Supplemental Material: Human health, economic and environmental assessment of onsite non-potable reuse systems for a large, mixed use urban building

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S1. Treatment System Design and Inventory Development

Life cycle inventories (LCI) were developed for each treatment configuration based on the designs necessary to achieve the desired effluent water quality discussed in the main document. This supplementary information section provides additional detail as to the specific design details of individual treatment system unit process. It is intended to support the overview provided in Section 2.1 of the main text. Table S1 [1] provides the physical/chemical water quality parameters assumed for mixed wastewater and source-separated graywater, as well as applicable effluent quality guidelines. The remainder of the section discusses the selection process and specific design details for individual unit processes.

Table S1. Wastewater Influent Characteristics and Target Effluent Quality for Unrestricted Urban Reuse

|  |  |  |
| --- | --- | --- |
| Water Quality Characteristics | *Influent Values* | *Target Effluent Quality* |
| Mixed WW | Graywater | Both |
| Characteristic | Unit | Medium Strength | Low Pollutant Load with Laundry | Effluent Quality for Unrestricted Urban Use |
| Suspended Solids | mg/L | 220 | 94 | <5 |
| Volatile Solids | % | 80 | 47 | - |
| cBOD5 | mg/L | 200 | 170 | - |
| BOD5 | mg/L | 240 | 190 | <10 |
| COD | mg/L | 510 | 330 | - |
| TKN | mg N/L | 35 | 8.5 | - |
| Ammonia | mg N/L | 20 | 1.9 | - |
| Nitrite | mg N/L | - | - | - |
| Nitrate | mg N/L | - | 0.64 | - |
| Total Phosphorus | mg P/L | 5.6 | 1.1 | - |
| Chlorine Residual | mg/L | - | - | 0.5-2.5 |

Table Acronyms: BOD – biochemical oxygen demand, cBOD- carbonaceous biochemical oxygen demand, COD – chemical oxygen demand

S1.1 Unit Process Selection to Achieve LRTs

Disinfection processes were specified for each of the wastewater treatment systems based on log reduction targets (LRTs) intended to achieve a risk level of 1 in 10,000 infections per person per year (ppy) considering several reuse applications. Log reduction values (LRVs) vary based on organism type, disinfection method, and applied dose as specified in Table S2. Biological processes also provide some level of treatment, which was taken into account when selecting disinfection unit processes so that the total (additive) LRT could be achieved. Table S3 shows LRVs assigned to individual biological and disinfection processes included in the study systems, and the corresponding disinfection dose.

Both MBR treatment processes were assigned a LRV of five for each pathogen class, which is conservative based on the LRV of six or more reported by [2]. Based on a lack of available data for the RVFW specifically, it was assigned LRVs for wetlands from Sharvelle et al. (2017), varying between 0.5 and 1 depending on organism type.

Most systems only require chlorine and ultraviolet (UV) disinfection processes to meet LRTs for non-potable reuse. Chlorination is legally required for all non-potable reuse systems, in order to maintain a free chlorine residual of 1 mg/L [2].

The RVFW treating mixed wastewater requires a third disinfection process, ozone, to meet the LRTs for viruses and protozoa.

Table S2. Log Reduction Values for Biological and Disinfection Processes (Sharvelle et al., 2017).

|   | **Enteric Viruses** | **Parasitic Protozoa** | **Enteric Bacteria** | **Units** |
| --- | --- | --- | --- | --- |
| **Membrane Bioreactora** | Log Reduction | 5 | 5 | 5 | log |
| **Wetland** | 0.5 | 1 | 0.8 | log |
| **Free Chlorine** | 1 Log10 | n/a | 2000-2600 | 0.4-0.6 | mg-min/L |
| 2 Log10 | 1.5-1.8 | n/a | 0.8-1.2 | mg-min/L |
| 3 Log10 | 2.2-2.6 | n/a | 1.2-1.8 | mg-min/L |
| 4 Log10 | 3-3.5 | n/a | 1.6-2.4 | mg-min/L |
| **Ozone** | 1 Log10 | n/a | 4-4.5 | 0.005-0.01 | mg-min/L |
| 2 Log10 | 0.25-0.3 | 8-8.5 | 0.01-0.02 | mg-min/L |
| 3 Log10 | 0.35-0.45 | 12-13 | 0.02-0.03 | mg-min/L |
| 4 Log10 | 0.5-0.6 | n/a | 0.03-0.04 | mg-min/L |
| **UV Radiation** | 1 Log10 | 50-60 | 2-3 | 10-15 | mJ/cm2 |
| 2 Log10 | 90-110 | 5-6 | 20-30 | mJ/cm2 |
| 3 Log10 | 140-150 | 11-12 | 30-45 | mJ/cm2 |
| 4 Log10 | 180-200 | 20-25 | 40-60 | mJ/cm2 |

a Log reduction values for AeMBRs and AnMBRs are based on the use of ultrafiltration membranes.

Table S3. Log Reduction Values of Selected Wastewater Treatment Processes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| MBR - mixed WW | Virus | Protozoa | Bacteria | Dose | Dose Units |
| Technology | LRV | LRV | LRV |
| Membrane bioreactor | 5 | 5 | 5 | n/a | n/a |
| Ozone | - | - | - | - | - |
| UV | 0 | 4 | 2 | 30 | mJ/cm2 |
| Chlorination | 4 | 0 | 4 | 32 | mg-min/L |
| Total System LRV | 9 | 9 | 11 |   |
| MBR - graywater | Virus | Protozoa | Bacteria | Dose | Dose Units |
| Technology | LRV | LRV | LRV |
| Membrane bioreactor | 5 | 5 | 5 | n/a | n/a |
| Ozone | - | - | - | - | - |
| UV | 0 | 4 | 2 | 30 | mJ/cm2 |
| Chlorination | 4 | 0 | 4 | 32 | mg-min/L |
| Total System LRV | 9 | 9 | 11 |   |
| RVFW - mixed WW | Virus | Protozoa | Bacteria | Dose | Dose Units |
| 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/cm2 |
| Chlorination | 4 | 0 | 4 | 32 | mg-min/L |
| Total System LRV | 9.5 | 7 | 12.8 |   |
| RVFW - graywater | Virus | Protozoa | Bacteria | Dose | Dose Units |
| Technology | LRV | LRV | LRV |
| RVFW | 0.5 | 1 | 0.8 | n/a | n/a |
| Ozone | - | - | - | - | mg-min/L |
| UV | 2 | 4 | 4 | 95 | mJ/cm2 |
| Chlorination | 4 | 0 | 4 | 32 | mg-min/L |
| Total System LRV | 6.5 | 5 | 8.8 |   |

S1.2 Pre-treatment

Each of the three treatment systems utilize a fine screen and equalization chamber for pre-treatment. The fine screen removes large particles and debris from influent that could damage or impede operation of the biological treatment units. Screenings are disposed of in a municipal solid waste landfill. A slant plate clarifier also precedes the RVFW to prevent unnecessary clogging of the media beds. Equalization chambers were sized to dampen fluctuation in hourly wastewater generation within the building. The LCI of these three processes includes electricity use and basic infrastructure materials (steel, concrete, and piping).

S1.3 Aerobic membrane bioreactor

The AeMBR combines a continuously-stirred aerobic reactor with a submerged membrane filter for solids separation. Solids are pumped from the reactor and disposed of in the sanitary sewer, where they are treated with the rest of the municipal waste stream.

Table S4 presents basic design values for the mixed wastewater and graywater AeMBR treatment processes. LCI electricity consumption accounts for aeration energy demand to provide both biological process aeration and membrane cleaning, permeate pumping, sludge pumping, and miscellaneous additional uses. The membrane is made out of polyvinyl fluoride and was sized based on the wastewater flowrate and the design membrane flux of 20 liters per m2 per hour (LMH). The analysis assumes a membrane lifespan of ten years [3]. Inputs of concrete and steel for tank construction were estimated based on the presented unit dimensions. Sodium hypochlorite is used for membrane cleaning and was estimated assuming that 950 liters of 12.5% NaOCl are used annually per 1,650 m2 of membrane area [4].

| Table S4. AeMBR Design Values |
| --- |
| **Parameter** | **Mixed Wastewater** | **Graywater** | **Units**  |
| Solids Retention Timea | 15 | days |
| Hydraulic Retention Timea | 5 | hours |
| Mixed Liquor Suspended Solidsb  | 12,000 | 11,000 | mg/L |
| Dissolved Oxygen Setpoint | 2 | mg O2/L |
| Membrane flux | 20 | LMH |
| Backflush fluxc | 40 | LMH |
| Membrane area, operation | 200 | 130 | m2 |
| Membrane area, total | 300 | 190 | m2 |
| Tank depth, operational | 2.7 | 2.7 | m |
| Tank length | 3.3 | 2.1 | m |
| Tank widthd | 1.1 | 1.1 | m |
| Tank volume, operational | 20 | 13 | m3 |
| Physical cleaning intervale | 10 | minutes |
| Physical cleaning duratione | 45 | seconds |
| Chemical cleaning intervale | 84 | hours |

a [5]

b Output of GPS-X model, dependent on selected SRT.

c Twice membrane flux [5].

d Tank width refers to individual tank. AeMBR consists of three parallel tanks.

e [6]

Table Acronyms: LMH – liters per m2 per hour

The LCI includes process greenhouse gas (GHG) emissions of methane and nitrous oxide developed using the IPCC Guidelines of National Inventories [7]. Methane and nitrous oxide emissions were estimated based on the quantity of BOD and total kjeldahl nitrogen (TKN) entering the AeMBR treatment process, respectively. GPS-X™ was used to estimate BOD and TKN concentrations influent to the AeMBR.

S1.4 Anaerobic membrane bioreactor

The AnMBR is a psychrophilic treatment process intended to operate at ambient temperatures, eliminating heat demand typical of many anaerobic processes, and producing methane as a beneficial by-product that is assumed to be used as an alternative heat source for the building’s hot water supply. The treatment process includes an anaerobic continuously stirred tank reactor (CSTR) and additional tanks to house the submerged membranes. Neither nitrogen or phosphorus are removed from wastewater in anaerobic reactors [8]. Therefore, downflow-hanging sponge (DHS) and zeolite adsorption post-treatment processes are necessary to ensure that treated effluent meets the criteria for unrestricted urban reuse. The DHS reactors recover or destroy methane dissolved in AnMBR permeate and have the additional benefit of removing 55% and 73% of COD and BOD remaining the wastewater. A zeolite adsorption system is used to remove ammonium from the wastewater to allow establishment of a free chlorine residual without excessive sodium NaOCl demand.

The AnMBR is a psychrophilic treatment process intended to operate at ambient temperatures, eliminating heat demand typical of many anaerobic processes, and producing methane as a beneficial by-product. The assumed temperature of influent mixed wastewater and graywater is 23⁰C and 30⁰C, respectively. Graywater temperature was calculated as the median of values reported in literature reviews of graywater treatment and reuse studies [9–12]. The mixed wastewater temperature is typical of medium strength domestic wastewater [13]. The treatment process includes an anaerobic continuously stirred tank reactor (CSTR) and additional tanks to house the submerged membranes.

Table S5 lists basic design and operational parameters of the mixed wastewater and graywater AnMBRs. The AnMBR has a 60 day solids retention time (SRT). Dimensions of the CSTR were estimated based on the influent flowrate and a hydraulic retention time (HRT) of eight hours. Membrane area and material requirements were determined based on wastewater flowrate and the design membrane flux of 7.5 LMH.

Inputs of concrete and steel needed for tank construction were estimated based on the presented unit dimensions. Electricity consumption of the AnMBR includes sludge pumping, operation of CSTR mixers, permeate pumping, and biogas recirculation (i.e., sparging) for membrane cleaning. The baseline scenario models continuous biogas sparging to ensure consistent performance, while intermittent sparging is assessed in a sensitivity analysis [14]. Sodium hypochlorite is used for periodic chemical cleaning of the membrane, with the same chemical requirement as discussed for the AeMBR.

| Table S5. AnMBR Design Values |
| --- |
| **System Component** | **Parameter** | **Mixed Wastewater** | **Graywater** | **Units** |
| Anaerobic Reactor | Solids retention timea | 60 | days |
| Hydraulic retention time | 8 | hours |
| Mixed liquor suspended solids | 12,000 | mg/L |
| COD/BOD removal | 90% | of influent concentration |
| Tank diameter | 4 | 3.5 | m |
| Tank height | 4.8 | 4 | m |
| Mixing power | 0.84 | 0.53 | HP |
| Biogas production | 14 | 6.3 | m3/day |
| Biogas recirculationa | 120 | 76 | m3/hour |
| Membrane Tank | Fluxa | 7.5 | LMH |
| Membrane area, operational | 530 | 340 | m2 |
| Membrane area, total | 790 | 500 | m2 |
| Tank depth, per train | 3.7 | m |
| Tank length, per trainc | 0.73 | 0.47 | m |
| Tank width, per trainc | 2.7 | m |

a [15,16]

Table Acronyms: BOD – biochemical oxygen demand, COD – chemical oxygen demand, LMH – liters per m2 per hour

Anaerobic processes generate methane which is trapped under the floating cover. The LCA quantifies the benefit of avoiding natural gas consumption, assuming that generated biogas is used as an alternative heat source for the building’s hot water supply. Biogas production was estimated as a function of COD removal, assuming that 90% of influent COD is removed [15,17,18]. Methane is produced at a rate of 0.25 and 0.26 m3 CH4 per kg of COD removed in the 23⁰C and 30⁰C reactors, respectively [19]. Five percent of produced methane was assumed to be lost through gaps in the floating cover, contributing process GHG emissions [20]. Neither nitrogen or phosphorus are removed from wastewater in anaerobic reactors [8]. All influent TKN was assumed to be released in the form of ammonia. Membrane processes produce effluent with less than 2 mg/L of total suspended solids [21].

Downflow-hanging sponge (DHS) and zeolite adsorption post-treatment processes are necessary to ensure that treated effluent meets the criteria for unrestricted urban reuse. The DHS reactors recover or destroy methane dissolved in AnMBR permeate and have the additional benefit of removing 55% and 73% of COD and BOD remaining the wastewater. Performance of the two-stage DHS system was based on the research of [22]. Methane removed from permeate in the stage-one reactor is recovered, contributing additional avoided natural gas benefits. Overall, the DHS reactor recovers or destroys 99.3% of permeate methane. Methane remaining in the treated wastewater following the DHS reactor was assumed to be off-gassed contributing further process GHG emissions. Electricity consumption of the DHS reactors includes wastewater pumping and blower operation. Steel, concrete, and piping material requirements were estimated based on unit dimensions.

A zeolite adsorption system is used to remove ammonium from the wastewater to allow establishment of a free chlorine residual without excessive sodium NaOCl demand. Ammonium adsorbs to zeolite in a packed bed reactor, which is then flushed with sodium chloride (NaCl) facilitating reuse of zeolite media. The resulting nitrogen rich brine solution is disposed of via deepwater injection, requiring 1.8 kWh of electricity per cubic meter of injected brine. Deng et al. [23] indicates that such a system should be able to remove greater than 95% of influent ammonium. The system was designed assuming an initial zeolite adsorption capacity of 3.1 mg NH4-N per gram of zeolite media, which maintains sufficient adsorption capacity throughout nine regeneration cycles. Average adsorption capacity across the nine regeneration cycles is 2.4 mg NH4-N per gram zeolite. Sodium hydroxide (NaOH) is also included in the LCI to raise the pH of the regeneration fluid, considerably reducing the NaCl requirement [23].

S1.5 Recirculating vertical flow wetland

The RVFW is a wetland based treatment process that uses active and continuous wastewater recirculation [24,25] to minimize land area requirements, making the process suitable for urban environments. Clarified wastewater is circulated over the surface of wetland planters. Wastewater filters downward through a 0.6 meter thick media bed consisting of crushed limestone and gravel. The media bed is suspended 0.5 meters above a concrete collection tank, into which wastewater falls, facilitating aeration. From the collection tank, water is recirculated to the surface.

Wastewater recirculation was determined based on results of a pilot-scale system (Gross et al. 2007), which reports that 8-12 hours of recirculation were sufficient to reach steady-state BOD and TSS removal when recirculating 300 liters of wastewater over one square meter of wetland area. This corresponds to treatment of 0.6 cubic meters of wastewater per square of wetland area per day. Sklarz et al. [25] identified an optimal recirculation rate of 1.5 meters (depth) per hour over the entire wetland surface. On average the system was assumed to remove 94% and 98% of influent TSS and BOD, respectively [24–27]

Process GHG emissions of nitrous oxide were estimated based on an emission factor of 0.006 kg N2O/m2 wetland area per year [28]. Methane emissions were estimated using the IPCC method and the average methane correction factor specified for vertical subsurface flow constructed wetlands [7].

Pump electricity requirements were estimated using the identified recirculation rate and estimated headloss in the distribution piping. Steel grating is included in the wetland design to suspend the media bed above the concrete collection basin. High-density polyethylene piping is used for wastewater distribution.

S1.6 Disinfection Processes

All treatment systems use chlorination and UV disinfection processes while the RVFW treating mixed wastewater requires a third disinfection process. Ozone was selected for its effectiveness against both viral and protozoan pathogens and the desire for a second barrier of protection against protozoa.

Liquid sodium hypochlorite (NaOCl) is used as the chemical disinfectant. Development of the result LCI value considers instantaneous chlorine demand due to ammonia and total organic carbon (TOC) present in the treated wastewater as well as chlorine decay in the contact basin. Electricity consumption was estimated for operation of the peristaltic pump.

The UV disinfectant dose is based on delivered UV intensity considering nominal UV intensity, transmittance of the quartz sleeve, bulb age, and bulb output in the UV spectrum. Commercially available Sanitron® UV units were specified based on the required delivered dose necessary to meet LRTs. Manufacturer specifications provide estimates of electricity consumption [29].

Ozone is produced from liquid oxygen in a Primozone® GM series ozone generator. Manufacturer specifications were used to develop LCI quantities for liquid oxygen and electricity consumption [30]. Ozone is injected into the effluent stream at the beginning of a three basin contact chamber. Instantaneous ozone demand is satisfied in the first chamber and is assessed on the basis of residual COD. Average ozone concentration in the second two chambers is used as the basis of effective ozone dose, considering ozone decay. Ozone decay was assessed assuming first-order decay and an average ozone half-life of 20 minutes [31].

S1.7 Thermal recovery

The analysis also looked at scenarios where the AeMBR treatment process was paired with a thermal recovery system. A heat pump is used to extract thermal energy from influent wastewater, transferring that thermal energy to the building’s hot water system, and avoiding natural gas consumption. Wastewater and graywater enter a heat pump at 23⁰C and 30⁰C, respectively. A coefficient of performance (COP) is used to express the efficiency of the heat recovery process. Combined COPs, which consider both compressor and pump operation, of 2.5 and 2.6 were used for mixed wastewater and graywater treatment systems, respectively [32]. Estimates of obtainable thermal power are based on the temperature difference between wastewater as it enters and exits the heat pump, which was estimated to be 4.2⁰C and 4.3⁰C for mixed wastewater and graywater treatment systems, respectively [32]. Total thermal recovery is the sum of obtainable thermal power plus the fraction of compressor power transferred to the working fluid less internal loss in the heat pump [33]. The thermal recovery LCI also includes electricity consumption of the pump and compressor, fugitive emissions of the R-134a refrigerant used in the heat pump [34], and avoided natural gas consumption.

S1.8 Collection and Distribution Systems

Distribution of the recycled water for NPR requires its own piping system. Graywater recycling also requires a separate collection system. The collection and distribution systems were modelled as polyvinyl chloride (PVC) for the main vertical and zone risers, while crosslinked polyethylene (PEX) was modelled for in-unit main and distribution piping [35]. Recycled water was assumed to displace potable water treatment and distribution, with a 20% loss rate of water modelled during centralized treatment and distribution [36]. Displaced energy requirements from potable water distribution were based on the national median value from the review of literature sources in Xue et al. [37]. Although other background inventories were based on conditions reflective of the San Francisco region, the city’s unique water supply system is gravity fed and distribution energy is anomalously low [38]. Net pumping energy for delivery of onsite recycled water was calculated as the difference between gross onsite pumping requirements and energy for potable water vertical pumping after taking into account the distribution pressure of the potable water supply [39].

S1.9 System Scaling

To adapt LCIs to different treatment capacities in a way that maintained original design characteristics and isolated the effects of treatment capacity on system cost and environmental impact, LCI components of individual unit processes were scaled in ways that maintained original design specifications (e.g., HRT, oxygen transfer rates, chemical dosage rates, etc.) but updated applicable dimensional line items (e.g., concrete, steel, energy, etc.). Tables S6 through S8 provide detail as to how individual LCI components of AeMBR, AnMBR and RVF systems were scaled. Impacts and cost of thermal recovery units were held constant per unit of flow. Final LCIs are provided in Tables S9 through S14.

Table S6. Scaling approach for AeMBR LCI components

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Unit Process | Parts Description | Unit | Constant/Variablea | Scaling Approach |
| Fine Screen | Electricity | kWh | Variable | Energy use equation from [40] |
| Fine Screen | Screening Disposal | kg | Constant | Constant fraction of flow |
| Fine Screen | Steel | kg | Constant | Constant screen area per unit of flow |
| Equalization | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Electricity | kWh | Variable | Pumping energy varied as function of flow, adherence to original design equations |
| AeMBR | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| AeMBR | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| AeMBR | Polyvinyl Fluoride | kg | Constant | Constant membrane area per unit of flow |
| AeMBR | Sodium Hypochlorite | kg | Constant | Constant dose rate |
| AeMBR | Electricity | kwh | Variable | Pumping energy varied as function of flow, adherence to original design equations |
| AeMBR | Methane | kg | Constant | Constant fraction of flow |
| AeMBR | N2O | kg | Constant | Constant fraction of flow |
| AeMBR | Sludge | m3 | Constant | Constant fraction of flow |
| UV | Electricity | kWh | Constant | Constant dose rate |
| UV | Steel | kg | Constant | Number of units increased/decreased to maintain constant UV dose |
| Chlorination | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Electricity | kwh | Constant | Constant electricity per unit of flow |
| Chlorination | Sodium Hypochlorite | kg | Constant | Constant dose rate |
| Storage | HDPE | kg | Constant | Number of units increased/decreased to maintain constant storage capacity |
| a Constant refers to line items that are constant per unit of flow treated. Examples include chemical dose rates, such as 3 mg of NaOCl per liter of water treated. |

| Table S7. Scaling approach for AnMBR LCI components |
| --- |
| **Unit Process** | **Parts Description** | **Unit** | **Constant/Variablea** | **Scaling Approach** |
| Fine Screen | Electricity | kWh | Variable | Energy use equation from [40] |
| Fine Screen | Screening Disposal | kg | Constant | Constant fraction of flow |
| Fine Screen | Steel | kg | Constant | Constant screen area per unit of flow |
| Equalization | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Electricity | kWh | Variable | Pumping energy varied as function of flow, adherence to original design equations |
| AnMBR | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| AnMBR | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| AnMBR | HDPE | kg | Variable | Updated to account for new basin dimensions |
| AnMBR | Polyvinyl Fluoride | kg | Constant | Constant membrane area per unit of flow |
| AnMBR | Sodium Hypochlorite | kg | Constant | Constant dose rate |
| AnMBR | Electricity | kwh | Variable | Pumping energy varied as function of flow, adherence to original design equations |
| AnMBR | Methane | kg | Constant | Constant fraction of flow |
| AnMBR | Sludge | m3 | Constant | Constant fraction of flow |
| AnMBR | Biogas Recovery | m3 | Constant | Constant fraction of flow |
| DHS | Electricity | kWh | Constant | Constant per unit of flow |
| DHS | Methane | kg | Constant | Constant per unit of flow |
| DHS | Natural Gas | m3 | Constant | Constant per unit of flow |
| DHS | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| DHS | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| DHS | HDPE | kg | Variable | Updated to account for new basin dimensions |
| Zeolite  | Zeolite | kg | Constant | Constant per unit of flow |
| Zeolite  | NaCl (99+%) | kg | Constant | Constant per unit of flow |
| Zeolite  | NaOH | kg | Constant | Constant per unit of flow |
| Zeolite  | Electricity | kWh | Variable | Scaled according to head associated with modified reaction chamber |
| Zeolite  | Disposal, Brine Injection | m3 | Constant | Constant fraction of flow |
| UV | Electricity | kWh | Constant | Constant dose rate |
| UV | Steel | kg | Constant | Number of units increased/decreased to maintain constant UV dose |
| Chlorination | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Electricity | kwh | Constant | Constant electricity per unit of flow |
| Chlorination | Sodium Hypochlorite | kg | Constant | Constant dose rate |
| Storage | HDPE | kg | Constant | Number of units increased/decreased to maintain constant storage capacity |
| a Constant refers to line items that are constant per unit of flow treated. Examples include chemical dose rates, such as 3 mg of NaOCl per liter of water treated. |

| Table S8. Scaling approach for RVFW LCI components |
| --- |
| **Unit Process** | **Parts Description** | **Unit** | **Constant/Variablea** | **Scaling Approach** |
| Fine Screen | Electricity | kWh | Variable | Energy use equation from [40] |
| Fine Screen | Screening Disposal | kg | Constant | Constant fraction of flow |
| Fine Screen | Steel | kg | Constant | Constant screen area per unit of flow |
| Clarifier | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Clarifier | Sludge Disposal | m3 | Constant | Constant fraction of flow |
| Clarifier | Electricity | kWh | Constant | Constant per unit of flow |
| Equalization | Concrete | m3 | Constant | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Equalization | Electricity | kWh | Variable | Pumping energy varied as function of flow, adherence to original design equations |
| RVFW | Concrete | m3 | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | Steel - Pumps | kg | Constant | Pump size held constant, number of pumps changed based on flow |
| RVFW | Steel - Grating | kg | Constant | Number of basins varied to maintain constant loading rate |
| RVFW | Steel - Rebar | kg | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | HDPE | kg | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | Electricity | kwh | Variable | Varied to account for new basin dimensions |
| RVFW | Lower Media, Crushed Limestone | kg | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | Middle Media, Gravel | kg | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | Organic Cover, Wood Chips | kg | Variable | Number of basins varied to maintain constant loading rate |
| RVFW | Methane | kg | Constant | Constant fraction of flow |
| RVFW | CO2, biogenic | kg | Constant | Constant fraction of flow |
| RVFW | N2O | kg | Constant | Constant fraction of flow |
| UV | Electricity | kWh | Constant | Constant dose rate |
| UV | Steel | kg | Constant | Number of units increased/decreased to maintain constant UV dose |
| Chlorination | Concrete | m3 | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Steel | kg | Variable | Basin volume scaled to maintain HRT and depth to area ratio. |
| Chlorination | Electricity | kwh | Constant | Constant electricity per unit of flow |
| Chlorination | Sodium Hypochlorite | kg | Constant | Constant dose rate |
| Storage | Electricity | kWh | Constant | Constant electricity per unit of flow |
| Storage | HDPE | kg | Constant | Number of units increased/decreased to maintain constant storage capacity |
| a Constant refers to line items that are constant per unit of flow treated. Examples include chemical dose rates, such as 3 mg of NaOCl per liter of water treated. |

S1.10 Life cycle inventories

Resulting LCIs for each treatment system are provided in Table S9-S11.

Table S9. Graywater AeMBR LCI.

| Unit Process | Inventory Item | Scenario 1 | Scenario 2 | Scenario 3 | Units (per m3 treated graywater) |
| --- | --- | --- | --- | --- | --- |
| Partial Treatment | Full Treatment | Excess Treatment |
| Centralized Wastewater | Solids and Residual Blackwater | 1.40 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1.00 | 1.00 | 0.830 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 4.07E-3 | 4.07E-3 | 4.07E-3 | kg |
| Steel | 2.14E-3 | 1.65E-3 | 1.34E-3 | kg |
| Equalization | Concrete | 1.82E-5 | 1.62E-5 | 1.48E-5 | m3 |
| Steel | 1.08E-3 | 9.64E-4 | 8.81E-4 | kg |
| Electricity | 0.095 | 0.095 | 0.095 | kWh |
| AeMBR | Concrete | 2.94E-5 | 2.59E-5 | 2.36E-5 | m3 |
| Steel | 1.87E-3 | 1.63E-3 | 1.47E-3 | kg |
| Polyvinyl Fluoride | 5.92E-4 | 5.92E-4 | 5.92E-4 | kg |
| Sodium Hypochlorite | 7.19E-4 | 7.19E-4 | 7.19E-4 | kg |
| Electricity | 0.428 | 0.428 | 0.428 | kwh |
| Methane | 4.86E-3 | 4.86E-3 | 4.86E-3 | kg |
| N2O | 5.01E-5 | 5.01E-5 | 5.01E-5 | kg |
| Sludge | 8.32E-3 | 8.32E-3 | 8.32E-3 | m3 |
| UV | Electricity | 0.017 | 0.017 | 0.017 | kWh |
| Steel | 3.42E-5 | 3.42E-5 | 3.42E-5 | kg |
| Chlorination | Concrete | 1.92E-6 | 1.73E-6 | 1.59E-6 | m3 |
| Steel | 5.18E-5 | 4.64E-5 | 4.26E-5 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 3.20E-3 | 3.20E-3 | 3.20E-3 | kg NaOCl |
| Storage | HDPE | 7.21E-4 | 1.11E-3 | 9.01E-4 | kg |
| Recycled Water Delivery | Electricity | 0.100 | 0.100 | 0.100 | kWh |
| PEX pipe, 1/2" | 3.66E-4 | 3.66E-4 | 3.66E-4 | m |
| PEX pipe, 1" | 2.40E-3 | 2.40E-3 | 2.40E-3 | m |
| PVC pipe, 1" | 8.53E-4 | 8.53E-4 | 8.53E-4 | m |
| PVC pipe, 2" | 2.79E-4 | 2.79E-4 | 2.79E-4 | m |
| Thermal Recoverya | Electricity | 4.10 | 4.10 | 4.10 | kWh |
| Electricity, Avoided | 7.52 | 7.52 | 7.52 | kWh |
| Natural Gas, Avoided | 0.901 | 0.901 | 0.901 | m3 |
| R-134a, emission to air | 1.56E-5 | 1.56E-5 | 1.56E-5 | kg |

a Optional unit process.

Table S10. Mixed Wastewater AeMBR

| Unit Process | Inventory Item | Scenario 1 | Scenario 2 | Scenario 3 | Units (per m3 treated wastewater) |
| --- | --- | --- | --- | --- | --- |
| Partial Treatment | Full Treatment | Excess Treatment |
| Centralized Wastewater | Treatment of Offsite Water | 1.40 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1.00 | 1.00 | 0.830 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 9.54E-3 | 9.54E-3 | 9.54E-3 | kg |
| Steel | 2.14E-3 | 1.65E-3 | 1.34E-3 | kg |
| Equalization | Concrete | 1.82E-5 | 1.62E-5 | 1.48E-5 | m3 |
| Steel | 1.08E-3 | 9.64E-4 | 8.81E-4 | kg |
| Electricity | 0.095 | 0.095 | 0.095 | kWh |
| AeMBR | Concrete | 2.94E-5 | 2.59E-5 | 2.36E-5 | m3 |
| Steel | 1.87E-3 | 1.63E-3 | 1.47E-3 | kg |
| Polyvinyl Fluoride | 5.92E-4 | 5.92E-4 | 5.92E-4 | kg |
| Sodium Hypochlorite | 7.19E-4 | 7.19E-4 | 7.19E-4 | kg |
| Electricity | 0.622 | 0.622 | 0.622 | kwh |
| Methane | 5.94E-3 | 5.94E-3 | 5.94E-3 | kg |
| N2O | 2.03E-4 | 2.03E-4 | 2.03E-4 | kg |
| Sludge | 0.014 | 0.014 | 0.014 | m3 |
| UV | Electricity | 0.014 | 0.014 | 0.014 | kWh |
| Steel | 3.15E-5 | 3.15E-5 | 3.15E-5 | kg |
| Chlorination | Concrete | 1.86E-6 | 1.68E-6 | 1.55E-6 | m3 |
| Steel | 5.08E-5 | 4.56E-5 | 4.19E-5 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 3.60E-3 | 3.60E-3 | 3.60E-3 | kg NaOCl |
| Storage | HDPE | 7.21E-4 | 1.11E-3 | 9.01E-4 | kg |
| Recycled Water Delivery | Electricity | 0.100 | 0.100 | 0.100 | kWh |
| PEX pipe, 1/2" | 3.66E-4 | 3.66E-4 | 3.66E-4 | m |
| PEX pipe, 1" | 2.40E-3 | 2.40E-3 | 2.40E-3 | m |
| PVC pipe, 1" | 8.53E-4 | 8.53E-4 | 8.53E-4 | m |
| PVC pipe, 2" | 2.79E-4 | 2.79E-4 | 2.79E-4 | m |
| Thermal Recoverya | Electricity | 4.21 | 4.21 | 4.21 | kWh |
| Electricity, Avoided | 7.40 | 7.40 | 7.40 | kWh |
| Natural Gas, Avoided | 0.887 | 0.887 | 0.887 | m3 |
| R-134a, emission to air | 9.98E-6 | 1.00 | 2.00 | kg |

a Optional unit process

| Table S11. Graywater AnMBR LCI. |
| --- |
| **Unit Process** | **Inventory Item** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Units (per m3 treated graywater)** |
| **Partial Treatment** | **Full Treatment** | **Excess Treatment** |
| Centralized Wastewater | Treatment of Offsite Water | 1.40 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1.00 | 1.00 | 0.830 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 4.07E-3 | 4.07E-3 | 4.07E-3 | kg |
| Steel | 2.14E-3 | 1.65E-3 | 1.34E-3 | kg |
| Equalization | Concrete | 1.82E-5 | 1.62E-5 | 1.48E-5 | m3 |
| Steel | 1.08E-3 | 9.64E-4 | 8.81E-4 | kg |
| Electricity | 0.095 | 0.095 | 0.095 | kWh |
| Chlorination | Concrete | 1.92E-6 | 1.73E-6 | 1.59E-6 | m3 |
| Steel | 5.18E-5 | 4.64E-5 | 4.26E-5 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 5.79E-3 | 5.79E-3 | 5.79E-3 | kg NaOCl |
| AnMBR | Concrete | 6.53E-5 | 5.58E-5 | 4.97E-5 | m3 |
| Steel | 3.56E-3 | 3.01E-3 | 2.66E-3 | kg |
| HDPE | 1.56E-4 | 1.24E-4 | 1.04E-4 | kg |
| Polyvinyl Fluoride | 1.58E-3 | 1.58E-3 | 1.58E-3 | kg |
| Sodium Hypochlorite | 1.92E-3 | 1.92E-3 | 1.92E-3 | kg |
| Electricity | 0.726 | 0.749 | 0.768 | kwh |
| Electricity Sensitivity | 0.149 | 0.150 | 0.152 | kwh |
| Methane | 2.42E-3 | 2.42E-3 | 2.42E-3 | kg |
| Sludge Disposal | 7.25E-3 | 7.25E-3 | 7.25E-3 | m3 |
| Biogas Recovery | Natural Gas | 0.045 | 0.045 | 0.045 | m3 |
| DHS | Electricity | 0.035 | 0.035 | 0.035 | kWh |
| Methane | 1.29E-4 | 1.29E-4 | 1.29E-4 | kg |
| Natural Gas | 0.013 | 0.013 | 0.013 | m3 |
| Concrete | 3.07E-5 | 2.75E-5 | 2.53E-5 | m3 |
| Steel | 1.40E-3 | 1.28E-3 | 1.19E-3 | kg |
| HDPE | 3.43E-5 | 2.76E-5 | 2.33E-5 | kg |
| Zeolite | Zeolite | 0.112 | 0.112 | 0.112 | kg |
| NaCl (99+%) | 0.055 | 0.055 | 0.055 | kg |
| NaOH | 0.200 | 0.200 | 0.200 | kg |
| Electricity | 0.025 | 0.029 | 0.034 | kWh |
| Disposal, Brine Injection | 5.51E-3 | 5.51E-3 | 5.51E-3 | m3 |
| UV | Electricity | 0.017 | 0.017 | 0.017 | kWh |
| Steel | 3.42E-5 | 3.42E-5 | 3.42E-5 | kg |
| Storage | HDPE | 7.21E-4 | 1.11E-3 | 9.01E-4 | kg |
| Recycled Water Delivery | Electricity | 0.100 | 0.100 | 0.083 | kWh |
| PEX pipe, 1/2" | 3.66E-4 | 3.66E-4 | 3.66E-4 | m |
| PEX pipe, 1" | 2.40E-3 | 2.40E-3 | 2.40E-3 | m |
| PVC pipe, 1" | 8.53E-4 | 8.53E-4 | 8.53E-4 | m |
| PVC pipe, 2" | 2.79E-4 | 2.79E-4 | 2.79E-4 | m |

| Table S12. Mixed Wastewater AnMBR LCI |
| --- |
| **Unit Process** | **Inventory Item** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Units (per m3 treated wastewater)** |
| **Partial Treatment** | **Full Treatment** | **Excess Treatment** |
| Centralized Wastewater | Treatment of Offsite Water | 1.40 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1.00 | 1.00 | 0.830 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 9.54E-3 | 9.54E-3 | 9.54E-3 | kg |
| Steel | 2.14E-3 | 1.65E-3 | 1.34E-3 | kg |
| Equalization | Concrete | 1.82E-5 | 1.62E-5 | 1.48E-5 | m3 |
| Steel | 1.08E-3 | 9.64E-4 | 8.81E-4 | kg |
| Electricity | 0.095 | 0.095 | 0.095 | kWh |
| Chlorination | Concrete | 1.95E-6 | 1.75E-6 | 1.62E-6 | m3 |
| Steel | 5.25E-5 | 4.71E-5 | 4.32E-5 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 0.012 | 0.012 | 0.012 | kg NaOCl |
| AnMBR | Concrete | 6.53E-5 | 5.58E-5 | 4.97E-5 | m3 |
| Steel | 3.56E-3 | 3.01E-3 | 2.66E-3 | kg |
| HDPE | 2.69E-4 | 2.12E-4 | 1.77E-4 | kg |
| Polyvinyl Fluoride | 1.58E-3 | 1.58E-3 | 1.58E-3 | kg |
| Sodium Hypochlorite | 1.92E-3 | 1.92E-3 | 1.92E-3 | kg |
| Electricity | 0.715 | 0.737 | 0.755 | kwh |
| Electricity Sensitivity | 0.148 | 0.150 | 0.151 | kwh |
| Methane | 3.49E-3 | 3.49E-3 | 3.49E-3 | kg |
| Sludge Disposal | 7.25E-3 | 7.25E-3 | 7.25E-3 | m3 |
| Natural Gas | 0.070 | 0.070 | 0.070 | m3 |
| DHS | Electricity | 0.035 | 0.035 | 0.035 | kWh |
| Methane | 1.46E-4 | 1.46E-4 | 1.46E-4 | kg |
| Natural Gas | 0.014 | 0.014 | 0.014 | m3 |
| Concrete | 3.07E-5 | 2.75E-5 | 2.53E-5 | m3 |
| Steel | 1.40E-3 | 1.28E-3 | 1.19E-3 | kg |
| HDPE | 6.35E-5 | 5.16E-5 | 4.40E-5 | kg |
| Zeolite | Zeolite | 0.360 | 0.360 | 0.360 | kg |
| NaCl (99+%) | 0.227 | 0.227 | 0.227 | kg |
| NaOH | 0.200 | 0.200 | 0.200 | kg |
| Electricity | 0.024 | 0.029 | 0.034 | kWh |
| Disposal, Brine Injection | 0.023 | 0.023 | 0.023 | m3 |
| UV | Electricity | 0.034 | 0.026 | 0.021 | kWh |
| Steel | 3.15E-5 | 3.15E-5 | 3.15E-5 | kg |
| Storage | HDPE | 7.21E-4 | 1.11E-3 | 9.01E-4 | kg |
| Recycled Water Delivery | Electricity | 0.100 | 0.100 | 0.083 | kWh |
| PEX pipe, 1/2" | 1.15E-3 | 1.15E-3 | 1.15E-3 | m |
| PEX pipe, 1" | 7.56E-4 | 7.56E-4 | 7.56E-4 | m |
| PVC pipe, 1" | 2.68E-4 | 2.68E-4 | 2.68E-4 | m |
| PVC pipe, 2" | 8.78E-5 | 8.78E-5 | 8.78E-5 | m |

Table S13. Graywater RVFW LCI.

| Unit Process | Inventory Item | Scenario 1 | Scenario 2 | Scenario 3 | Units (per m3 treated graywater) |
| --- | --- | --- | --- | --- | --- |
| Partial Treatment | Full Treatment | Excess Treatment |
| Centralized Wastewater | Treatment of Offsite Water | 1.40 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1.00 | 1.00 | 0.830 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 4.08E-3 | 4.08E-3 | 4.08E-3 | kg |
| Steel | 2.14E-3 | 1.65E-3 | 1.34E-3 | kg |
| Chlorination | Concrete | 1.93E-6 | 1.74E-6 | 1.60E-6 | m3 |
| Steel | 6.85E-5 | 5.27E-5 | 4.28E-5 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 1.50E-3 | 1.50E-3 | 1.50E-3 | kg NaOCl |
| RVFW | Concrete | 7.45E-5 | 5.73E-5 | 9.32E-5 | m3 |
| Steel | 4.99E-5 | 3.84E-5 | 6.24E-5 | kg |
| Steel | 7.86E-3 | 7.86E-3 | 7.86E-3 | kg |
| Steel | 2.13E-3 | 1.64E-3 | 2.67E-3 | kg |
| HDPE | 6.66E-4 | 5.12E-4 | 8.32E-4 | kg |
| Electricity | 0.338 | 0.260 | 0.423 | kwh |
| Lower Media, Crushed Limestone | 0.017 | 0.013 | 0.022 | kg |
| Middle Media, Gravel | 0.061 | 0.047 | 0.076 | kg |
| Organic Cover, Wood Chips | 0.065 | 0.050 | 0.081 | kg |
| Methane | 7.45E-4 | 7.45E-4 | 7.45E-4 | kg |
| CO2, biogenic | 0.015 | 0.012 | 0.019 | kg |
| N2O | 2.61E-5 | 2.00E-5 | 3.26E-5 | kg |
| Clarifier | Steel | 6.07E-3 | 4.67E-3 | 3.80E-3 | kg |
| Sludge Disposal | 7.32E-3 | 7.32E-3 | 7.32E-3 | m3 |
| Electricity | 6.41E-4 | 6.41E-4 | 6.41E-4 | kWh |
| Equalization | Concrete | 1.74E-5 | 1.80E-5 | 1.86E-5 | m3 |
| Steel | 4.98E-4 | 5.16E-4 | 5.34E-4 | kg |
| HPDE | 7.23E-5 | 5.56E-5 | 7.92E-5 | kg |
| Electricity | 0.197 | 0.197 | 0.197 | kWh |
| UV | Electricity | 0.056 | 0.056 | 0.056 | kWh |
| Steel | 7.88E-5 | 6.06E-5 | 4.92E-5 | kg |
| Storage | HDPE | 2.16E-3 | 1.66E-3 | 1.80E-3 | kg |
| Electricity | 0.045 | 0.045 | 0.045 | kWh |
| Recycled Water Delivery | Electricity | 0.100 | 0.100 | 0.083 | kWh |
| PEX pipe, 1/2" | 3.66E-4 | 3.66E-4 | 3.66E-4 | m |
| PEX pipe, 1" | 2.40E-3 | 2.40E-3 | 2.40E-3 | m |
| PVC pipe, 1" | 8.53E-4 | 8.53E-4 | 8.53E-4 | m |
| PVC pipe, 2" | 2.79E-4 | 2.79E-4 | 2.79E-4 | m |

Table S14. Mixed Wastewater RVFW LCI

| Unit Process | Inventory Item | Scenario 1 | Scenario 2 | Scenario 3 | Units (per m3 treated wastewater) |
| --- | --- | --- | --- | --- | --- |
| Partial Treatment | Full Treatment | Excess Treatment |
| Centralized Wastewater | Treatment of Offsite Water | 1.4 | 0.919 | 0.593 | m3 |
| Potable Water | Avoided | 1 | 1 | 0.83 | m3 |
| Fine Screen | Electricity | 0.137 | 0.119 | 0.107 | kWh |
| Screening Disposal | 9.54E-03 | 9.54E-03 | 9.54E-03 | kg |
| Steel | 2.14E-03 | 1.65E-03 | 1.34E-03 | kg |
| Chlorination | Concrete | 1.92E-06 | 1.73E-06 | 1.60E-06 | m3 |
| Steel | 5.15E-05 | 4.63E-05 | 4.25E-05 | kg |
| Electricity | 0.081 | 0.081 | 0.081 | kwh |
| Sodium Hypochlorite | 1.57E-03 | 1.57E-03 | 1.57E-03 | kg NaOCl |
| RVFW | Concrete | 7.35E-05 | 5.65E-05 | 9.18E-05 | m3 |
| Steel | 1.50E-04 | 1.15E-04 | 9.36E-05 | kg |
| Steel | 7.86E-03 | 7.86E-03 | 7.86E-03 | kg |
| Steel | 2.10E-03 | 1.62E-03 | 2.63E-03 | kg |
| HDPE | 6.66E-04 | 5.12E-04 | 8.32E-04 | kg |
| Electricity | 0.338 | 0.26 | 0.423 | kwh |
| Lower Media, Crushed Limestone | 0.017 | 0.013 | 0.022 | kg |
| Middle Media, Gravel | 0.061 | 0.047 | 0.076 | kg |
| Organic Cover, Wood Chips | 0.065 | 0.05 | 0.081 | kg |
| Methane | 9.05E-04 | 9.05E-04 | 9.05E-04 | kg |
| CO2, biogenic | 0.015 | 0.012 | 0.019 | kg |
| N2O | 2.61E-05 | 2.00E-05 | 3.26E-05 | kg |
| Clarifier | Steel | 9.11E-03 | 7.01E-03 | 5.69E-03 | kg |
| Sludge Disposal | 0.017 | 0.017 | 0.017 | m3 |
| Electricity | 1.50E-03 | 1.50E-03 | 1.50E-03 | kWh |
| Equalization | Concrete | 1.36E-05 | 1.40E-05 | 1.44E-05 | m3 |
| Steel | 3.89E-04 | 4.00E-04 | 4.12E-04 | kg |
| HPDE | 7.15E-05 | 5.50E-05 | 7.82E-05 | kg |
| Electricity | 0.197 | 0.197 | 0.197 | kWh |
| UV | Electricity | 0.089 | 0.068 | 0.056 | kWh |
| Steel | 7.88E-05 | 6.06E-05 | 4.92E-05 | kg |
| Storage | HDPE | 2.89E-03 | 2.77E-03 | 2.71E-03 | kg |
| Electricity | 0.045 | 0.045 | 0.045 | kWh |
| Ozone | Electricity | 0.21 | 0.21 | 0.21 | kWh |
| Oxygen | 0.131 | 0.131 | 0.131 | kg |
| Recycled Water Delivery | Electricity | 0.1 | 0.1 | 0.083 | kWh |
| PEX pipe, 1/2" | 1.15E-03 | 1.15E-03 | 1.15E-03 | m |
| PEX pipe, 1" | 7.56E-04 | 7.56E-04 | 7.56E-04 | m |
| PVC pipe, 1" | 2.68E-04 | 2.68E-04 | 2.68E-04 | m |
| PVC pipe, 2" | 8.78E-05 | 8.78E-05 | 8.78E-05 | m |

S2. Water Use Scenarios

Indoor flows were defined following [35] using data that reflect the implementation of water conservation efforts typical of new building construction. Residential demand is defined as 35.8 gallons per capita per day (gpcd), less than the national average of 52 gpcd [41]. Commercial demand is defined as 11.3 gpcd following [42]. Graywater generation is assumed to be 72% of residential indoor demand [41] and 37% of commercial indoor demand [43], with the remainder of each flow allocated to blackwater. These assumptions result in the onsite generation of 0.016 million gallons per day (MGD) of graywater or 0.025 MGD of mixed wastewater.

Even with water conservation efforts, non-potable demand, which is defined here as the water required for toilet flushing, laundry and outdoor irrigation, has the potential to vary depending on actual indoor water use efficiency and outdoor irrigation demand. For example, Morelli et al. [35] developed two scenarios to contrast the implementation of high efficiency fixtures and low irrigation demand with average efficiency fixtures and high irrigation demand, with resulting building-wide non-potable demands of 0.0082 MGD and 0.018 MGD, respectively. For this study, an average of the two, or 0.013 MGD, is assumed.

|  |
| --- |
| Table S15. Water Use Scenarios (Million Gallons per Day) |
| **Flows within Large Building(1110 Occupants)** | **Partial Treatment** | **Full Treatment** | **Excess Treatment** |
| **Treatment System Size < Non-potable Demand** | **Treatment System Size = Non-potable Demand** | **Treatment System Size > Non-potable Demand** |
| Non-potable Demanda | 0.013 | 0.013 | 0.013 |
| Graywater Generationb | 0.016 | 0.016 | 0.016 |
| Mixed Wastewater Generationb | 0.025 | 0.025 | 0.025 |
| Treatment System Sizec | 0.010 | 0.013 | 0.016 |
| Potable Offsetd | 0.010 | 0.013 | 0.013 |

a Average of high reuse and low reuse scenarios described in [35]

b [35]

c Treatment system size equal to 80%, 100% and 120% of non-potable demand for Scenarios 1, 2 and 3, respectively

d Equivalent to non-potable demand satisfied

S3. QMRA Methods

Details of QMRA methodology including exposure routes, use of reference pathogens and dose-response functions, characterization of pathogen concentrations and pathogen treatment are listed in Sections S3.1-S3.4. Section S3.5 lists treatment performance (TP) of specific unit processes for the associated dose.

S3.1 Exposure routes

For toilet flush water and clothes washing, we assumed that 4×10-5 L of water was consumed per day for 365 days a year and 10-3 L per day for irrigation for 50 days a year, adopted from [44]. We also included accidental ingestion of the treated water for one day of the year for 10% of the population at a volume of 2 L, to be consistent with the exposure assumptions included in the LRT calculation [45].

S3.2 Reference pathogens and dose-response

Of the human-infectious enteric viruses, bacteria and protozoa included in [42], we narrowed the list to the dominant hazards (i.e., *Norovirus* and *Cryptosporidium* spp*.*). We selected commonly used dose-response models that relate a healthy adult’s dose to a probability of infection based on ingestion (see [45] for more details). For *Norovirus* (doses in genome copies (gc)), two dose-response models were selected to represent the lower- and upper-bounds of predicted risk across the range of available models. The upper-bound, a hypergeometric model for disaggregated viruses [46], predicts relatively high risks among the available models in the relevant dose range. The lower-bound, a fractional Poisson model [47] predicts similar risks as the majority of the published *Norovirus* dose-response models with good empirical fit to the available data (reviewed in Abel et al. [48]). For *Cryptosporidium* spp*.* (doses in oocysts), we adopted an exponential model based on the U.S. EPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2) Economic Analysis [49] and a fractional Poisson model [47], which results in risks that are much greater than previously predicted in the LT2. LRTs from the guidance document (Table 1) are based primarily on the lower-bound dose-response for *Norovirus* and the upper-bound for *Cryptosporidium* (Sharvelle et al., 2017).

S3.3 Characterization of pathogens in waters

We adopted previously simulated onsite graywater and wastewater pathogen concentrations [50], which used an epidemiology-based approach to describe distributions of pathogen concentrations. The epidemiological approach used data describing population illness rates (as a surrogate for infection) and pathogen shedding characteristics during an infection.

The mixed-use building (with a 1,100-person collection) was modeled using the pathogen concentration simulations from a reference 1,000-person residential building collection system (described in detail in [50]). This simplification was made since most of the collected water in the mixed-use system was from residential use and the difference in population size was small between the reference system and the mixed-use systems.

S3.4 Pathogen treatment

To provide a realistic estimate of risk, we accounted for variability in treatment performance for the MBR and ozone systems, for which pathogen (or surrogate) monitoring data was available (see Tables S16–18 for TP characterizations). Chlorine disinfection performance was set to the LRVs in Table S3 based on the available performance data which showed minimal variation [51,52]. For the RVFW and UV, we did not identify performance data to characterize performance probabilistically; rather, we used the LRVs in Table S3.

The MBR treatment performance was modeled as normal (described in [42]) based on a review of the literature on treatment performance for full scale AeMBR reclaimed water systems between 1992 and 2015 [53]. We did not identify performance data for the AnMBR and assumed that performance was the same. For the ozone treatment performance, we adopted an inverse gaussian characterization based on performance measured over the course of one year at a direct potable reuse plant [51], but we shifted the mean to align with dosing requirements for non-potable treatment (while maintaining the same variance).

Although we did not model UV performance probabilistically, we included a sudden UV treatment failure event, which has been identified previously as a potential problem for finished water quality in potable reuse [51,52]. We modeled a 15-minute UV failure event (UV TP=0) during which poorly treated water mixes with stored, treated water and is consumed over the course of one day. This duration was selected based on previous work [51,52] and assumed that UV treatment failure triggers an alarm and garners a quick response in the form of a manual value close. We modelled the occurrence of a lamp or ballast failure as one event per year [51,54].. For comparison, we also separately modeled risk using the LRVs in Table S3 for indoor use (excluding the irrigation).

S3.5 Treatment Performance

Table S16. Variable Treatment Performance (TP) for Aerobic and Anaerobic MBRs: Mixed Wastewater and Graywatera

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Unit Process | Virus | Protozoa | Bacteria | Dose | Dose Units |
| MBR | N(5.6,1) b | N(5.0,0.65) | n/a | n/a | n/a |
| Ozone | n/a | n/a | n/a | n/a | n/a |
| UV | 0 | 4.0 or 0c | n/a | 30 | mJ/cm2 |
| Chlorination | 4 | 0 | n/a | 32 | mg-min/L |
| a Source: MBR [53], UV and chlorination [2]  |
| b Where N denotes a normal distribution with parameters (mu,sigma) |
| c A LRT of 0 for 15 minutes for 1 day a year due to sudden lamp or ballast failure [51,54] |

Table S17. Variable Treatment Performance (TP) for Recirculating Vertical Flow Wetland: Mixed Wastewatera

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Unit Process | Virus | Protozoa | Bacteria | Dose | Dose Units |
| RVFW | 0.5 | 1 | n/a | n/a | n/a |
| Ozone | Inverse Gaussian (mu=4.0, lambda= 48.7) | Inverse Gaussian (mu=2.0, lambda= 6.03) | n/a | 8.3 | mg-min/L |
| UV | 1.0 or 0b | 4.0 or 0b | n/a | 55 | mJ/cm2 |
| Chlorination | 4 | 0 | n/a | 32 | mg-min/L |
| a Source: RVFW, UV and Chlorination Guidance [2]  |
| bA LRT of 0 for 15 minutes for 1 day a year due to sudden lamp or ballast failure (Pecson et al., 2017, Tng et al., 2015) |

Table S18. Variable Treatment Performance (TP) for Recirculating Vertical Flow Wetland: Source-Separated Graywatera

| Unit Process | Virus | Protozoa | Bacteria | Dose | Dose Units |
| --- | --- | --- | --- | --- | --- |
| RVFW | 0.5 | 1 | n/a | n/a | n/a |
| Ozone | n/a | n/a | n/a | n/a | n/a |
| UV | 2.0 or 0b | 4.0 or 0b | n/a | 95 | mJ/cm2 |
| Chlorination | 4 | 0 | n/a | 32 | mg-min/L |
| aSource: RVFW, UV and Chlorination [2]  |

S4. LCCA Methods

Direct cost factors listed in Table S19 were multiplied by unit process costs to estimate the cost of integrating individual treatment processes within the larger wastewater treatment system. Indirect cost factors listed in Table S20 were multiplied by the sum of unit process and direct costs to estimate the cost of professional services, profit and contingency spending. Table S21 lists the estimated life span of individual system components that determine the time of equipment replacement.

Table S19. Direct Cost Factors

|  |  |
| --- | --- |
| Direct Cost Elements | Direct Cost Factor |
| Mobilization | 0.05 |
| Site Preparation | 0.07 |
| Site Electrical | 0.15 |
| Yard Piping | 0.10 |
| Instrumentation and Control | 0.08 |

Table S20. Indirect Cost Factors

|  |  |
| --- | --- |
| Indirect Cost Elements | Indirect Cost Factor |
| Miscellaneous Costs | 0.05 |
| Legal Costs | 0.02 |
| Engineering Design Fee | 0.15 |
| Inspection Costs | 0.02 |
| Contingency | 0.10 |
| Technical Services | 0.02 |
| Profit | 0.15 |

| Table S21. Estimated Lifespan of System Components |
| --- |
| **Unit Process** | **Component** | **Component Lifespan (years)** |
| Equalization Basin | Basin | 40 |
| Floating Aerator/Mixer | 15 |
| Fine Screen | Screen Equipment | 15 |
| AeMBR | Basin | 40 |
| Blowers | 15 |
| Diffuser Swing Arm | 20 |
| Diffusers | 10 |
| Membrane | 10 |
| Permeate Pumps | 25 |
| Sludge Pumps | 25 |
| AnMBR | Basin | 40 |
| Blower, Biogas Recirculation | 15 |
| Diffuser Swing Arm | 20 |
| Diffusers | 10 |
| Floating Cover  | 40 |
| Gas Safety Equipment | 15 |
| Membrane | 10 |
| Mixer | 15 |
| Permeate Pumps | 25 |
| Sludge Pumps | 25 |
| Unit Piping | 50 |
| Downflow Hanging Sponge | Blower | 15 |
| Sponge Media | 10 |
| Vessels | 40 |
| Zeolite Adsorption System | Feed System | 25 |
| Vessel | 40 |
| Zeolite Regeneration System | 15 |
| Zeolite Replacement System | 15 |
| Recirculating Vertical Flow Wetland | Basins | 40 |
| Gravel Media | 40 |
| Piping | 50 |
| Pumps | 25 |
| Slant Plate Clarifier | Sludge Pump | 25 |
| Unit | 40 |
| UV  | Bulb | 1 |
| Quartz Sleeve | 5 |
| Unit | 30 |
| Chlorination | Chlorine Pump | 25 |
| Contact Basin | 40 |
| Ozone | Contact Basin | 40 |
| Monitoring Equipment | 10 |
| Ozone Generator | 10 |

Equation S1 presents the equation used to estimate interest costs during construction.

$$I\_{C}=\sum\_{}^{}\left(Unit Process Costs+Direct Costs+Indirect Costs\right)×T\_{CP}×\left(\frac{i\_{r}}{2}\right)$$

Equation S1

Where:

IC (2016 $) = Interest paid during construction

Unit Process Costs (2016 $) = Total unit process equipment and installation cost

Direct Costs (2016 $) = Total direct costs

Indirect Costs (2014 $) = Indirect costs, including miscellaneous items, legal costs, engineering design fees, inspection costs, contingency and technical services

TCP = Construction period, 3 years based on CAPDETWorks™ default construction period (Hydromantis, 2014)

ir = Interest rate during construction, %

S5. LCA Methods

Acidification potential, eutrophication potential, and particulate matter formation potential were assessed using U.S. EPA’s Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI) impact assessment method, version 2.1 [55,56]. Results for global warming potential (GWP) category are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100-year time horizon [57]. Fossil fuel depletion potential (FDP) is based on the heating value of the fossil fuel and according to the ReCiPe impact assessment method [58]. Cumulative energy demand (CED) and water use (WU) are inventory indicators and not representative of potential end impacts. CED assesses non-renewable energy extracted and renewable energy utilized. WU is calculated as an inventory of consumptive freshwater withdrawals which are evaporated, incorporated into products and waste, transferred to different watersheds, or disposed into the sea after usage.

| Table S22. LCA Metrics |
| --- |
| **Impact/Inventory Category** | **Description** | **Unit** |
| Acidification Potential (AP) | AP quantifies the acidifying effect of substances on their environment. Important emissions leading to terrestrial acidification include sulfur dioxide (SO2), NOx and ammonia (NH3). Results are characterized as kg SO2 eq according to the TRACI impact assessment method. | kg SO2 eq |
| Cumulative Energy Demand (CED) | The CED indicator accounts for the total usage of non-renewable fuels (natural gas, petroleum, coal and nuclear) and renewable fuels (such as biomass and hydro). Energy is tracked based on the higher heating value of the fuel utilized from point of extraction, with all energy values summed together and reported on a megajoule (MJ) basis (Hischier et al. 2010). | MJ |
| Eutrophication Potential (EP) | EP assesses the potential impacts from excessive loading of macro-nutrients to the environment and eventual deposition in freshwater and marine environments. Impacts were assessed according to the TRACI impact assessment method, which calculates a generic eutrophication potential impact that is not specific to either marine or freshwater environments. Both nitrogen and phosphorous compounds are expressed on an equivalent Nitrogen (N) basis. | kg N eq |
| Fossil Fuel Depletion Potential (FDP) | FDP captures the consumption of fossil fuels, primarily coal, natural gas and crude oil. All fuels are standardized to kg oil eq based on the heating value of the fossil fuel, according to the ReCiPe impact assessment method. | kg oil eq |
| Global Warming Potential (GWP) | The GWP impact category represents the heat trapping capacity of GHGs over a 100-year time horizon. All GHGs are characterized as kg carbon dioxide equivalents (CO2 eq) according to the intergovernmental panel on climate change (IPCC) 2013 5th Assessment Report global warming potentials (IPCC 2013). | kg CO2 eq |
| Water Use (WU) | The water use indicator accounts for use of freshwater resources abstracted from surface and groundwaters. Water use is an inventory indicator that does not reflect specifically consumptive uses. | m3 H2O |
| Particulate Matter Formation Potential (PMFP) | PMFP results in health impacts such as effects on breathing and respiratory systems, damage to lung tissue and premature death (Goedkoop et al. 2013). Primary pollutants (including PM2.5) and secondary pollutants (e.g., SOx and NOx) leading to PM formation are characterized here as kg PM2.5 eq based on the TRACI impact assessment method. | kg PM2.5 eq |
| Smog Formation Potential (SFP) | SFP results determine the formation of reactive substances that cause harm to human health and vegetation. Results are characterized here as kg of ozone (O3) eq according to the TRACI impact assessment method. Some key emissions leading to SFP include CO, methane (CH4), NOx, NMVOCs and SOx. | kg O3 eq |

S6. Detailed Results

Tables S23 and S24 contain detailed QMRA results listing 95th percentile annual probability of infection for each mixed wastewater and graywater treatment scenario for individual reference pathogens and combined risk.

Table S23. 95th percentile annual probability of infection (ppy) for non-potable reuse including treatment variability and selected failuresa,b

|  |  |
| --- | --- |
| Reference hazard | Scenario |
| WW MBR | WW Wetland | GW MBR | GW Wetland |
| 1 Cryptosporidium low  | 8.1E-07 | 1.2E-04 | 2.6E-09 | 1.6E-05 |
| 2 Cryptosporidium up | 6.6E-06 | 1.0E-03 | 2.1E-08 | 1.2E-04 |
| 3 Norovirus low  | 3.9E-05 | 4.3E-05 | 3.0E-07 | 4.4E-05 |
| 4 Norovirus up  | 2.1E-02 | 2.4E-02 | 2.0E-04 | 2.4E-02 |
| Combined risk low (1,3) | 4.2E-05 | 2.0E-04 | 3.2E-07 | 7.0E-05 |
| Combined risk mid-range (2,3) | 5.2E-05 | 1.1E-03 | 3.8E-07 | 2.0E-04 |
| Combined risk up (2,4) | 2.1E-02 | 2.6E-02 | 2.0E-04 | 2.4E-02 |

a. Assumed 4×10-5 L of water consumed per day for 365 days a year; 10-3 L of water consumed per day for 50 days a year; and 10% of the population ingesting 2 L per day for 1 day of the year

b. For combined risk, numbers in parentheses indicate the pathogen-specific risk used to calculate annual combined risk, using the upper- (up) or lower- (low) bound dose-response

Table S24. 95th percentile annual probability of infection (ppy) for non-potable reuse using LRVs a,b

| Reference hazard | Scenario |
| --- | --- |
| WW MBR | WW Wetland | GW MBR | GW Wetland |
| 1 Cryptosporidium low  | 6.9E-08 | 7.3E-06 | 3.5E-10 | 3.7E-06 |
| 2 Cryptosporidium up | 5.6E-07 | 6.0E-05 | 2.9E-09 | 3.1E-05 |
| 3 Norovirus low  | 2.2E-05 | 6.6E-06 | 8.5E-08 | 2.8E-05 |
| 4 Norovirus up  | 1.2E-02 | 4.1E-03 | 5.5E-05 | 1.5E-02 |
| Combined risk low (1,3) | 2.2E-05 | 1.4E-05 | 8.5E-08 | 3.2E-05 |
| Combined risk mix (2,3) | 2.2E-05 | 6.6E-05 | 8.8E-08 | 5.8E-05 |
| Combined risk up (2,4) | 1.2E-02 | 4.2E-03 | 5.5E-05 | 1.5E-02 |

a Assumed 4×10-5 L of water consumed per day for 365 days a year with 10% of the population ingesting 2 L per day for 1 day of the year

b. For combined risk, numbers in parentheses indicate the pathogen-specific risk used to calculate annual combined risk, using the upper- (up) or lower- (low) bound dose-response risk

Tables S25 and S26 list summary LCA results for mixed wastewater and graywater treatment systems, respectively.

| Table S25. Summary LCA Results for Mixed Wastewater Treatment Systems |
| --- |
| **Impact Category** | **AeMBR** | **AnMBR** | **RVFW** | **Units** |
| **No T.R.** | **Electric T.R.** | **Natural Gas T.R.** | **Intermittent** | **Continuous** |
| Acidification Potential | -5.40E-4 | -3.46E-3 | 9.50E-4 | 1.88E-3 | 2.43E-3 | -3.30E-4 | kg SO2 eq |
| Cumulative Energy Demand | -1.80 | -32.3 | 5.41 | -4.94 | 0.743 | -0.441 | MJ |
| Eutrophication Potential | 4.81E-3 | 4.64E-3 | 5.09E-3 | 5.12E-3 | 5.17E-3 | 4.99E-3 | kg N eq |
| Fossil Depletion Potential | -0.039 | -0.464 | -0.257 | -0.098 | -0.019 | -0.024 | kg oil eq |
| Global Warming Potential | 0.054 | -1.19 | -0.263 | 0.086 | 0.321 | -0.048 | kg CO2 eq |
| Particulate Matter Formation Potential | -5.29E-5 | -2.40E-4 | 8.63E-5 | 7.91E-5 | 1.20E-4 | -2.35E-6 | kg PM2.5 eq |
| Smog Formation Potential | 2.77E-3 | -0.055 | 0.036 | 0.079 | 0.090 | 6.29E-3 | kg O3 eq |
| Water Use | -1.19 | -1.20 | -1.19 | -1.19 | -1.19 | -1.19 | m3 H2O |

| Table S26. Summary LCA Results for Graywater Treatment Systems |
| --- |
| **Impact Category** | **AeMBR** | **AnMBR** | **RVFW** | **Units** |
| **No T.R.** | **Electric T.R.** | **Natural Gas T.R.** | **Intermittent** | **Continuous** |
| Acidification Potential | -7.30E-4 | -3.84E-3 | 6.30E-4 | 1.60E-4 | 7.20E-4 | -6.00E-4 | kg SO2 eq |
| Cumulative Energy Demand | -3.68 | -36.3 | 2.07 | -4.84 | 0.953 | -2.84 | MJ |
| Eutrophication Potential | 4.72E-3 | 4.53E-3 | 4.99E-3 | 4.88E-3 | 4.93E-3 | 4.85E-3 | kg N eq |
| Fossil Depletion Potential | -0.064 | -0.518 | -0.308 | -0.087 | -6.03E-3 | -0.058 | kg oil eq |
| Global Warming Potential | -0.101 | -1.42 | -0.480 | -0.110 | 0.129 | -0.163 | kg CO2 eq |
| Particulate Matter Formation Potential | -6.55E-5 | -2.70E-4 | 6.60E-5 | -7.73E-6 | 2.91E-5 | -2.54E-5 | kg PM2.5 eq |
| Smog Formation Potential | -9.50E-4 | -0.063 | 0.030 | 0.022 | 0.033 | 1.40E-3 | kg O3 eq |
| Water Use | -1.19 | -1.20 | -1.19 | -1.19 | -1.19 | -1.19 | m3 H2O |

| Table S27. Summary LCA Results for Graywater Treatment Systems |
| --- |
| System Type | Thermal Recovery | Scenario | System Costs over 30 Year Lifespan |
| Electricity | Capital | Materials | Labor | Energy Offset | Centralized Treatment Cost | Avoided Utility Cost | Net NPV |
| GW AeMBR | None | One |  35,161  |  1,231,889  |  285,099  |  1,653,523  |  -  |  1,096,516  |  (1,254,056) |  3,048,133  |
| GW AeMBR | None | Two |  44,623  |  1,473,988  |  305,428  |  1,767,678  |  -  |  936,616  |  (1,630,273) |  2,898,061  |
| GW AeMBR | None | Three |  53,988  |  1,703,919  |  326,297  |  1,866,863  |  -  |  1,152,759  |  (1,880,325) |  3,223,501  |
| GW AeMBR | Electricity | One |  225,754  |  1,289,927  |  293,791  |  1,662,215  |  (349,321) |  1,096,516  |  (1,254,056) |  2,964,827  |
| GW AeMBR | Electricity | Two |  292,394  |  1,549,438  |  316,727  |  1,778,977  |  (454,117) |  936,616  |  (1,630,273) |  2,789,763  |
| GW AeMBR | Electricity | Three |  358,937  |  1,796,780  |  340,204  |  1,880,770  |  (558,913) |  1,152,759  |  (1,880,325) |  3,090,211  |
| GW AeMBR | Natural Gas | One |  225,754  |  1,289,927  |  293,791  |  1,662,215  |  (123,219) |  1,096,516  |  (1,254,056) |  3,190,928  |
| GW AeMBR | Natural Gas | Two |  292,394  |  1,549,438  |  316,727  |  1,778,977  |  (160,185) |  936,616  |  (1,630,273) |  3,083,694  |
| GW AeMBR | Natural Gas | Three |  358,937  |  1,796,780  |  340,204  |  1,880,770  |  (197,151) |  1,152,759  |  (1,880,325) |  3,451,973  |
| Mixed WW AeMBR | None | One |  43,998  |  832,501  |  254,483  |  1,664,916  |  -  |  1,096,516  |  (1,258,578) |  2,633,836  |
| Mixed WW AeMBR | None | Two |  56,111  |  953,031  |  264,279  |  1,773,414  |  -  |  936,616  |  (1,636,151) |  2,347,299  |
| Mixed WW AeMBR | None | Three |  68,127  |  1,061,156  |  275,014  |  1,866,740  |  -  |  1,152,759  |  (1,887,560) |  2,536,235  |
| Mixed WW AeMBR | Electricity | One |  239,598  |  879,640  |  261,542  |  1,671,975  |  (343,889) |  1,096,516  |  (1,258,578) |  2,546,804  |
| Mixed WW AeMBR | Electricity | Two |  310,391  |  1,014,311  |  273,456  |  1,782,591  |  (447,056) |  936,616  |  (1,636,151) |  2,234,158  |
| Mixed WW AeMBR | Electricity | Three |  381,087  |  1,136,578  |  286,309  |  1,878,035  |  (550,223) |  1,152,759  |  (1,887,560) |  2,396,984  |
| Mixed WW AeMBR | Natural Gas | One |  239,598  |  879,640  |  261,542  |  1,671,975  |  (121,303) |  1,096,516  |  (1,258,578) |  2,769,390  |
| Mixed WW AeMBR | Natural Gas | Two |  310,391  |  1,014,311  |  273,456  |  1,782,591  |  (157,694) |  936,616  |  (1,636,151) |  2,523,520  |
| Mixed WW AeMBR | Natural Gas | Three |  381,087  |  1,136,578  |  286,309  |  1,878,035  |  (194,085) |  1,152,759  |  (1,887,560) |  2,753,122  |
| GW RVF | None | One |  37,507  |  1,428,279  |  108,836  |  1,896,965  |  -  |  1,096,516  |  (1,254,056) |  3,314,047  |
| GW RVF | None | Two |  42,969  |  1,751,480  |  129,927  |  2,023,241  |  -  |  936,616  |  (1,630,273) |  3,253,960  |
| GW RVF | None | Three |  64,012  |  2,077,401  |  150,930  |  2,136,575  |  -  |  1,152,759  |  (1,880,325) |  3,701,352  |
| Mixed WW RVF | None | One |  48,771  |  1,107,654  |  63,069  |  2,305,142  |  -  |  1,096,516  |  (1,258,578) |  3,362,575  |
| Mixed WW RVF | None | Two |  56,378  |  1,339,783  |  70,564  |  2,421,086  |  -  |  936,616  |  (1,636,151) |  3,188,276  |
| Mixed WW RVF | None | Three |  79,566  |  1,565,766  |  77,708  |  2,523,578  |  -  |  1,152,759  |  (1,887,560) |  3,511,816  |
| GW AnMBR | None | One |  51,755  |  1,737,043  |  390,436  |  1,847,523  |  (7,875) |  1,096,516  |  (1,254,056) |  3,861,342  |
| GW AnMBR | None | Two |  67,833  |  2,044,487  |  425,215  |  1,983,161  |  (10,238) |  936,616  |  (1,630,273) |  3,816,802  |
| GW AnMBR | None | Three |  84,288  |  2,335,166  |  460,110  |  2,101,111  |  (12,600) |  1,152,759  |  (1,880,325) |  4,240,507  |
| Mixed WW AnMBR | None | One |  49,635  |  1,456,476  |  384,154  |  1,823,172  |  (11,568) |  1,096,516  |  (1,258,578) |  3,539,807  |
| Mixed WW AnMBR | None | Two |  63,845  |  1,652,476  |  416,224  |  1,949,876  |  (15,039) |  936,616  |  (1,636,151) |  3,367,847  |
| Mixed WW AnMBR | None | Three |  78,398  |  1,830,731  |  448,415  |  2,058,725  |  (18,509) |  1,152,759  |  (1,887,560) |  3,662,959  |
| GW AnMBR | None | One |  31,896  |  1,737,043  |  390,436  |  1,847,523  |  (7,875) |  1,096,516  |  (1,254,056) |  3,841,482  |
| GW AnMBR | None | Two |  40,833  |  2,044,487  |  425,215  |  1,983,161  |  (10,238) |  936,616  |  (1,630,273) |  3,789,802  |
| GW AnMBR | None | Three |  49,826  |  2,335,166  |  460,110  |  2,101,111  |  (12,600) |  1,152,759  |  (1,880,325) |  4,206,046  |
| Mixed WW AnMBR | None | One |  31,577  |  1,456,476  |  384,154  |  1,823,172  |  (11,568) |  1,096,516  |  (1,258,578) |  3,521,749  |
| Mixed WW AnMBR | None | Two |  39,295  |  1,652,476  |  416,224  |  1,949,876  |  (15,039) |  936,616  |  (1,636,151) |  3,343,297  |
| Mixed WW AnMBR | None | Three |  47,063  |  1,830,731  |  448,415  |  2,058,725  |  (18,509) |  1,152,759  |  (1,887,560) |  3,631,625  |

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