{18}O$ and δD) of the geothermal brine between meteoric and "andesitic" – fossil water (Taran et al. 1989, Giggenbach 1992) indicates mixing processes between both components in the reservoir ("Mixing line" in Fig. 3) (Birkle et al. 2001). The contribution of magmatic fluids in the geothermal mixture is estimated to be 30% at the Los Azufres field. The lack of a straight-line relationship between Cl and ^{2}H concentrations indicates that mixing is not the dominating formation process of the reservoir fluids (Birkle et al. 2001a). Secondary water-rock interaction processes in the form of sericitation caused probably a further shift from the meteoric water line towards more positive values, camouflaging the real proportion of the meteoric component (González et al. 2000a). In general, low temperature sericitic alteration is characterized by various mixtures between late-stage magmatic water and meteoric water (Sheppard et al. 1971, Hedenquist & Lowenstern 1994).

Age determinations with the ^{14}C method resulted in values below or close to detection limit (< 0.8 pmc), indicating, a) a residence time of more than 40,000 years for the meteoric component and/or, b) the dilution of the original ^{14}C content with ^{14}C-free magmatic CO_2 gas. The second

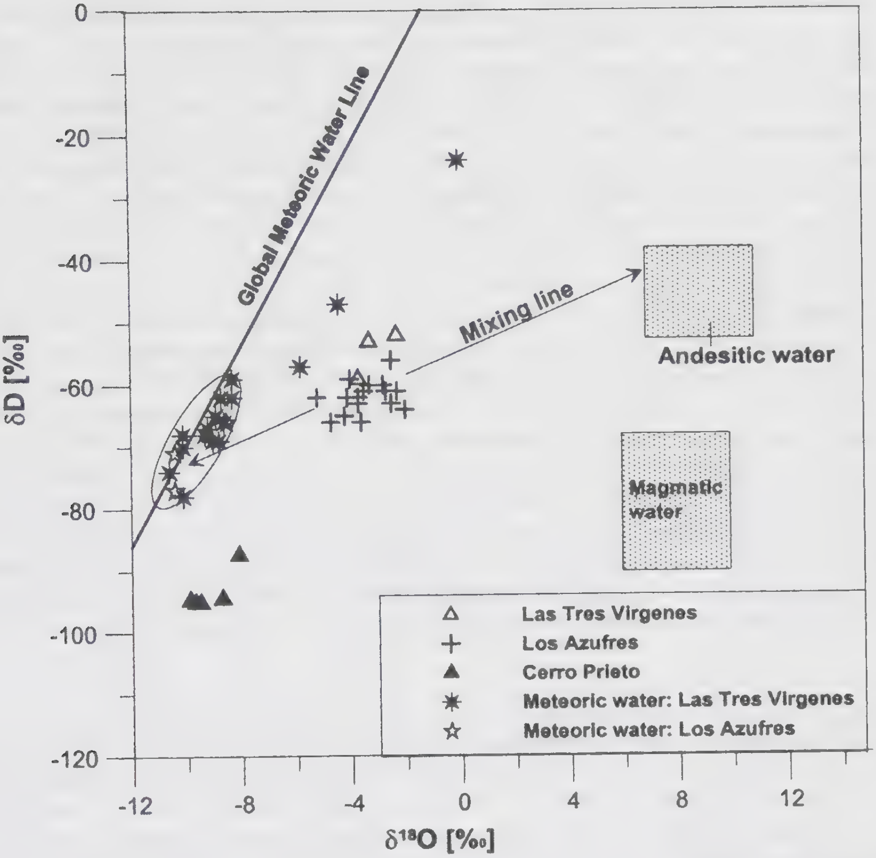

Figure 3. $\delta^{18}O$ vs. δD from reservoir fluids from the Los Azufres, Las Tres Vírgenes and Cerro Prieto geothermal field. Also shown is the composition of recent meteoric water from the Las Tres Vírgenes and Los Azufres regions in northern and central Mexico, respectively, and the hypothetical composition of magmatic and andesitic water (Taran et al. 1989, Giggenbach 1992) (figure updated from Birkle 2001a, 2001b).

case implies the limitation of the ^{14}C-method for the interpretation of the origin of geothermal fluids, especially those with elevated gas content (Birkle et al. 2001a). The detection of meteoric and evaporated marine water of Late Pleistocene age at extreme, up to 6000 m deep oilfield reservoirs at the Mexican Gulf coast (Birkle 2001b, Birkle et al. 2002) is an indirect evidence for the probable existence of non-fossil fluids (and recent circulation processes) in Mexican geothermal reservoirs. Additionally, low $\delta^{13}C$-values for the liquid (−19.5‰ in Az-43) and gas phase (−5.4‰ to −16.1‰) may be due to the influence of surface water, enriched in atmospheric and organic CO_2 (Birkle et al. 2001a).

The calculations of a hydrological balance considering climatological, atmospheric and vegetation data, resulted in a potential infiltration rate of 446 mm ± 206 mm per m^2/a of recent meteoric water into the subsoil, which corresponds to 33.5% of the annual precipitation rate (Birkle et al. 2001a). On the other hand, low permeable ignimbrite layers in the upper part of the reservoir, could restrict the downward infiltration of meteoric water: The combination of a high density distribution of intermittent surface runoffs (during rain season) with a low density of the dry season network reflects the low permeable infiltration behavior for most of the shallow rhyolitic and dacitic domes of the geothermal field area (El Guangoche, Mozo, San Andrés domes) (Birkle et al. 1997). On the other hand, highly fractured andesitic lava flows in the southwestern and northern part of the field as well as porous pyroclastic layers in the southern part could represent potential units for meteoric infiltration on a local scale (Birkle et al. 1997).

Artificial tracer tests were not able to detect hydraulic communication between the reinjection and production zone (Aragon 1985, Iglesias et al. 1985, Gutiérrez & Suárez 1992), but changes in the abundance of natural gas (CO_2, N_2) were observed in adjacent production wells during reinjection (Horne & Puente 1989, Barragán et al., in press). Also, the reinjection of cooled geothermal brine caused the lowering of production well temperatures (Molinar et al. 1986). Since 1991, a simultaneous oscillation of the amount of produced and reinjected fluid is registered in Los Azufres. Salt concentrations have increased in several 2-phase wells since June 1986 (Gutiérrez & Suárez 1992, Suárez et al. 1995).

Comparing the trend of the stable isotopes ^{18}O and D since the beginning of production in 1980, most of the production wells show a homogeneous isotopic composition with average $\delta^{18}O$ and δD values of $-4.2‰$ and -62.5 ‰ in 1980–1981 (Nieva et al. 1983), respectively, and similar values of $-3.7‰$ and $-60.4‰$ in 1998 (Barragán et al. 1999). A slight isotopic and chemical enrichment can only be observed in production wells adjacent to reinjection zones (Barragán et al. 1999, Suárez et al. 1995).

The correlation of chemical and isotopic date between surface manifestations and geothermal wells reflects a possible recharge zone towards the SE of the geothermal field (Ramírez-Domínguez 1988, Verma et al. 1989). Lower homogenization temperatures in fluid inclusions from the SW-part of the reservoir may indicate recharge from the SW during the formation of hydrothermal minerals (González et al. 2000a).

2.1.4 *Conceptual reservoir model*

The application of tracer tests and radioactive isotopes during the exploration and exploitation phase of the geothermal field were not able to provide direct evidence for the residence time, direction of flow migration and recharge components of the Los Azufres reservoir fluids. On the other hand, indications for the influence of magmatic water within the reservoir are extreme positive δD and $\delta^{18}O$ values, as well as a mixing line tendency between a meteoric and magmatic end member. Negative $\delta^{13}C$-values and hydrological balance calculations indicate, a) the organic input from atmospheric surface water within the reservoir, and b) the potential infiltration of recent precipitation into the fractured underground. A continuous increase of $\delta^{18}O$ and δD values in several production wells (Az-2, Az-46, Az-16) during production, as well as ascending N_2 concentrations in production fluids from Az-6, Az-17, and Az-37, indicate the input of, a) cold water and, b) an atmospheric component during reinjection (Barragán et al., in press). Lateral hydraulic communication between some local production and reinjection wells is indicated by the simultaneous oscillation of produced and reinjected fluid volumes and salinities (Gutiérrez & Suárez 1992, Suárez et al. 1995).

Figure 2 illustrates a conceptual hydrogeological model of the Los Azufres geothermal reservoir. The model does not pretend to define the detailed location of the deep ground water circulation pathways, but to characterize in a semi-quantitative manner: a) the participating water types and sources, b) lateral tendencies of flow migration, and c) a mass balance of the participating hydrological members, reflected by the width of the illustrated pathways. The model illustrates the natural hydrogeological components, but not hydraulic changes by exploitation and reinjection processes: A conductive system is heating up the reservoir by a deep situated magma chamber from a depth at several kilometers, whereby the quantitative thermal potential of this heat source is unknown. As part of the convective system, heated magmatic/andesitic water is rising towards the main zone of the geothermal reservoir by almost vertical, E-W directed normal fault systems. The magmatic component gets mixed with a major regional aquifer system, probably of fossil, meteoric character. Rising towards the surface, the mixture becomes separated into a two phase system: liquid-dominated at a depth between 1200 and 1700 m a.s.l., and vapor-dominated between 1700 and 2400 m a.s.l. (Iglesias & Arellano 1988). Fractions of the vaporized geothermal fluid reach the surface along extensional faults, being exposed in form of thermal springs. Recent recharge of the geothermal reservoir by infiltrating meteoric water is not proven by direct methods, but the existence of vertical conducts, transporting fossil fluids towards the surface, is reflected by tritium-free thermal springs (Birkle et al. 2001a). Fossil recharge events can be related to major periods of increased humidity, such as observed for Northern Mexico at the end of Late Pleistocene (18–11 ka BP) and Early Holocene (11–8.9 ka BP) (Ortega-Ramírez et al. 1998). The major part of the cooled, depressurized fluids gets incorporated again into the geothermal reservoir by its vertical descend.

2.1.5 *Future potential*

The reservoir pressure has decreased due to the continuous extraction of reservoir fluids since 1982 to supply steam to 10 power plants (Torres-Rodríguez & Flores-Armenta 1998). 51 mio tons of produced thermal fluid in the Tejamaniles reservoir represent an estimated 11% of the total amount of estimated fluid reserves (Gutiérrez & Suárez 1992). The total amount of exploitable thermal energy of 442.06×10^{16} Joules would be sufficient to maintain a production rate of 127 MW in Tejamaniles for the next 20 years (Suárez 1991, Suárez et al. 1990). As production will continue, the pressure drop in the reservoir is causing the transition of the geothermal fluids from a liquid water enthalpy to a vapor dominated enthalpy system (Torres-Rodríguez & Flores-Armenta 1998). As the production rate decreases slowly at an annual rate of 1.2%, a natural alimentation of the reservoir by a regional, deep groundwater and/or the infiltration of local, meteoric water must be deduced to explain the quasi steady-state hydraulic conditions (Birkle et al. 2001a).

2.2 *Los Humeros geothermal field*

2.2.1 *Reservoir development*

Los Humeros geothermal field, situated in the eastern part of the Mexican Volcanic Belt, has a total installed electric capacity of 35 MWe (Fig. 1). It is one of the most challenging geothermal fields in Mexico, consisted of two reservoirs: the shallow one contains vapor and liquid, whereas superheated steam at high temperature (>350°C) in the deeper one. The production of HCl vapor in the deeper reservoir is a result of water-rock interaction at high temperature and low amount of water. The high corrosiveness and scaling in the wells due to these deeper fluids has limited the exploitation to the upper reservoir (Barragán et al. 1989, Truesdell 1991, Verma et al. 1998, Tello et al. 2000).

2.2.2 *Previous studies*

Petrography, surface and structural geology were performed by Ferriz (1982), Lira (1982), Yañez (1982), De la Cruz (1983), Garduño (1984), Ferriz & Mahood (1984), Ferriz (1985) and Venegas et al. (1985). Prol & González-Moran (1982), Verma et al. (1990) and Andaverde et al. (1993) carried out the thermal conduction modeling for the geothermal reservoir. Geophysical (Flores et al. 1978, Palacios & García 1981) and geochemical (Barragán et al. 1989, Verma et al. 1998, Martínez et al. 1996, Tovar 1996, Tello et al. 2000) studies have contributed considerably in understanding the Los Humeros geothermal reservoir characteristics and rational exploitation of its geothermal resources. Hydrological studies are discussed by Cedillo (1988, 2000) and Moro (1994), which support a local recharge to the reservoir.

2.2.3 *Reservoir structure*

The reservoir consists of complex geological units of calcite, ignimbrite, andesite and minor dacite and rhyolite. Verma et al. (1998) and Tello et al. (2000) presented a simplified vertical cross-section, consisted of four principal units. The first unit is of thickness of 500 to 600 m from the surface and formed by recent basalt and andesite flows, which are covered by pyroclastic deposits. This unit is permeable and contains rocks with high water-storage capacity. The second unit lies in a depth between 600 and 1000–1200 m. It is formed of ignimbrite and is highly fractured within the caldera, but it is sealed with the hydrothermal deposition and acts as caprock of the geothermal reservoir. The unit III (1500 m thickness) is formed by andesite and contains the geothermal reservoir. Below 2500 m, there is basement unit IV, consisting of sedimentary rocks. Arellano et al. (2001) obtained unperturbed pressure distribution profiles.

2.2.4 *Hydrology of the region*

Cedillo (1988) presented the first preliminary study of regional hydrology of the Los Humeros field. He divided the region in catchment blocks and calculated infiltration and runoff with the precipitation data for each block. Moro (1994) compiled the hydrological studies in the region. The N-E part of the region has a high precipitation rate (2000 mm), whereas the precipitation is 492 mm within the caldera. This is an effect of the topography of the region. Verma et al. (1998) conducted a study to measure isotopic composition of rainwaters in seven stations in the region to define the local meteoric water line (LMWL).

2.2.5 *Geochemical studies*

The Los Humeros geothermal reservoir has very different characteristics than that of Los Azufres, although both of them are in the same volcanic province (MVB). Both reservoirs are formed of andesitic rock. The one-dimensional, vertical layer structured model of Los Azufres reservoir suggests the existence of fluid layers in the order superheated steam, two-phase vapor dominated, two-phase liquid dominated. The lower one has hot compressed liquid, whereas in case of Los Humeros reservoir characteristics are quite different. Some workers have identified two reservoirs (Barragán et al. 1991, Tello 1992, 1994, Portugal et al. 1994, Verma et al. 1998). The shallow reservoir has two-phase fluids, whereas the deep reservoir has superheated steam. Barragán et al. (1989) mentioned that the generation of HCl vapor in the deeper reservoir was due to high temperature (300–350°C), high salinity (3000–7000 ppm) and low pH. The exploitation of this reservoir had produced the transport of HCl in some wells, which could have corroded and produced scaling in the wells. Extensive petrographic studies of well H-16 showed that the principal minerals deposited in the well were anhydrite ($CaSO_4$) and silica (amorphous and quartz).

Barragán et al. (1991) carried out a geochemical study to investigate reservoir processes, which were responsible to the observed fluid chemical composition. The wells H-1, H-6, H-7, H-8 and H-12 produce two-phase fluid. These wells are located in the "Corredor de Mastaloya". The well H-1 is fed from the upper reservoir and has no excess steam, whereas the wells H-10, H-11, H-15, H-16 and H-23 produce only vapor phase and are located in the Central Collapse.

Tello (1994) presented the chemical and isotopic behavior of geothermal fluids. The chemical characteristics of the fluids showed that the brine is low-saline water, whose geochemical character varied according to well type and production zone. The shallow wells produced sodium-bicarbonate type water, whereas the deeper wells exhibited a sodium-chloride type. He also confirmed that the well H-1 is located within the liquid dominated zone, while the other wells were in the two-phase zone. Tello (1994) and Tello et al. (2000) argued the existence of only one geothermal reservoir, as there is no impermeable rock layer to separate the reservoirs. The origin of acidic fluid in the lower part of the reservoir could be explained as a consequence of low permeable basement rocks (sedimentary rocks of geological unit IV) and high temperatures. This limits the infiltration of water and creates to produce HCl vapor as observed in laboratory (Bischoff et al. 1995). So, it explains the difference between the Los Azufres and Los Humeros reservoirs, although both of them are in the same geological province.

Truesdell (1991) explained the occurrence of acid fluid in geothermal reservoirs, as it could be either the introduction of volcanic fluids or from the volatilization and transport of HCl in superheated steam. Acid from volatilization of HCl is expected to appear in boiling high-temperature reservoirs as they lose reservoir liquid and start producing superheated steam. The occurrence of superheated, high HCl steam at Los Humeros is unusual because the steam is produced by flow from a deep dry reservoir to a shallow water-saturated reservoir with strong corrosion and scaling resulting from fluid mixing and reaction with casing and rock.

Tovar (1996), Tello (1994) and Tello et al. (2000) reported variations in the separated water characteristics, caused by changes in the wellhead opening. They attributed it to the change in the well production zone with changing wellhead orifice. Verma (1997) developed a two-phase flow method to calculate the deep reservoir parameters including the effect of well parameters, such as diameter, depth, and opening of wellhead orifice. The method will be applied in deep reservoir parameter calculations in the future work. Tovar (1996) plotted the averaged chemical compositions of geothermal fluid from most of the wells in a triangular Na, K and Mg diagram. The diagram was suggested by Giggenbach (1988) to determine the state of geothermal fluid in the reservoir. The fluids are classified as shallow and partially equilibrated waters.

2.2.6 *Isotope geochemistry*

Verma et al. (1998) conducted a monitoring the chemical and isotopic composition of rainwater at Los Humeros and its surroundings to determine the rainwater quality in the region. The isotopic data had a wide spread in the isotopic data. The effects of altitude, precipitated volume and temperature are very prominence. However, the data show a good linear correlation between δD and $\delta^{18}O$ values. The LMWL ($\delta D = 8.64\ \delta^{18}O + 14.0$) together with the precipitation volume weighted average isotopic composition of rainwater (−10.90‰ and −82.4‰ for $\delta^{18}O$ and δD, respectively) are shown in Figure 4.

The isotopic composition ($\delta^{18}O$ and δD) of surface manifestations (spring and hydrological well) is taken from Tello (1992). Figure 4 shows the isotopic composition of all water types in the region, including local and world meteoric water lines. The tritium values were analyzed by the IAEA, Vienna, for the samples of 1987 (Tello 1992) and 1995 (Verma et al. 1997). The data shows a quite interesting behavior: There is no appreciable change in tritium values for the samples, which had low values of tritium (>4 TU) in 1987. Samples with higher initial tritium values showed a decrease in their values, which could be associated with different sampling periods and/or a decay of natural tritium in the region. The tritium values for the geothermal wells as well as one deep hydrological well within the caldera of Los Humeros are close to zero. This indicates that both, the deep hydrological aquifers and the geothermal reservoir are composed of relatively old meteoric waters.

The averaged isotopic compositions of geothermal wells (production and reinjection wells) are also plotted in Figure 4. The deep reservoir composition is calculated with conservation enthalpy approach. The wellhead enthalpy depends on the wellhead opening. Thus it would be more accurate to calculate the deep reservoir composition with the two-phase flow approach, presented by Verma (1997). There is a wide spread in the total discharge composition of production wells, which could be associated with the mixing of different types of deep geothermal reservoir fluids. Although the rainwater data are only for one year, the variation with altitude, precipitated volume, and annual temperature are quite consistent as observed in the isotopic data of WMO-IAEA data for the world wide sampling stations.

The isotopic data of the shallow well within the caldera are −11.89‰ and −85.0‰ for $\delta^{18}O$ and δD, respectively. These are slightly lighter than the averaged rainwater data. Geothermal wells are heavier in both oxygen and deuterium, which could be an effect of evaporation.

2.2.7 *Conceptual model*

With geological, hydrogeological and geochemical evidences, it is possible to construct a hydrothermal model of the Los Humeros geothermal reservoir (Fig. 5). The Los Humeros

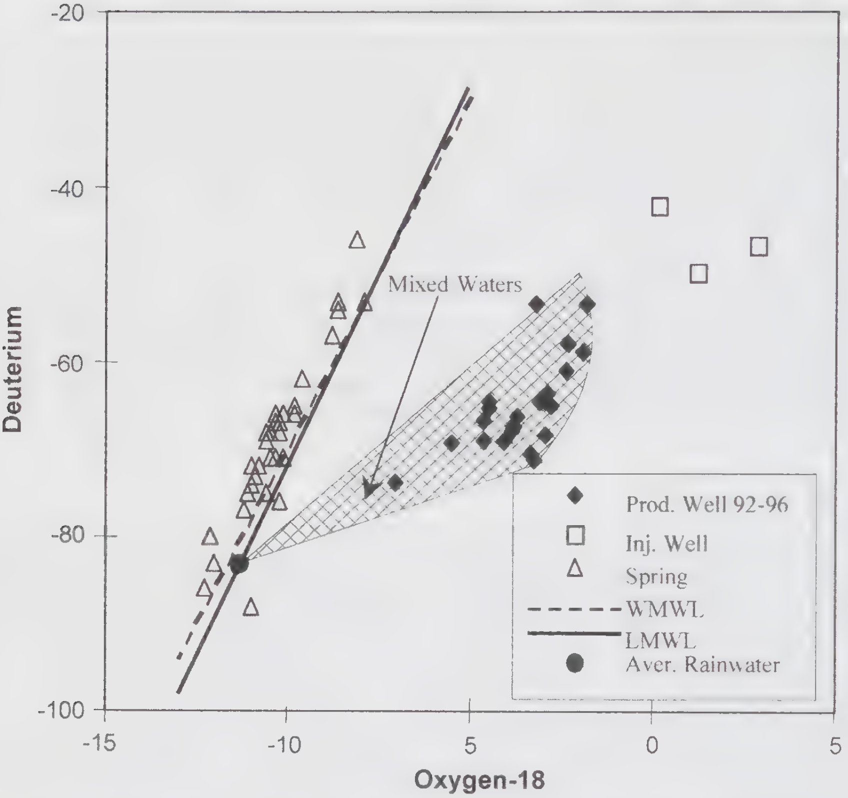

Figure 4. Isotopic composition of the fluid from geothermal wells, natural manifestation and weighted averaged rainwater in the Los Humeros geothermal field (after Verma et al. 1998). WMWL represents world meteoric water line whereas LMWL is local meteoric water line.

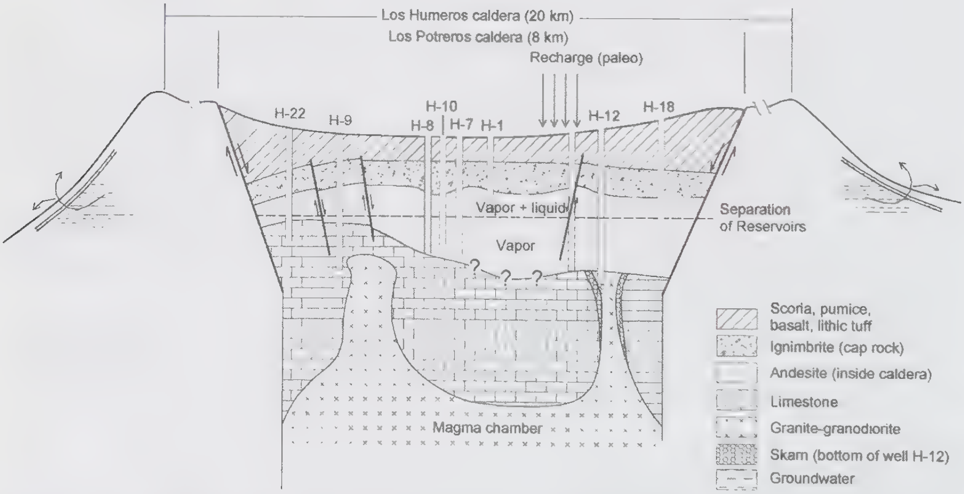

Figure 5. Conceptual hydrogeological model of the Los Humeros geothermal reservoir.

caldera is located on the boundary between two regional aquifers, thus it is difficult to explain the association between regional hydrology and the formation of the hydrothermal system.

Besides, preliminary hydrological studies indicate, that the impermeable nature of the caldera wells limited the hydrological connection of the caldera with the rest of the region. It means, that precipitation within the caldera infiltrated into the subsoil and reached the reservoir. There are no surface manifestations within the caldera except steaming ground. Presently, there is no direct recharge to the system. The ignimbrite layer acts as caprock.

The geothermal reservoir is formed in andesitic rocks and the lower part of the reservoir has sedimentary rocks (calcite). The sedimentary basement rocks show low permeability characteristics, whereas the heat source is still very hot and nearby to the reservoir. This produces superheated steam and HCl vapor (Bischoff et al. 1996). If so, the reinjection in the deeper reservoir could help in neutralization of its acidity. The existence of a vapor-dominated reservoir in the lower part could be explained through the PVT characteristics of water (Verma 2002). The CFE has measured temperature higher than 400°C. Thus, there could be only compressed liquid or superheated steam at such high temperature. If the total specific volume is less than the critical volume of water, there will be superheated steam in the reservoir.

2.3 *Las Tres Vírgenes geothermal field*

2.3.1 *Reservoir development – previous studies*

In order to satisfy the increasing energy consumption of the Peninsula of Baja California, the CFE initiated exploratory studies in the Las Tres Vírgenes geothermal field in 1980's. The field with a recent installed capacity for electricity generation of 10 MWe is located in the northern part of Baja California Sur (Fig. 1). Seven wells have been drilled since 1982: four are producers and three are injectors.

Geophysical, geological and geochemical feasibility studies on the Las Tres Vírgenes region were published by Ballina & Herrera (1984), Lira et al. (1984) and Quijano (1984). Based on information from the first exploratory wells LV-2, Tello (1988), Vargas & Garduño (1988), Bigurra (1989) and López et al. (1989) elaborated preliminary models of the geothermal reservoir. In a second stage, structural studies of the hydrothermal system (Tovar 1989, Gutiérrez 1990, Viggiano 1992, López et al. 1993, Bigurra 1998, García & González 1998) facilitated information on further prospects of drilling wells. Recently, Tello (1996), Portugal (1998a,b) and González et al. (2001) published data on the geochemical composition of thermal springs and reservoir fluids. A first conceptual hydrogeological-hydrochemical model of the fluid migration processes within the geothermal reservoir was presented by Portugal et al. (2000).

2.3.2 *Reservoir structure*

On a regional scale, the NW-SE trending faults in the Las Tres Vírgenes region represent the probable extension of the lateral San Andreas fault system, which caused the opening of the Proto-Gulf of California since Late Miocene (Coletta & Angelier 1981, Karig & Jensky 1972). During Pliocene, N-S trending fault systems were formed during reactivation of older faults (Coletta & Angelier 1981). On a local scale, the Las Tres Vírgenes geothermal system forms as a part of NW-SE-oriented Plio-Quaternary depression, called Santa Rosalía basin, which is formed by a series of NW-SE directed extensional fault systems (Demant 1981).

The Las Tres Vírgenes region is dominated by intrusive and volcanic activity. The basement is formed by a granodioritic intrusion of Cretaceous age (91–84 Ma) (Viggiano 1992) at a variable depth between 900 and 1100 m, covered by, a) volcano-sedimentary sediments of Upper Oligocene to Middle Miocene phosphoric sandstones, clayey conglomerates and lava fragments (Grupo Comondú) with a maximum thickness of 750 m, b) andesitic lava of Middle to Upper Miocene age (Formación Santa Lucia) (Gutiérrez 1990, López 1998), c) 10 m to over 300 m of marine sandstones, and continental and littoral conglomerates formed during opening of the Baja California Peninsula (Formación Santa Rosalía) (Wilson 1948). Besides, three N-S trending volcanic cones dominate the surface morphology (López et al. 1989, 1993): a) the Quaternary El Viejo, El Azufre and La Virgen domes of dacitic and basaltic composition (0.44 Ma to recent), b) the Aguajito complex with andesitic core (6.5 Ma), and ignimbrite (0.6–0.5 Ma) and dacite (0.7 Ma) cover, and, c) the resurgent caldera of Reforma with an andesitic core, followed by rhyolitic tuffs, ash falls and domes, as well as basaltic dykes (4–5 Ma).

In general, the lithological column of the study area is characterized by low-permeability conditions: Permeability and effective porosity values between 0.01 and 0.09 mD and 1.1 and 5.0%, respectively, were measured for granodiorite core samples (Contreras & García 1998). Cementation processes caused the sealing of the volcano-clastic sediments of the Grupo Comondú samples (González & Torres 1996). Conglomerates and andesitic lava of the Santa Lucía Formación in the northern part of the study area, as well as sand and conglomerate strata from the Santa Rosalía Formación, show relatively good permeability characteristics (Portugal et al. 2000, López et al. 1993, López 1998).

2.3.3 *Origin of reservoir fluids*

Arid climatic conditions with extreme low precipitation rates of 40.6 mm in winter and 21.7 mm in summer (Vargas 1988) indicate the lack of recent infiltration of surface water into the underground (Portugal et al. 2000). López et al. (1995) proposed slow and low recharge processes towards deep aquifer zones. The meteoric component is probably related to paleo-infiltration processes during Holocene or Pleistocene period, as shown for deep formation water in oil fields of the Mexican Gulf coast (Birkle 2001b). In contrary, the rise of geothermal vapor and liquid along vertical faults towards the surface is indicated by the abundance of thermal manifestation of sulfate-type and Na-Cl-HCO_3-type waters, respectively.

Boron and silica concentrations of recent meteoric water (from surface manifestations) and geothermal fluids follow a linear trend, reflecting a non-marine, meteoric origin of the reservoir fluids (Portugal et al. 2000). Therefore, the intrusion of seawater from the adjacent Gulf of California or from the Pacific Ocean into the geothermal reservoir seems to be unlikely. Based on $\delta^{18}O$ and δD tendencies, the contribution ratio of a magmatic-"andesitic" component and a fossil meteoric type water is estimated to be 30:70 (Portugal et al. 2000).

2.3.4 *Conceptual model*

As the primary permeability of the geothermal reservoir is very low, secondary permeability in form of fractures within the granodioritic intrusion and the Grupo Comondú facilitate the rise of geothermal fluids towards the surface (Portugal et al. 2000). Vertical communication is restricted to vertical faults and microfractures: mainly NW-SE directed fault system form hydraulic pathways between the shallow groundwater and the deeper geothermal reservoir. The mixture of rising geothermal steam with shallow aquifer water is reflected by sulfate type thermal springs in the northern part of the study zone. The discharge of Na-Cl-HCO_3 spring water adjacent to the Reforma Caldera indicates the mixture of rising magmatic fluid with a meteoric component in a shallow aquifer zone. The future potential of the geothermal production depends on the availability of non-renewable formation fluids, as recent recharge of the geothermal system can be excluded due to arid climatic conditions.

2.4 *Cerro Prieto geothermal field*

Cerro Prieto, a most extensively studied geothermal field in Baja California, Mexico, is located in the southern part of the Salton Trough, about 30 km south of the US-Mexico border (Fig. 1). The reservoir is formed by sandstones and shales of the Colorado River delta and is located

Table 1. Installed electricity generating capacity at Cerro Prieto (updated after Lippmann et al. 1991).

Starting	Total installed capacity (MWe)
April 1973	37.5
October 1973	75
January 1979	112.5
March 1979	150
November 1981	180
January 1986	400
September 1986	510
June 1987	620
December 2000	720

within the San Andreas tectonic system. The average elevation of the field is 11 m a.s.l. with an area of 150 km^2. The energy prospects of the Cerro Prieto area were predicted because of its proximity to the rhyodacitic Cerro Prieto volcano, and the presence of abundant hot springs, boiling pools, fumaroles, and mud pots in the very early stage of geothermal exploration in Mexico in 1950's. The first exploration well was drilled in 1959. Commercial production of electricity through a 37.5 MWe plant began in April, 1973. Presently, it has a total installed capacity of 720 MWe. Table 1 summarizes the electricity generation growth of the field.

Mercado (1968) proposed the first conceptual model of Cerro Prieto geothermal reservoir. It contemplates the presence of an intrusive magma body at shallow depth (~6 km) and highly fractured reservoir. The field was created by the movement of the right-lateral Imperial and Cerro Prieto faults (Lomnitz et al. 1970, Elders et al. 1972, Halfman et al. 1984). The heat source is supplied by an intrusive basalt dike system typical of oceanic spreading centers (Elders et al. 1984; Halfman et al., 1984). The Na/K ratio from wells and natural manifestations were used to define the movement of geothermal fluid in the reservoir (Mercado, 1976).

Halfman et al. (1984, 1986) presented a comprehensive geological model of the Cerro Prieto geothermal field, based on the geophysical and lithologic well logs. The fluid moves westward through sandstone beds and rises to shallow depth through faults and permeable sandy gaps in the overlaying shale layers. Some of the hot fluid was reaching the surface in the western part of the field in form of natural manifestations prior to field exploitation. Slowly, the natural features diminished due to exploitation of the reservoir. Presently, there is an evaporation pond with ~14 km^2 in the zone of the manifestations to store and precipitate saturated minerals, such as silica from the separated geothermal brine.

The Cerro Prieto geothermal system produces about 4 m^3/s geothermal brines, and 1 m^3/s of it is reinjected back as hot water. The rest of the brine (3 m^3/s) flows or is pumped to the evaporation pond. After cooling and saturated mineral precipitation, the brine is reinjected into the reservoir. Chemical and isotopic monitoring of geothermal fluid has been used to predict the flow patterns, boiling and mineral precipitation in the reservoir (Truesdell et al. 1979, Williams & Elders 1984, Stallard et al. 1987, Truesdell & Lippmann 1990, Puente & Rodríguez 2000).

Figure 6 shows the updated conceptual model of the Cerro Prieto reservoir (after Halfman et al. 1984, Lippmann et al. 1991). The Colorado River water infiltrates into the reservoir, whose basement is formed of granite. Lippmann et al. (1991) noted the presence of hyper saline brines at the bottom of the reservoir. The infiltrated water got heated and mixed with the hyper saline brines. The alpha shallow reservoir produces through the "L" fault and the beta reservoir through "H" fault. It has been discussed the presence of a deeper reservoir ("gamma") in the southeast of the field, but its feasibility for exploitation is yet to be proven. A calculation, based on the extracted amount of geothermal fluid, reservoir volume and porosity indicates that the reservoir has been evacuated more than four times.

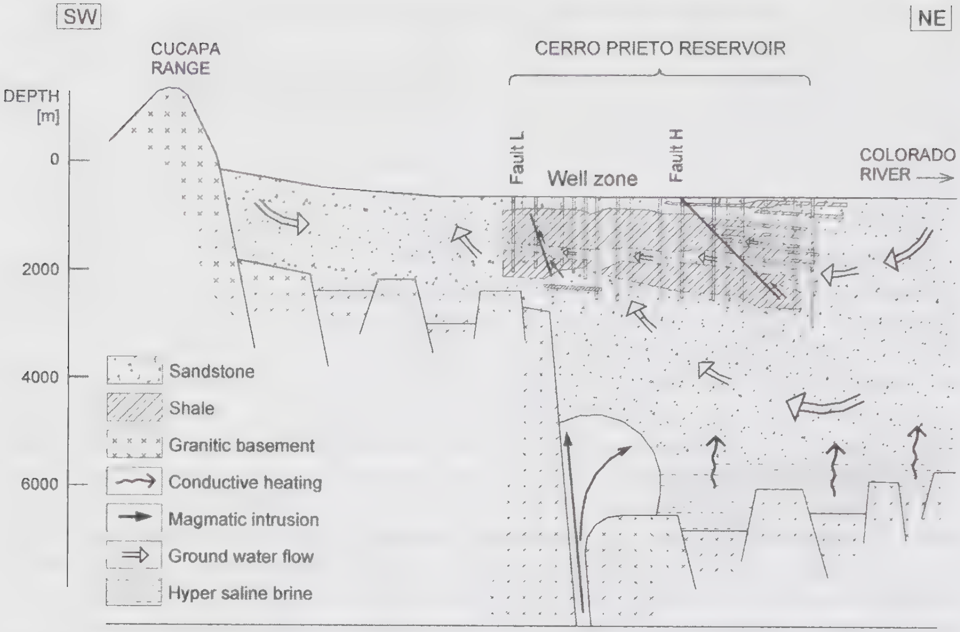

Figure 6. Hydrogeological conceptual model of the Cerrro Prieto geothermal reservoir with recharge by the Colorado river and conductive heating up by a deep heat source (after Halfman et al. 1984, Lippmann et al. 1991).

Presently, there are some projects undergoing to estimate groundwater infiltration into the geothermal reservoir, prevention of groundwater contamination due to storing of hyper saline brine in the evaporation pond and evaluation of the economic prospects for the exploitation of the deeper gamma geothermal reservoir.

3 CONCLUSIONS

In Mexico, a total of 1380 sites with geothermal characteristics, distributed over 27 states, are identified (Torres et al. 1993). Four of them, the high enthalpy fields of Cerro Prieto (State: Baja California Norte), Los Azufres (Michoacán), Los Humeros (Puebla) and Las Tres Vírgenes (Baja California Sur) are exploited for electricity production, generating about 3% of the national electricity consumption. The Cerro Prieto reservoir is part of a sedimentary basin as extension of the lateral San Andreas fault, whereas the other reservoirs are dominated by volcanic and intrusive host rock. Mostly, ignimbrite and rhyolitic layers form sealing caps above the volcanic reservoirs. In general, fluid migration by microfractures and vertical faults are the dominating process of the convective hydraulic systems. Several observations, such as a) little temporal changes in the isotopic and chemical composition of the fluids during production, b) minor pressure drop and production decline rates, combined with little evidence for hydraulic communication between the injection and production zone (shown by tracer tests in Los Azufres), c) a constant production during the last 20 (Los Azufres) and 30 years (Cerro Prieto), indicate the renewable character of most of the exploited Mexican reservoirs.

All the spent geothermal brines is reinjected into the deeper part of the high temperature reservoir at Los Humeros in order to neutralize its acidic fluid. The amount of reinjected water is still relative low to observe beneficial effects of reinjection.

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Geothermal energy resources of India

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ABSTRACT: Indian geothermal provinces are located in areas with high heat flow (75 to 468 mW/m^2) and geothermal gradients. The heat flow (59 to 234°C/km). Exploration studies and reservoir modeling have been carried out between 1995 and 1998 to understand the reservoir characteristics. Thermal gas discharges from several thermal provinces recorded high helium concentration varying from 0.5 to 6.9%. Gas data together with heat flow and thermal gradient data suggest presence of granites and related intrusives with high U concentration (0.19 to 10.7%) in these provinces. Geothermal provinces in the Himalayas with such granite intrusives are best suited for initiating HDR geothermal projects. Pilot power plants commissioned at certain thermal discharge sites proved the power generating capacity of these provinces. The estimated power generating capacity of the thermal discharges is about 10,600 MW. Recently India has initiated proposal to install a 1 MW power plant at Tattapani in central India. In future if India is compelled to sign the Kyoto protocol, then coal based power project will have a set back while geothermal based power plant will have good future.

1 INTRODUCTION

The seven potential geothermal provinces in India are associated with mid-continental rifts (The SONATA-Son-Narmada-Tapi rift), subduction (Himalayan suture zone), sedimentary basins (Cambay basin) and Cretaceous-Tertiary volcanism (The Deccan volcanic province) (Fig. 1). In recent years, the Barren island has become one the most important geothermal provinces in the Indian subcontinent. The estimated energy that can be obtained from these thermal discharges is equivalent to 5.7 billion tonnes of coal or 28 million barrels of oil. If these energy resources are utilized for power and direct applications, it will substitute about 10,600 MW of power (Ravi Shanker, 1996). The estimated future power demand is above 43,000 MW. Geophyscial investigations carried out along the west coast, Cambay basin and Himalayas indicate presence of potential sites for future development through deep exploratory drilling.

2 GEOPHYSICAL EXPLORATION ACTIVITIES

Across SONATA, which encloses the famous Tattapani Geothermal province, DSS results indicate deep seated faults extending up to mantle depths. However, primordial ^{3}He has not been detected in the gases from this province (Minissale et al., 2000). Therefore these "deep seated faults" may be sealed thus preventing escape of ^{3}He from the mantle or they may represent other structures. Detailed geological, gravity, magnetic and seismic investigation (CRUMANSONATA, 1995) delineate these deep seated faults to be paleo-suture zones developed during collision of the Deccan protocontinent with the Bundalkhand protocontinent (Jain et al., 1995). The Tattapani Geothermal

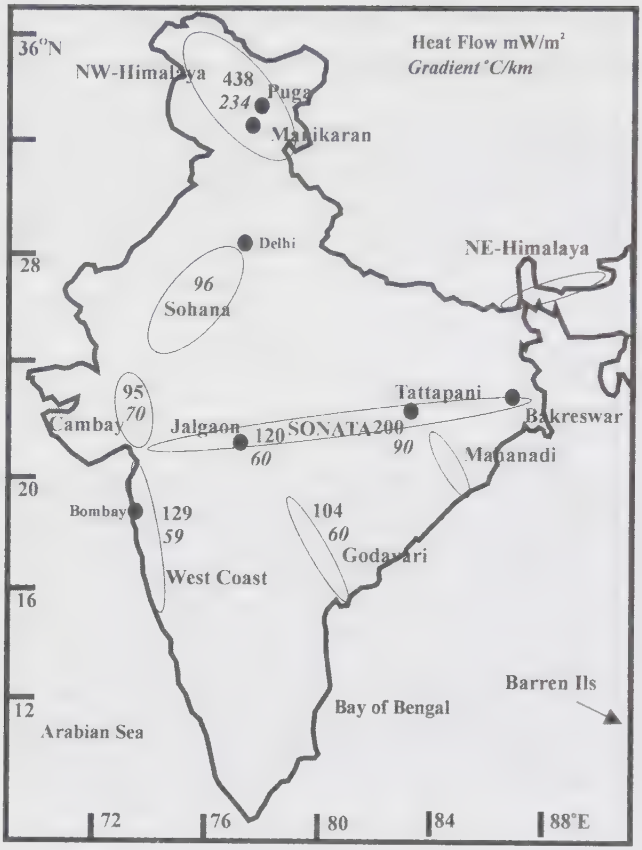

Figure 1. Geothermal Provinces of India.

province falls north of this paleo-suture zone. The R/R_A ratio in the thermal gases also support the presence of such structure in this region (Minissale et al., 2000). Bore hole logs in this province indicate the presence of Gondwana sedimentary formations lying over the Proterozoic basement intruded by younger granites and pegmatites.

Cambay basin is enclosed by failed arms of the triple junction related to the Deccan volcanism (Sheth and Chandrasekharam, 1997). Shallow and deep section delineated from DSS along this basin, reveals that the basin is bounded by step faults on the eastern and western margins of the basin with several deep seated faults extending to mantle depths. Towards the southern part of the basin the Moho is encountered at a depth of about 18 km (Kaila and Krishna, 1992; Singh et al., 1991) and the 1250°C isotherm is located at a depth of about 40 km. The presence of high density material at shallow depth in this area is further supported by positive gravity anomaly (+35 mgals). Granite intrusives, like the Godhra granite, with radiametric age of about 955 Ma outcrop within the basin near Tuwa. These geological and tectonic features are contributing to high heat flow value in this region which ranges from $67–93\,\mathrm{mW/m^2}$, with thermal gradient as high as 70°C/km. (Gupta, 1981; Ravi Shanker, 1988). Mantle degassing through such deep seated faults is indicated by relatively higher R/R_A ratio (0.3) and higher CO_2 content (3%) in the gases from Tuwa thermal province (Minissale et al., 2001).

Magnetotelluric investigation across Tapi basin, which encloses the Jalgaon geothermal province, indicates presence of a granite intrusive between 2 and 10 km depth covered by thick Gondwana sedimentary formation (Rao et al., 1995; Chandrasekharam and Prasad, 1998). Thus the geothermal province (heat flow: 120 mW/m^2; thermal gradient: 60°C/km; Ravi Shanker, 1988) in this basin is related to the above magmatic body.

The NW Himalayan region includes the well known Puga, Manikaran and Chummathang geothermal provinces. A conceptual 2D computer model for Puga geothermal province using MULCOM computer programme (using SHAFT 79; O'Sullivan, 1985) has been developed, to assess the potential of the reservoir for electrical power generation. Two dimensional resistivity structure of Puga (Himalaya geothermal province) using magnetotelluric recordings and geoelectromagnetic induction tomography (GEMIT) has been carried out (Singh and Nabetani, 1995). Puga valley is located at 4000 m altitude, lies towards the southern margin of the Tsangpo suture zone and is well known for its numerous thermal springs with temperature up to 90°C (boiling of water at that elevation). The results indicate the presence of a shallow reservoir capable of generating 45 MW power in this province. It may be mentioned that the Yangbajing geothermal field in China, which is located about 1200 km ESE of Puga, is already producing 25 MW of power (Chandrasekharam, 2000). One kilometer pilot power plant installed at Manikaran in Himachal Pradesh by the Geological Survey of India has already proved the capability of the thermal provinces in generating electricity (Chandrasekharam, 2000).

Regional stress analysis based on earthquake focal mechanism, bore-hole blow-outs and hydrofracturing (Gowd et al., 1992) indicates that the entire Himalayan belt in general and the Himalayan Geothermal province in particular, is under compressive stress regime due to the northward movement of the Indian plate and net resistive forces at the Himalayan collision zone. Thus the central and northern India including Nepal, the Great Himalayas and Pakistan fall under this stress province characterized by NNE-ENE oriented S_{Hmax}. Investigation carried out around Zanskar (north of Kulu, in the Himalayan Geothermal province) by Pierre Dèzes (1999) also shows compressive regime in this region. Compressional stress regime is favourable to create several sub-horizontal reservoirs in granites by hydrofracturing, interconnected by boreholes (Baria et al., 1999; Wyborn, 2001). The entire subduction tectonic regime along the Himalayan Geothermal province appears to be similar to Hijiori and Kansai provinces in Japan where HDR prospect is being evaluated. International HDR feasibility study can be initiated in this region with local Himachal Pradesh Govt. support and support from the independent power producers.

International Deep Profiling of Tibet and the Himalayas (INDEPTH) project located seismic bright spots in Tibet region (east of the Indian Geothermal provinces) which are attributed to the presence of magmatic melts and or saline fluids within the crust. Highly saline fluids are also found in Ladakh granites (~60 Ma) as inclusions which are attributed to the high volatile content in the granitic melts. Though INDEPTH investigation has not been carried out, considering the proximity of INDEPTH site in Tibet, probability of occurrence of such seismic bright spots within the Himalayan Geothermal province is high. This inference gains strength from the 1 Ma anatexis process recognized in Nanga Parbat (Chichi granite massive) in Pakistan Himalayas and similar processes must be in operation on the eastern side of Nanga Parbat also. These evidences confirm that the present day observed high heat flow value (>100 mW/m^2) and geothermal gradient is related to crustal melting process at shallow depth in this region (Chandrasekharam, 2001).

3 GEOCHEMICAL STUDIES ON THERMAL GASES AND WATERS

The investigation based on reconnaissance survey by the U.N. organization and the Geological Survey of India on majority of thermal springs are reported in the "Geothermal Atlas of India" (G.S.I., 1991). Further investigation by several authors suggest that many geothermal provinces can be exploited for power generation and for direct utilization (Chandrasekharam, et al., 1992; Chandrasekharam and Antu, 1995; Chandrasekharam et al., 1996; Chandrasekharam and Prasad, 1998; Pitale and Padhi, 1996; Minissale et al., 2000; Minissale et al., 2001). Although several authors have reported major ion data on the thermal springs (Giggenbach, 1976; Giggenbach et al., 1983; Gonfianti, 1977; Nevada and Rao, 1991; Chandrasekharam et al., 1989, 1997), detailed investigation on the isotopic signature of the thermal waters and associated thermal gas phase were missing. In order to fill this gap, under a collaborative project between the Department of Sciences and Technology, Govt. of India and the Ministry of Foreign Affairs, Italy a sound data based on the chemical and isotopic signatures on the thermal waters and thermal springs have been generated over the last three years (Minissale et al., 2000, 2002). This data base can be used for further exploration and identification of sites for exploratory drilling. The gases from these provinces are rich in N_2 and Ar, which are apparently atmospheric in origin. The most remarkable finding is the high ^{4}He concentration in these gases which range from 0.5 to 6.9%. Such large ^{4}He concentration in the thermal gases is suppressing the mantle ^{3}He thereby registering low R/R_A ratio. Deep and prolonged circulation of thermal waters and presence of anomalous geothermal gradients have been recorded in the above three provinces (Chandrasekharam et al., 1997; Minissale et al., 2000). Such high ^{4}He is apparently due to the presence of a large reservoir of He in the Precambrian rocks lying below the Deccan volcanic flows. Similar He concentration (1.4 to 2.77%) in the thermal waters from the Bakreswar geothermal province in West Bengal has been reported by the Atomic Minerals Division (Nagar et al., 1996). Even the soils around this geothermal province have registered anomalous high He concentration (46.6 to 82.8 ppm). Like the above three geothermal provinces, high He in thermal waters of Bakreswar obviously is being produced by decaying U and Th in the Precambrian crystallines. This is further supported by high heat flow value of 145–200 mW/m^2, a value which is greater than twice the average global value and is similar to the value reported for young spreading ocean ridge, such as the Red Sea ridge axis (Gettings et al., 1986). Similar heat flow values have been reported for the Godavari geothermal province. Geochemical exploration carried out on the Godavari geothermal province indicates two promising areas, i) the Bugga and ii) Manuguru, for geothermal energy development. The thermal reservoir here appears to be the Talchir sandstone (Gondwana Super group), a secondary reservoir with storage capacity of 35 million cubic meters. With surface flow rate of 1000 l m, the reservoir, with power generating capacity of about 38 MW, should yield thermal waters for 75 years (Chandrasekharam, 2000).

The Barren Island volcano, located over a trench in the Andaman sea (12°17'30" N; 93°52'30" E) is the only active volcano in the Indian subcontinent. This volcano erupted in 1991 after lying dormant for two centuries. Super heated steam and gas started emanating from the volcano since 1950s (Raina, 1987). A number of centres with fumerolic activity and thermal manifestation are seen around the volcano as well as within the crater (Bandyopadhyaya et al., 1973). Detailed geothermal exploration activity is being planned in collaboration with the Department of Earth Sciences, University of Florence, Italy and Italian National science Council (CNR), Italy.

4 DRILLING ACTIVITIES

All the previous exploratory bore-holes drilled in the geothermal provinces of west coast, SONATA, Cambay and Himalayas (Fig. 1) are shallow, reaching maximum depth of about 600 m. These bore-holes lie in an area of anomalous high thermal gradient and high heat flow (For example at Tattapani, Central India: ~90°C/km and 200 mW/m^2 respectively were recorded). The Tattapani wells (Fig. 1) are yielding 1800 l/m of hot water at 112°C. With this flow rate and at 6% plant efficiency, electrical energy potential calculated is about 11 MWe for twenty years. Temperature of the order of 160°C is envisaged at a depth of 1.5 km (Sharma et al., 1996). Reservoir temperature of 217°C has been estimated at 3 km depth for this thermal province, based on experimental results and geochemical thermometers (Chandrasekharam and Antu, 1995). Recently, attempts are being made by the National Hydro Power Corporation to develop the Tattapani Geothermal province by drilling deep drill holes to generate 1 MW of electric power in collaboration with Geothermex, USA.

Six bore-holes drilled along the west coast geothermal province to a depth of 500 m recorded temperature gradients of 47–59°C/km and heat flow value of 75–129 mW/m^2 (Ravi Shanker, 1987). Though the surface flow rates of some of the thermal springs are low (48 l/m; Ravi Shanker, 1987), measured discharge through the bore-holes is 24 tonnes/h (Muthuraman, 1986). The continental crust is attenuated and foundered at several places along the west coast during the Deccan volcanic episode thereby recording positive gravity anomalies along the coast. Geophysical investigation along the coast and off-shore of Bombay recorded thin lithosphere (~18 km) and the 1250°C isotherm in this region is expected at a depth of 20 km (Chandrasekharam, 2000).

Based on magnetic, electrical and resistivity surveys over the Bakreswar-Tantloi geothermal province of West Bengal and Bihar, which registered heat flow value and geothermal gradient of 200 mW/m^2 and 90°C/km respectively (Ravi Shanker,1988), two exploratory bore-holes to a depth of 200 m at Tantloi in Bihar were drilled by the AMD. Thermal gases and waters with high concentration of He (1.4 to 2.77%) have been encountered in these bore-holes. The rate of flow of gas and that of water vary between 1–4 l/hr and 1500–2100 l/hr respectively (Nagar et al., 1996). High heat flow coupled with very high He concentration in the gases and thermal waters apparently indicate that the granites and gneisses through which the thermal waters are circulating are enriched in U minerals. A pilot He extraction plant has been commissioned by the above organization to recover He from the thermal gases and water.

About 34 bore holes were drilled in Puga and Parbati valley geothermal provinces of Himalayas. The bottom hole temperature in some of the bore holes recorded is ~140°C with pressures ranging from 2 to 3 kg/cm^2. Out of them, 17 are flowing wells with a total discharge of 190 tonnes/h and maximum discharge measured for a single bore-well is 30 tonnes/h. Geothermal gradients greater than 200°C/km and heat flow varying from 140 to 468 mW/m^2 have been recorded from these bore wells (Ravi Shanker, 1988). A large number of granite, granitoid and pegmatite intrusives with radiometric ages ranging from 3.4 Ma to 495 Ma, and with U_2O_3 content varying from 0.19 to 10.7%, which appear to the main source of heat, have been reported from several localities in these geothermal provinces (Ravi Shanker et al., 1977; Srikantia and Bhargava, 1998; Chandrasekharam, 2001a). Space heating experiments using hot waters from the bore-well have been conducted by the Geological Survey of India (G.S.I., 1991). These space heated huts have been used to extract and refine borax and S (at Puga) which occur in large quantities here.

5 OTHER DEVELOPMENTAL ACTIVITIES

As on today the effect of binary fluids used in the geothermal binary power plants is not well documented. In order to eliminate any such effect on the ozone layer by CFCs, attempts have been made to develop new binary fluids in the power plants. Experimental and thermodynamic analyses have been carried on such new binary fluids (HFC-134a) to assess its performance. The advantages of using this fluid are, the irreversibility of the flashing binary cycles are much lower and hence the utilization factors are substantially higher as compared to the conventional cycles (Tyagi and Bhave, 1996).

A cost effective 1-6 tube and shell heat exchanger has been designed to dehydrate onions using the thermal waters of Bugga and Manuguru, with an estimated reservoir temperature of 170°C, located in the Godavari basin geothermal province of Andhra Pradesh. This heat exchanger appears to be most suitable for this province and can dehydrate 10,000 lb/h of onions with an air volume of 20,000 m^3/h (Chandrasekharam, 2000 and references therein).

6 CONCLUSIONS

Exploration and pre-feasibility studies on promising geothermal provinces have clearly demonstrated that geothermal energy resources programme in India has come to a stage where commercial exploitation of the reserves has to be initiated on large scale. The high heat flow and geothermal gradients in most of the thermal fields, supported by anomalously high ^{4}He concentration is related to the magmatic intrusives with high U and Th contents. Gamma-ray spectrometer analysis on several rock samples collected from high heat flow regions reveal that high heat flow is closely related to high heat generation of the formations which in turn is related to high concentrations of U and Th in the rocks (Rao et al., 1976). Thus, many of the geothermal provinces discussed above are excellent sites for hot dry rock (HDR) programme as well (Chandrasekharam, 2001a). The present scenario in India is similar to that of Australia, where buried granites with sedimentary blankets, at depths varying from 2 to 5 km, with temperature exceeding 250°C are identified as the prime sites for HDR programme. The high heat flow here is attributed to high heat generation by these granites (Burns et al., 1995). Experimental programmes like those conducted at Fenton Hill, New Mexico (Jelacic and Hooper, 1996) and like those proposed to be undertaken for the Muswellbrook site, Australia, to generate 20 MW power from 1 km^3 of hot rock (250°C) at a depth of 5 km (Somervillie et al., 1994), should be initiated at some of the geothermal provinces in India. Deep drill hole to a depth of 2 km in the geothermal provinces discussed above should be able to generate substantial power and also support several industries. The present mood of the Indian industries is upbeat with many private power companies are prepared to invest on geothermal energy resources with foreign collaboration.

Himachal Pradesh, where many geothermal areas of the Himalaya province are located, has varied agro-climatic conditions suitable for growing different varieties of fruits. The state is successfully growing apple, pear, peach, plum, almond, walnut, citrus, mango, raisin grapes etc. The total area under fruit cultivation in Himachal Pradesh is about 2000 km^2 with a production of about 5000 MTs of all kinds of fruits. Apple is the major fruit accounting for more than 40% of total area under fruits and about 88% of total fruit production in the state. The present two fruit processing plants has a combined capacity to process about 20,000 MT of fruit every year. But, then the region has to depend on other farm foods from other parts of the country (Chandrasekharam, 2001b). If local geothermal resources are put to use, this region can be one of the major food producing and processing regions in the country. The Himachal Pradesh geothermal province is best suited to initiate state-of-art technology in food processing (dehydration and greenhouse cultivation) using geothermal energy. Beside the agro-based industry, large cold storage facilities can be commissioned along the west coast geothermal province where fishing is a major business.

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This book demonstrates how geothermal energy can be a driving force for an economically sound and sustainable development. It looks at the provision of geothermal energy within the framework of sustainable energy development in developing countries for power generation, rural electrification and direct use to support several small scale industries like food processing, green house cultivation, pisciculture etc. The book gives an overview of the geothermal resources available around the world and their possible uses as function of temperature and economical availability, suitable geothermal exploration techniques, and optimal geothermal exploitation methods.

Environmental aspects and benefits of geothermal energy resources utilization and related reductions of green house gases are discussed in the framework of local environmental protection and in the frame-work of the global climate change policies including the use of Clean Development Mechanism (CDM) opportunities for non Anex-I countries of the Kyoto Framework Convention of Climate Change FCCC. Institutional, policy regulation and financial obstacles which hinder the promotion of geothermal energy and methods to overcoming such obstacles are addressed. Methods to get international support for capacity building and increasing public awareness for popularising of geothermal energy are elaborated.

The role of private sector participation to overcome financial obstacles and incentives necessary to attract private sectors' participation in geothermal energy resources development are also addressed.

Written in simple English, the book will be a useful guide for non-specialists, academicians and policy makers as well as those working on sustainable energy development projects. The book is addressed to: energy decision makers, energy sector representatives and administrators, policy makers, business leaders, energy engineers/scientists, academicians and power producers, international development banks as well as hydrogeologists, water resources managers and engineers, land planners, agronomists, intellectuals, etc. who are concerned about the energy related problems of their country.