A COMPARISON OF ENERGY USE AND CARBON GENERATED FROM THE OPERATION AND MAINTENANCE OF PASSIVE ONSITE AND CENTRALIZED WASTEWATER TREATMENT SYSTEMS

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ABSTRACT

With rapid population growth worldwide, green building and development is becoming increasingly important. It is estimated that the world's population is increasing at a rate of 80 million people per year, with the United States adding over 6,000 people per day from 2010 to 2016 (Suez Environmental, 2013; U.S. Census Bureau, 2017). In addition, the United States is currently experiencing human migration trends from the Northeast and Midwest regions to the South and West regions (U.S. Census Bureau, 2017). The combination of population growth and relocation creates an increased demand for potable water, leading to amplified domestic wastewater production. The wastewater infrastructure supporting a population must change in response to population shifts on a local level. This frequently means the construction of new homes served by an onsite wastewater treatment system or expansion of the footprint and capacity of centralized wastewater treatment plants (WWTPs).

The economic and environmental benefits provided through the operation and maintenance (O&M) of centralized WWTPs and passive onsite wastewater treatment systems were quantitatively examined through an analysis of the unit cost, embodied carbon, and embodied energy of wastewater treatment. O&M data was collected from seventeen centralized WWTPs located in eight states. Average influent flows were broken down for this analysis into less than and greater than 7.5 million liters per day (2.0 million gallons per day).

The same analysis was performed for two types of onsite wastewater treatment systems: gravity and pump. Pump systems represent both pump-to-gravity systems and pressurized systems. For both centralized and onsite wastewater treatment systems, averages were calculated for the unit treatment cost, embodied carbon (kg CO_2), and embodied energy (MJ) per kilogram of biochemical oxygen demand (kg BOD) and total suspended solids (kg TSS) removed, and liter treated.

For centralized WWTPs less than 7.5 million liters per day, the average costs per kg BOD and kg TSS removed were found to be $7.94 and $7.96, respectively; the average embodied carbon per kg BOD, kg TSS, and liter ($x10^6$) were calculated to be 5.21, 5.04, and 940, respectively; and the average embodied energy per kg BOD, kg TSS, and liter ($x10^6$) were calculated to be 3.70, 3.58, and 670, respectively.

For centralized WWTPs treating greater than 7.5 million liters per day, the average costs per kg BOD and kg TSS removed were found to be $2.24 and $2.17, respectively; the average embodied

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carbon per kg BOD, kg TSS, and liter (x10^6) were calculated to be 2.30, 2.27, and 520, respectively; and the average embodied energy per kg BOD, kg TSS, and liter (x10^6) were calculated to be 1.64, 1.63, and 380, respectively. In comparison to centralized WWTPs, gravity and pump onsite wastewater treatment systems had a reduction in cost of treatment, embodied carbon footprint, and embodied energy footprint.

When evaluating the means by which the wastewater generated from population growth and shifts will be managed, it is important that stakeholders consider the tangible benefits of onsite wastewater treatment compared to those of centralized WWTPs. One-third of new homes built in the United States use onsite wastewater treatment systems (U.S. EPA, 1997). At present, 30 million American homes are served by an onsite wastewater treatment system, supporting 25% of the country's population, and treating four billion gallons of wastewater daily. These are some of the reasons that the United States Environmental Protection Agency (U.S. EPA, 1997) cited adequately managed onsite wastewater systems as "cost effective and long-term option for meeting public health and water quality goals". With clear economic and environmental benefits, onsite wastewater treatment can be a sustainable method to efficiently and effectively manage increased domestic wastewater production. Through sustainable wastewater management, efforts can be made to investigate the challenges presented to wastewater infrastructure systems, mitigating the need for sewer extensions and centralized WWTP expansions.

INTRODUCTION

Centralized vs Onsite Wastewater Management

Domestic wastewater contains chemicals, viruses, and bacteria that pose a potential exposure risk to humans and the environment. As a result, treatment is required to protect public health and the environment prior to the release of wastewater to the environment. This can be achieved using a wastewater treatment and dispersal system located on or near the site where the wastewater is generated. Such systems are referred to as onsite wastewater treatment and dispersal, or when a localized treatment and dispersal system serves a limited number of nearby wastewater sources, the system is referred to as decentralized wastewater treatment system. Alternatively, treatment can be achieved using a centralized WWTP, where wastewater is collected from a large number of wastewater sources across a broad area and treated in a centralized location prior to release. This analysis examines the economic and environmental benefits provided through the O&M of centralized WWTPs compared to passive onsite wastewater treatment systems. The analysis examines the unit cost of wastewater treatment, embodied carbon, and embodied energy to ascertain the benefits of green building in terms of financial and environmental costs.

Soil-based treatment systems combine physical, chemical, and biological processes to remove chemicals, viruses, and bacteria from wastewater. The system typically includes a septic tank designed to separate solids and liquid, followed by a dispersal area where the clarified liquid that has discharged from the septic tank enters the soil for treatment. The dispersal and treatment area is designed to account for the projected daily wastewater flow. Because 90% of the septic tank effluent treatment occurs in the soil for properly installed systems, onsite wastewater treatment systems can have relatively low O&M requirements and cost (Lowe, 2008). Wastewater may be dispersed using gravity-flow or pressurized methods. Use of gravity dispersal does not require electricity to operate, while pressurization of the wastewater for a single-family home typically requires the use a small electric pump. Neither system type requires intensive maintenance. When properly designed, constructed and maintained, soil-based treatment systems provide a high degree of treatment and are a proven method of controlling the detrimental public health and environmental effects of untreated sewage.

Previous investigators identified substantial differences between the installed cost of onsite and centralized WWTP sewer extensions, with onsite wastewater treatments systems providing comparatively lower installed cost, embodied energy, and embodied carbon (Kautz, 2015). This analysis was based on information from a regional wastewater study in Southwest Virginia. The study examined the environmental and economic benefits provided through the manufacture and construction of onsite wastewater systems compared to centralized WWTPs, which were quantitatively examined for embodied energy, embodied carbon, and installed cost. The findings showed that the average onsite wastewater treatment system versus connecting to a sewer extension reduced embodied energy, embodied carbon, and installed cost by 75% (117,538 MJ), 73% (5,099 kg CO2,), and 68% ($12,636), respectively. This O&M study examines the post-construction status of onsite wastewater treatment systems once they are in operating mode.

Centralized WWTPs currently treat approximately 75% of the wastewater produced in the United States by conveying wastewater through a network of gravity pipes and force mains via pump stations from individual homes and businesses to a WWTP where wastewater is treated and typically dispersed into a local surface water body. When properly designed, constructed and maintained, centralized WWTPs provide a high degree of treatment and are a proven method of controlling the negative public health and environmental effects of untreated sewage. During dry-weather flows, WWTPs generally treat all of the wastewater that is generated daily. During wet-weather flows, however, sewer networks and WWTPs are often overwhelmed, requiring relief points along the network where raw sewage is directly discharged into surface waters; these locations are called sanitary or combined sewer overflows (SSOs or CSOs). According to the U.S. EPA, CSO discharges account for approximately 1.26 trillion gallons of untreated wastewater entering surface waters nationwide each year (U.S. EPA, 2001).

It is important to note that homeowner awareness is essential in the sustainability for both onsite septic systems and centralized sewers. For homeowners connected to onsite wastewater treatment systems, education on the use and maintenance can ensure the longevity and proper performance of an onsite wastewater treatment system. Flushing detrimental liquids (e.g., grease) and chemicals (e.g., bleach) can lead to clogging of the drainfield infiltrative surface or disruption of biological treatment processes, respectively. Periodic septic tank pump-outs maximize primary treatment through settling, and can prevent back-up of sewage into homes and potential impacts to local waters. Centralized WWTPs can be impacted by the discharge of harmful chemicals that affect biological processes at the facility, possibly leading to disruptions in treatment processes. Centralized WWTPs that are connected to stormwater systems are also susceptible to impacts from precipitation events that exceed the capacity of the facility, resulting in SSOs or CSOs that release untreated sewage to surface waters.

The primary purpose of the Clean Water Act of 1972 is to regulate the release of contaminants into the water system. Both centralized and onsite wastewater treatment systems share a common objective of treating wastewater constituents before they enter the environment. Over 25% of United States homes currently utilize onsite wastewater treatment along with 33% of all new residential developments, treating 4 billion gallons of wastewater daily. (U.S. EPA, 2004; U.S. EPA, 1997). While onsite and decentralized wastewater treatment systems serve a substantial number of Americans, only approximately 0.4% of the Clean Water State Revolving Fund is allocated to decentralized wastewater treatment and a fraction of that toward onsite wastewater treatment. With usage high and funding low, it is important that stakeholders consider the tangible benefits of onsite wastewater treatment compared to those of centralized WWTPs when evaluating options for managing wastewater associated with land development. Critical factors that should be investigated include the possibility that onsite wastewater treatment is used to obviate the need for sewer extensions and centralized WWTP expansion having high capital and O&M costs (Kautz, 2015). Onsite wastewater treatment offers sound performance with both installation and O&M costs shifted away from the municipality and to the homeowner, while creating private-sector business opportunities. And because soil-based treatment systems disperse water into the soil, onsite treatment systems are one of the few technologies that recharge the nation's dwindling groundwater supplies.

METHODS AND CALCULATIONS

Overview

An analysis was performed to quantitatively determine the cost for treatment, embodied carbon, and embodied energy associated with the O&M of centralized WWTPs and two types of passive onsite wastewater treatment systems. This report presents a method for comparing the benefits and O&M costs of onsite and centralized wastewater treatment facilities, as a means of gauging both the cost effectiveness and environmental sustainability of managing domestic wastewater using strategies other than the expansion of centralized WWTPs. Most rural and suburban areas in the United States that rely on decentralized wastewater treatment systems do not require nutrient reduction to comply with state regulatory requirements. For this reason, this analysis is limited to comparisons that do not include nutrient reduction. In some areas of the United States, nutrient reduction in wastewater is required by local or state regulation. In these areas, a separate analysis would be required for the cost and embodied carbon and energy associated with nutrient reduction.

Publicly available O&M information was obtained from seventeen centralized WWTPs located in eight states, including Arizona (1), Florida (4), Idaho (3), North Carolina (1), New Mexico (1), New York (4), Washington (2), and Wisconsin (1). Information was obtained under state freedom of information laws. Centralized WWTPs size was divided into above and below 7.5 million liters per day, with no single centralized WWTP average influent flow exceeding 82.4 million liters per day. Five centralized WWTPs were below 7.5 million liters per day and 12 were above 7.5 million liters per day and below 82.4 million liters per day. The average daily flow for the seventeen centralized WWTPs is presented in Appendix 1. Centralized WWTP capacity selection toward the small-to-medium end of the size spectrum is based on the typical location and type of decisions being made by local government entities on sewer extensions and centralized WWTP capacity increases. These evaluations typically occur in rural and suburban areas that are served by small-to-medium-sized centralized WWTPs, rather than very large centralized WWTPs serving densely populated urban areas within cities. Large centralized WWTPs serving densely populated urban areas are generally not treating wastewater originating from lower-population-density areas at the periphery of the urbanized area. Information obtained from the centralized WWTPs included: wastewater flow, electrical usage and cost, fuel usage and cost, O&M costs, influent and effluent water quality parameters, and the types and quantities of chemicals used for treatment. Common types of chemicals and fuels reported by centralized WWTPs are listed in Appendix 2.

The total O&M cost included the cost of electricity, fuel, chemicals, and maintenance. This study assumes an average residential cost for electricity of around $0.13/kWh (United States average). According to the United States Energy Information Administration, a residential end-user in May 2017 will pay anywhere from around $0.10/kWh in Washington to around $0.29/kWh in Hawaii. This can create a large variation in calculated cost per kilogram of BOD and TSS treated. Through the analysis of centralized WWTPs, exact energy costs were given based on the geographic location of the treatment facility. However, the United States average energy cost needed to be used to analyze pump systems (U.S. EIA, 2017).

Unit conversion factors for embodied carbon and embodied energy were multiplied by the embodied carbon and energy associated with the WWTP-reported energy and chemical use to calculate the final embodied carbon footprint and embodied energy footprint (He, 2013; Patnaik, 2002; Ecoinvent, 2013). A complete list of sources for the embodied carbon and embodied energy unit conversion factors is provided in Appendix 2 for the energy sources and chemicals reported by the 17 WWTPs examined in this study.

For onsite wastewater treatment systems, information on two system types was developed: gravity and pump. In the analysis of gravity and pump system types, an average 3-bedroom daily household flow rate of 640 liters per day was used to estimate residential wastewater production (WERF, 2007). The 640 liter-per-day flow estimate is based on a median indoor flow rate of 230 liters/capita/day and an average of 2.8 capita per household (WERF, 2007). Nationally, design flow rates vary from as low as 380 liters per bedroom per day (100 gallons per bedroom per day) in Florida to as high as 568 liters per bedroom per day in Alabama and Indiana (150 gallons per bedroom per day). The selected household flow rate is approximately half of the typical state design flow rate, but is based on data from occupied homes that were metered in a large-scale study by the Water Environment Research Foundation. For gravity and pump systems, raw sewage and septic tank effluent BOD and TSS concentrations was found through literature review (Gross, 2004). An average of 90% BOD and TSS removal was utilized for domestic wastewater passing through a soil-based treatment system (Siegrist, 2014).

O&M costs associated with gravity onsite wastewater treatment systems incorporated septic tank pumping via diesel-powered pump trucks every four years and inspections (Barnstable County Wastewater Cost Task Force, 2010). Pump systems had an added O&M cost for pump replacements every 11 years and pump electricity costs. Pump usage data was based on 12 different monitored residential sites in North Carolina (Menser, 2014). Pump data and run times were monitored for at least one year at these sites as part of a North Carolina Department of Health and Human Services field demonstration program. Specific pump size and run times were used to calculate site-specific kilowatt hours. The United States average price per kilowatt hour was used to calculate the O&M electrical cost contribution (U.S. EIA, 2017; U.S. EPA, 1984; Jackson, 2010; Siegrist, 2014). Diesel-powered pump trucks contributed to the embodied carbon and energy for both gravity and pump onsite wastewater treatment systems. Electricity for the pump systems also contributed to the overall embodied carbon and energy (U.S. EIA, 2017; He, 2013; Patnaik, 2002; Ecoinvent, 2013).

Processes

Factors when calculating the embodied carbon and energy associated with the O&M of wastewater treatment include energy sources (e.g. electricity, gasoline, diesel) and chemicals used for treatment (e.g. chlorine, lime, bleach). Centralized WWTPs utilize both energy sources and chemicals to conduct wastewater treatment processes. However, onsite systems generally do not use chemical additions to conduct wastewater treatment processes because the soil-based treatment system uses natural, non-electric physical, chemical, and biological processes. The two passive onsite systems have associated embodied carbon and energy from diesel pump trucks. Electricity contributed to the O&M cost, embodied carbon, and embodied energy for all systems except passive onsite gravity systems. Embodied carbon and embodied energy unit values for the energy and chemicals used in each system were found through literature review, with sources provided in Appendix 2. For example, aluminum sulfate, which is a common chemical in use at centralized WWTPs, has an embodied carbon unit value of 0.458 kg CO_2/kg aluminum sulfate and an embodied energy unit value of 0.559 MJ/kg aluminum sulfate. So, if the centralized WWTP uses 100,000 kg of aluminum sulfate per year, then the annual embodied carbon and energy are 45,800 kg CO_2 and 55,900 MJ, respectively.

Outputs

Annual operating costs for centralized and onsite wastewater treatment systems were divided by the BOD and TSS removal rates to obtain the average unit costs for treatment. The total embodied carbon and embodied energy expended yearly were divided by the kilograms of BOD and TSS removed and liters of wastewater treated annually to calculate the overall embodied carbon footprint and embodied energy footprints. Calculating unit values provided the ability to compare the cost, embodied carbon, and embodied energy use of both centralized and onsite wastewater treatment technologies.

RESULTS

Treatment Cost

A summary of the total cost per kilogram of BOD and TSS treatment for centralized and onsite wastewater treatment systems is shown in Figure 1. When compared to centralized WWTPs less than 7.5 million liters per day, gravity and pump systems achieve approximately 78% and 74% cost reduction per kilogram of BOD and TSS treated, respectively. When compared to centralized WWTPs greater than 7.5 million liters per day, gravity and pump systems achieve approximately 19% and 5% cost reduction per kilogram of BOD and TSS treated, respectively.

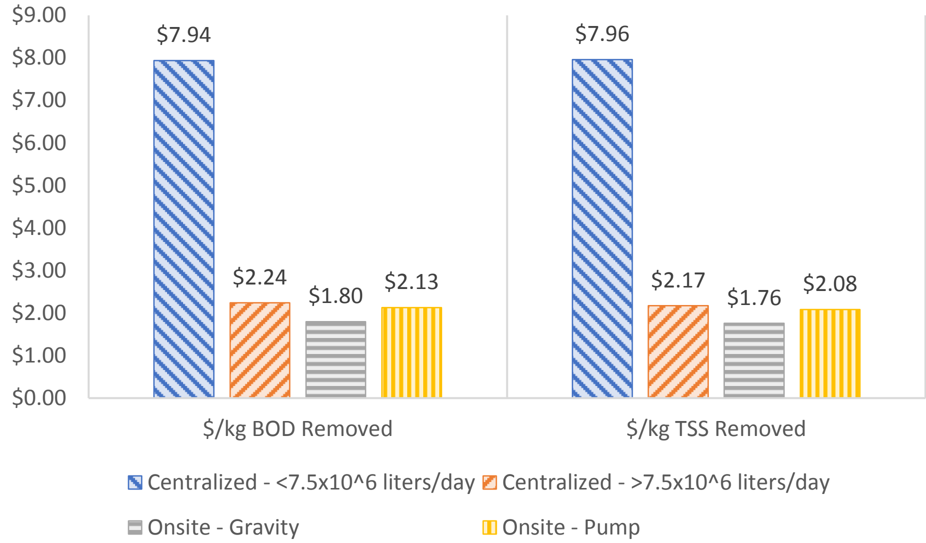

Figure 1. Average treatment cost for centralized and onsite wastewater treatment systems

Embodied Carbon Footprint

The average embodied carbon footprint for centralized and onsite wastewater treatment systems is shown in Figure 2 and Figure 3. As shown in Figure 2, gravity and pump systems were calculated to have only a fraction of the embodied carbon footprint as centralized WWTPs. On a per liter basis, Figure 3 shows significant reductions in embodied carbon for gravity and pump systems when compared to centralized WWTPs. The notable difference in embodied carbon footprint between onsite and centralized treatment systems is approximately the same whether the centralized WWTP is above or below 7.5 million liters per day.

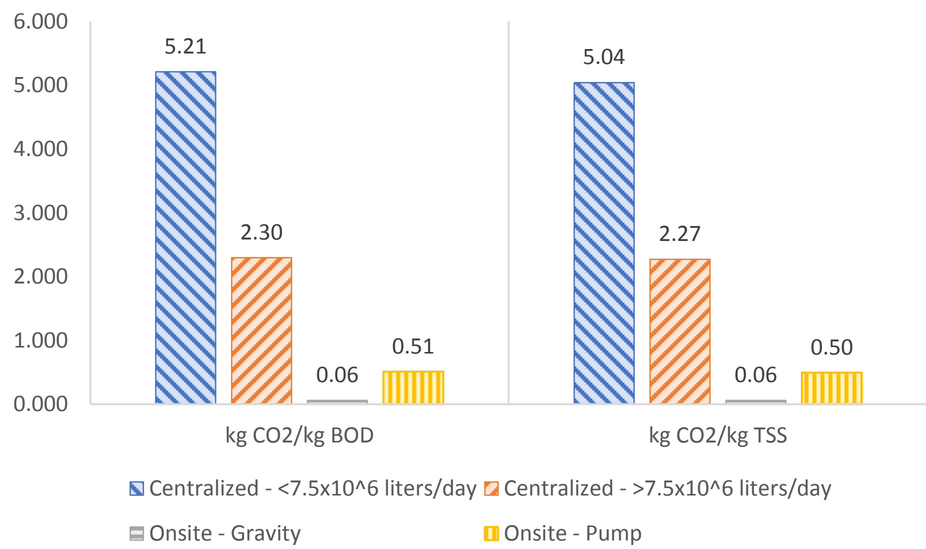

Figure 2. Average embodied carbon footprint per kilogram of BOD and TSS removal for centralized and onsite wastewater treatment systems

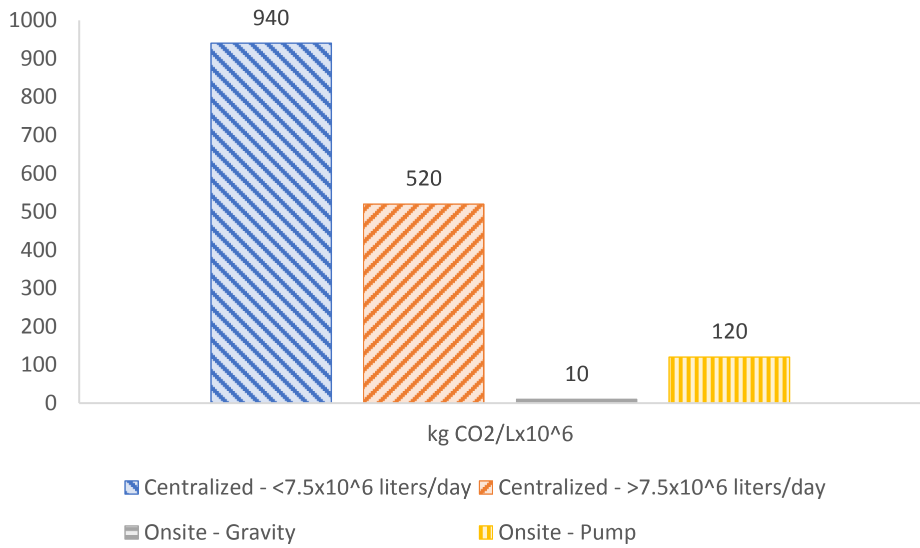

Figure 3. Average embodied carbon footprint per liter for centralized and onsite treatment systems

Embodied Energy Footprint

The average embodied energy footprint for centralized and onsite wastewater treatment systems is shown in Figure 4 and Figure 5. Onsite wastewater treatment is shown to have a reduced embodied energy footprint from centralized treatment whether the centralized WWTP is above or below 7.5 million liters per day.

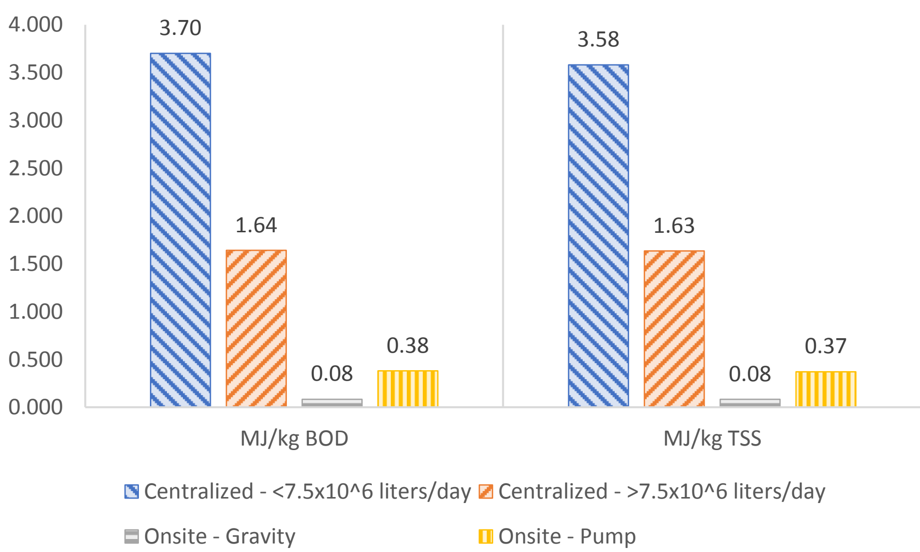

Figure 4. Average embodied energy footprint per kilogram of BOD and TSS removal for centralized and onsite wastewater treatment systems

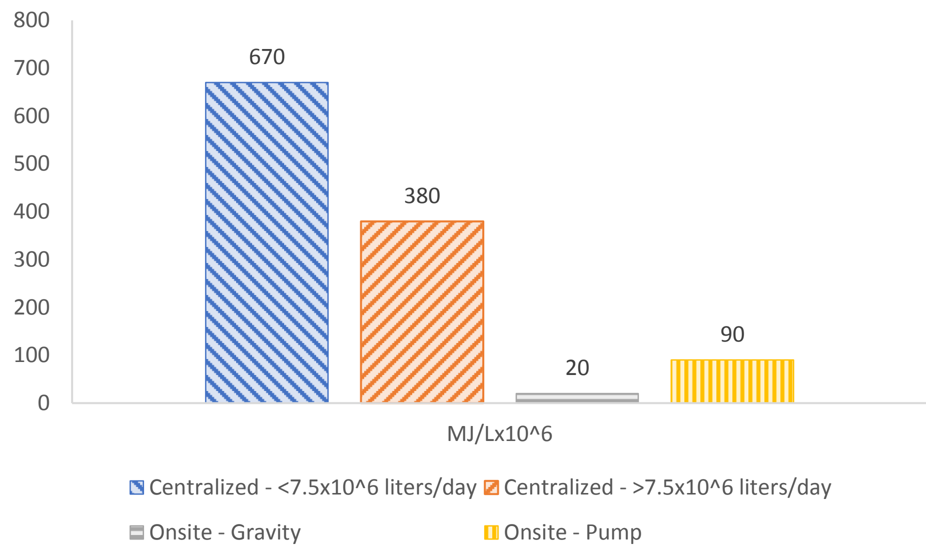

Figure 5. Average embodied energy footprint per liter for centralized and onsite treatment systems

DISCUSSION

The average percent reductions of treatment cost, embodied carbon, and embodied energy between centralized systems and onsite systems are shown in Table 1. As shown, gravity and pump systems provide a high reduction of treatment cost, embodied carbon, and embodied energy over centralized WWTPs. This applies for centralized WWTPs handling above and below 7.5 million liters per day. Passive onsite wastewater treatment provides substantial O&M cost savings relative to treatment at a centralized WWTP. The passive nature of soil-based treatment systems, where natural physical, chemical, and biological processes remove chemicals, viruses, and bacteria from wastewater is the biggest differentiator, as there is no cost to perform the treatment process itself. When an onsite wastewater treatment system includes a pump, the cost of treating BOD and TSS is incrementally higher due to the energy input for the pump, but still substantially lower than the cost in a centralized WWTP. Similar to the cost of treatment, the lack of substantial energy input and absence of chemical additions provide a similar effect for embodied carbon and energy, where onsite wastewater treatment is superior to treatment at a centralized WWTP relative to embodied carbon and energy.

Table 1. Average cost of treatment, embodied carbon, and embodied energy for centralized WWTPs and onsite systems

		Centralized – <7.5x10^6 liters/day	**Centralized - >7.5x10^6 liters/day**	**Onsite – Gravity**	**Onsite – Pump**
Cost	$/kg BOD	$7.94	$2.24	$1.80	$2.13
	$/kg TSS	$7.96	$2.17	$1.76	$2.08
Embodied Carbon	kg CO_2/kg BOD	5.21	2.30	0.06	0.51
	kg CO_2/kg TSS	5.04	2.27	0.06	0.50
	kg CO_2/Lx10^6	940	520	10	120
Embodied Energy	MJ/kg BOD	3.70	1.64	0.08	0.38
	MJ/kg TSS	3.58	1.63	0.08	0.37
	MJ/Lx10^6	670	380	20	90

In terms of green building initiatives, the data presented in Table 1 fully supports the concept that passive onsite wastewater treatment can provide substantially lower O&M cost and reduced embodied carbon and energy as compared to a centralized WWTP option. Any decision-making process on how to cost-effectively manage wastewater should consider both onsite and centralized WWTP options to ensure that a complete understanding of the options and associated costs and environmental considerations can be weighed. If these types of analyses were conducted on a nationwide basis, leading to the selection of onsite and decentralized wastewater treatment solutions over centralized WWTP solutions, the cumulative effect over time would be substantial in the form of reduced O&M costs and delivery of decreased embodied carbon and energy.

Table 2 shows a comparison of the annual cost, embodied energy, and embodied carbon savings per household from switching from small and medium centralized WWTPs to passive onsite wastewater treatment systems.

Table 2. Annual Cost, Embodied Energy, and Embodied Carbon Savings from Centralized WWTPs to Passive Onsite Wastewater Treatment Systems

		Gravity Savings per Year per Household from Small Centralized WWTPs	**Gravity Savings per Year per Household from Medium Centralized WWTPs**	**Pump Savings per Year per Household from Small Centralized WWTPs**	**Pump Savings per Year per Household from Medium Centralized WWTPs**
Cost	$/kg BOD	341.22	24.45	322.88	6.11
	$/kg TSS	353.24	23.36	335.01	5.13
Embodied Carbon	kg CO_2/kg BOD	286.20	124.21	261.25	99.25
	kg CO_2/kg TSS	283.96	126.03	259.01	101.07
Embodied Energy	MJ/kg BOD	200.95	86.47	184.45	69.97
	MJ/kg TSS	199.35	88.37	182.83	71.85

As shown in Table 2, substantial cost, embodied carbon, and embodied energy savings can be gained using onsite wastewater treatment systems. The North Carolina Department of Health and Human Services reports the operation of over 321,000 gravity and pump onsite wastewater treatment systems in the state (NC DHHS, 2017). For this comparative analysis, it is conservatively assumed that 60% of the reported North Carolina onsite wastewater treatment systems are gravity-flow and 40% are pump systems. The annual cost savings that is realized for the state's 321,000 gravity and pump systems is $218 million, as compared to the cost to operate centralized WWTPs. The quantity of carbon dioxide emissions reduction achieved from operating the North Carolina onsite wastewater treatment systems for one year instead of centralized WWTPs is equivalent to removing over 37,000 cars from the road for one year (U.S. EPA, 2017). From an embodied energy perspective, the annual energy savings gained from North Carolina's existing onsite wastewater treatment systems is equivalent to removing over 2,400 homes from the electrical grid for a period of one year (U.S. EIA, 2009).

CONCLUSIONS

Benefits of Onsite Wastewater Management

It has long been cited that properly managed onsite wastewater treatment systems are viable and sustainable alternatives to centralized wastewater facilities (U.S. EPA, 2003; U.S. EPA, 2011). Onsite wastewater treatment systems often only rely on passive processes in septic tanks and soil to treat wastewater. These non-electric, natural, physical, chemical, and biological processes lower O&M requirements, energy requirements, and operating cost. Of the two types of onsite wastewater treatment systems examined, the O&M cost and energy required differs, but both effectively treat domestic wastewater in a manner that is protective of public health and the environment when properly designed, sited, and maintained. These benefits collectively support the use of onsite wastewater treatment as a viable means of managing wastewater associated with land development, possibly alleviating the need for sewer extensions and centralized WWTP expansion and the capital and O&M costs associated with this infrastructure (Kautz, 2015). A previous study found that the installed cost, embodied energy, and embodied carbon of an onsite wastewater treatment system can be lower than those of a centralized WWTP sewer extension (Kautz, 2015). Based on the finding of the earlier study on installed cost and this study on O&M, passive onsite wastewater treatment systems can be more cost effective to construct, operate, and maintain, as compared to a centralized WWTP (Kautz, 2015).

The use of onsite wastewater treatment as a solution promotes private-sector jobs created by small businesses and shifts the installation and O&M costs associated with wastewater to the homeowner, rather than the municipality. Onsite wastewater treatment has multiple applications in urban, suburban and rural settings and can be designed to serve individual homes or entire communities. And because it disperses water into the soil, it is one of the few technologies that can help recharges groundwater supplies.

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APPENDIX 1

Facility Number	Centralized WWTP Location	Average Daily Flow (Million Liters per Day)
1	Fallsburg, NY	0.9
2	Ketchum, ID	4.3
3	Cheney, WA	5.5
4	Fallsburg, NY	6.5
5	Chehalis, WA	7.3
6	Tolleson, AZ	19.1
7	Orlando, FL	20.1
8	Santa Fe, NM	21.5
9	Charlotte, NC	35.6
10	Boise, ID	43.1
11	Bellingham, WA	46.2
12	Boca Raton, FL	50.2
13	Orlando, FL	53.2
14	Boise, ID	61.9
15	Orlando, FL	79.9
16	Albany, NY	81.2
17	Albany, NY	82.4

APPENDIX 2

Material	EC (kg CO2/unit)	Unit	EE (MJ/unit)	Unit	Density	Unit
Electricity (grid)[1]	0.748	kWh	0.504	kWh		
Electricity (wind)[2,3,4]	0.010	kWh	0.111	kWh		
Natural Gas[5,6,7]	5.312	therm	3.226	therm	0.712	kg/m3
Gasoline[5,8,9]	8.890	gal	17.827	gal		
Diesel[5,8,9]	10.160	gal	15.578	gal		
Bio-diesel[10,11,12]	8.119	gal	23.622	gal		
On-Road Diesel[5]	10.160	gal	15.578	gal		
Off-Road Diesel[5]	10.160	gal	15.578	gal		
Methane[5,6,7]	5.312	therm	3.226	therm	0.712	kg/m3
Fuel Oil[8,9,13]	12.040	gal	9.546	gal		
Propane[5,8,9,14]	5.760	gal	5.825	gal	4.230	lb/gal
Aluminum Chlorohydrate (polyaluminium chloride) (Antipersperant) (PAC)[15,16,26]	0.537	kg	0.835	kg	1.380	g/L
Poly-aluminium chloride (Aluminum Chlorohydrate)[15,16,26]	0.537	kg	0.835	kg	1.380	g/L
Aluminum Sulfate[1,17]	0.458	kg	0.559	kg	2.710	g/cm3
Bioxide (Calcium Nitrate)[17,18,19,26]	0.268	kg	0.835	kg	2.500	g/cm3
Carbon (Carbon Black)[10,20,26]	2.380	kg	0.835	kg	1.800	g/cm3
Chlorine 100%[10,21,26]	1.080	kg	0.835	kg	1.468	g/L
Ferric Chloride (Iron (III) Chloride)[1,17]	1.543	kg	1.410	kg	2.898	g/cm3
Iron Sulfate ($FeSO_4$)[22,23]	0.167	kg	0.001	MMBtu/lb	15.000	lb/gal
Hydrogen peroxide 27% (H_2O_2) (dioxidane) (oxidanyl) (perhydroxic acid)[17,22]	0.643	kg	0.005	MMBtu/lb	1.092	g/mL
Lime (Calcium Oxide)[1,17]	0.757	kg	0.519	kg	3.340	g/cm3
Magnesium Oxide[10,23,26]	1.060	kg	0.835	kg	3.580	g/cm3
Polymer[24,25,26]	1.500	kg	0.835	kg	8.340	lb/gal
Salt (Sodium Chloride)[10,17,26]	0.200	kg	0.835	kg	2.165	g/cm3
Sodium Aluminate ($NaAlO_2$)[27]	0.837	kg	0.835	kg		
Sodium Bicarbonate (Soda Ash) (Na_2CO_3)[10,26]	1.170	kg	0.835	kg		
Sodium Bisulfite 38% (Sodium Hydrogen Sulfite) ($NaHSO_3$)[10,23,26]	0.167	kg	0.835	kg	1.480	g/cm3
Sulfur Dioxide (SO_2)[10,26]	0.440	kg	0.835	kg		
Sodium Hydroxide 25% (Caustic Soda) (NaOH)[1,17]	0.505	kg	0.448	kg	2.130	g/cm3
Sodium Hydroxide 50% (Caustic Soda) (NaOH)[1,17]	1.010	kg	0.896	kg	2.130	g/cm3
Caustic soda (Sodium hydroxide) (NaOH)[1,17]	2.020	kg	1.792	kg	2.130	g/cm3
Sodium Hypochlorite 12.5% (NaClO) (Bleach)[1,17]	0.636	kg	0.726	kg	1.600	g/cm3
12% Bleach (Sodium Hypochlorite) (NaClO)[1,17]	0.610	kg	0.697	kg	1.600	g/cm3
Sulfuric acid[1,23]	0.086	kg	0.154	kg	15.000	lb/gal

Notes:

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3. http://www.acua.com/green-initiatives/renewable-energy/windfarm/
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23. https://pubchem.ncbi.nlm.nih.gov/compound/ferrous_sulfate#section=Experimental-Properties
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25. http://www.wvdhhr.org/oehs/eed/swap/training&certification/documents/Formula_Sheet.pdf
26. EE: average value from other chemicals since no value could be found in literature
27. EC and EE: average value from other chemicals since no value could be found in literature