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Post-Mining—a Holistic Approach

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Abstract
The European climate and energy framework for 2030 is highlighting the reduction of man-made CO_2 by increasing the use of renewable energy to mitigate climate change. In this spirit, Germany has decided to erase the coal use as an energy source by 2038 completely. Inevitably, this strategy promises a feasible, responsible, and sustainable post-mining management, because 200 years of coal mining have created numerous challenges necessary to tend to once the mining ends. Thus, the Research Institute for Post-Mining (FZN) at the TH Georg Agricola University in Bochum, Germany, has developed a holistic approach to meet these post-mining challenges including further expertise present at our university. Here, the four strategic research pillars are (1) technical geoecology and hydrogeology to avoid and mitigate risks underground, (2) geomonitoring to evaluate and protect the surface, (3) industrial heritage preservation and engineering to secure and reuse brownfields such as mine sites, and (4) economic transformation planning of mining regions to enable a prosper future for generations to come. In all efforts, we aim to achieve the fundamental goals of the UN to deal with the resources of our planet responsibly and sustainably. Furthermore, we are synergizing increasingly with national and international networks in the interest of social, economic, and environmental stakeholders.

Keywords Germany · Coal · Post-mining · Sustainable development · Geoecology · Geomonitoring · Industrial heritage · Transformation

1 Introduction

Today, abandoned mines exist all over the world. For instance, Australia has recorded 50,000 abandoned mines [1], the USA more than 22,000 mine sites [2], and Canada estimating more than 10,000 abandoned sites [3]. In Germany, 50% of the municipalities in the federal state of North Rhine-Westphalia (NRW) are impacted by abandoned mine sites (Fig. 1) [4].

The sustainable development of these legacies requires a holistic approach identifying the related risks and opportunities and setting up an appropriate risk management as well as a comprehensive monitoring system. Contemporaneously, the institutions managing these abandoned mines have to take into consideration the demands of the local municipalities to create the best situation and output from these mining residues for the upcoming generations.

The necessary treatment of former mine sites requires a very long time, because mining effects on nature and communities are irreversible mostly. Notably, mine sites can remain in a post-mining period longer than they were in operations. In Germany, hard coal mining lasted around 200 years. However, pumping of mine water and subsidence-related groundwater issues due to underground workings will remain a permanent task constantly.

During the post-mining period, it is useful to revisit the post-mining goals and outcomes on a periodic basis. Hence, the imperative post-mining strategy needs to:

- minimize the negative consequences of closure processes
- maximize potential positive benefits of closures
- minimize the likelihood of not-met closure goals, and
- maximize the likelihood of capturing all opportunities regarding lasting benefits.

2 Post-Mining. An Overview

All processes and duties involved when taking care of an area previously used to extract natural resources are referred to as "post-mining." An implementation of long-lasting repository and regional management besides directly incurring technical

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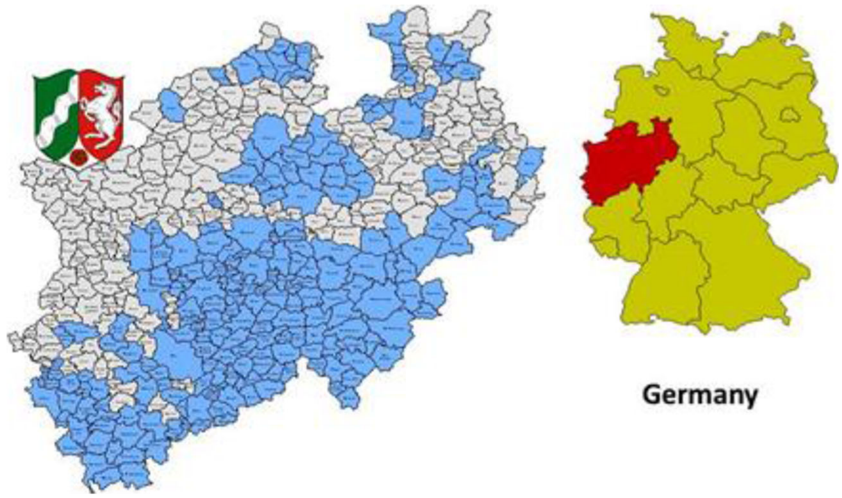

Fig. 1 Areas in NRW affected by abandoned mine sites

activities is necessary to secure and redevelop mining legacies in a feasible and sustainable manner.

In this context, renaturation, re-cultivation, and a comprehensive risk management are essential to address all repercussions of former mining activities.

Classic issues include the risk management as well as the renaturation and re-cultivation of areas previously used for mining. Here, key aspects are the groundwater and mine water management, safekeeping of brownfields, and the dismantling and backfilling of production wells used for exploration and extraction. Within these, monitoring the post-mining processes and field interactions such as mining subsidence including damages closely is essential. Therefore, holistic data, information, and knowledge management approach is the backbone of post-mining. Unfortunately, a systemic and multidisciplinary understanding is yet to achieve.

To cluster its expertise and work on a useful, all-embracing, and sensible management of these diverse mining impacts all over the world, the TH Georg Agricola University (THGA) established a Research Institute for Post-Mining (German: Forschungszentrum Nachbergbau, FZN) successfully. Notably, the research executed here profits from synergic expertise university-wide. Here, new methods of geoengineering are developed and tested to accomplish and offer a sustainable management of mining impacts.

In doing so, our post-mining research includes four areas: (1) geoecology and mine water management, (2) geomonitoring, (3) materials science for the preservation of industrial plants, and (4) reactivation and transition of mining regions (Fig. 2).

Within these, our researchers explore the arising questions due to mine closures: How can the affected regions cope with the mine water rebound? What risks are associated with remaining mine gas? How can we decommission and reuse abandoned mines for novel and innovative activities? How can we monitor mining-induced impacts most accurately?

3 Geoecology and Mine Water Management

Extracting raw materials from open or underground pits has manifold effects on the regional water balance. Usually, closing these implies a subsequent mine water rebound up to the original groundwater level. Within this process, hydrogeological, hydrochemical, and geomechanical changes are associated. The corresponding research activities focus on modeling and monitoring these complex processes and their interdependencies resulting in an environmental impact prediction and developing an integrated understanding.

Strikingly, the mine water drainage is the biggest challenge. Mine water is rainwater that infiltrates the ground along impervious rock layers and crevices dissolving minerals (e.g., salts) while migrating and possibly becoming brines. During the operational phase of underground hard coal mining, pumps transport this mine water constantly to the surface. Otherwise, it floods the mine and makes any exploitation of raw materials impossible.

In light of the progressing climate change, the energetic use and general reuse of mine water are of prime importance in post-mining. Currently, the application of temperate mine water focuses on local geothermal heat utilization in individual domestic and industrial projects. However, there is a global technical potential to convert the mine water's thermal energy into electricity. Thus, the FZN is developing innovative technologies to tackle the most efficient use of this resource. Furthermore, separation techniques to remedy clean water from mining areas and industrial brownfields are being developed and tested.

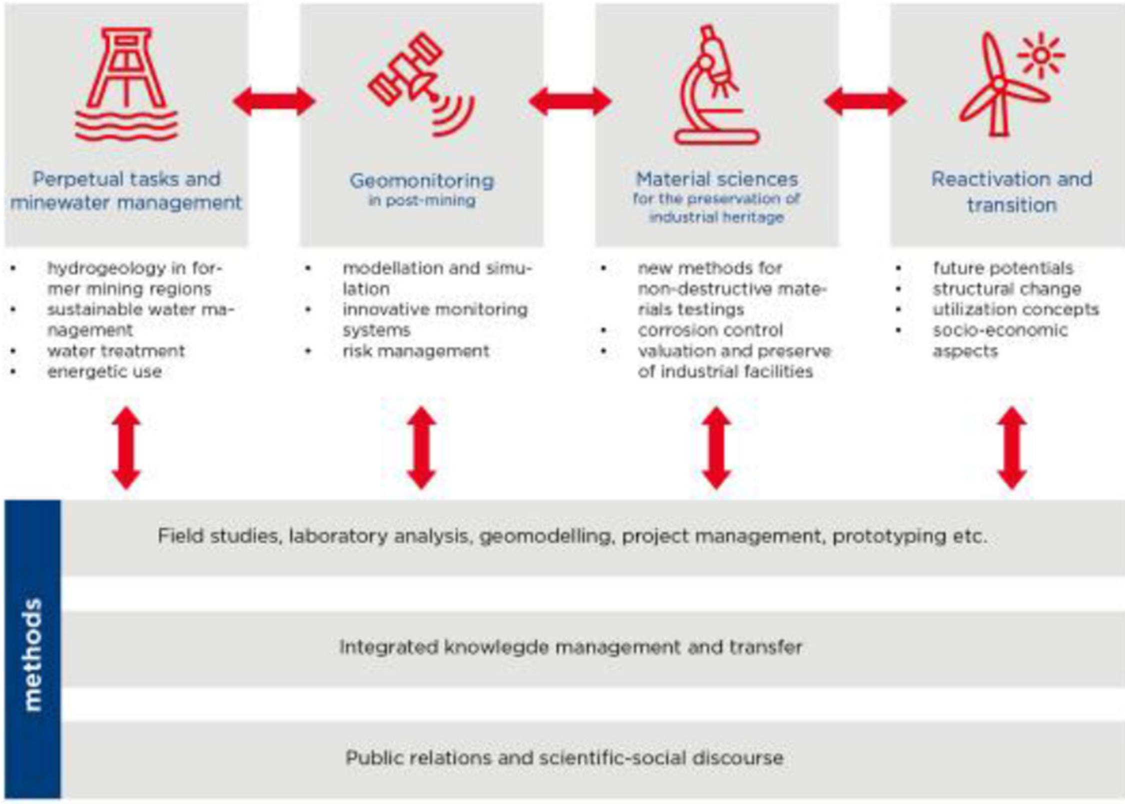

Fig. 2 Research areas of the FZN at the THGA

With particular regards to post-mining, the mining authorities collaborated with mining companies to develop a risk management guideline that enables them to recognize risks (Fig. 3) and define suitable measures [4].

4 Geomonitoring

Intrinsic features of mining processes include a large area coverage and long-lasting operations. At the same time, there

Fig. 3 Risks and tasks in post-mining ((1) ©THGA; (2) ©RAG; (3) ©RAG; (4) ©THGA; (5) JERS data ©JAXA, SAR, and InSAR processing by Gamma Remote Sensing AG, 1998; ©Brüggemann)

are processes happening on a smaller scale and shorter durations. Examples for the latter are discontinuity zones at tectonic faults, subsidence at shaft constructions, or the breaking of dams at tailing ponds. Consequently, we are searching for specifically tailored strategies to achieve an omniscient analysis and reliability regarding the post-mining processes in question. Depending on the process, the design of a highly refined technique or an integrated multidisciplinary approach is a premise.

Therefore, the FZN develops monitoring systems by combining remote sensing, classic sensors, robotics, modeling, and/or simulations and integrates them per process to create a solid analytic foundation for a most effective monitoring system.

Furthermore, we use the open-access data available from the Copernicus Program launched by the EU and the European Space Agency (ESA), which provides an up-to-date and high-performing infrastructure for earth observation and geoinformation services thus supplying high-resolution environmental data of remote sensing for both space and time. By this, the Copernicus Program particularly leverages the development of the Copernicus Sentinels—seven satellite missions designed especially for geomonitoring purposes from outer space (Fig. 4).

In turn, the Sentinel satellites generate massive data amounts that need further processing, long-term storage, and handling their sustainable usage.

Together with partners, the FZN works on data usage concepts for remote sensing and monitoring post-mining processes. Here, the focus is set on the following aspects: groundwater management, ground movements, and land use as well as coverage. Especially, the reliable monitoring data offered from space is linked to information generated by the satellite-supported ground-based sensors and terrestrial expertise. Fittingly, Fig. 5 displays an example of satellite-based monitoring of different wetland formation stages.

The site presented in Fig. 5 is the Kirchheller Heide, a heath located in the northern part of the Ruhr area, which served as a study area to monitor changes in aquifer and soil moisture due to mining-related ground movements. Here, mine-related water level changes can be evaluated either directly by monitoring changes in receiving water distribution or indirectly by observing changes in vegetation provoked by changes in soil moisture and water emergence (Garcia Millan et al. 2014). Interestingly, the vegetation around mine-related wetlands simply dies, and peripheral trees in different stages of decay can be observed (shown in Fig. 5 also).

Fig. 4 Sentinel 1A (© ESA)

Terrestrial monitoring systems include for example:

- geodesy and mine-surveying data
- air-based remote sensing instruments
- on-site inspection
- photography and photogrammetry
- meteorological measuring facilities
- probes at weather balloons
- measuring buoys, stream gauging devices.

Information resources derived from terrestrial monitoring are for example:

- digital topographic maps
- digital elevation models
- ortho-photos
- topical maps (e.g., forest areas, settlements, water bodies)
- mining charts [5].

Looking forward, suitable monitoring systems tending to all essential processes in post-mining are reachable, and thus, preventive measures can be initiated accordingly in the future.

5 Preservation of Industrial Plants

Especially in the German Ruhr region, the industrial development had a formative societal and architectural impact. Driven by the availability of hard coal, an agglomeration of industrially influenced cities arose since the early nineteenth century. Today, these cities are a large metropolitan area with more than five million inhabitants. In this setting, numerous coal mining sites concerning extraction, production, transport, and infrastructure were built and are still visible imprinting signs of the "coal age" in Germany (e.g., colliery and coking plant Zollverein in Essen (Fig. 6), a World Heritage site on the UNESCO list).

Mining has left related objects such as headframes, buildings, machine halls, coking plants, and blast furnaces, and also individual machines and equipment. They are recognized as elements of industrial heritage and culture. In Germany, mining communities and local communities are eager to preserve this heritage for future generations, but also to reuse it beneficially. The preservation of these

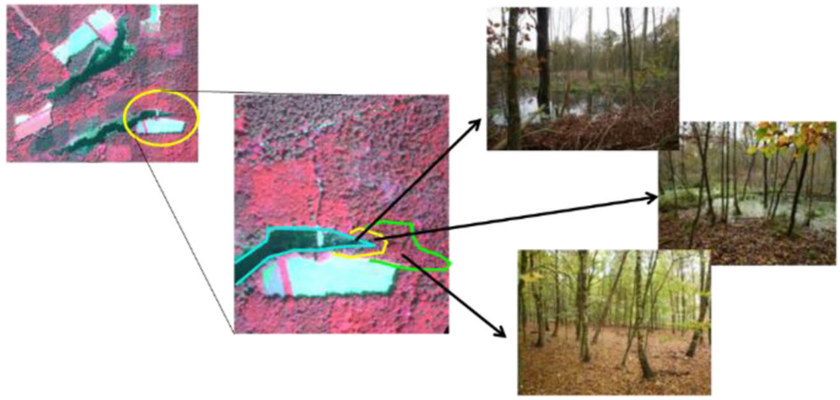

Fig. 5 Stages of wetland formation in the heath Kirchheller Heide. AISA-Eagle airborne sensor infrared composition. Photos taken in October 2012

objects requires material-oriented solutions and a specifically tailored material handling.

In this matter, materials science can offer solutions for these highly individual objects. Most important is here that as different as these objects and materials may be, they have one thing in common: their old age. Only when the aging processes of these materials have been researched and fully understood, their decay can be slowed down or, at best, the object can be preserved. Therefore, methods to estimate the durability of materials under specific stress conditions need to be developed. In addition, researchers examine corrosion processes, test preservatives on damaged materials, and analyze to what extent materials can be stabilized and the process of deterioration be reduced [6].

A positive result in the preservation and development of a mine site for new purposes will be achieved only with a consensus between the stakeholders concerned. Thus, a very puristic preservation of a mine site by simply keeping most of the object in its original condition may be a success for the preservation authorities, but may also cause the disinterest of owners and investors regarding the future use of the object. However, a reuse of the site just with the consideration of the user's interest might result in a reconstruction that has nothing to do with the former monument. In this case, the uniqueness, the public image, and the charisma of the object are gone and ultimately, its cultural value vanishes.

Fig. 6 Industrial monument: pit headframe of shaft XII of colliery Zollverein (Photo ©Zollverein Foundation/Jochen Track)

The tourist project entitled in German "Route der Industriekultur" ("The Industrial Heritage Trail"), an approximately 400-kilometer-long circuit in the Ruhr area is a core project to explain the region's industrial heritage to visitors. Twenty-five so-called anchor points make up the network of the trail, including six museums of technical and social history, panorama sites, and a series of significant coal miner's settlements. The trail offers free access to important witnesses of the industrial history in the region including the process of economic transformation. Notably, the brownfields—many of which are under a preservation order—are not sites of nostalgia and regret: They have been transformed into lively industrial venues and attractive centers for cultural and tourism events [7].

The efforts in the last thirty years have created a new atmosphere in the entire Ruhr region. Furthermore, the declaration of the city of Essen together with the Ruhr region as the cultural capital of Europe in 2010 was an important milestone for transitioning into a post-mining era. Enthusiasm created by the identification of the inhabitants with their region and an increasing number of foreign tourists [8] illustrates that industrial culture—and hence, mining culture in particular has become the regional brand. To name a cultural highlight, the annual "ExtraSchicht (ExtraShift) - Night of the Industrial Culture" attracts over 200,000 visitors nowadays [9].

Taking the Ruhr mythology of coal and steel as a starting point, the Capital of Culture intended to give birth to a new metropolis capable of moving Europe through art and culture [8]. In the year 2017, Essen, the biggest city in the Ruhr region, won the European Green Capital Award by the EU. The EU commissioner responsible, Karmenu Vella, pointed out that Essen has used the lessons from its industrial past to build an environmentally sound future [10].

6 Transformation

Sustainable transformation is actively developing a mining region while looking far ahead into the future. Following management principles (defining goals, strategies, and undertaking measures) can be defined as "the sum or composition of all related/possible/suitable philosophies, visions, ideas, goals, concepts, programs, plans, measures, and actions in order to achieve a sustainable development in urban and rural areas" [11]. It can be recognized as a type of "place-based policy" [12] tailored to a defined region.

Consequently, a sustainable transformation is a "knowledge-based procedure" [13]. It aims towards long-term enhancements in the economical, ecological, and social capabilities of the region in question and comprises the long-term consequences—risks as well as opportunities. Technologies and methods to survey, monitor, plan, and develop a former mining region available should always work efficiently while being improved continuously.

Why is a sustainable transformation so important for mining regions? Because potentially, a mining region will need an entire generation to compensate for the socio-economic effects of the decision to close mining operations. In NRW, the decline of hard coal mining started in the 1960s. Even today, the socio-economic situation of the mining regions is worse than in other western regions in Germany.

The concept of sustainable development (SD) is based fundamentally on a model of progress where ecological, economic, and social dimensions are developed equally and positively. However, this gives reason to the following questions: How can SD be realized in stagnating or declining industries without guarantees for companies to remain in business? How can the SD of a mining region be secured, if a harvesting or disinvestment strategy is the strategically rational choice for mining enterprises? How can declining mining regions progress sustainably into a better future to meet the needs of future generations?

In our post-mining research, the effects of reactivation and transition under socio-economic aspects are crucial for every research project. Here, one example is the analysis of the market and innovation potential arising in post-mining by conducting accompanying socio-economic SWOT analyses. In particular, these investigations help stakeholders to further develop strategies, consider innovations, and market the potential of the post-mining region.

In the Ruhr area, the intensive cooperation of various stakeholders from politics, economy, and society has realized an essential element of the social dimension of post-mining sustainability: the avoidance of a significant increase in unemployment in the former mining areas. However, the long-term avoidance in unemployment increase was not achieved (Fig. 7). Especially for low-skilled people, there were no sufficient alternative employments close by. To date, the unemployment rate in the Ruhr area was 10.2% in June 2020 compared with 6.2% in Germany on average [14].

Figure 7 indicates the importance to create new suitable job opportunities for the regional miners. If there are no jobs available, especially the younger generations will leave the region. At the same time, it takes those generations to transform a "coalfield" environment into a post-industrial service sector and creative zone [17]. Despite many political efforts including the foundation of twenty-four universities and eleven research institutes from scratch during the last fifty years, the Ruhr area has seen a loss of 600,000 inhabitants from 5.7 to 5.1 million people between 1970 and 2017 [15].

Notably, the German energy industry entered a paradigm change towards renewable energies in the last years. This transition features opportunities to create new jobs to the post-mining regions in the renewable energy sector besides other future-orientated uses of former operating areas. In the Ruhr area, several applications were developed and various are already in use or exist as research projects. In detail, prototypes, ideas, and visions are:

- Photovoltaic plants in mining areas (Fig. 8(1)).
- Mine water as a heat source (Fig. 8(2))
- Wind turbines on dump hills (Fig. 8(3))
- Energy production from methane released from coal beds ("mine gas")
- Production of biomass on former mining areas, especially dump hills
- Pump-storage power plants using dump hills and underground mine structures
- Production of geothermal energy [4].

An example of reshaping a mine site to generate renewable energies is the so-called "Creative Quarter Lohberg" (Fig. 9).

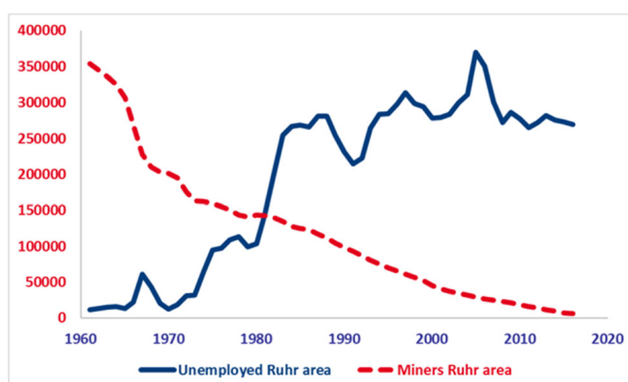

Fig. 7 Unemployment rates of the Ruhr area overall compared with the mining workforce [15, 16]

Fig. 8 Creating renewable energy, an opportunity of post-mining. (1) Photovoltaic plant on a mud pond. (2) Heat generation from mine water. (3) Windmill on a dump hill [4]

This development project illustrates the transformation of a former mine site into the first CO_2 neutral suburb of Germany. An important feature of this site is the combination of modern and listed architecture that runs entirely on renewable energy resources such as photovoltaic plants, mine water heat, biomass, wind turbines, and geothermal energy [18].

7 Sustainability and Post-Mining

Published by the United Nations in 1987, the Brundtland Report defined the term sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs [19]. Furthermore, sustainability is about three basic aims: (1) the share of wealth for as many people as possible (social sustainability), (2) a durable positive economic development (economic sustainability), and (3) the preservation of nature (environmental sustainability) [20]. From this point of view, the ground in a coal-mining region is economically a profitable real estate, socially a place to live together as a community, and ecologically a natural resource enabling life.

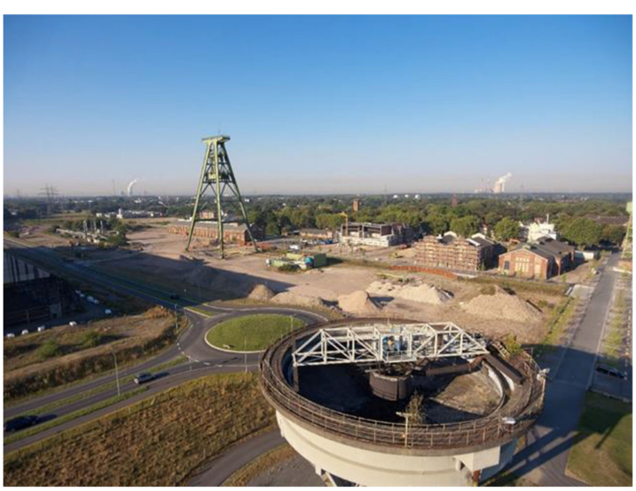

Fig. 9 Kreativ Quartier Lohberg. Overview (RAG/Klingenburg)

Moreover, this three-dimensional approach to sustainability can be translated to post-mining activities. This entails (1) limiting environmental damages caused by emissions and subsidence (environmental dimension), (2) keeping management costs of both mining damage and permanent obligations as low as possible (economic dimension), and (3) offering the population living in the mining regions future prospects to ensure their standard of living and well-being post-mining (social dimension).

Most importantly, these aims are only achievable entirely, if their implementation is done straight from the beginning, which means when planning to operate a mine and all mining cycles, respectively, as all mining and post-mining activities cause impacts on land, water, the climate, as well as the flora, fauna, and people.

While today's mining industry is diverse globally, the scope and nature of typical post-mining activities highlight common opportunities to contribute to the UN Sustainable Development Goals (SDGs) (Fig. 10).

The installation of renewable energy generation facilities such as wind mills on waste dumps contributes to combat climate change (SDG 13) while providing clean and affordable energy (SDG 7). Other important post-mining tasks such as restoring and rehabilitating the landscape, preserving the environment, and mitigating ground, surface water, and air

Fig. 10 The 17 SDGs [21]

pollution relate directly to SDGs 6 (Clean Water and Sanitation) and 15 (Life on Land).

In the post-mining phase, mining companies, authorities, and governmental stakeholders are responsible to achieve these environmental goals. Generally, all four main fields of post-mining can contribute to reaching these goals. Yet, the consensus on providing the necessary financial means is usually hard to reach.

Mining generates significant revenues through taxes, royalties, and dividends for governments to invest in economic and social developments as well as business and job opportunities locally. In the post-mining phase, the missing revenues from mining have to be compensated. If an adequate transformation system creating economic revenues is not in place, it is likely that the unemployment rate will increase and the contribution to SDG 1 (no poverty) and SDG 2 (zero hunger) decrease significantly.

By establishing new local businesses in the transformation period, the former mining region is able to generate and sustain new economic opportunities for local communities. Business investments, adapting the local infrastructure to the requirements of start-ups and enterprises, and professional training as well as reskilling employees can contribute to SDGs 9 (Industry Innovation and Infrastructure) and 8 (Decent Work and Economic Growth).

8 Post-Mining Education—the Basis for Excellence in Post-Mining

Excellence in post-mining requires a high motivation as well as high-level skills. Without the complete package including ideas and visions, research and development, the integration of surface and underground challenges, and a suitable and all-including risk management system, post-mining will be inefficient.

To competently develop post-mining technologies and management skills, a sufficient number of experts and executives have to be qualified in this field. Thus, the THGA offers a unique Master's program called "Geoengineering and Post-Mining" [22].

This Master of Engineering combines scientific and technical qualifications. The goal is to train engineers at the interface of mining, mine surveillance, and geotechnical engineering enabling them to plan, execute, and direct the complex processes of mine closures, rehabilitation, and aftercare in a leading position. The curriculum enables graduates to analyze mining, geological, and hydrogeological conditions qualitatively and apply scientific methods to quantitatively express and further process these results by using engineering methods.

Our future post-mining experts gain knowledge and skills in geology, hydrogeology, hydrochemistry, rock mechanics and geotechnology, mining, mine site rehabilitation, socio-economic issues, law, business administration, management tools, monitoring techniques, and digitalization but also knowledge in understanding mine maps, subsidence, and more. In particular, graduates are able to define, structure, plan, and process complex projects in the area of geoengineering and post-mining. Furthermore, they learn to pay attention to the current global, economic, ecological, and social context. Therefore, they are trained to develop interdisciplinary solutions.

The demand for these highly qualified engineers is increasing worldwide to secure an orderly closure and aftercare of for example hard coal mining, lignite mining, uranium, and metalliferous mines, and salt caverns.

9 Conclusion

Post-mining no longer means simply avoiding certain hazards. It has to be recognized as an evolutionary sustainable process that is based on risk management and seizing opportunities. This process must be encouraged by suitable governmental regulations and incentives to promote ideas, support research and development, and run transformation projects profitably. The implementation of innovative projects at old mine sites is often a milestone for mining communities on their long road to a sustainable future.

The FZN at the THGA is developing a holistic and integrated approach for all areas of post-mining. The global dissemination of existing knowledge and research results is being designed as open as possible, because they are relevant for all mining regions worldwide. For this purpose, the FZN is planning and executing research projects as well as tailored training programs for mining companies, authorities, governmental organizations, and NGOs amongst others.

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