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TECHNICAL ARTICLE

Emergy and Carbon Footprint Analysis of the Construction of Passive and Active Treatment Systems for Net Alkaline Mine Drainage

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Abstract Multi-criteria sustainability assessments were completed for the construction of a net-alkaline mine drainage passive treatment system (PTS) in northeastern Oklahoma to compare resource use and greenhouse gas emissions with a hypothetical active treatment system (ATS) alternative. Emergy analysis, an environmental accounting method assessing resource use, and carbon footprint analysis, a tool to evaluate greenhouse gas emissions, were completed for the construction of both systems. Assessing sustainability using multiple criteria is important in evaluating systems on the basis of resource use and environmental impact. Construction of the hypothetical ATS required seven times more emergy purchased from the economy and emitted three times more carbon dioxide equivalents than construction of the PTS. Concrete was the largest factor in both the emergy analysis (ATS and PTS) and carbon footprint (ATS only). Diesel fuel was the largest factor in the carbon footprint of PTS construction. This multi-criteria sustainability assessment shows that a hypothetical ATS alternative to the PTS would have used more resources and emitted more greenhouse gases during construction.

Keywords Passive treatment · Ecological engineering · Sustainability

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Introduction

A PTS was constructed to treat three mine drainage discharges (seeps) near Commerce, Oklahoma in late 2008. The 3,100 km^2 Tri-State Mining District of Oklahoma, Kansas, and Missouri was the location of over a century of intensive lead–zinc mining that ended in the 1970s. Mining activities left behind millions of tons of metal-contaminated waste material and artesian-flowing mine drainage that have detrimentally impacted surface water bodies (WQS 2000). This PTS was designed for metal removal using a single initial oxidation pond followed by two parallel treatment trains of surface flow wetlands, vertical flow bioreactors, re-aeration ponds and horizontal flow limestone beds, and a common final polishing cell (Nairn et al. 2010). Re-aeration is achieved using solar- and wind-powered aerators. The PTS design and construction cost \$1.2 million and has a design life of 30 years (Nairn et al. 2010). Initial efforts to evaluate the carbon emissions from this system were completed by Nairn (2013).

Emergy analysis, an environmental accounting technique, can be used to evaluate the use of natural resources from an energy perspective (Odum 1996). The total available energy previously used, directly and indirectly, is the emergy. Available energy, here, refers to the maximum amount of work possible from a process. Also called exergy, this property of a system is typically measured in joules. In emergy analysis, the total available energy requirements for creating a product or service are normalized to solar energy equivalents, represented by the solar emjoule. The transformity is the ratio of the amount of solar emjoules used to create a product or service (emergy) to the total available energy comprising that product or service (Odum 2007). For example, the transformity of lumber would be the emergy used in the production of that lumber divided by the product of the energy density of lumber and its mass (i.e. lumber's available energy). The transformity for lumber varies by location, wood type, and production process, but has been estimated as 7.7×10^4 sej/J (Buranakarn 1998). By definition, it takes 1 solar emjoule to make 1 joule of solar energy, thus the transformity for solar energy is 1 sej/J.

Carbon footprint analysis (CFA) is another accounting technique that evaluates the direct and indirect emission of CO_2 and other greenhouse gases from a production process or other system (Wiedmann 2009). Although CFA techniques are not standardized, practitioners often use a hybrid approach that embodies both the inputs to a production process for construction and operation and the emissions from that process during operation. Using emissions factors, the amount of CO_2 equivalents can be determined for each type of material (concrete, fuel, etc.) or service (material delivery, power, etc.) that is used in the system. Additionally, CFA is commonly used to determine emissions from the process within the system, such as CO_2 released from off-gassing or combustion, e.g. Uggetti et al. (2012).

These two analytical techniques are complementary. Emergy analysis is an "upstream" approach, meaning the inputs to the system are used to evaluate a system based on the amount of solar emjoules required. These inputs represent all of the energy required, even that of resource formation, and can be referred to as the "ecological footprint" based on the calculation of environmental support required by that system (Ulgiati et al. 2006). Conversely, CFA is generally a "downstream" approach, meaning the resulting environmental impact from a system's processes is evaluated (Wiedmann 2009). Similar to emergy analysis, CFA uses one unit, mass of CO_2 equivalents (CO_2e), to make comparisons. Because both methods have gained considerable traction in the literature in recent years, more comparisons between systems can be made. Multi-criteria assessments of sustainability using emergy analyses, life cycle assessments, and carbon footprint analyses have been done (Hanegraaf et al. 1998; Jamali-Zghal et al. 2013; Toffolo and Lazzaretto 2002; Ulgiati et al. 2006). However, to the authors' knowledge, this is the first time that a PTS for mine drainage is being evaluated using both emergy analysis and CFA.

Both emergy and carbon are important aspects that can be used to compare system sustainability and environmental impact (Jamali-Zghal et al. 2013). In this study, the Mayer Ranch PTS (described in Nairn et al. 2010) was evaluated using emergy analysis and CFA. For comparison, a hypothetical ATS sized according to commonly accepted guidelines was also analyzed. Resource use (emergy) and greenhouse gas emissions (carbon footprint) were compared for construction of active and PTSs for mine drainage at Mayer Ranch. This initial assessment focused on construction and not long-term operation of the systems.

Methods

This study evaluated the construction of the Mayer Ranch PTS and the hypothetical ATS using emergy analysis and CFA. Amounts of materials used to construct the PTS were calculated using design specifications and construction diary notes from the design/build contractor, CH2M Hill, provided to the project lead investigators at the University of Oklahoma (2009). This document also provided enough information to estimate fuel used during construction based on heavy equipment use and transportation to the site by the construction crew and inspectors. Similarly, construction materials and fuels were estimated for the hypothetical ATS based on design specifications (Winfrey 2012; Winfrey et al. 2010).

Mayer Ranch Passive Treatment System

CH2M Hill, the design/build contractor, provided construction details for the PTS at Mayer Ranch (CH2M Hill 2009). Figure 1 shows a schematic of the PTS and its flow regime. The 2.7-ha PTS treats net-alkaline mine drainage flowing from seeps through the system. Water flows in parallel following the oxidation pond (Fig. 1). This system was designed to treat the mine drainage using a gravity-flow regime and renewable-based energy inputs. In the re-aeration pond, air compressors are powered by a solar photo-voltaic charged battery in one pond and mechanically by a windmill in another pond. The system design life is estimated at 30 years.

Construction materials include limestone, concrete, lumber (for boardwalk supports), geotextile liners, and plumbing and aeration equipment. A mix of spent mushroom compost, wood chips, and manufactured limestone sand was required for the vertical flow bioreactors. The organic portion of this mix was omitted from emergy and carbon footprint analyses because it was a waste material that did not represent a use of resources nor carbon emissions (i.e. production of compost was assumed to be a net carbon sink). However, the use of fuel for delivery of all materials was

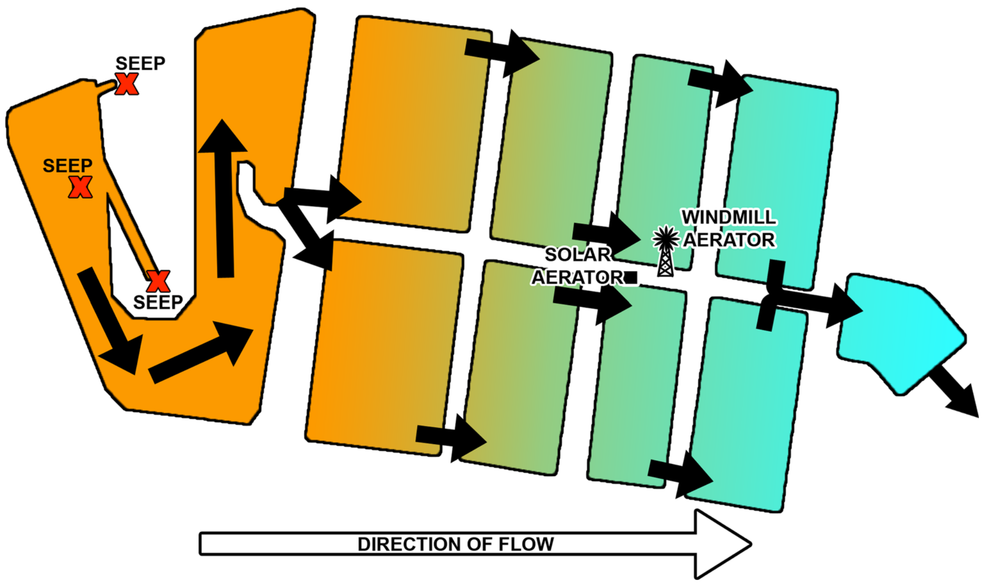


Fig. 1 Schematic of the Mayer Ranch PTS, adapted from CH2M Hill (2009); not to scale

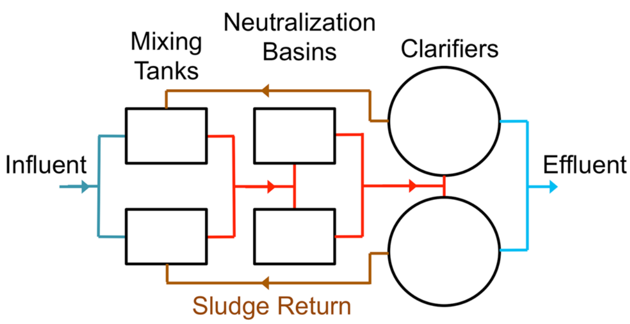


Fig. 2 Schematic of the hypothetical ATS; not to scale

evaluated. Most of the remaining site work consisted of delivering and installing construction materials and excavating site material (CH2M Hill 2009).

Hypothetical Active Treatment System

A hypothetical ATS was sized using the software application AMDTreat (OSMRE 2010) by using the water quality data of the seeps as the input data and specifications from Younger et al. (2002), INAP (2009), and Jang and Kwon (2011). AMDTreat was designed to be used to aid treatment system design and estimate system cost for polluted coal mine drainage (McKenzie 2005; Cravotta et al. 2010). Using the recommendations of the AMDTreat software, the ATS has two parallel trains consisting of an aeration tank followed by a neutralization basin for lime dosing and, finally, a clarifier. Just as the PTS was designed with redundancy and excess capacity, the ATS was as well. The ATS was designed to have a lifespan of 30 years, just as the PTS (Fig. 2).

Construction materials include PVC, concrete, steel, plumbing, and aeration equipment. Concrete aeration tanks and neutralization basins were designed for 2,100 L capacity with 0.3 m wall thickness. Clarifiers were 5.6 m in diameter with 0.3 m wall thickness. The design called for pumps for influent and high-density sludge return. Aerators and mixers were sized for aeration tanks and neutralization basins, respectively. The system was gravity-fed between unit processes. A lime hopper with a 54.4 t capacity and a utility shed were included in the design. Treatment performance and flow capacity of the ATS was designed to be identical to that of the PTS to provide meaningful comparisons. Additionally, resources (i.e. diesel, gasoline, concrete, and labor) used for isolating, diverting, and consolidating mine water seeps in early stages of construction of the ATS was assumed to be identical to that required for the PTS. Remaining site work was estimated to take 60 days and use heavy machinery to deliver and install construction materials.

Emergy Analysis

Emergy Analyses were completed on both systems using guidelines in Odum (1996). First, a systems diagram was drawn that represents the physical parts of each treatment system, the interconnectedness of these parts via energy and material flows, and inputs and outputs to the system. From this diagram, inputs from the environment and economy could be identified and calculated. These inputs, generally calculated in terms of mass or energy, are multiplied by a factor that represents the amount of emergy per unit (i.e. g or J) called the specific emergy or transformity. These factors have been calculated in the past through other emergy evaluations and were found using The Emergy Database (Tilley et al. 2012). The inflowing energy or material multiplied by its transformity or specific emergy, respectively, is equal to the emergy input for that energy or material. These emergy values are tabulated and categorized.

The resulting emergy in each category was used to calculate common emergy indices, such as the emergy yield ratio (EYR), environmental loading ratio (ELR), the percent renewability (%REN), and the Emergy Sustainability Index (ESI) (Brown and Ulgiati 1997). These indices can be used to compare the evaluated systems based on how much emergy yields from the amount invested by the economy (EYR), the amount of stress on the local environment (ELR), the amount of renewable, environmental inputs relative to economic and non-renewable inputs (%REN), and the relative sustainability based on emergy (ESI) (Brown and Ulgiati 1997).

Inputs from construction of the PTS and ATS were evaluated based on the 30-year design life. These inputs were determined by evaluating the mass of building/fill materials and the amount of fuel used during construction from the design specifications and construction diary (CH2M Hill 2009). In order to calculate emergy indices, environmental inputs (e.g. rain, wind, sun) were evaluated on an annual basis and multiplied by the 30-year life. A full emergy analysis was completed that encompasses the construction, maintenance, and operation of PTS and ATS in Winfrey et al. (2010), Winfrey (2012). Emergy calculations used the 15.83×10^{24} sej/year global baseline for transformities (Odum et al. 2000). Emergy inputs from the economy were also split into two categories for comparison: construction materials and fuel used during construction.

Carbon Footprint Analysis

Carbon dioxide equivalents were used to represent the carbon footprint. This measure, typically on a mass basis, can be comprised of carbon dioxide, methane, and nitrous oxide converted to CO_2e based on their relative global warming potential (IPCC 2007). The global warming potentials for CH_4 and N_2O are 25 gCH_4/gCO_2e and 298 gN_2O/gCO_2e, respectively (IPCC 2007). To evaluate the carbon footprint of the construction of a system, all materials and fuel used during construction are multiplied by their respective emissions factors.

Construction material inputs and fuel consumption from the Emergy Analyses of the PTS and ATS were multiplied by emissions factors found in the literature (EPA 2011; IPCC 2013; Nisbet et al. 2002). CO_2e were split into two categories for comparison: construction material and fuel used during construction.

Results

Emergy Analyses

Systems diagrams were drawn for the PTS (Fig. 3) and hypothetical ATS (Fig. 4). These diagrams provide details on the inputs, outputs, and internal flows of material and energy in both systems. The emergy tables for the PTS (Table 1) and ATS (Table 2) were completed using information from the systems diagrams. Emergy indices for both treatment systems were compared in Table 3.

Carbon Footprint Analyses

Carbon dioxide equivalents for construction materials and fuel consumption during construction were calculated and tabulated for the PTS (Table 4) and ATS (Table 5).

Emergy Analyses and Carbon Footprint Analyses Comparison

Construction materials and fuel consumed during construction were compared in terms of emergy and carbon footprint (Table 6). Materials and fuel used in construction of both systems were itemized and compared in Fig. 6.

Discussion

Emergy Analyses

The hypothetical ATS required about 1.4 times more emergy purchased from the economy for construction than the PTS at Mayer Ranch (Table 3). Most of the emergy required to construct the ATS was in concrete (Fig. 6). Arias and Brown (2009) also compared an ATS and a PTS and found that a sequencing batch reactor for treating municipal wastewater in Colombia would require about three times more emergy purchased from the economy than a constructed wetland. Zhou et al. (2009) found active treatment of municipal wastewater using an activated sludge system would require 10 times more purchased emergy (i.e. emergy sourced from the economy) than using a constructed wetland. These results correspond with the trend that most ATSs require more purchased emergy than PTSs, even when corrected for size and treatment capacity (Chen et al. 2009).

Traditional emergy indices can be compared between the two treatment systems. However, because this emergy analysis did not include emergy of the treatment operations and maintenance over the lifetime of the system, it is not appropriate to compare traditional emergy indices such as EYR, ELR, %REN, and ESI to similar systems in the

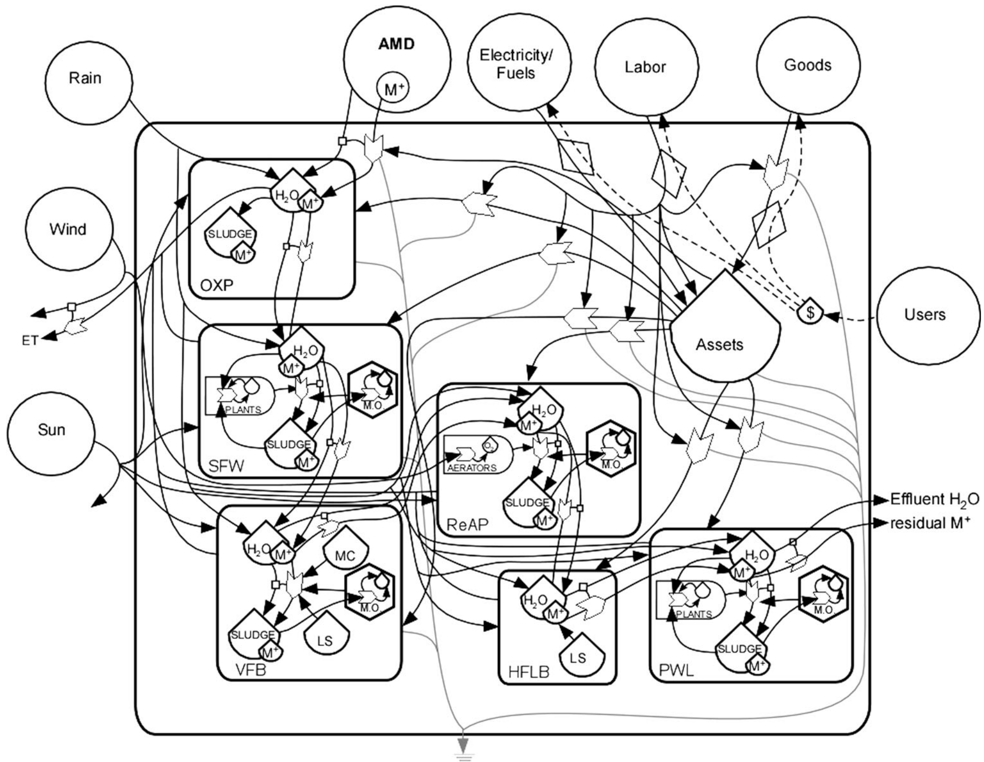


Fig. 3 Systems diagram of construction of the Mayer Ranch PTS (from Winfrey et al. 2010)

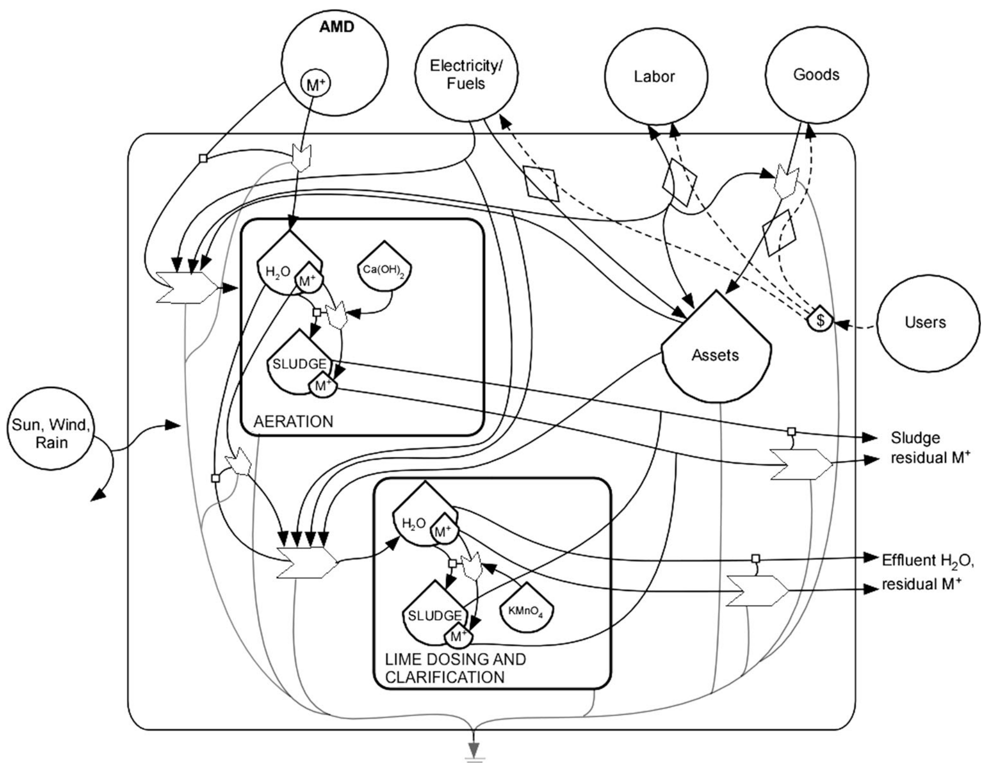


Fig. 4 Systems diagram of construction of a hypothetical ATS (adapted from Winfrey et al. 2010)

Table 1 Emergy table for construction of the Mayer Ranch PTS

Item	Unit	Amount	Solar transformity (sej/unit)	Ref. for transformity	Solar emergy (E15 sej)
Environmental inputs					
Sunlight	J	4.67×10^{15}	1.0	By definition	5
Wind	J	1.31×10^{12}	1.50×10^{3}	Odum (1996)	2
Rain chemical potential	J	4.27×10^{12}	3.06×10^{4}	Odum (1996)	130
Rain nitrogen	g	1.50×10^{6}	2.41×10^{10}	Brandt-Williams (2002)	40
Rain phosphorus	g	6.04×10^{4}	2.20×10^{10}	Brandt-Williams (2002)	1
Rain OM	J	1.45×10^{10}	3.19×10^{4}	Brown and Bardi (2001)	0.5
ET	J	4.39×10^{12}	3.06×10^{4}	Odum (1996)	130
Emergy of environmental inputs to system[a]					130
Purchased goods and services					
Construction materials					
Limestone	g	7.02×10^{8}	2.10×10^{9}	Odum (1996)	1,500
Geotextile liner	g	4.71×10^{6}	8.50×10^{9}	Buranakarn (1998)	40
Concrete	g	1.11×10^{6}	1.15×10^{10}	Odum (1996)	13
PVC	g	6.71×10^{4}	9.90×10^{9}	Buranakarn (1998)	0.7
Valves	g	4.07×10^{6}	2.99×10^{9}	Odum (1996)	12
Water control devices	g	2.64×10^{6}	1.13×10^{10}	Odum et al. (1987)	30
Photovoltaic unit	m^2	0.5	2.18×10^{15}	Brown et al. (2012)	1
Solar aerator	g	8.25×10^{5}	1.13×10^{10}	Odum et al. (1987)	9
Windmill aerator	g	7.83×10^{5}	1.13×10^{10}	Odum et al. (1987)	9
Lumber	g	7.64×10^{5}	1.48×10^{9}	Buranakarn (1998)	1
Fuel					
Diesel fuel	J	1.26×10^{12}	1.21×10^{5}	Ingwersen (2010)	150
Gasoline fuel	g	2.42×10^{6}	2.92×10^{9}	Bastianoni et al. (2009)	7
Purchased services					
Construction labor	h	4.22×10^{3}	1.06×10^{12}	Odum (1996)	5
Total emergy of goods and services[b]					1,800
Total emergy inputs[c]					1,900

[a] Emergy of environmental input to system is equal to the largest of environmental inputs; [b] Emergy of goods and services is equal to sum of purchased goods and services; [c] Total emergy inputs is equal to emergy of environmental inputs and emergy goods and services

literature. The PTS yielded 7 % more emergy per unit of emergy invested (higher EYR), had a 700 % lower impact on the environment (lower ELR), used 600 % more renewable emergy (higher %REN), and overall is more sustainable to construct (700 % higher ESI). The ATS required 43 % more purchased emergy than the PTS (Table 3).

Carbon Footprint Analyses

The hypothetical ATS emitted about three times more CO_2e than the PTS based on materials and fuel used during construction (Tables 4 and 5). The largest source of CO_2e in the carbon footprint for the PTS was diesel fuel, while concrete was the largest source in the ATS. Construction materials used for the ATS emitted 1.8 times more CO_2e from their production than those used in the PTS. The ATS had 37 % higher carbon footprint due to fuel used during construction, which was indicative of the higher estimated fuel use in the ATS compared to the PTS. Although there were no results found in the literature from studies comparing these types of systems, the findings comport with those of Lehtoranta et al. (in press), who found CO_2e for construction of small "active"-type sewage treatment plants (i.e., sequential batch reactors, fluidized bed treatment) to be greater than "passive"-type approaches (i.e. buried sand filters, soil infiltration).

Most CFAs for wastewater treatment systems encompass treatment operations and waste disposal (i.e. "downstream" impacts) rather than construction (Gusek et al. 2011; Jordahl et al. 2009; Rosso and Bolzonella 2009).

Table 2 Emergy table for the hypothetical ATS

Item	Unit	Amount	Solar Transformity (sej/unit)	Ref. for Transformity	Solar Emergy (10^{15} sej)
Environmental inputs					
Sunlight	J	8.65×10^{14}	1.0	By definition	0.9
Wind	J	2.4×10^{11}	1.50×10^{3}	Odum (1996)	0.4
Rain chemical potential	J	7.90×10^{11}	3.06×10^{4}	Odum (1996)	20
Rain nitrogen	g	2.78×10^{5}	2.41×10^{10}	Brandt-Williams (2002)	7
Rain phosphorus	g	1.12×10^{4}	2.20×10^{10}	Brandt-Williams (2002)	0.2
Rain OM	J	2.68×10^{9}	3.19×10^{4}	Brown and Bardi (2001)	0.1
ET	J	8.13×10^{11}	3.06×10^{4}	Odum (1996)	25
Emergy of environmental inputs to system[a]					25
Purchased goods and services					
Construction materials					
Concrete	g	1.85×10^{8}	1.15×10^{10}	Odum (1996)	2,100
PVC	g	3.07×10^{6}	9.90×10^{9}	Buranakarn (1998)	30
Steel	g	9.63×10^{6}	2.99×10^{9}	Odum (1996)	30
Machinery	g	6.00×10^{5}	1.13×10^{10}	Odum et al. (1987)	7
Pumps	g	9.00×10^{5}	1.10×10^{10}	Arias and Brown (2009)	10
Fuel					
Diesel	J	1.84×10^{12}	1.21×10^{5}	Ingwersen (2010)	200
Gasoline	g	4.66×10^{6}	2.92×10^{9}	Bastianoni et al. (2009)	14
Purchased services					
Labor	h	8.37×10^{4}	1.06×10^{12}	Odum (1996)	89
Total emergy of goods and services[b]					2,500
Total emergy inputs[c]					2,500

[a] Emergy of environmental input to system is equal to the largest of environmental inputs; [b] Emergy of goods and services is equal to sum of purchased goods and services; [c] Total Emergy Inputs is equal to emergy of environmental inputs and emergy goods and services

Table 3 Emergy indices for the PTS and ATS

Index	Meaning	PTS	ATS
R (10^{15} sej)	Renewable emergy from the environment	134	25
F (10^{15} sej)	Emergy purchased from the economy	1,800	2,500
EYR	Emergy yield ratio, (R + F)/F	1.08	1.01
ELR	Environmental loading ratio, F/R	13	100
%REN	Percent renewability, R/(F + R)*100	7 %	1 %
ESI	Emergy sustainability index, EYR/ELR	0.08	0.01

Nairn (2013) used mesocosms to estimate that 79,500 kg of CO_2/year is emitted from the Mayer Ranch PTS, due to the elevated pCO_2 in the untreated mine waters and subsequent degassing to the atmosphere. From this study, about 16,000 kg CO_2/year is emitted if the construction emissions are distributed over the 30-year lifespan of the system. Because the operational carbon footprint could be much larger than the construction footprint on an annual basis, there is a need to complete the overall CFA on the Mayer Ranch PTS.

Comparison of Resource Use and Carbon Footprint

Results of the Emergy Analyses showed that most of the emergy inputs during construction of both the PTS and ATS were from construction materials (Fig. 5). Conversely, the CFAs showed fuels used during construction emitted more CO_2e than construction materials in the PTS (Table 6). Due to the large carbon footprint of concrete in the ATS, construction materials emitted 5 % more CO_2e than fuels in the ATS (Fig. 5). Construction materials for the PTS had a much lower carbon footprint than fuel due to the fact that the organic mix in the vertical flow bioreactors was omitted from the CFA as a construction material, although the fuel used to deliver it to the site was calculated. Most components in these assessments resulted in large disparities between carbon footprint and emergy; that is, the resource use and greenhouse gas emissions comprised very varied amounts of the overall evaluation in the respective analyses. However, concrete and limestone had relatively similar carbon footprints and emergy, likely because their production requires considerable resources and fuel use. Similar construction materials used in PTS and ATS varied most greatly in the use

Table 4 Carbon Footprint table for the Mayer Ranch PTS

Item	Unit	Amount	Ref. for emissions factor(s)	CO_2	CH_4	N_2O	CO_2e
Construction materials							
Limestone	kg	702,000	Korre and Durucan (2009)	1,400	n.a.[a]	n.a.	1,400
Geotextile liner	kg	4,700	Harding et al. (2007)	n.a.	n.a.	n.a.	14,300[†]
Concrete	kg	1,100	Nisbet et al. (2002)	120	0.01	n.a.	120
Plumbing and aerators	kg	8,800	IPCC (2013)	14,000	0.002	0.35	14,20
Lumber	kg	760	Milota et al. (2005)	490	0.3	n.a.	500
Fuel							
Diesel	L	35,000	EPA (2011)	94,000	3,900	740	413,000
Gasoline	L	3,400	EPA (2011)	7,800	340	70	37,000
Total carbon footprint							480,000

[a] Not applicable; no emissions factor for this greenhouse gas was reported in the literature for this item; [†] this calculation of CO_2e was determined using an emissions factor in terms of kg material/CO_2e

Table 5 Carbon footprint table for the hypothetical ATS

Item	Unit	Amount	Ref. for emissions factor(s)	CO_2	CH_4	N_2O	CO_2e
Construction materials							
Steel	kg	9,600	IPCC (2013)	15,400	n.a.[a]	n.a.	15,400
PVC	kg	3,100	IPCC (2013)	900	0.1	n.a.	900
Concrete	kg	185,000	Nisbet et al. (2002)	20,000	60	n.a.	20,000
Pumps and aeration	kg	11,000	IPCC (2013)	17,800	n.a.	0.35	17,900
Fuel							
Diesel	L	46,000	EPA (2011)	124,000	5,100	980	543,000
Gasoline	L	6,500	EPA (2011)	15,000	650	140	72,000
Total carbon footprint							670,000

[a] Not applicable; no emissions factor for this greenhouse gas was reported in the literature for this item

Table 6 Emergy and carbon dioxide equivalents (CO_2e) of construction materials and fuel use of the PTS and ATS

Analysis	Type	PTS	ATS
Emergy (10^{15} sej)	Construction materials	1,600	2,200
	Fuel	160	200
CO_2e (kg)	Construction materials	30,000	60,000
	Fuel	450,000	620,000

of concrete (Fig. 6). While pumping and aeration machinery used in the ATS resulted in a higher carbon footprint than PTS, the emergy of pumping and aeration in the PTS was higher due to the use of solar photovoltaic cells, which have a relatively high transformity (Fig. 6, Brown et al. 2012).

These results were expected, as emergy analysis represents resource use and CFA represents emissions. In Jamali-Zghal et al. (2013), the sustainability of electricity production using wood in lieu of fossil fuels was evaluated on the basis of resource use and greenhouse gas emissions using emergy and CFA, respectively. They found that emergy analysis resulted in a smaller disparity between systems than the CFA. In this study, the opposite was true; the ratio of purchased emergy in the construction of ATS to PTS was higher than the ratio of carbon footprints for the ATS to PTS. This is likely due to the nature of the studied systems. This study focused only on the construction, so materials played a much larger role in the overall emergy analyses. Also, the Jamali-Zghal et al. (2013) study evaluated greenhouse gas-emitting energy production systems.

This study is unique in producing a focused representation of resource use and greenhouse gas emissions on the construction of two approaches to treating mine drainage. In Ulgiati et al. (2006), the importance of assessing sustainability using multiple criteria was stressed. Because emergy analysis can capture resource use on local and global scales, it is important to use it for sustainability assessments. However, because greenhouse gas emissions are important from a policy standpoint, CFA can be an effective management tool. Generally, these two assessment methods agree, but it should be noted that emergy analysis encompasses more factors of environmental performance, thereby revealing more about its relative sustainability than CFA alone.

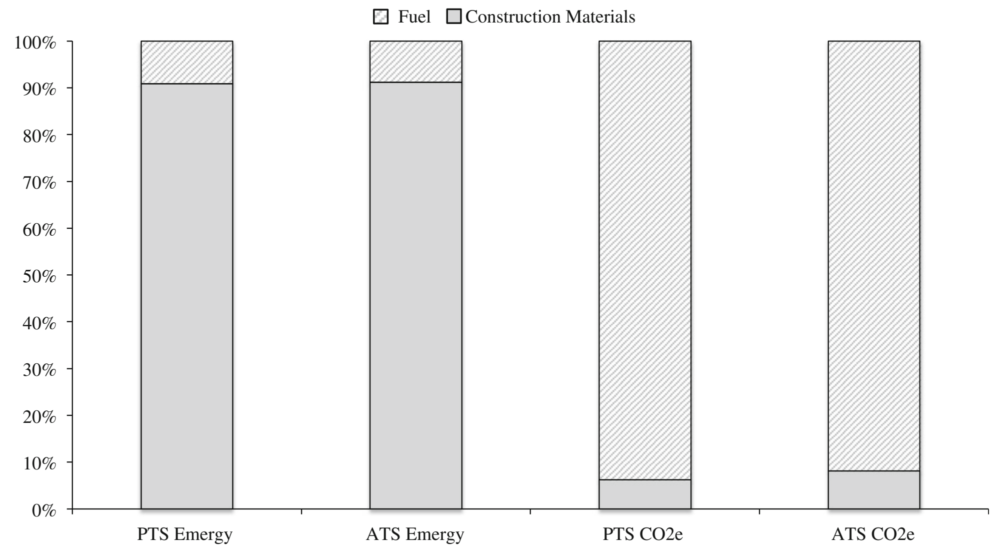
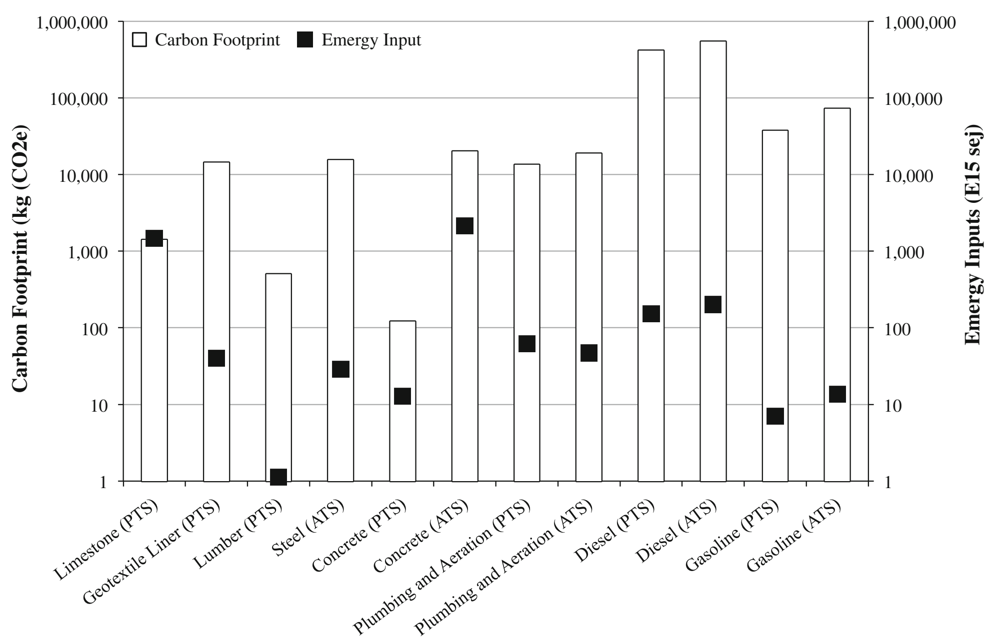


Fig. 5 Relative amount of emergy and CO_2e used in construction materials and fuel for the Mayer Ranch PTS and hypothetical ATS

Fig. 6 Emergy (square marker indicates value) and carbon footprint (column indicates value) results for each item used in construction of the Mayer Ranch PTS and hypothetical ATS. *Note*: y-axes are log scale



Conclusion

This study evaluated the construction of a PTS and its hypothetical alternative ATS using two complementary sustainability assessment methods. The emergy and CFA showed that the PTS required fewer resources and resulted in less emission of greenhouse gases. From an emergy standpoint, materials used during construction comprised the largest portion of the inputs. In the carbon footprint, fuels used during construction were generally more important. Because these analyses included only resources used and carbon emitted during construction of the treatment systems, it is difficult to compare it to other studies that encompass the entire life cycle, including operation and maintenance. In this study, CFA was effectively an “upstream” assessment since the evaluation captured emissions primarily associated with system inputs, rather than emissions of system processes. To compare “upstream” and “downstream” assessments, a CFA of the operating PTS should be completed (building on the Nairn 2013 study) and compared to a complete emergy analysis.

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