Life Cycle Assessment and Cost Analysis of Mixed Wastewater and Graywater Distributed Treatment for Non-Potable Reuse in San Francisco

Ben Morelli[1], Sarah Cashman[2], Cissy Ma[3], Jay Garland[4], Diana Bless[5], and Michael Jahne[6]
[1]Eastern Research Group, Lexington, Massachusetts USA
[2] Eastern Research Group, Lexington, Massachusetts USA
[3]United States Environmental Protection Agency, Center for Environmental Solutions and Emergency Response, Cincinnati, Ohio USA
[4]United States Environmental Protection Agency, Center for Environmental Solutions and Emergency Response, Ohio USA
[5] United States Environmental Protection Agency, Center for Environmental Solutions and Emergency Response, Cincinnati, Ohio USA
[6] United States Environmental Protection Agency, Center for Environmental Solutions and Emergency Response, Cincinnati, Ohio USA
[1]Email: Ben.Morelli@erg.com
[2]Email: Sarah.Cashman@erg.com
[3]Email: Ma.Cissy@epa.gov
[4]Email: Garland.Jay@epa.gov
[5]Email: Bless.Diana@epa.gov
[6]Email: Jahne.Michael@epa.gov

ABSTRACT

This research uses life cycle assessment (LCA) and life cycle cost assessment (LCCA) to evaluate three wastewater treatment technologies for decentralized, building scale treatment of mixed wastewater and graywater for non-potable reuse (NPR). The study develops life cycle inventory data for aerobic membrane bioreactors (AeMBR), anaerobic membrane bioreactors (AnMBR), and recirculating vertical flow wetlands (RVFW), and compares environmental impacts and costs based on wastewater generation and treatment. The study compares results across three reuse scenarios, that vary the quantity of treated wastewater and graywater that can be used on-site for NPR, thereby displacing potable water production. Study results show that there are environmental benefits to matching the supply of treated wastewater or graywater to water demand for NPR. The AeMBR treatment process demonstrates the lowest environmental impacts and life cycle costs among the three treatment systems.

KEYWORDS

Non-potable reuse (NPR), decentralized treatment, life cycle assessment (LCA), life cycle cost assessment (LCCA), aerobic membrane bioreactor (AeMBR), anaerobic membrane bioreactor (AnMBR), recirculating vertical flow wetland (RVFW), mixed wastewater, graywater, thermal recovery

INTRODUCTION & BACKGROUND

Water scarcity, aging infrastructure, city ordinances, and sustainability goals are pushing many industries, communities, and building project developers to explore alternative water resources for reuse, such as municipal wastewater, industry process water, stormwater, and cooling water. In the U.S., it was estimated that of the 33 billion gallons a day of treated municipal wastewater, only 7 percent is currently reused (Rauch-Williams et al., 2018). This is an untapped resource and demonstrates significant potential. The development of a National Water Reuse Action Plan is being facilitated by the U.S. Environmental Protection Agency (U.S. EPA) along with federal, state, tribal, and water sector stakeholders (U.S. EPA, 2019). More actions are called for to increase acceptance and use of safe and affordable reused water. This work is a part of the U.S. EPA's Safe and Sustainable Water Resources (SSWR) National Research Program. The research adopts integrated metrics and tools to identify the next generation of water and wastewater best practices using holistic, systems approaches. As part of the larger efforts, U.S. EPA is exploring the concepts of water resource recovery facilities (WRRF) including decentralization, energy and nutrient recovery, and water reuse to achieve sustainability goals. This study examines the environmental and cost implications of several mixed wastewater or graywater treatment configurations for decentralized, mixed-use building scale non-potable reuse (NPR) projects.

In this analysis life cycle assessment (LCA) and life cycle cost assessment (LCCA) methodologies were specifically applied to several wastewater and graywater treatment configurations in an urban case-study that examines building scale on-site wastewater treatment systems in San Francisco. San Francisco is moving aggressively forward with implementation of NPR reuse (SPFUC, n.d.), and considering a suite of environmental and economic metrics will help project developers and the community meet a complex set of goals.

The study developed extensive life cycle inventory (LCI) data for aerobic membrane bioreactors (AeMBRs), anaerobic membrane bioreactors (AnMBRs), and recirculating vertical flow wetlands (RVFWs) treating both mixed wastewater and graywater for NPR. The analysis showcased an integrated assessment framework to evaluate next generation water systems on the horizon and explores the sustainability trade-offs in NPR from a holistic perspective. The study results provide critical insights into system performance characteristics needed before informed decisions can be made for any community to transition towards the adoption of such innovative technologies and the decentralization concept. While the study was conducted in the context of San Francisco, data developed can be adapted in future research steps for other urban communities across the U.S.

METHODOLOGY

Study Scope

LCA studies are based on the definition of a functional unit, which provides the basis of comparison for the analysis. This paper presents LCA results using two separate functional units. Summary LCA results for all impact categories are presented using a functional unit of treatment of one cubic meter of either municipal wastewater or graywater. Detailed results for global warming potential (GWP), cumulative energy demand (CED) and life cycle costs are presented based on a functional unit of one cubic meter of wastewater generation at the building site. The first formulation of the functional unit focuses interpretation on the on-site wastewater treatment processes, holding the volume of water treated (1 m^3) constant. The second formulation of the functional unit expands the system boundaries to include centralized treatment of solids and the blackwater fraction of wastewater in the case of graywater systems allowing direct comparison of results for mixed wastewater and graywater systems. Both functional units are dependent on the influent and flowrate characteristics listed in Table 1. Table 1 compares influent quality to target effluent quality criteria intended for unrestricted urban reuse (U.S. EPA, 2012). The definition of graywater used in this study includes bathroom faucets, showers, baths, and laundry machines (Sharvelle et al., 2013). Water from kitchen sinks and dishwashers contributes to blackwater flows.

Table 1. Building Characteristics, Mixed Wastewater and Graywater Influent Characteristics, and Target Effluent Quality

<table>
<tr><th colspan="2" rowspan="2">Water Quality Characteristics</th><th colspan="2">Influent Values</th><th>Target Effluent Quality</th></tr>
<tr><th>Mixed WW</th><th>Separated GW</th><th>Both</th></tr>
<tr><th>Characteristic</th><th>Unit</th><th>Medium Strength (Building & District)</th><th>Low Pollutant Load with Laundry</th><th>Effluent Quality for Unrestricted Urban Use</th></tr>
<tr><td>Total Wastewater Flowrate</td><td>m^3/day</td><td colspan="2">95 (0.025 mgd)</td><td rowspan="5">N/A</td></tr>
<tr><td>Treated Water Volume</td><td>m^3/day</td><td>95 (0.025 mgd)</td><td>61 (0.016 mgd)</td></tr>
<tr><td>Building Floor Area</td><td>m^2</td><td colspan="2">35,000 (380,000 ft^2)</td></tr>
<tr><td>Residential Occupants</td><td>count</td><td colspan="2">520</td></tr>
<tr><td>Office Workers</td><td>count</td><td colspan="2">590</td></tr>
<tr><td>Suspended Solids</td><td>mg/L</td><td>220</td><td>94</td><td><5</td></tr>
<tr><td>Volatile Solids</td><td>%</td><td>80</td><td>47</td><td>-</td></tr>
<tr><td>$cBOD_5$</td><td>mg/L</td><td>200</td><td>170</td><td>-</td></tr>
<tr><td>BOD_5</td><td>mg/L</td><td>240</td><td>190</td><td><10</td></tr>
<tr><td>Soluble BOD_5</td><td>mg/L</td><td>140</td><td>120</td><td>-</td></tr>
<tr><td>Soluble $cBOD_5$</td><td>mg/L</td><td>120</td><td>100</td><td>-</td></tr>
<tr><td>COD</td><td>mg/L</td><td>510</td><td>330</td><td>-</td></tr>
<tr><td>Soluble COD</td><td>mg/L</td><td>200</td><td>150</td><td>-</td></tr>
<tr><td>TKN</td><td>mg N/L</td><td>35</td><td>8.5</td><td>-</td></tr>
<tr><td>Soluble TKN</td><td>mg N/L</td><td>21</td><td>6.9</td><td>-</td></tr>
<tr><td>Ammonia</td><td>mg N/L</td><td>20</td><td>1.9</td><td>-</td></tr>
<tr><td>Total Phosphorus</td><td>mg P/L</td><td>5.6</td><td>1.1</td><td>-</td></tr>
<tr><td>Nitrite</td><td>mg N/L</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Nitrate</td><td>mg N/L</td><td>-</td><td>0.64</td><td>-</td></tr>
<tr><td>Average Summer</td><td>deg C</td><td>23</td><td>30</td><td>-</td></tr>
<tr><td>Average Winter</td><td>deg C</td><td>23</td><td>30</td><td>-</td></tr>
<tr><td>Chlorine Residual</td><td>mg/L</td><td>N/A</td><td>N/A</td><td>0.5-2.5</td></tr>
</table>

The analysis was performed for three separate wastewater treatment systems, AeMBR, AnMBR, and RVFW, designed to treat mixed wastewater and graywater for a hypothetical mixed-use building in downtown San Francisco. Table 1 lists the basic features of the building and the associated mixed wastewater and graywater flowrates. The building is 19 stories tall and has a total floor area of 35,000 m^2 (380,000 ft^2). Seventy percent of the building's total floor area is dedicated to residential units and associated common areas, providing housing for an estimated

520 persons. The remaining 30 percent of floor area is dedicated to commercial businesses employing an estimated 590 office workers.

Per capita generation of mixed wastewater was modeled as 136 liters per day (lpd) [35.8 gallons per day (gpd)], which is approximately 70 percent of the national average of 197 lpd (52 gpd) (DeOreo et al., 2016). This wastewater generation rate reflects the focus on water conservation in new developments in the San Francisco region. This level of water use can be compared to a high-efficiency water use estimate of 153 lpd (40.5 gpd) (DeOreo et al., 2016). Each office worker was assumed to generate 43 lpd (11.3 gpd) of wastewater (Schoen et al., 2018).

Seventy-two percent of residential indoor water use is associated with fixtures that generate graywater, with the remaining 28 percent contributing to blackwater flows (DeOreo et al., 2016). A larger fraction, 63 percent, of indoor commercial water use was assumed to be associated with blackwater flows based on survey results from four commercial office buildings (Dziegielewski et al., 2000). Life cycle inventory data were developed for the three on-site wastewater treatment systems capable of processing the quantity of mixed wastewater or graywater listed in Table 1. All treatment configurations were developed to ensure that guidelines for indoor NPR were met (Sharvelle et al., 2017). The building-scale treatment systems are transitional solutions that are connected to the centralized sewer system for disposal and treatment of primary and waste activated sludge. Figure 1 presents a system diagram that defines the boundaries of the modeled systems.

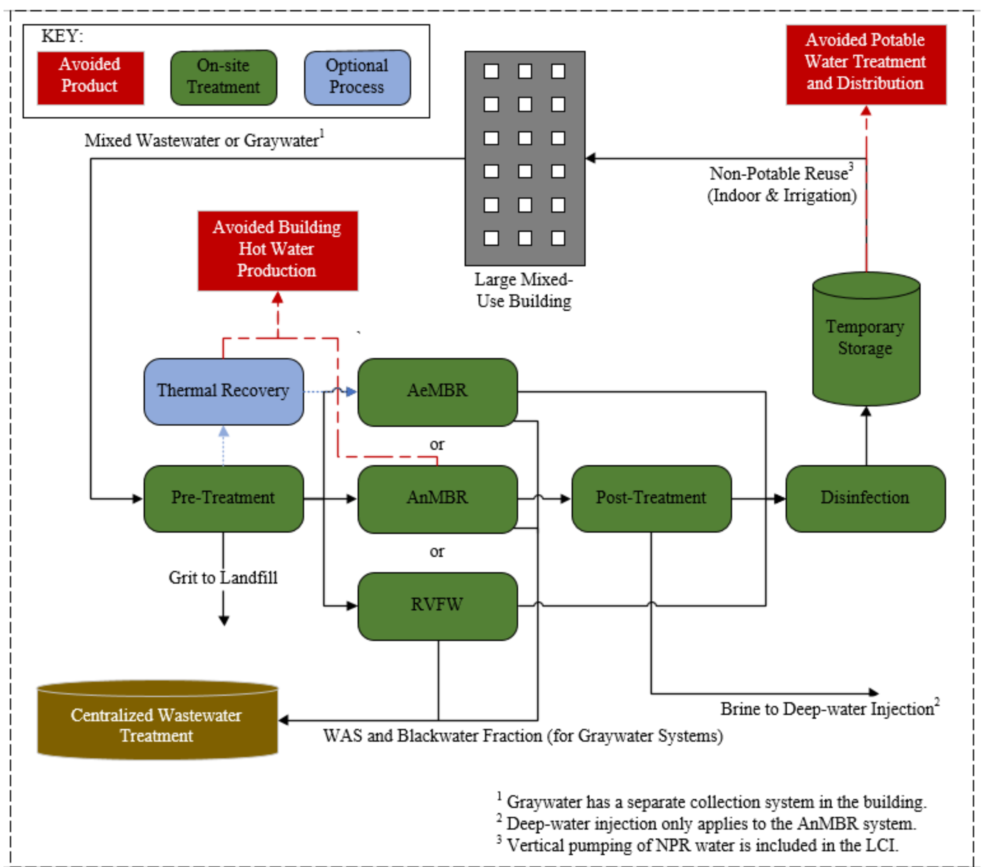

Figure 1. System Diagram Showing the Basic Layout of On-site Treatment Processes and Integration with the Mixed-Use Building.

The analysis considers three scenarios related to the quantity of mixed wastewater or graywater that is used for on-site NPR applications, both to assess the sensitivity of results to on-site reuse potential and to represent uncertainty regarding the quantity of water that can be reused on-site. Reuse water was assumed to replace potable drinking water, thereby limiting the quantity of water extracted by the local utility and avoiding the environmental burdens of treating water to potable quality. Environmental burdens of electricity use and water loss associated with distributing the potable water from the centralized facility to the building are also displaced.

The avoided burdens of potable treatment were based on LCI data for the Greater Cincinnati Water Works (GCWW) Richard Miller Treatment Plant (Cashman et al., 2014). LCI data were adjusted to reflect San Francisco drinking water treatment processes and the background electrical grid (Presidio Trust, 2016). Modeled drinking water treatment processes include: source water acquisition, flocculation, sedimentation, conditioning, UV disinfection, fluoridation, and chlorination. The model includes a 19% loss of incoming potable water during treatment and distribution, which leads to additional water demand. Electricity consumption during distribution was estimated using the median of reported distribution energy requirements from the literature (EPRI, 1996; IAMU, 2002; Hutson et al., 2004; Lundie et al., 2004; Carlson and Walburger, 2007; Lassaux et al., 2007; DeMonsabert et al., 2008; Maas, 2009; Amores et al., 2013). Estimation of environmental impacts associated with electricity consumption throughout the analysis was based on the 2016 California electrical grid mix.

Table 2 provides details on wastewater generation and on-site reuse potential for the three reuse scenarios. The low and high reuse scenarios were generated based on a range of estimates for irrigation water consumption and the fraction of total indoor water use attributable to toilet flushing and laundry water. The high reuse scenario was based on (Tchobanoglous et al., 2014), which estimates that 28 and 23 percent of indoor water use is attributable to toilet flushing and laundry water, respectively. Irrigation water consumption in the high reuse scenario was based on water use factors of 139 liters per square meter (3.4 gal/ft^2) and 244 liters per square meter (6 gal/ft^2) for residential and commercial building area, respectively (Refocus, 2015). The low reuse scenario values were based on (Sharvelle et al., 2013), which estimates that 15 and 11 percent of indoor water use is attributable to toilet flushing and laundry water, respectively. Irrigation water consumption in the low reuse scenario was based on California's Water Budget Workbook, version 1.01 (CDWR, 2010). The full reuse scenario assumes a hypothetical 100% reuse potential, but does not allocate usage to specific functions. Full utilization of treated wastewater could be feasible if buildings are able to share treated water with adjacent buildings or buildings with larger surface areas for irrigation.

Table 2. Water Reuse Scenarios.

Wastewater Scenario[1]		Low Reuse	High Reuse	Full Reuse
Wastewater Generation (m^3/year)	**Mixed WW**	34,600		
	Graywater	22,100		
On-site Reuse (m^3 year)	**Indoor Non-potable**	9,460	18,500	N/A[2]
	Irrigation	2,270	6,060	
Fraction of Mixed WW Reused On-site		35%	72%	100%
Fraction of Graywater Reused On-site		55%	100%	100%

[1] Values in the table have been rounded to three significant figures.
[2] The full reuse scenario assumes a hypothetical 100% reuse potential, but does not allocate usage to specific functions.

The LCI and cost analysis includes additional building materials required for the plumbing networks associated with distribution of reuse water and graywater collection, where applicable. Piping networks that are required regardless of water source or type were excluded from the system boundary as they will not affect the comparison among treatment options. Electricity consumption required to pump recycled water throughout the building was also included in the inventory. Electricity estimates are based on the differential increase in energy required to pump NPR water instead of potable water. The potable water system has an assumed system pressure of 586 kPa (85 psi) at the street connection. Table 3 lists material and energy LCI values associated with distribution of recycled water within the building.

Values are presented in Table 3 per cubic meter of wastewater or graywater treated. Due to the nature of the reuse scenarios the fraction of treated wastewater or graywater that can be reused on-site is not the same for wastewater and graywater, as displayed in Table 2. This difference should be considered when attempting to use or interpret the study results.

All treatment systems are connected to the centralized sewer for disposal of sludge and the blackwater portion of generated wastewater, in the case of graywater treatment systems. When the functional unit is expressed as a cubic meter of wastewater generated, the burdens of centralized treatment are included within the system boundary to allow a direct comparison between graywater and mixed wastewater treatment systems. The centralized wastewater treatment facility was modeled as a conventional activated sludge treatment plant, which is similar to San Francisco’s treatment system. The LCI also models anaerobic digestion of solids and energy recovery for the generated biogas using a combined heat and power system. Biosolids were assumed to be landfilled following dewatering.

Pretreatment

All treatment systems include equalization chambers and fine screening prior to the biological treatment process. The RVFW also includes a slant plate clarifier to minimize clogging of the media beds. An equalization chamber was included so that the biological treatment processes receive a consistent flow of influent wastewater or graywater. LCI data for the pretreatment processes includes estimates of major building materials (steel and concrete), electricity consumption, and disposal of screenings in a sanitary landfill (see Table 3).

Table 3. Summary Life Cycle Inventory Data

Unit Process	Input/Output	AeMBR, Building, Graywater	AeMBR, Building, Mixed Wastewater	AnMBR, Building, Graywater	AnMBR, Building Mixed Wastewater	RVFW, Building, Graywater	RVFW, Building, Mixed Wastewater	Units (per m^3 treated wastewater or graywater)
Fine Screen	**Electricity**	0.11	0.08	0.11	0.08	0.11	0.08	kWh
	Screening Disposal	4.1E-3	9.5E-3	4.1E-3	9.5E-3	4.1E-3	9.5E-3	kg
	Steel	1.3E-3	8.6E-4	1.3E-3	8.6E-4	1.3E-3	8.6E-4	kg
Equalization	**Concrete**	1.4E-5	1.1E-5	1.4E-5	1.1E-5	1.9E-5	1.6E-5	m^3
	Steel	8.0E-4	6.8E-4	8.0E-4	6.8E-4	5.3E-4	4.5E-4	kg
	Electricity	0.11	0.10	0.11	0.10	0.22	0.19	kWh
	HDPE	N/A	N/A	N/A	N/A	7.8E-5	7.2E-5	kg
Clarification	**Steel**	N/A	N/A	N/A	N/A	3.8E-3	3.6E-3	kg
	Sludge Disposal					7.3E-3	0.02	m^3
	Electricity					6.4E-4	1.5E-3	kWh
Biological Process	**Concrete**	2.5E-5	2.1E-5	5.0E-5	4.0E-5	9.3E-5	8.9E-5	m^3
	Steel	1.5E-3	1.3E-3	2.7E-3	2.1E-3	0.01	0.01	kg
	HDPE	-	-	1.0E-4	1.2E-4	8.3E-4	8.0E-4	kg
	Polyvinyl Fluoride	5.9E-4	5.9E-4	1.6E-3	1.6E-3	N/A	N/A	kg
	Lower Media, Crushed Limestone	N/A	N/A	N/A	N/A	0.02	0.02	kg
	Middle Media, Gravel					0.08	0.07	kg
	Organic Cover, Wood Chips					0.08	0.08	kg
	Sodium Hypochlorite	7.2E-4	7.2E-4	1.9E-3	1.9E-3	N/A	N/A	kg
	Electricity	0.43	0.62	0.82	0.81	0.42	0.41	kWh
	Methane (CH4) emissions	4.9E-3	5.9E-3	2.4E-3	3.5E-3	7.5E-4	9.1E-4	kg CH_4

Table 3. Summary Life Cycle Inventory Data

<table>
<tr><th>Unit Process</th><th>Input/Output</th><th>AeMBR, Building, Graywater</th><th>AeMBR, Building, Mixed Wastewater</th><th>AnMBR, Building, Graywater</th><th>AnMBR, Building Mixed Wastewater</th><th>RVFW, Building, Graywater</th><th>RVFW, Building, Mixed Wastewater</th><th>Units (per m^3 treated wastewater or graywater)</th></tr>
<tr><td rowspan="2"></td><td>Nitrous oxide (N_2O) emissions</td><td>5.0E-5</td><td>2.0E-4</td><td>-</td><td>-</td><td>3.3E-5</td><td>3.1E-5</td><td>kg N_2O</td></tr>
<tr><td>Sludge</td><td>8.3E-3</td><td>0.01</td><td>7.3E-3</td><td>7.3E-3</td><td>N/A</td><td>N/A</td><td>m^3</td></tr>
<tr><td rowspan="4">Thermal Recovery</td><td>Electricity</td><td>4.1</td><td>4.2</td><td rowspan="4" colspan="4">N/A</td><td>kWh</td></tr>
<tr><td>R-134a refrigerant emissions</td><td>1.6E-5</td><td>1.0E-5</td><td>kg</td></tr>
<tr><td>Natural Gas, Avoided</td><td>0.90</td><td>0.89</td><td>m^3</td></tr>
<tr><td>Electricity, Avoided</td><td>7.5</td><td>7.4</td><td>kWh</td></tr>
<tr><td>Biogas Recovery</td><td>Natural Gas, Avoided</td><td>N/A</td><td>N/A</td><td>0.05</td><td>0.07</td><td>N/A</td><td>N/A</td><td>m^3</td></tr>
<tr><td rowspan="6">Downflow Hanging Sponge</td><td>Electricity</td><td rowspan="11">N/A</td><td rowspan="11">N/A</td><td>0.04</td><td>0.04</td><td rowspan="11">N/A</td><td rowspan="11">N/A</td><td>kWh</td></tr>
<tr><td>Methane (CH_4) emissions</td><td>1.3E-4</td><td>1.5E-4</td><td>kg CH_4</td></tr>
<tr><td>Natural Gas</td><td>0.01</td><td>0.01</td><td>m^3</td></tr>
<tr><td>Concrete</td><td>2.5E-5</td><td>2.1E-5</td><td>m^3</td></tr>
<tr><td>Steel</td><td>1.2E-3</td><td>1.0E-3</td><td>kg</td></tr>
<tr><td>HDPE</td><td>2.3E-5</td><td>3.2E-5</td><td>kg</td></tr>
<tr><td rowspan="5">Zeolite</td><td>Zeolite</td><td>0.11</td><td>0.36</td><td>kg</td></tr>
<tr><td>NaCl (99+%)</td><td>0.06</td><td>0.23</td><td>kg NaCl</td></tr>
<tr><td>NaOH</td><td>0.20</td><td>0.20</td><td>kg NaOH</td></tr>
<tr><td>Electricity</td><td>0.03</td><td>0.05</td><td>kWh</td></tr>
<tr><td>Disposal, Brine Injection</td><td>5.5E-3</td><td>0.02</td><td>m^3</td></tr>
</table>

Table 3. Summary Life Cycle Inventory Data

Unit Process	Input/Output	AeMBR, Building, Graywater	AeMBR, Building, Mixed Wastewater	AnMBR, Building, Graywater	AnMBR, Building Mixed Wastewater	RVFW, Building, Graywater	RVFW, Building, Mixed Wastewater	Units (per m^3 treated wastewater or graywater)
UV	**Electricity**	0.02	0.01	0.02	0.01	0.06	0.04	kWh
	Steel	3.4E-5	3.2E-5	3.4E-5	3.2E-5	4.9E-5	3.2E-5	kg
Chlorination	**Concrete**	3.4E-6	3.0E-6	3.4E-6	3.0E-6	3.4E-6	3.0E-6	m^3
	Steel	8.5E-5	7.4E-5	8.5E-5	7.4E-5	8.5E-5	7.4E-5	kg
	Electricity	0.08	0.05	0.08	0.05	0.08	0.05	kWh
	Sodium Hypochlorite	3.2E-3	3.6E-3	5.8E-3	0.01	1.5E-3	1.6E-3	kg NaOCl
Ozone	**Electricity**	N/A				-	0.21	kWh
	Oxygen					-	0.14	kg
Water Storage	**HDPE**	9.0E-4	8.7E-4	9.0E-4	8.7E-4	1.8E-3	1.7E-3	kg
	Electricity	N/A	N/A	N/A	N/A	0.05	0.05	kWh
Building Reuse	**PEX Piping, 2.5 cm (1 in)**	2.4E-3	7.6E-4	2.4E-3	7.6E-4	2.4E-3	7.6E-4	m
	PEX Piping, 1.3 cm (1/2 in)	3.7E-4	1.1E-4	3.7E-4	1.1E-4	3.7E-4	1.1E-4	m
	PVC Piping, 2.5 cm (1 in)	8.6E-4	2.7E-4	8.6E-4	2.7E-4	8.6E-4	2.7E-4	m
	PVC Piping, 5 cm (2 in)	2.8E-4	8.8E-5	2.8E-4	8.8E-5	2.8E-4	8.8E-5	m
	Electricity	0.13	0.09	0.13	0.09	0.13	0.09	kWh

Aerobic Membrane Bioreactor

The AeMBR treatment process was modeled as a continuously-stirred tank reactor with a submerged membrane filter. The process was modeled in GPS-X™ version 7.0.1 to determine many of the primary LCI values (Hydromantis, 2017). The process has a 15-day solids retention time (SRT) and a 5-hour hydraulic retention time (HRT) for the combined biological and filtration process. Both values are within the range of reasonable estimates specified by Yoon (2016). GPS-X™ estimates a steady-state mixed liquor suspended solids concentration of approximately 12,000 mg/L, based on the specified SRT.

A permeate flux of 20 liters per m^2 per hour (LMH) was set in the GPS-X™ model and was used to determine the required membrane area in combination with the systems average daily flowrate. Membrane material estimates were based on hollow fiber membrane dimensions (Suez, 2017b). We assumed a ten-year membrane lifespan (Cote et al., 2012).

Aeration energy requirements were based on standard oxygen transfer efficiencies of 0.07 (Tarallo et al., 2015) and 0.02 (Sanitaire, 2014) per meter for fine and coarse bubble aeration. Tank depth was estimated to be 2.7 meters based on the required tank volume needed to achieve the design HRT and default depth-to-volume ratios drawn from GSP-X™. Coarse bubble aeration was used for cross membrane airflow intended for membrane cleaning. Due to the use of a single tank, membrane cleaning energy also satisfies a portion of biological oxygen demand. Cross-flow aerations requirements were estimated assuming a scour air demand of 0.225 m^3/m^2/hour. Membrane backflush occurs for 45 seconds every ten minutes at a flowrate of 40 LMH. Sodium hypochlorite is used for membrane cleaning and was estimated assuming that 950 liters of 12.5 percent NaOCl are required annually for a membrane surface area of 1,650 m^2 (Suez, 2017a). Electricity consumption for the AeMBR equals the sum of energy required for permeate pumping, backflush pumping, compressor operation, sludge pumping energy, and minor miscellaneous uses. Total electricity use for the AeMBR treating mixed wastewater was estimated to be 0.62 kWh/m^3 of treated wastewater.

Process greenhouse gas (GHG) emissions of methane (CH_4) and nitrous oxide (N_2O) were estimated using methods described in the IPCC Guidelines for National Inventories (Doorn et al., 2006). GPS-X™ was used to estimate biological oxygen demand (BOD) and total kjeldahl nitrogen (TKN) concentrations influent to the AeMBR treatment process, which serve as the basis of CH_4 and N_2O emissions estimates, respectively.

LCA results were also calculated for an AeMBR treatment process paired with thermal recovery of heat in the influent wastewater. Thermal energy is recovered prior to wastewater treatment. Wastewater and graywater enter the evaporator side of the heat pump at 23 and 30°C, respectively. The efficiency of heat recovery is expressed as a coefficient of performance (COP), which varies based on influent water temperature and equipment performance. Combined COPs, including both compressor and pump operation, of 2.5 and 2.6, were used for the mixed wastewater and graywater treatment systems, respectively (Kahraman and Çelebi, 2009). The same study was used to determine the difference in temperature between the inlet and outlet side of the evaporator, 4.2 and 4.3°C, for the mixed wastewater and graywater systems, which determines obtainable thermal power. Total thermal energy transferred to the building's hot water heating system is the sum of obtainable thermal power plus the share of compressor power that is transferred to the working fluid minus internal loss in the heat pump (Cipolla and

Maglionico, 2014). Two scenarios were generated where recovered thermal energy replace building hot water provided by either electric or natural gas hot water heaters. Energy factors for the natural gas and electric hot water heaters are 0.69 and 0.925, respectively (Hoeschele et al., 2012). The final heat pump LCI includes compressor and pump electricity consumption, avoided electricity or natural gas use, and fugitive emissions of the refrigerant R-134a (Greening and Azapagic, 2012).

Table 3 lists the LCI values used to estimate environmental impacts associated with operation of the AeMBR.

Anaerobic Membrane Bioreactor

The modeled AnMBR is a psychrophilic process that operates at ambient temperatures of approximately 23°C. The ability of MBRs to decouple HRT and SRT allows for the accumulation of slower growing psychrophilic organisms (Smith et al., 2013), making this technology possible. Biogas generated in the AnMBR is recovered to supplement provision of the building's hot water demand.

The AnMBR was based on the design of a continuously stirred tank reactor with a floating cover and mechanical mixing. A series of three parallel external tanks were specified to house the membrane units. The main AnMBR tank has an SRT of 60 days, an HRT of 8 hours (Song et al., 2018), and an MLSS concentration of 12,000 mg/L. The AnMBR was assumed to achieve a 90% reduction in influent chemical oxygen demand (COD) and BOD (Ho and Sung, 2009; Ho and Sung, 2010; Chang 2014). Effluent BOD concentration was estimated assuming a BOD:COD ratio of 0.3 (Tchobanoglous et al., 2014). Both nitrogen and phosphorus were assumed to have negligible removal within the AnMBR (Mai et al., 2018), with all influent TKN leaving the reactor as ammonia. The effluent TSS concentration was assumed to be less than 2 mg/L (Christian et al., 2010).

Electricity demand for mechanical mixing was estimated assuming an energy requirement of 13 watts/m^3 (0.5 HP/1000 ft^3), and a motor efficiency of 88% (Harris et al., 1982). The membrane surface area requirement was determined based on an assumed permeate flux of 7.5 LMH (Chang, 2014). Biogas sparging and periodic backflushing are used to prevent membrane fouling. Results are presented for both continuous and intermittent biogas sparging. A biogas recirculation rate of 0.23 Nm^3/m^2/hr was specified for both the continuous and intermittent sparging scenarios (Smith et al., 2014). Intermittent sparging occurs for 15 minutes out of every 2 hours (Feickert et al., 2012). Use of continuous membrane sparging is a more conservative choice that is less likely to experience membrane fouling. Membrane backflushing occurs for 45 seconds every ten minutes at a flowrate of 40 LMH. Sodium hypochlorite is used for membrane cleaning and was estimated assuming that 950 liters of 12.5 percent NaOCl are required annually for a membrane surface area of 1,650 m^2 (Suez, 2017a).

Biogas production was estimated based on methane production factors of 0.25 and 0.26 kg CH_4/kg COD removed in the 23 and 30°C reactors, respectively. Methane production factors were derived from (Martinez-Sosa et al., 2011) by linearly scaling based on reactor temperature. Energy recovery was estimated assuming 99% thermal efficiency of the biogas boiler, assuming 5% fugitive losses from the AnMBR reactor (UNFCCC, 2012). Avoided natural gas combustion is based on methane's higher heating value (HHV) and an assumed boiler efficiency of 80%.

Apart from carbon dioxide, emissions associated with biogas combustion were assumed to be equivalent to those of natural gas.

A downflow-hanging sponge (DHS) and zeolite adsorption system were utilized for post-treatment of AnMBR effluent for recovery and destruction of permeate methane and ammonium removal, respectively. It was estimated that between 21 and 27 percent of produced methane remains dissolved in permeate that exits the AnMBR. The first stage of the DHS reactor strips 73% of incoming methane from the permeate in a counter-flow reactor (Matsuura et al., 2015). The low airflow rate, 313 L/m^3 reactor volume/day, ensures that the methane concentration in the off-gas remains above 30% allowing successful energy recovery. The second stage of the DHS reactor oxidized the remaining methane, assuming 99% methane destruction (Matsuura et al., 2015). Remaining methane was assumed to be off-gassed, contributing fugitive emissions. The second-stage reactor has an airflow rate of 2,500 L/m^3 reactor volume/day. Additionally, the DHS reactor reduces COD and BOD concentrations by 55 and 73% and nitrifies 22% of influent ammonium. The DHS LCI consists of electricity consumption, fugitive methane emissions, steel, concrete, piping materials, and polyethylene sponge.

A zeolite adsorption system follows the DHS reactor to remove the majority of remaining effluent ammonium. Ammonium adsorbs to zeolite in a packed bed reactor. A solution of Sodium Chloride (NaCl) is circulated through the packed bed once effluent ammonium concentrations exceed five percent of the influent value. The zeolite system was assumed to be able to remove 95% of influent ammonium based on the work of Deng et al. (2014). The system design is based on natural zeolite with an initial adsorption capacity of 3.1 mg NH_4-N/g of zeolite. The media remains productive through nine regeneration cycles experiencing a 39% reduction in adsorption capacity. An average adsorption capacity of 2.4 mg NH_4-N/g zeolite was used to estimate the zeolite media requirement. An NaOH dose of 0.2 kg/m^3 of treated wastewater was used in the analysis (Deng et al., 2014). NaOH is used to raise the pH of the regeneration fluid, reducing the NaCl requirement. The resulting nitrogen rich brine solution is injected into deep wells, requiring 1.8 kWh of electricity per cubic meter of injected fluid. The zeolite system is expected to reduce effluent ammonium concentrations to less than 1.5 mg/L for both mixed wastewater and graywater systems.

Recirculating Vertical Flow Wetland

The RVFW treatment process was adapted from a pilot-scale project (Sklarz et al., 2010), that uses pumped re-circulation to minimize wetland space requirements while achieving high treatment performance. Clarified wastewater is distributed over the surface of a 0.6 meter thick media bed consisting of crushed limestone (lower layer), gravel, and a thin layer of soil. Water filters downwards through the media bed before dropping 0.5 meters into a collection basin, facilitating aeration. The media bed is supported by suspended stainless steel grating in a concrete planter box.

Gross et al. (2007a) suggests that 8 to 12 hours of active recirculation is sufficient to reach steady-state TSS and BOD removal. This finding corresponds to recirculation of 300 liters of wastewater over a 1 m^2 wetland cell, which corresponds to a treatment capacity of 0.6 m^3 wastewater/m^2 wetland area/day. This treatment capacity and a 12-hour recirculation period were used to determine the required wetland area. Sklarz et al. (2010) identified an optimal wastewater recirculation rate of 1.5 meters (water depth) per hour as applied to the surface of the wetland.

Average, respective, TSS and BOD removal efficiencies of 94% and 98% were assumed for both mixed wastewater and graywater (Gross et al., 2007a; Gross et al., 2007b; Gross et al., 2008; Sklarz et al., 2009; Sklarz et al., 2010; Alfiya et al., 2013), as treatment performance was found not to vary considerably with influent wastewater quality, when results are expressed as percent removal (Alfiya et al., 2013).

Pump power and associated electricity requirements were estimated considering vertical pumping distance, friction losses during pumped recirculation, and system flowrate. The modeled LCI also includes process GHG emissions of nitrous oxide (N_2O) (Teiter and Mander, 2005) and methane (CH_4) (IPCC, 2014).

Disinfection Processes

Disinfection processes were specified for each treatment system and wastewater type to meet or exceed log reduction targets (LRTs) appropriate for indoor NPR (Sharvelle et al., 2017). Table 4 lists NPR LRTs for mixed wastewater and graywater across three organism classes and the corresponding long reduction values (LRVs) achieved by each treatment system. LRVs for the three disinfection processes are dose dependent and are therefore specific to the dose values listed in the right two columns of Table 4. All LRTs and LRVs are based on the work of Sharvelle et al. (2017).

Table 4. Log Reduction Targets for Non-Potable Reuse and Corresponding Log Reduction Values for the Studied Wastewater Treatment Systems

Log reduction targets		**Enteric Viruses**	**Parasitic Protozoa**	**Enteric Bacteria**	**Units**	
Indoor NPR	**Mixed Wastewater**	8.5	7	6	10^{-4} infection risk	
	Graywater	6	4.5	3.5		
Irrigation, unrestricted	**Mixed Wastewater**	8	7	6		
	Graywater	5.5	4.5	3.5		
MBR - mixed WW		**Virus**	**Protozoa**	**Bacteria**		
Technology		**LRV**	**LRV**	**LRV**	**Dose**	**Dose Units**
Membrane bioreactor		5	5	5	n/a	n/a
Ozone		-	-	-	-	-
UV		-	4	2	30	mJ/cm^2
Chlorination		4	-	4	32	mg-min/L
Total System LRV		9	9	11		
MBR - graywater		**Virus**	**Protozoa**	**Bacteria**		
Technology		**LRV**	**LRV**	**LRV**	**Dose**	**Dose Units**
Membrane bioreactor		5	5	5	n/a	n/a
Ozone		-	-	-	-	-
UV		-	4	2	30	mJ/cm^2
Chlorination		4	-	4	32	mg-min/L
Total System LRV		9	9	11		
RVFW - mixed WW		**Virus**	**Protozoa**	**Bacteria**	**Dose**	**Dose Units**

Table 4. Log Reduction Targets for Non-Potable Reuse and Corresponding Log Reduction Values for the Studied Wastewater Treatment Systems

Technology	LRV	LRV	LRV		
RVFW	0.5	1	0.8	n/a	n/a
Ozone	4	2	4	8.3	mg-min/L
UV	1	4	4	55	mJ/cm^2
Chlorination	4	-	4	32	mg-min/L
Total System LRV	9.5	7	13		
RVFW - graywater	**Virus**	**Protozoa**	**Bacteria**		
Technology	**LRV**	**LRV**	**LRV**	**Dose**	**Dose Units**
RVFW	0.5	1	0.8	n/a	n/a
Ozone	-	-	-	-	mg-min/L
UV	2	4	4	95	mJ/cm^2
Chlorination	4	-	4	32	mg-min/L
Total System LRV	6.5	5	8.8		

The AeMBR and AnMBR treatment processes are expected to have an LRV of five or greater for all three organism classes, functionally reducing the need for additional high-dose disinfection steps. The RVFW is less effective at pathogen removal and requires additional disinfection steps or higher doses to make up the difference and achieve system LRTs.

Chlorination was specified for all treatment systems, and is legally required to maintain a free chlorine residual of 1 mg/L. Liquid sodium hypochlorite (NaOCl), 15% solution, was used as the disinfectant. Estimation of the required chlorine dose considers instantaneous chlorine demand of total organic carbon (from GPS-X™) and ammonia. Chlorine decay during the 30-minute contact time was estimated using a first-order decay equation. In addition to chemical requirement, the developed LCI includes electricity consumption for peristaltic pump operation and steel and concrete infrastructure requirements (Table 3).

Ultraviolet disinfection was specified for all treatment systems, with a minimum dose of 30 mJ/cm^2 (BGLUMR, 2014). Delivered intensity was determined based on nominal UV intensity as augmented by transmittance of the bulb's quartz sleeve (0.85) (Pirnie et al., 2006), a lamp aging factor (0.7) (Hiltunen et al., 2002), and the estimated fraction of bulb output in the UV spectrum (0.85) (Tchobanoglous et al., 2014). The listed unitless factors are multiplied by nominal intensity to estimate average delivered UV intensity. The effective UV dose is a function of delivered UV intensity and contact time. Electricity consumption was based on manufacturer specifications of the appropriate Sanitron® UV purifier (Atlantic UV Corp., 2007). The unit's mass in steel was included in the LCI as an estimate of infrastructure materials.

The RVFW system treating mixed wastewater required ozone disinfection to meet the LRT for viruses and protozoa. Estimation of the required ozone dose considers COD ozone demand. COD demand is exerted in the first chamber of a three-chamber ozone contact basin. The effective ozone dose was determined based on average ozone concentration and contact time (6 minutes) in the second two chambers. A first-order decay equation and an estimated ozone half-life of 20 minutes (Lenntech, 2018), was used to estimate the average ozone concentration.

Liquid oxygen and electricity consumption requirements were modeled based on manufacturer specifications for the Primozone® GM series of ozone generators (Primozone®, 2014).

Life Cycle Assessment Metrics and Scope

Table 5 lists the LCA impact categories along with their associated method and units. The U.S. EPA's Tool for the Reduction and Assessment of Chemical and environmental Impacts (TRACI), version 2.1 (Bare et al., 2002; Bare, 2011) was the primary methods source. Global warming potential 100-year characterization factors were taken from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (Myhre et al., 2013). Water Use and fossil fuel depletion potential were estimated using the ReCiPe life cycle impact assessment (LCIA) method (Goedkoop et al., 2009). The CED inventory indicator was adapted from Althaus et al., (2010), and includes all extraction and input of renewable and non-renewable energy.

Table 5. Summary of LCA and Cost Metrics

Metric	Method	Unit
Acidification Potential	TRACI 2.1	kg SO_2 eq.
Cost (Net Present Value)	LCCA	USD (2016)
Cumulative Energy Demand	Ecoinvent	MJ
Eutrophication Potential	TRACI 2.1	kg N eq.
Fossil Depletion Potential	ReCiPe	kg oil eq.
Global Warming Potential	TRACI 2.1	kg CO_2 eq.
Particulate Matter Formation Potential	TRACI 2.1	kg $PM_{2.5}$ eq.
Smog Formation Potential	TRACI 2.1	kg O_3 eq.
Water Use	ReCiPe	m^3

Life Cycle Cost Assessment

The life cycle cost of each treatment system was estimated considered one-time, periodic, and annual costs using the net present value (NPV) calculation depicted in Equation 1 (Fuller and Petersen, 1996). The analysis assumes a real discount rate of 3%, and does not include escalation rates beyond the standard inflation rate for any cost categories except for energy costs. Electricity costs were escalated using escalation factors specific to the California region (Lavappa et al., 2017).

$$Net\ Present\ Value = \sum \left(\frac{Cost_x}{(1+i)^x} \right)$$

Equation 1

Where:

NPV (2016 \$) = Net present value of all costs and revenues necessary to construct and operate the wastewater treatment facility
$Cost_x$ = Cost in future year x
i (%) = Real discount rate
x = number of years in the future

Total capital cost was calculated as the sum of unit process costs, direct costs, and indirect costs. Unit process costs include purchased equipment and installation expenditures. Direct costs represent expenditures required to integrate individual unit processes to the rest of the wastewater treatment system. Indirect costs include other expenditures such as professional services, profit, and contingency costs. Direct costs were estimated by applying cost factors to unit process costs. Indirect costs were estimated by applying indirect cost factors to the sum of unit process and direct costs plus estimated interest during construction (Equation 2). The 2017 interest rate from California's Clean Water State Revolving Fund, 1.7%, was used in the analysis (CWB, 2018).

$$I_C = \sum (Unit\ Process\ Costs + Direct\ Costs + Remaining\ Indirect\ Costs) \times T_{CP} \times \left(\frac{i_r}{2}\right)$$

Equation 2

Where:

I_C (2016 \$) = Interest paid during construction
Unit Process Costs (2016 \$) = Total unit process equipment and installation cost
Direct Costs (2016 \$) = Total direct costs
Remaining Indirect Costs (2014 \$) = Indirect costs, including miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, and technical
T_{CP} = Construction period, 3 years based on CAPDETWorks™ default construction period (Hydromantis, 2014)
i_r = Interest rate during construction, %

Total annual cost was estimated as the sum of operation and maintenance labor, material, chemical, and energy purchases. None of the treatment systems provide direct revenue. The cost of equipment replacement is included in material cost, considering the expected lifespan of plant components. Table 6 summarizes systems life cycle costs within the high reuse scenario.

Table 6. Summary of Life Cycle Costs for the High Reuse Scenario

Wastewater Type	Treatment System	Process	Interest[1]	Capital	O&M Labor	Material	Chemical	Energy
Mixed Wastewater	AeMBR	Thermal Recovery[2]	2,444	95,824	17,660	39,765	-	-
		Equalization	2,822	110,679	48,373	34,014	-	11,252
		Fine Screen	1,775	69,600	141,789	28,883	-	9,731
		AeMBR	10,404	408,015	400,566	265,307	817	72,170
		UV	283	11,088	19,982	2,757	-	1,588
		Chlorination	2,773	108,732	65,198	40,722	4,085	6,002
		Building Reuse	14,540	570,188	58,248	72,737	-	-
		Utility Payments	-	-	-	316,389	-	-
		Administration	-	-	1,370,314	-	-	-
		Total[3]	35,041	1,374,126	2,122,130	800,574	4,902	100,743
	AnMBR	Equalization	2,822	110,679	48,373	34,014	-	11,252
		Fine Screen	1,775	69,600	141,789	28,883	-	9,731
		AnMBR[4]	19,278	756,000	412,518	389,112	2,176	93,639
		Zeolite	8,834	346,439	137,214	44,432	110,541	5,262
		DHS	3,585	140,607	70,915	26,165	-	-
		UV	283	11,088	19,982	2,757	-	1,588
		Chlorination	2,773	108,732	96,143	40,722	14,092	6,002
		Building Reuse	14,540	570,188	58,248	72,737	-	-
		Utility Payments	-	-	-	163,117	-	-
		Administration	-	-	1,370,314	-	-	-
		Total	53,890	2,113,333	2,355,496	801,938	126,809	127,474
	RVFW	Equalization	3,338	130,901	55,976	39,081	-	21,930
		Clarification	4,181	163,945	292,643	11,392	-	-
		Fine Screen	3,944	154,651	242,978	64,177	-	9,731
		Wetland	21,568	845,809	389,182	103,926	-	47,070
		Ozone	4,080	159,990	461,445	92,501	9,741	24,320
		UV	580	22,736	20,626	7,087	-	4,119
		Chlorination	2,773	108,732	52,847	40,722	1,787	6,002
		Building Reuse	14,540	570,188	58,248	72,737	-	-
		Utility Payments	-	-	-	389,277	-	-
		Administration	-	-	1,370,314	-	-	-
		Total	55,004	2,156,952	2,944,259	820,900	11,528	113,172
Graywater	AeMBR	Thermal Recovery[2]	1,925	75,506	13,916	31,333	-	-

Table 6. Summary of Life Cycle Costs for the High Reuse Scenario

Wastewater Type	Treatment System	Process	Interest[1]	Capital	O&M Labor	Material	Chemical	Energy
		Equalization	2,494	97,815	44,313	31,512	-	7,875
		Fine Screen	1,344	52,699	129,300	21,869	-	7,875
		AeMBR	8,355	327,645	279,469	237,744	522	31,728
		UV	233	9,126	19,874	1,770	-	1,296
		Chlorination	2,723	106,793	55,853	40,315	2,323	6,002
		Building Reuse	26,292	1,031,059	95,577	109,967	-	-
		Utility Payments	-	-	-	831,998	-	-
		Administration	-	-	1,262,277	-	-	-
		Total[3]	43,366	1,700,643	1,900,579	1,306,509	2,845	54,776
	AnMBR	Equalization	2,494	97,815	44,313	31,512	-	7,875
		Fine Screen	1,344	52,699	129,300	21,869	-	7,875
		AnMBR[4]	13,639	534,879	343,615	338,242	1,393	60,671
		Zeolite	6,140	240,769	98,163	51,992	33,264	2,498
		DHS	2,158	84,625	62,846	17,509	-	-
		UV	233	9,126	19,874	1,770	-	1,296
		Chlorination	2,723	106,793	65,313	40,315	4,204	6,002
		Building Reuse	26,292	1,031,059	95,577	109,967	-	-
		Utility Payments	-	-	-	834,033	-	-
		Administration	-	-	1,262,277	-	-	-
		Total	55,023	2,157,765	2,121,278	1,447,210	38,861	86,217
	RVFW	Equalization	2,970	116,462	51,732	36,563	-	16,445
		Clarification	2,765	108,422	289,090	7,310	-	-
		Fine Screen	2,986	117,097	206,010	48,593	-	7,912
		Wetland	14,379	563,872	259,455	69,281	-	31,379
		UV	579.768	22,736	20626.36	7087.474	0	4,119
		Chlorination	2,723	106,793	47,097	40,315	1,088	6,002
		Building Reuse	26,292	1,031,059	95,577	109,967	-	-
		Utility Payments	-	-	-	836,465	-	-
		Administration	-	-	1,262,277	-	-	-
		Total	52,695	2,066,441	2,231,863	1,155,583	1,088	65,857

[1] Interest during construction, [2] Costs in this row are only applicable to the AeMBR with thermal recovery, [3] Total includes costs associated with the thermal recovery system., [4] AnMBR costs correspond to the system operating with continuous membrane sparging.

RESULTS

Figure 2 and Figure 3 present GWP and CED results for the three wastewater treatment systems in several water reuse and operational scenarios. Results are presented per cubic meter of wastewater generated within the building. In the mixed wastewater scenarios, 100% of generated wastewater is treated on-site. For the graywater scenarios, only the graywater fraction of generated wastewater (64%) is treated in the building, while the blackwater fraction is discharged to the sewer and is treated at the centralized wastewater treatment plant. The environmental burdens of centralized treatment are shown in the figure, and are generally minimal.

Stacked columns in the figures correspond to results for the high reuse scenario. Net impact results for the low reuse and full reuse scenarios are marked with a black “x” and “-“, respectively. Bar segments and net impact results that fall below the x-axis represent environmental credits and net environmental benefits, respectively. Bar segments titled “Water Recycling” are prominent environmental credits that represent avoided production and delivery of potable water. The environmental benefits of water recycling are consistent across wastewater treatment technologies for a given wastewater type. For most treatment systems, the graywater treatment option produces lower net GWP and CED for any given reuse scenario largely because it has sufficient flow to provide for NPR and has lower treatment requirements. The full reuse scenario yields net environmental impacts that are more comparable between the mixed wastewater and graywater treatment options.

The addition of a thermal recovery system to the AeMBR treatment process results in considerable GWP environmental benefits regardless of the type of water heater that is replaced with recovered thermal energy. Figure 2 and Figure 3 show that for both impact categories, it is more beneficial to replace an electric hot water heater when taking a life cycle perspective. Although, the electric hot water heater is more efficient at the point-of-use, the upstream inefficiencies during electricity generation and distribution provide a considerable avoided benefit when replaced with recovered thermal energy. This same reasoning explains why replacing a natural gas hot water heater with recovered thermal energy leads to a net increase in CED, indicating that the recovered thermal energy is not enough to outweigh the CED of the heat exchangers pump and compressor operation. Thermal recovery could also be successfully paired with the RVFW treatment system, yielding similar benefits.

Excluding the consideration of thermal recovery, what is most clear from the figure is the greater overall impact of the AnMBR treatment system assuming continuous biogas sparging, despite the environmental benefits associated with energy recovery. Net environmental burdens of the AnMBR biological treatment process are similar in magnitude to those of the AeMBR, but the post-treatment and brine disposal requirements considerably increase both GWP and CED.

All three treatment systems can produce net GWP benefits when treating graywater. In the low and high reuse scenarios all three treatment systems produce net environmental impacts when treating mixed wastewater, indicating that the benefits of avoiding potable treatment do not outweigh the impacts of establishing decentralized treatment systems in the San Francisco context.

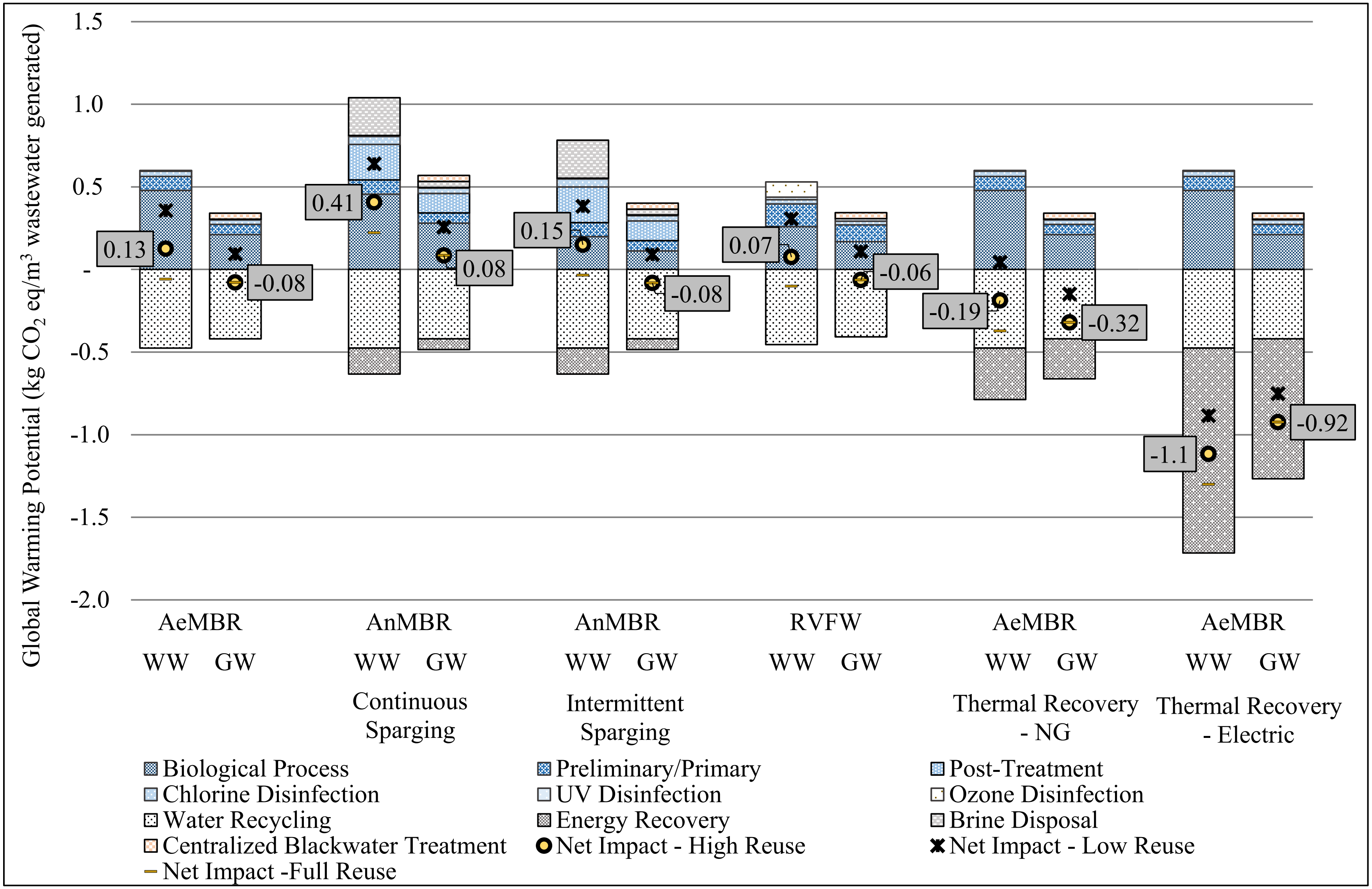

Figure 2. Global Warming Potential per Cubic Meter of Wastewater Generated for a Large Mixed Used Building for Several Types and Operational Modes of On-Site Wastewater Treatment (Bars Represent the High Reuse Scenario).

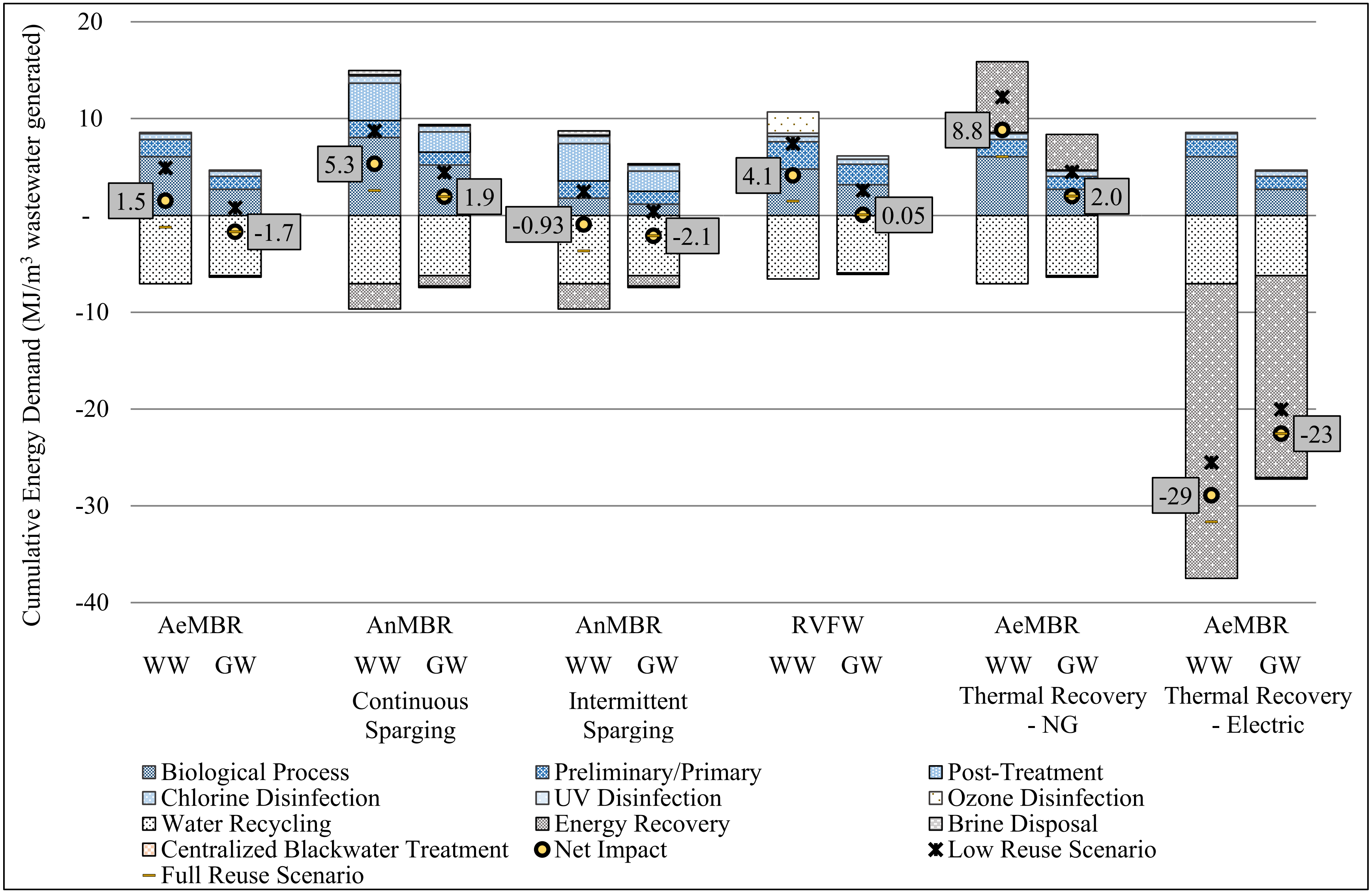

Figure 3. Cumulative Energy Demand per Cubic Meter of Wastewater Generated for a Large Mixed Used Building for Several Types and Operational Modes of On-Site Wastewater Treatment (Bars Represent the High Reuse Scenario).

Figure 4 presents LCCA results broken out by treatment stage for the high reuse scenario. Costs are presented as system NPV, calculated over a 30-year period. The AeMBR treatment system has the lowest system cost over a thirty-year period for both the mixed wastewater and graywater treatment options. The costs of installing and maintaining the biological treatment process is more expensive for the AnMBR than for the other two treatment systems. The AnMBR also incurs considerable costs associated with the DHS and zeolite post-treatment processes. The AnMBR is the most expensive graywater treatment option. The RVFW is the most expensive treatment option for treating mixed wastewater, due to high preliminary/primary treatment costs and the need for ozone disinfection. The "Other" cost treatment category is similar for the three treatment systems and is dominated by administrative and laboratory expenditures. Sludge handling and disposal costs include fees paid to the centralized wastewater treatment utility for disposal of WAS and the blackwater fraction, in the case of graywater treatment systems. LCCA results for the AeMBR with thermal recovery represent only the minor increase in cost associated with investment in the heat pump system. No avoided costs are included associated with reductions in natural gas consumption or avoided utility costs due to on-site treatment.

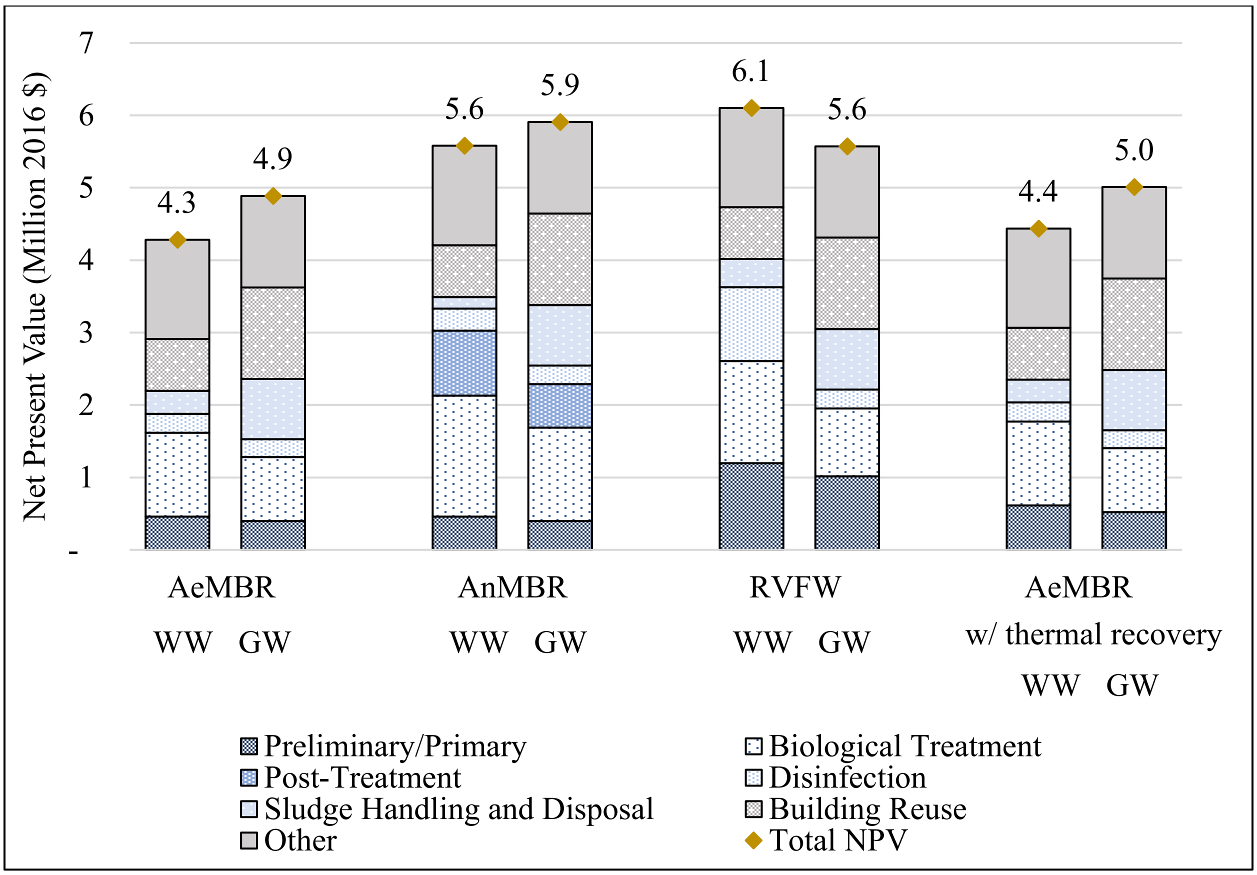

Figure 4. Life Cycle Cost Results for the High Reuse Scenario.

LCA and LCCA results presented in Table 7 and Table 8 are presented per cubic meter of mixed wastewater or graywater treated in the on-site treatment system assuming potable water displacement per the high reuse scenario. Using this formulation of the functional unit, it is not advisable to compare impacts directly between mixed wastewater and graywater treatment options, but rather to focus on comparisons between treatment technologies.

Table 7. Summary LCA and LCCA results for the Mixed Wastewater Treatment Systems in the High Reuse Scenario[1]

Indicator	Unit (/m^3 WW treated)	AeMBR	AeMBR - Thermal Recovery[b]	AnMBR - Continuous Sparging	AnMBR - Intermittent Sparging	RVFW
Acidification Potential	***kg SO_2 eq***	-3.6E-4	1.1E-3	2.6E-3	2.0E-3	-5.4E-5
Cumulative Energy Demand	***MJ***	1.5	8.7	5.3	-0.97	4.0
Eutrophication Potential	***kg N eq***	2.8E-4	5.6E-4	6.0E-4	5.5E-4	4.4E-4
Fossil Depletion Potential	***kg oil eq***	0.01	-0.20	0.06	-0.03	0.04
Global Warming Potential	***kg CO_2 eq***	0.12	-0.19	0.41	0.15	0.07
Particulate Matter Formation Potential	***kg $PM_{2.5}$ eq***	-3.8E-5	1.0E-4	1.3E-4	8.9E-5	1.4E-5
Smog Formation Potential	***kg O_3 eq***	3.9E-4	0.03	0.09	0.08	6.1E-3
Water Use	***m^3 H_2O***	-0.86	-0.86	-0.86	-0.86	-0.86
Cost (NPV)	***2016 $***	$ 4,300,000	$ 4,400,000	$ 5,600,000	$ 5,500,000	$ 6,100,000

Table 8. LCA and LCCA results for Graywater Treatment Systems in the High Reuse Scenario[1]

Indicator	Unit (/m^3 GW treated)	AeMBR	AeMBR - Thermal Recovery[b]	AnMBR - Continuous Sparging	AnMBR - Intermittent Sparging	RVFW
Acidification Potential	***kg SO_2 eq***	-9.8E-4	3.8E-4	5.3E-4	-7.9E-5	-6.6E-4
Cumulative Energy Demand	***MJ***	-2.4	3.3	3.2	-3.1	0.32
Eutrophication Potential	***kg N eq***	1.9E-4	4.6E-4	4.0E-4	3.4E-4	3.4E-4
Fossil Depletion Potential	***kg oil eq***	-0.04	-0.29	0.03	-0.05	-0.01
Global Warming Potential	***kg CO_2 eq***	-0.18	-0.56	0.08	-0.18	-0.16
Particulate Matter Formation Potential	***kg $PM_{2.5}$ eq***	-8.6E-5	4.5E-5	1.2E-5	-2.9E-5	-3.2E-5
Smog Formation Potential	***kg O_3 eq***	-8.5E-3	0.02	0.03	0.02	-2.4E-3
Water Use	***m^3 H_2O***	-1.2	-1.2	-1.2	-1.2	-1.2
Cost (NPV)	***2016 $***	$ 4,900,000	$ 5,000,000	$ 5,900,000	$ 5,900,000	$ 5,600,000

[1] Values are rounded to two significant figures.

DISCUSSION & CONCLUSIONS

Comparison of net impacts in the low reuse, high reuse, and full reuse scenarios clearly indicates the benefits of fully utilizing decentralized treatment of wastewater to avoid potable water production and distribution. Only in the full reuse scenario are the AeMBR, AnMBR (intermittent), and RVFW able to yield net GWP benefits from the switch to decentralized treatment of mixed wastewater. Given this finding, it is important to note that when reusing mixed wastewater only for NPR applications, there will always be a mismatch between the supply and demand for on-site, treated mixed wastewater. The analysis shows that supply and demand is well aligned when treating graywater in the high reuse scenario. The ability to sell or share treated wastewater or graywater with neighboring properties and businesses would alleviate this challenge in the short-term, until decentralized treatment becomes more widespread. These findings also point towards the opportunity that lies in direct potable reuse, to fully offset potable water production, while more closely aligning supply and demand for treated wastewater for an individual site or in more comprehensive community water reuse planning.

The AeMBR treatment system is an attractive option for decentralized wastewater treatment both in terms of cost and environmental impact. Table 7 and Table 8 show that the AeMBR treatment system yields the lowest environmental impacts per unit of treated wastewater in the majority of environmental impact categories. The RVFW treatment system produces competitive environmental impacts, but is generally outperformed by the AeMBR. Assuming continuous biogas sparging, the AnMBR is generally associated with the highest estimated environmental impact. Intermittent sparging makes the AnMBR more competitive, but it is unclear currently if intermittent sparging can produce consistent system performance. The AnMBR and RVFW treatment systems are currently more expensive to install and maintain than is the AeMBR treatment system. The AeMBR treatment option is commercially available, and is more mature than the other two treatment systems, which may improve in both performance and cost as the systems see wider deployment.

An important finding of this research concerns the importance of matching the volume of wastewater or graywater treated on-site to the expected demand for recycled water. Without the benefits of avoiding potable water treatment and distribution it will be challenging for small, decentralized treatment systems to match the performance of centralized treatment systems.

Results of this study are strongly linked to the environmental burdens of the local potable water treatment system, distribution network, and centralized wastewater treatment plant. The relative benefits of decentralized wastewater treatment are therefore expected to vary regionally depending on the configuration and efficiency of centralized water and wastewater utilities. Future work in this topic area will look to expand on the case-study approach taken in this analysis to produce a set of results that are more generalized and applicable in varying geographical contexts.

DISCLAIMER

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