



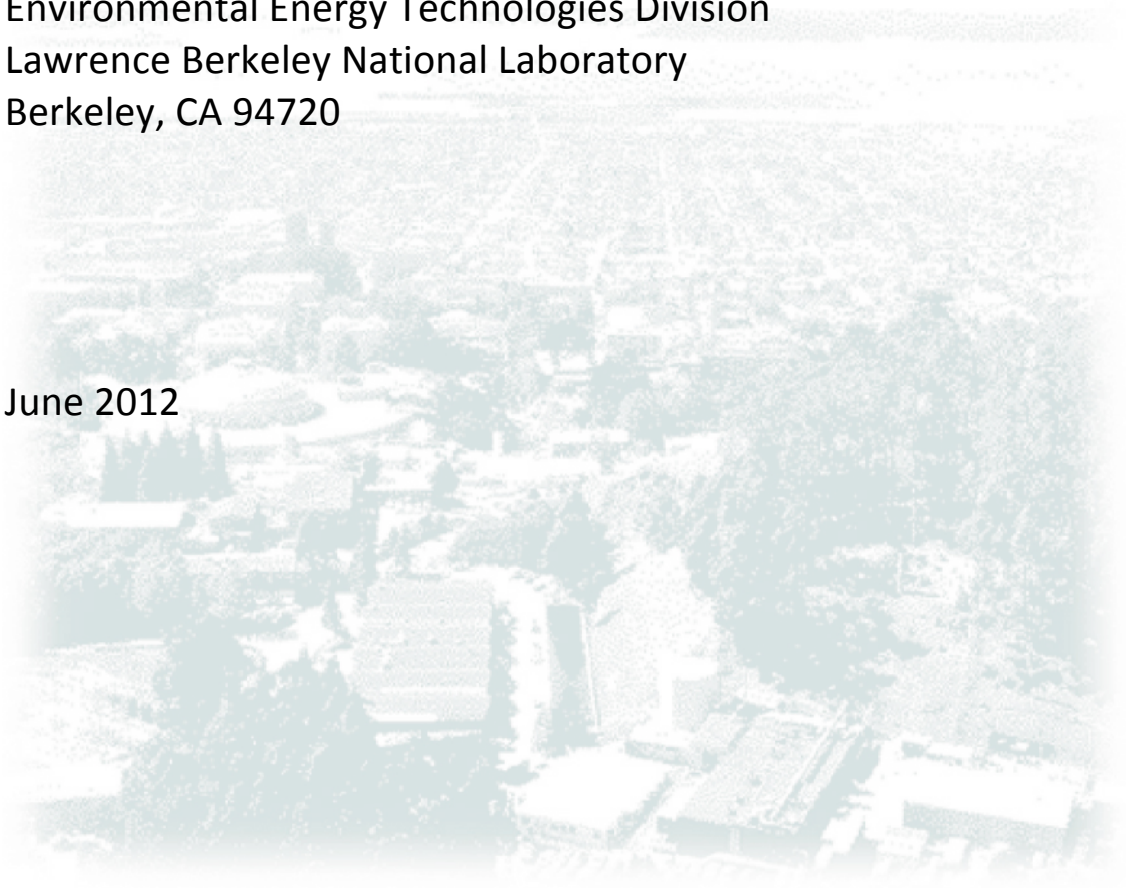
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Arman Shehabi, Jennifer R. Stokes, and Arpad Horvath

Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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Energy and Air Emission Implications of a Decentralized Wastewater System

Arman Shehabi ^a, Jennifer R. Stokes ^b, and Arpad Horvath ^b

^a Environmental Energy Technologies Division, Lawrence Berkeley
National Laboratory, Berkeley, CA 94720, USA

^b Department of Civil and Environmental Engineering,
University of California, Berkeley, CA 94720-1710, USA

Abstract

Both centralized and decentralized wastewater systems have distinct engineering, financial, and societal benefits. This paper presents a framework for analyzing the environmental effects of decentralized wastewater systems and an evaluation of the environmental impacts associated with two currently operating systems in California, one centralized and one decentralized. A comparison of energy use, greenhouse gas emissions, and criteria air pollutants from the systems shows that the scale economies of the centralized plant help lower the environmental burden to less than a fifth of that of the decentralized utility for the same volume treated. The energy and emission burdens of the decentralized plant are reduced when accounting for high-yield wastewater reuse if it supplants an energy-intensive water supply like desalination. The centralized facility also reduces greenhouse gases by flaring methane generated during the treatment process, while methane is directly emitted from the decentralized system. The results are compelling enough to indicate that the life-cycle environmental impacts of decentralized designs should be carefully evaluated as part of the design process.

Introduction

Decentralized wastewater treatment has been proposed as a strategy to help reduce potable water consumption (e.g., Wilderer and Schreff, 2000) and as a cost-efficient alternative to more centralized treatment (e.g., Engin and Demir, 2006). Decentralized treatment systems are defined as the collection, treatment, and distribution of water and wastewater near the point of use or generation (Crites, 1998). These decentralized systems reduce collection transport distances and have lower flow volumes that enable the use of smaller diameter piping, shallow installation depths, and vacuum and pressurized sewers (Nelson, 2005), all of which potentially reduce energy and material use. Complementing centralized water-related infrastructure with decentralized facilities has been described as a “soft path solution” (Gleick, 2003), partly because decentralized facilities allow water services and quality to be tailored to end-use needs. Decentralized systems are also more amenable to grey water separation technologies (Lienert and Larsen, 2006), which increase the potential reuse of wastewater and promote the return of treated wastewater within the watershed of origin (Massouda et al., 2009). Decentralized wastewater systems can be located adjacent to areas with high demands for non-potable water, such as golf courses and public landscaping, thereby redirecting large volumes of water for reuse (Allen and Vonghia, 2005). The significant capital investments required for centralized treatment infrastructure can be prohibitively high in developing countries (Rocky Mountain Institute, 2004) and decentralized wastewater systems are perceived as a more appropriate strategy with reduced costs, less maintenance, greater flexibility in planning for future growth, and reduced environmental impact (Engin and Demir, 2006). For these reasons, institutions like the World Bank consider decentralized systems as an alternative to traditional centralized systems (Wilderer and Schreff, 2000).

While there are many potential benefits of decentralized systems, the inherent loss of scale economies relative to larger centralized systems may result in increased unit energy, cost, and materials associated with facility operation as treatment plant capacity decreases. These benefits of centralized systems, however, are thought to diminish when building and maintaining the distribution and collection systems are considered (Lens et al., 2001). A proper environmental analysis and comparison of centralized and decentralized wastewater systems requires expanding the evaluation scope beyond facility operation to determine the impact at each stage of the process, including infrastructure construction and maintenance as well as material production and transport. This paper provides a framework for analyzing decentralized wastewater systems and evaluates the energy and environmental impacts associated with two currently operating case systems – one centralized and one decentralized – while accounting for the resources consumed and the pollutants released throughout the life-cycle of the collection, treatment, and distribution processes, as well as accounting for water treatment avoided through water reuse strategies available with decentralized systems.

Case Study

This article deploys the Wastewater-Energy Sustainability Tool (WWEST), discussed in Stokes and Horvath (2010), to conduct a system-wide life-cycle assessment (LCA) comparison of centralized and decentralized wastewater systems.

The decentralized wastewater case study is based on an operating treatment system in northern California. This community-scale system (Figure 1) provides wastewater treatment for a 47-lot suburban subdivision of Stonehurst in Martinez. The treatment system has operated since the

early 1990's and has been described as a successful and innovative decentralized wastewater treatment strategy for California (Crites, 1998). The details of this wastewater treatment system have been outlined in previous publications (Crites, 1998; Tchobanoglous et al., 2003). The system was designed to annually treat nearly 20 million liters of liquid wastewater and operates at capacity. Each lot includes a 5.7 m^3 concrete septic tank. Septic tanks are commonly used in rural areas and can be found near 25% of U.S. homes (USEPA, 2005). Effluent from septic tanks is typically distributed to an adjacent drainfield for aerobic treatment, requiring a large amount of open space. The footprint for the septic tanks in the decentralized wastewater case study is reduced through the use of a community wastewater collection system that transports the septic tank effluent for nearby treatment. Each onsite septic tank is connected to a 5-cm (two-inch) diameter sewer main. Thirty-two homes are located uphill of the sewer main and are connected through small diameter gravity-forced piping. Each of the other 15 homes, located downhill, has a small (0.2 kW) septic tank effluent pump (STEP) to transport wastewater to the sewer main. Approximately 5 km of sewer-main piping connects effluent from the homes to a single wet-pump station that uses two 1.5 kW pumps to transport the effluent to a community treatment plant. The treatment plant consists of a recirculating sand filter, where the wastewater is first sent to a recirculating tank and then pumped through a 0.6 m gravel bed approximately five times before being sent across an open three channel ultra-violet (UV) supply sump system for disinfection. An effluent pump station then transports the treated water to an 11.4 m^3 hilltop dosing tank where the water is distributed to a $10,000 \text{ m}^2$ community soil absorption field. Treated water in the dosing tank is also available for irrigation use through a subsurface drip system for a small nearby park. Septic tank cleanings are arranged by each individual

homeowner and assumed to occur every five years for this study. The removed biosolids are assumed to be transported to landfill.

The decentralized wastewater system is compared to a previously published WWEST case study for a large centralized wastewater utility in California (Stokes and Horvath, 2010). The centralized system serves approximately half a million residents over a 200 km² area and includes conventional liquid and sludge treatment process streams. The treatment processes used in this centralized plant are outlined in Figure 2. The liquid waste is treated with primary sedimentation, pure-oxygen activated sludge, secondary clarification, and disinfection. Solids are anaerobically digested and dewatered before disposal.

Table 1 summarizes the major energy and equipment demands that are used in the WWEST analysis for both wastewater systems. Information regarding the systems was obtained through publications and direct communication with utility employees. Methane from the treatment process is assumed to be flared for safety reasons (Sahely et al., 2006). While flaring will convert methane biogas to carbon dioxide, a conversion efficiency of 95% was assumed to account for any incomplete combustion and leaks that may occur (Monteith et al., 2005). Results are provided for the centralized plant assuming flaring. For comparison, Table 2 includes the estimated results if the methane was used to generate electricity. These data assume that the methane produced when treating 3785 m³ (one million gallons) per day with anaerobic digestion will produce the equivalent of 26 kW (USEPA, 2011). The centralized plant would produce 14,500 MWh per year assuming all the methane captured (95%) is used for electricity production. The U.S. Environmental Protection Agency reports that biogas is used to offset energy use at approximately 8% of wastewater plants where it is technically feasible and at less than half of the plants where this strategy would be considered economically feasible (i.e.,

payback in less than 7 years). These statistics indicate there is significant potential for future improvements in energy consumption and related emissions in the wastewater industry.

Results and Discussion

Figure 3 compares the life-cycle energy use, separated by life-cycle phase and treatment phase, for the decentralized treatment system evaluated in this study with the centralized plant case study from Stokes and Horvath (2010). The results show that the decentralized system used about 37 GJ of primary energy for every million liters of wastewater treated, while the centralized system used about 6.8 GJ for the same functional unit. The increased life-cycle energy associated with the decentralized system can be partially explained by the significantly greater direct operational electricity use for the decentralized system, as presented in Table 1. These operational electricity values for both the centralized and decentralized systems are obtained from utility meters that represent the entire treatment plants. No data were provided to effectively disaggregate by process. After normalizing for differences in treated waste volumes, utility records indicate that the decentralized system requires seven times more electricity to operate than the centralized system.

Additionally, the construction phase contributes significantly to the life-cycle energy of the decentralized system while the centralized system is dominated solely by the operational phase. Dixon et al. (2003) estimate life-cycle energy use for two small-scale wastewater treatment systems that are of equal magnitude to the life-cycle energy use of the centralized system presented in this study. However, those two small-scale designs – a reed bed system and an

aerated filter treatment unit- require minimal pump power at the treatment stage and pumping for collection and discharge was beyond of the boundaries of that analysis.

While the decentralized system in this study is a fairly low-technology design, the pumps required for collection, discharge, and recirculation through the sand filter, as well as the UV lights, require significant electricity during operation relative to the amount of treated water. An effluent pump station is required in the decentralized system to transport treated wastewater uphill to the holding tank, the effects of which can be seen in the discharge category of life-cycle energy distribution in Figure 3. The centralized treatment plant is located adjacent and above the final discharge into the San Francisco Bay so no effluent pumping is required.

Table 2 presents life-cycle energy and emissions of greenhouse gas and criteria pollutants for both the centralized and decentralized wastewater treatment system separated by activity. The influence of operational electricity demand on life-cycle impacts is highlighted by the *Energy Consumption* category in Table 2. The relatively large contribution of *Energy Consumption* to the total life-cycle impacts for both treatment systems supports previous work by Gaterell and Lester (2000) that suggests the majority of the environmental burdens from wastewater treatment are associated with consumption of energy during the operational phase.

Table 2 shows that the life-cycle energy required for *Material Production* is comparable to *Energy Consumption* in the centralized plant, which is partly due to the high embodied energy of chemicals used in the centralized treatment. *Energy Consumption* is responsible for most of the life-cycle energy needs in the decentralized system, with *Material Production* and *Onsite Equipment/Vehicle Use* also contributing significantly due to the relatively greater influence of the construction phase. When comparing greenhouse gas emissions (expressed in units of carbon dioxide equivalent, CO₂(e)), the difference between the two systems increases, primarily due to

direct methane losses from the decentralized septic tanks, represented in the *Direct Emissions* category of Table 2. Even after adjusting for new findings that indicate septic tank emissions are below previously established IPCC estimates (Diaz-Valbuena et al. 2011), the methane released from the decentralized system is still significantly higher compared to the centralized plant, which is designed to effectively flare methane produced during treatment. Furthermore, generating electricity from methane is becoming increasingly utilized in central treatment plants (Connelly 2011; USEPA, 2011). Methane emissions from landfilled biosolids contribute only slightly to overall greenhouse-gas emissions. Both treatment systems are assumed to have solid waste disposed at a nearby landfill with an 85% efficient gas recovery system.

Table 2 shows that the difference in criteria pollutant emissions between the two systems scales closely with the difference in operational electricity consumption shown in Table 1. This scaling is partly because electricity use is a significant source of criteria pollutants and both treatment plants are assumed to use electricity generated from California's average primary energy mix. The greater difference in particulate matter emissions between the two systems is due to increased influence of tailpipe emissions from off-road vehicle equipment needed for construction and maintenance of the decentralized system, as indicated in the *Onsite Equipment/Vehicle Use* category of Table 2. Off-road vehicle use also increases NO_x emissions associated with the decentralized plant, but a greater difference between the two systems is not observed here since the centralized plant's NO_x emissions also increase due to *Material Delivery* needs.

A key advantage to decentralized wastewater treatment is the potential for reduced potable water demand due to onsite or near-site water reuse. The environmental benefit of avoided water demand, and therefore the overall reduced impact of decentralized wastewater treatment, has

been shown to vary by water source. Stokes and Horvath (2009) estimated that imported water in California, currently a major source of water for this region, requires about 18 to 27 GJ per million liters, while water demand met through desalination would increase the energy requirement to about 43 GJ per million liters. These energy effects of water supply indicate that, even when taking avoided water demand into account, decentralized wastewater treatment may still require more energy than centralized treatment. However, a decentralized wastewater treatment plant with high-yield water reuse may be the lower energy option if the plant serves a region where water is supplied through desalination.

While septic systems are the most common form of decentralization, new forms of decentralized treatment such as membrane bio-reactors are being developed. High-technology decentralized systems may have different life-cycle impacts than the systems evaluated in this paper.

Additional decentralized systems should be evaluated as these emerging technologies become established and reliable data become available.

Multiple factors influence the choice of wastewater treatment strategies, and decentralized systems provide many benefits including lower initial investment costs, increased flexibility, the opportunity to reduce potable water needs through wastewater reuse, and the possibility of reduced ecological impacts outside the scope of this analysis. LCA methods are inherently limited and previous evaluation has shown that life-cycle energy impacts do not necessarily align with other qualitative considerations such as public amenity, ecosystem conservation, or aesthetics (Brix, 1999). The results presented in this study indicate that along with any social and environmental benefits from decentralized treatment comes the potential for an increase in life-cycle energy and air pollutants. Decision makers should be aware of this possible increase and

the life-cycle impacts of proposed decentralized designs should be evaluated to minimize environmental burdens of future wastewater treatment development.

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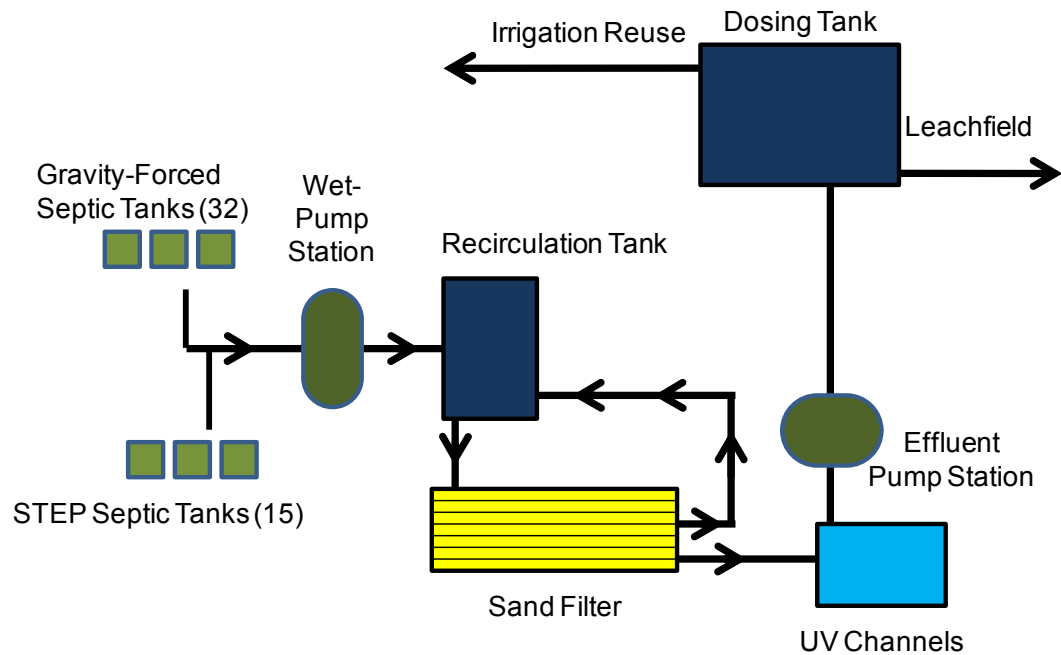
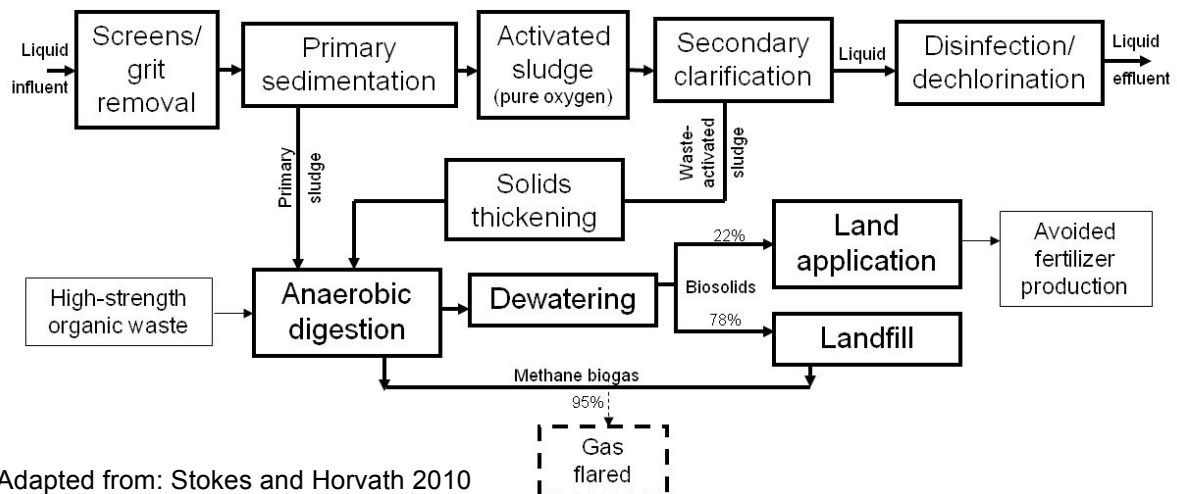


Figure 1: Unit operations of evaluated decentralized wastewater treatment system



Adapted from: Stokes and Horvath 2010

Figure 2: Unit operations of centralized wastewater treatment system

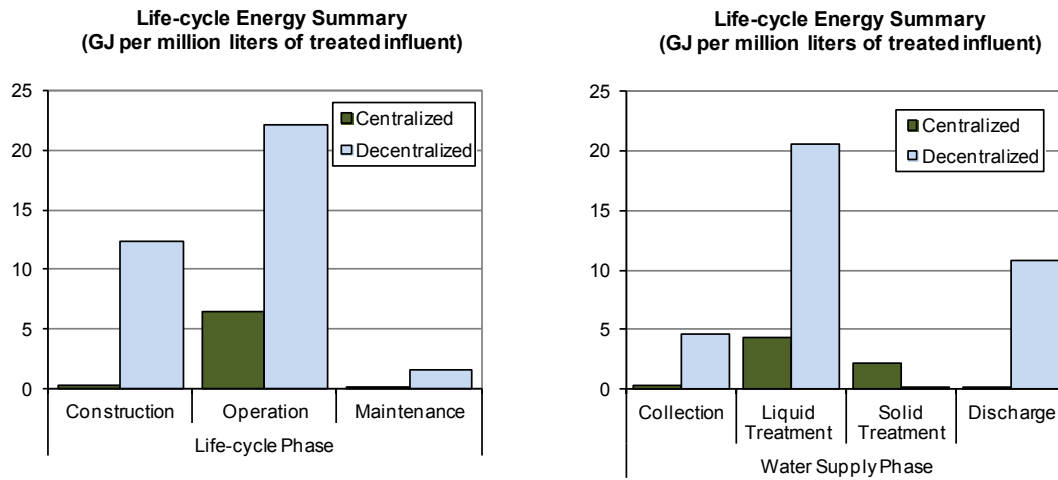


Figure 3: Case study life-cycle energy use for the centralized (6.8 GJ/million liters) and the decentralized (37 GJ/million liters), separated by life-cycle phase (left) and water supply phase (right). End-of-life impacts were not calculated since decommissioning of water infrastructure contributes <0.01% to overall results (Friedrich, 2002).

	Centralized			Decentralized		
	Collection	Treatment	Discharge	Collection	Treatment	Discharge
Treated Influent (Million liters/year)	92000			20		
Population Served	500,000			100		
Chemical Use (m ³ /year)	--	20,000	--	--		
Reinforced Concrete (m ³)	840	60,200	--	4	700	51
Electricity Use (MWh/year)	44,300 ^a			60 ^a		
Natural Gas Use (MBTU/year)	10,000 ^a			--		
Pumps (#)	39	640	--	17	8	2
Pipe (m)	63500	6700	6700	6700	6700	6700
Lift stations (#)	15	--	--	1 ^b	--	1 ^b

Table 1: Case study details. Annual values for the centralized system represent average consumption between 2005 and 2007. Decentralized energy use represents average consumption between 2008 and 2009.

Notes:

^a Operational energy use (electricity and natural gas) for both the centralized and decentralized systems is obtained from utility data representing the entire treatment plants and was not available at the scale of specific unit operations.

^b Represents the two wet-pump stations in the decentralized system.

Life-cycle Energy Use and Emissions
(per million liters of treated influent)

	Energy (GJ)	CO ₂ (e) (kg)	NO _x (kg)	PM (kg)	SO _x (kg)	VOC (kg)	CO (kg)
Decentralized							
Material Production ¹	9.6	757	1.7	0.6	1.8	1.2	7.4
Material Delivery ²	0.4	12	0.2	<0.1	<0.1	<0.1	<0.1
Onsite Equipment/ Vehicle Use ³	4.6	317	2.1	0.3	0.6	0.2	0.8
Energy Consumption ⁴	22	1250	0.9	0.3	3.5	0.6	1.0
Waste Disposal ⁵	<0.1	8.7	<0.1	<0.1	<0.1	<0.1	<0.1
Direct Emissions ⁶	-	909	-	-	-	-	-
Total	37	3255	5.0	1.2	5.9	2.1	9.2
Centralized							
Material Production	2.9	180	0.3	0.1	0.2	0.2	2.6
Material Delivery	0.3	8.6	0.1	<0.1	<0.1	<0.1	<0.1
Onsite Equipment/ Vehicle Use	0.1	6.5	<0.1	<0.1	<0.1	<0.1	0.1
Energy Consumption ⁷	3.5 (3.0)	196 (135)	0.2 (0.1)	<0.1 (<0.1)	0.5 (0.4)	0.1 (<0.1)	0.2 (0.2)
Waste Disposal	<0.1	6.4	<0.1	<0.1	<0.1	<0.1	<0.1
Direct Emissions	-	27	-	-	-	-	-
Total	6.8 (6.3)	424 (363)	0.6 (0.6)	0.1 (0.1)	0.8 (0.6)	0.3 (0.3)	2.9 (2.9)

Table 2: Case study life-cycle energy use and air emissions by activity.

Notes:

¹ Material production represents the manufacture and provision of materials used in the system.

² Material delivery includes the transportation of materials by truck, train, ship, or airplane.

³ Onsite equipment/vehicle use quantifies tailpipe emissions from construction equipment and maintenance vehicles.

⁴ Energy consumption represents the direct and upstream impacts of electricity, natural gas, and liquid fuels use.

⁵ Waste Disposal comprises transporting and disposing of sludge.

⁶ Direct Emissions quantifies CO₂(e) emitted by the treatment process.

⁷ Values in parentheses represent results when methane biogas that would have been flared is instead captured to generate 14,500 MWh of electricity onsite.

Key:

CO: Carbon monoxide; CO₂(e): Carbon dioxide equivalent; NO_x: Nitrogen oxides; PM: Particulate matter; SO_x: Sulfur oxides; VOC: Volatile organic compounds