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# Life Cycle Assessment and Cost Analysis of Water and Wastewater Treatment Options for Sustainability: Influence of Scale on Membrane Bioreactor Systems


National Exposure Research Laboratory
National Risk Management Research Laboratory
Office of Research and Development

# Life Cycle Assessment and Cost Analysis of Water and Wastewater Treatment Options for Sustainability: Influence of Scale on Membrane Bioreactor Systems

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## ABSTRACT

Future changes in drinking and wastewater infrastructure need to incorporate a holistic view of the water service sustainability tradeoffs and potential benefits when considering shifts towards new treatment technology, decentralized systems, energy recovery and reuse of treated wastewater. The main goal of this study is to determine the influence of scale on the energy and cost performance of different transitional membrane bioreactors (MBR) in decentralized wastewater treatment (WWT) systems by performing a life cycle assessment (LCA) and cost analysis. LCA is a tool used to quantify sustainability-related metrics from a systems perspective. The study calculates the environmental and cost profiles of both aerobic MBRs (AeMBR) and anaerobic MBRs (AnMBR), which not only recover energy from waste, but also produce recycled water that can displace potable water for uses such as irrigation and toilet flushing. MBRs represent an intriguing technology to provide decentralized WWT services while maximizing resource recovery. A number of scenarios for these WWT technologies are investigated for different scale systems serving various population density and land area combinations to explore the ideal application potentials. MBR systems are examined from 0.05 million gallons per day (MGD) to 10 MGD and serve land use types from high density urban (100,000 people per square mile) to semi-rural single family (2,000 people per square mile). The LCA and cost model was built with existing literature data sources, data from actual commercial units, and wastewater treatment plant design costing software simulations. The results focus on the energy demand and associated greenhouse gases (GHG) for the scenarios examined. However, a full suite of life cycle impact assessment results, including water savings, was calculated.

Net energy benefits, considering the drinking water displaced by the delivered recycled water, start at the 1 MGD scale for the AeMBR and at the 5 MGD scale for the AnMBR operated at 35˚C (mesophilic). For all scales investigated, the psychrophilic AnMBR reactor operated at 20˚C results in net energy benefits. This study supports the findings from other literature that AnMBRs operated at lower reactor temperatures are a potential technology for decreasing the environmental impacts of wastewater treatment systems. When examining the energy demand results normalized to a cubic meter of water treated, all energy demand impacts decrease as the scale increases due to economies of scales. While the AnMBR operating at ambient temperature results in notable energy and GHG benefits compared to the AeMBR, the AnMBR costs remain higher than the AeMBR under all scenarios. The main driver for this is the increase in operation and maintenance labor needed to operate the anaerobic reactor and, to a lesser extent, anaerobic reactor capital costs. The study found that all impacts decrease comparatively as the population density increases due to decreased pumping distances and piping requirements, with the highest burdens realized for the semi-rural single family land use and the greatest potential seen for the high-density urban land use. Ambient temperature played a key role, with the most benefits and least energy demand and GHG impacts from psychrophilic AnMBR operated in warm climate conditions with combined heat and power generation from methane recovered from both the headspace and the permeate.

While this study focused primarily on net energy demand and GHG impacts of the decentralized MBR systems, there is a potential significant water savings from using recycled wastewater. This study found that use of recycled water from decentralized MBR scenarios avoids 0.94 to 0.96 cubic meters of drinking water per cubic meter of wastewater treated by

MBR. While AeMBRs are largely commercialized at the scales investigated, the data behind the AnMBR model is based on bench-scale and pilot scale systems. As more full scale AnMBRs are commissioned and operational data is better understood, the LCA model framework presented in this work can be continually improved upon.

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# LIST OF ACRONYMS

| | |
|---|---|
| AeMBR | Aerobic Membrane Bioreactor |
| AnMBR | Anaerobic Membrane Bioreactor |
| BOD | Biological Oxygen Demand |
| CEPCI | Chemical Engineering Plant Cost Index |
| CFU | Colony Forming Units |
| CHP | Combined Heat and Power |
| COD | Chemical Oxygen Demand |
| DWT | Drinking Water Treatment |
| EPS | Expanded Polystyrene |
| GCWW | Greater Cincinnati Water Works |
| HRT | Hydraulic Retention Time |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Cost Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MBR | Membrane Bioreactor |
| MGD | Million Gallons per Day |
| MLSS | Mixed-Liquor Suspended Solids |
| MSDGC | Metropolitan Sewer District of Greater Cincinnati |
| NTU | Nephelometric Turbidity Units |
| ORD | U.S. EPA's Office of Research and Development |
| PFAS | Plug Flow Activated Sludge Diffused Aeration Reactor |
| PVDF | Polyvinylidene Fluoride |
| SSWR | Safe and Sustainable Water Resources Program |
| SRT | Solids Retention Time |
| TKN | Total Kjeldahl Nitrogen |
| TRACI | Tool for the Reduction and Assessment of Chemical and Environmental Impacts |
| VSS | Volatile Suspended Solids |
| WWT | Wastewater Treatment |
| WWTP | Wastewater Treatment Plant |

# 1.0 INTRODUCTION AND STUDY GOAL

The Office of Research and Development's (ORD), Safe and Sustainable Water Resources (SSWR) Program, is the principal research lead seeking metrics and tools to compare the tradeoffs between economic, human health, and environmental aspects of current and future municipal water and wastewater services. Changes in drinking water and wastewater management have typically resulted from new regulations, which focus on developing and implementing additions to the current treatment and delivery schemes. However, these additions are undertaken in the absence of a system's holistic view and can result in transferring issues from one problem area to another. Future alternatives need to address the whole water services physical system to aid in the provision of more sustainable water services such that water scarcity is alleviated. Furthermore, these sustainable systems must be based on overall resource recovery (water, energy, nutrients, etc.). Therefore, a range of integrated metrics and tools need to be used to evaluate the multifaceted solutions and identify "next-generation" sustainable municipal water and wastewater systems, as well as to identify possible regulatory/policy steps to facilitate this evolution. This study offers quantitative environmental and cost data from a systems perspective for transitional "next generation" decentralized wastewater (WWT) technologies.

The main goal of this study is to determine the influence of scale on the energy and cost performance of different membrane bioreactors (MBR) in wastewater mining systems as transitional technology by performing a life cycle assessment (LCA) and cost analysis. LCA is a tool used to quantify sustainability-related metrics from a systems perspective. The study calculates the environmental and cost profile of both aerobic MBRs (AeMBR) and anaerobic MBRs (AnMBR). MBRs represent an intriguing technology to provide decentralized WWT services. A number of scenarios for these WWT technologies are investigated for different scale systems serving various population density and land area combinations, assuming 100 gallons of wastewater generated per person per day (WaterSense and U.S. EPA, 2016). All scenarios considered are illustrated in Table 1-1. A total of 18 scale and density scenarios are modeled.

**Table 1-1. Scale and Population Density Scenarios**

| | Land Use Type | 0.05MGD (500 ppl served) | 0.1MGD (1,000 ppl served) | 1MGD (10,000 ppl served) | 5MGD (50,000 ppl served) | 10MGD (100,000 ppl served) |
|---|---|---|---|---|---|---|
| **100,000 #ppl/sqm** | High density urban | 0.005 sqm | 0.01 sqm | 0.1 sqm | 0.5 sqm | 1 sqm |
| **50,000 #ppl/sqm** | Multi family | 0.01 sqm | 0.02 sqm | 0.2 sqm | 1 sqm | 2 sqm |
| **10,000 #ppl/sqm** | Single family | 0.05 sqm | 0.1 sqm | 1 sqm | 5 sqm | 10 sqm |
| **2,000 #ppl/sqm** | Semi-rural single family | 0.25 sqm | 0.5 sqm | 5 sqm | N/A | N/A |

sqm = square mile; ppl = people; MGD = million gallons per day

# 2.0 STUDY SCOPE

This section covers the project scope necessary to meet the study's goals.

## 2.1 Functional Unit

A functional unit provides the basis for results comparison in an LCA. The key consideration in developing a functional unit is to ensure all systems are compared on an equivalent performance basis. The functional unit used in this study is based on providing WWT service to a specified number of people. The study considers the following number of people per service area of varying density (as laid out in Table 1-1): 500, 1,000, 10,000, 50,000, and 100,000. Only wastewater from households is incorporated in the study boundaries (e.g. wastewater from commercial buildings and industrial facilities as well as storm water is excluded). While AeMBR and AnMBR technologies are mainly compared on an annual basis of wastewater treated, results are normalized to a specified volume of wastewater treated (one cubic meter ($m^3$)) in order to assess the relative performance of a technology across different scales.

## 2.2 System Boundaries

All scenarios examined are considered theoretical U.S. decentralized wastewater treatment systems. For the MBR technologies examined, the system boundary starts at collection of wastewater and ends at downstream use of the recycled water. The system boundaries for the AeMBR analysis are illustrated in Figure 2-1, and the system boundaries for the AnMBR are presented in Figure 2-2. The AeMBR and AnMBR treatment systems are modeled as transitional "plug-in" systems, which explore sewer mining for energy recovery and divert wastewater that otherwise goes through the conventional activated sludge system in a centralized wastewater treatment plant (WWTP). The systems use existing wastewater collection infrastructure and sludge handling processes. The wastewater collection system in this study is modeled as a gravity sewer system, as is the case for the Metropolitan Sewer District of Greater Cincinnati (MSDGC), the existing plant assumed to handle the sludge discharged from the MBR treatment processes. The collection system is modeled equivalently for the AeMBR and AnMBR systems, but varies by the different population density scenarios. The avoided drinking water treatment and distribution is modeled based on a previously completed LCA for Greater Cincinnati Water Works.

Prior to treatment via MBR, the wastewater goes through a coarse screening and grit removal stage followed by fine screening. Coarse screening removes large debris from the wastewater flow through multiple screens. Grit removal extracts stone, grit, and other settleable debris. It is assumed debris from this stage is transported to a nearby landfill. Fine screening with mesh size 2 mm or smaller is important to prevent membrane fouling (Jeffery, 2005; U.S.EPA, 2007). The wastewater then undergoes treatment via MBRs. MBR combines biological treatment with solids removal via filtration (U.S. EPA, 2007). Biological treatment for the AeMBR is carried out in a plug flow activated sludge diffused aeration reactor, and an anaerobic reactor is the biological treatment method for AnMBR. In the baseline model, the AnMBR system includes electricity generation using the resulting biogas, reducing the need for purchased electricity. In some cases, more electricity is produced than required by the AnMBR system, resulting in a net electricity displacement credit. A sensitivity analysis presented in Section 5.0 examines the effect of using biogas for combined heat and power (CHP) operations. CHP generates electricity and utilizes the waste heat from combusting biogas to displace natural gas inputs for influent heating.

This sensitivity analysis includes an additional “worst case” scenario in which the biogas is flared and no energy is recovered.

The filter portion of the MBR is made of thousands of hollow fibers grouped into bundles and attached on the top and bottom in a frame called a module. Up to 48 modules are inserted into a larger frame called a cassette that is installed inside the reactor. Each hollow fiber has many microscopic pores that allow water to be drawn by a vacuum through the membrane into the inside of the fiber while blocking passage of solids and microbial biomass. The filtered water, or permeate, is then drawn out of the hollow fiber and sent to post-treatment. As with any filter, the membrane must be regularly cleaned in order to dislodge solids from the membrane pores and surfaces to allow permeate to flow through and prevent biofilm built-up. In the AeMBR system, the membrane is scoured by large air bubbles that rise up from the bottom of the tank and remove fouling on the membrane fibers. In the AnMBR systems, the membrane is scoured by rising bubbles of biogas. The membrane pores are cleaned periodically by membrane relaxation when the effluent vacuum pump that pulls permeate through the pores turns off briefly, allowing solids to fall away from the membrane. Lastly, membrane pores are cleaned with a periodic backflush of sodium hypochlorite (NaOCl).

For all scenarios, the remaining sludge after MBR treatment is discharged to the existing sewer for solids handling at the centralized WWTP. This study makes the simplifying assumption the centralized WWTP is large enough and the operation of the transitional treatment systems and any variations in waste returned to the sewer would have a negligible effect on the operations of the centralized WWTP. The WWTP in the MSDGC baseline scenario treats 114 million gallons per day (MGD), which is a much greater scale than the MBR systems investigated (see Table 1-1).[1] Therefore, treatment of the sludge from the MBRs is considered to be outside the system boundaries. It should be noted that more solids would be returned after treatment in the AeMBR as compared to the AnMBR as more of the waste is converted to methane and water in the anaerobic scenario, but this marginal difference in downstream centralized WWTP is considered insignificant here.

The effluent from the MBR systems then goes through a chlorination step with sodium hypochlorite to disinfect the recycled water to a condition that is suitable for use for a variety of purposes. The delivery of the recycled water to the use point includes the associated infrastructure and energy requirements for a pressurized distribution system. Similar to the infrastructure for the collection system, the recycled water infrastructure depends on the population density scenario and scale. Recycled water can be used for non-potable purposes such as toilet flushing, landscape irrigation, cooling towers, car washing, and other uses depending on the effluent quality and quantity. In this study, recycled water quality is not expected to comply with standards for drinking water used for human consumption. As a “worst case” scenario, this study assumes all recycled water returns to the same user who produced the wastewater, as opposed to use of the recycled water at a point closer to the facility such as a nearby park or golf course. In all cases, the use of recycled water is assumed to replace the equivalent quantity of potable water produced in Cincinnati (Cashman et al., 2014a). The baseline Cincinnati water treatment scheme is displayed in the large blue box in Figure 2-1 and Figure 2-2. The baseline water treatment system is based on the Greater Cincinnati Water Works (GCWW), Richard

[1] The baseline WWTP is modeled based on the MSDGC Mill Creek Plant for the year 2012.

Miller Treatment Plant. The data in the GCWW model is representative of the year 2011, in which 106 MGD of potable water were produced.

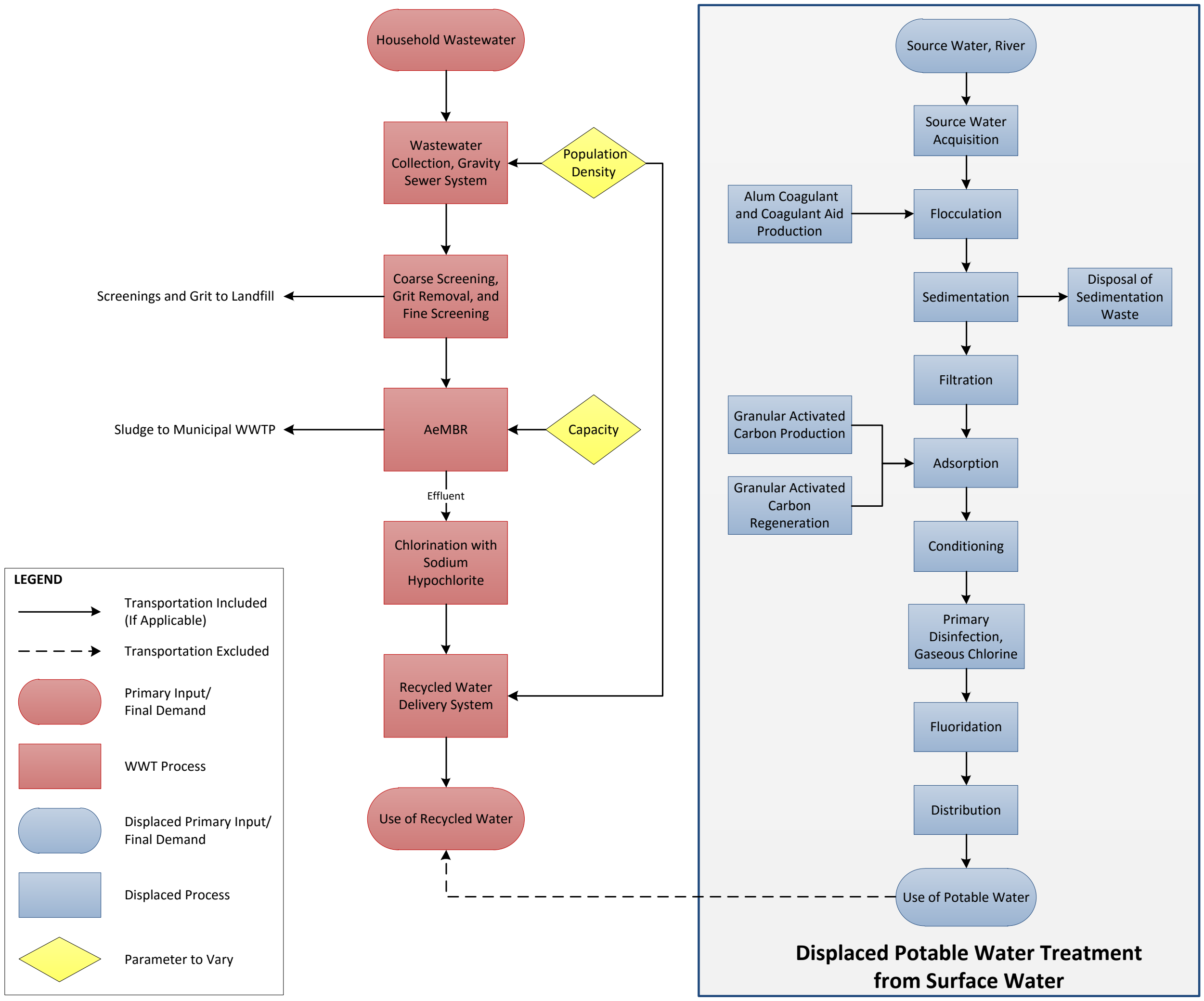


**Figure 2-1. System Boundaries for AeMBR Analysis**

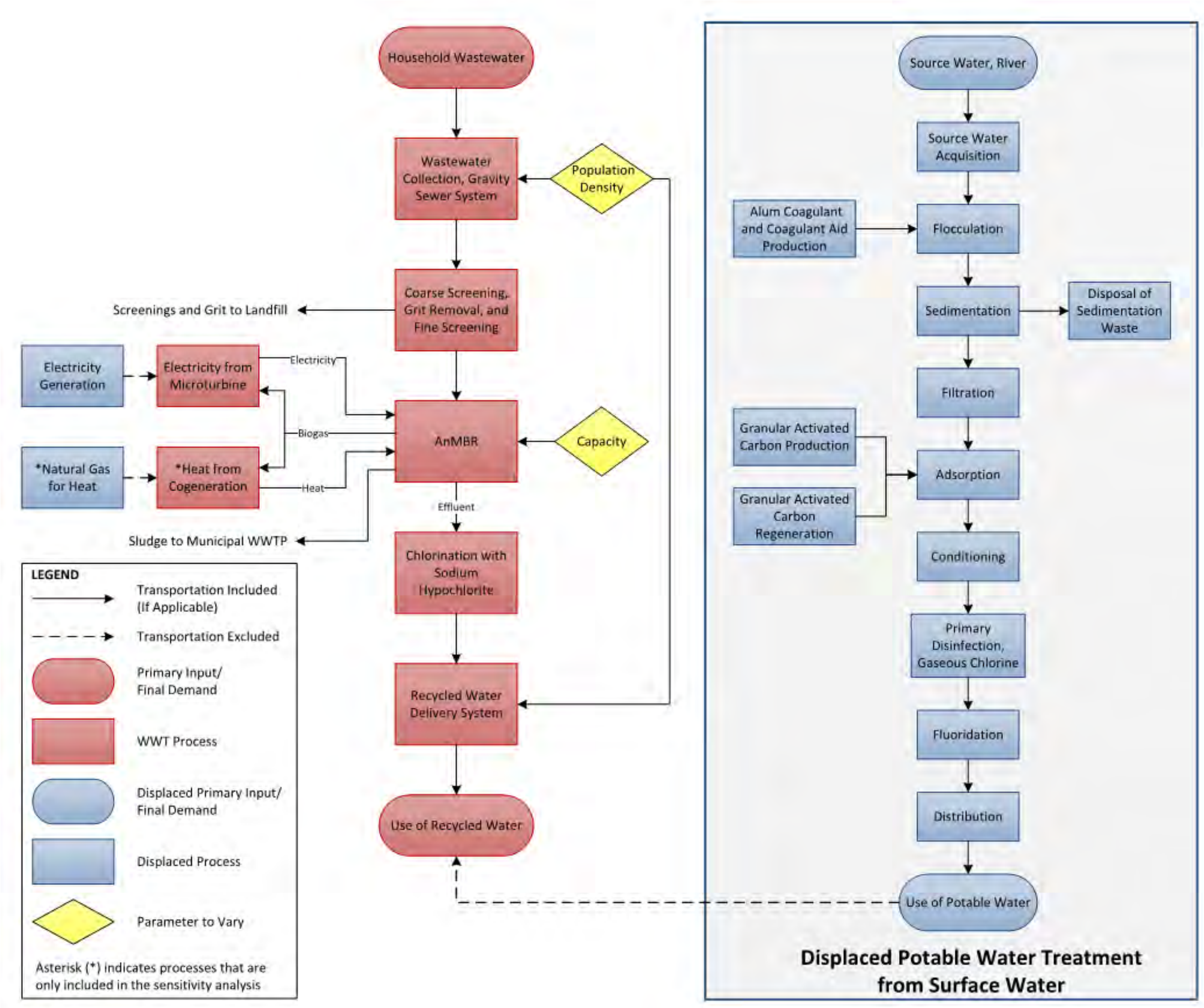


**Figure 2-2. System Boundaries for AnMBR Analysis**

## 2.3 Impact Assessment

Table 2-1 summarizes the complete list of impacts examined for the LCA model runs. This study addresses global, regional, and local impact categories. The life cycle impact assessment (LCIA) method provided by the Tool for the Reduction and Assessment of Chemical and environmental Impacts (TRACI), version 2.1, developed by the U.S. EPA specifically to model environmental and human health impacts in the U.S., is the primary LCIA method applied in this work (Bare et al. 2002). Additionally, the ReCiPe LCIA method is used to characterize fossil fuel depletion and blue water use (Goedkoop et al., 2008). Energy is tracked based on point of extraction using the cumulative energy demand method developed by ecoinvent (Ecoinvent Centre, 2010a). While the full suite of indicators identified in Table 2-1 are summarized in this report, the overall focus of the results discussion is energy demand and global warming potential. A companion cost analysis is conducted. The emphasis of the cost analysis is to understand the contribution of life cycle stages to the overall cost of treating the wastewater.

**Table 2-1. Life Cycle Impact Assessment Categories Used in the LCA Model**

| Impact Category | Methodology | Unit |
|---|---|---|
| Acidification | TRACI 2.1 | kg $SO_2$-eq (equivalent) |
| Ecotoxicity | TRACI 2.1 | CTU |
| Eutrophication | TRACI 2.1 | kg N-eq |
| Global warming | TRACI 2.1 | kg $CO_2$-eq |
| Human health criteria | TRACI 2.1 | PM10-eq |
| Human health toxicity – cancer | TRACI 2.1 | CTU(comparative toxic units) |
| Human health toxicity – non-cancer | TRACI 2.1 | CTU |
| Ozone depletion | TRACI 2.1 | kg CFC-11 eq |
| Smog | TRACI 2.1 | kg $O_3$-eq |
| Cumulative energy demand | Ecoinvent | MJ-eq |
| Fossil depletion | ReCiPe (H) | kg oil-eq |
| Water depletion | ReCiPe (H) | $m^3$ |

## 2.4 Initial Data Sources

This study largely relies upon existing data sources and CAPDETWorks™ Version 3.0,[2] a wastewater treatment design and costing software, to build the LCA models and cost analysis. The primary data sources for the main foreground processes in this analysis are listed in Table 2-2. If existing foreground data sources were not available for all MBR scenarios, the project team either (1) attempted to contact manufacturers to collect additional data or (2) derived required process inputs from publicly available equipment specifications on the manufacturer's website. As discussed in Section 1.0, certain baseline Cincinnati WWT and drinking water treatment (DWT) processes are incorporated into this analysis. These LCA processes were created for Cincinnati in a previous EPA project "Life Cycle Environmental and Economic Assessment of the Water and Wastewater Systems in Cincinnati" (Cashman et al., 2014a; 2014b). Upstream processes use information from the National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database (U.S. LCI), a publicly available life cycle inventory source (NREL, 2012). Where upstream data were not available from the U.S. LCI, ecoinvent v2.2, a private Swiss LCI database with data for many unit processes, is used (Ecoinvent Centre, 2010b).

**Table 2-2. Existing Data Sources for Main Foreground Processes**

| LCA Model Component | Existing Data Sources |
|---|---|
| Aerobic MBR | CAPDETWorks Version 3.0 (wastewater treatment design and costing software) Simulations; University of Michigan MBR LCA study (Smith et al., 2014) and other literature sources |
| | Correspondence with GE (manufacturers of AeMBRs, GE ZeeWeed® 500D hollow fiber membranes using LEAPmbr Aeration Technology) |
| Anaerobic MBR | Energy balance equations from Feickert et al. (2012), literature sources on existing pilot and lab-scale systems, and University of Michigan MBR LCA study (Smith et al., 2014) |

[2] Software developed by Hydromantis Environmental Software Solutions, Inc. http://www.hydromantis.com/CapdetWorks.html (Accessed 6/26/16)

**Table 2-2. Existing Data Sources for Main Foreground Processes**

| LCA Model Component | Existing Data Sources |
|---|---|
| | Correspondence with GE (manufacturers of AnMBRs, GE ZeeWeed® 500D hollow fiber membranes using LEAPmbr Aeration Technology) |
| Collection System Infrastructure | Cincinnati municipal wastewater treatment LCA completed by the U.S. EPA (Cashman et al., 2014b); Length calculation estimations from water infrastructure expert at PG Environmental, LLC (Rowlett, 2015) |
| Recycled Water Delivery System | Cincinnati municipal drinking water treatment LCA completed by the U.S. EPA (Cashman et al., 2014a); Length calculation estimations from water infrastructure expert at PG Environmental, LLC (Rowlett, 2015) |
| Displacement of Drinking Water Treatment | Cincinnati municipal drinking water treatment LCA completed by the U.S. EPA (Cashman et al., 2014a) |

# 3.0 METHODOLOGY

This section covers the methodology utilized to develop the life cycle inventory (LCI) for this study. The LCI data modules were constructed, in accordance with ISO 14040: 2006 recommendation, to include the following information:

Elementary inputs and outputs (to and from nature)

- Raw material inputs required;
- Air emission outputs; and
- Waterborne emission outputs.

Intermediate inputs and outputs (to and from the technosphere)

- Energy product inputs required;
- Economic goods (material) input required;
- Solid waste outputs to be managed; and
- Economic goods (material) output.

All LCI unit processes were built in the open-source LCA software OpenLCA version 1.4.2.[3]

## 3.1 Influent Water Quality and Quantity

The influent water quality characteristics assumed for all scenarios in this study are displayed in Table 3-1. This data is representative of medium strength municipal wastewater from individual residences (Metcalf and Eddy, 2014). The average summer and winter temperatures are based on the U.S. as a whole and, along with pH, cation, and anion concentration, are taken from CAPDETWorks default values.

**Table 3-1. Influent Water Quality Characteristics**

| Description | Value | Units |
|---|---|---|
| Suspended Solids | 195 | mg/L |
| % Volatile Solids | 78 | % |
| BOD | 200 | mg/L |
| Soluble BOD | 80 | mg/L |
| COD | 508 | mg/L |
| Soluble COD | 177 | mg/L |
| TKN | 35 | mgN/L |
| Soluble TKN | 22.4 | mgN/L |
| Ammonia | 20 | mgN/L |
| Total Phosphorus | 5.6 | mgP/L |
| pH | 7.6 | |
| Cations | 160 | mg/L |

[3] Software developed by GreenDelta GmbH. http://www.openlca.org/openlca (Accessed 6/26/16)

**Table 3-1. Influent Water Quality Characteristics**

| Description | Value | Units |
|---|---|---|
| Anions | 160 | mg/L |
| Settleable Solids | 10 | mL/L |
| Oil and Grease | 76 | mg/L |
| Nitrite | 0 | mgN/L |
| Nitrate | 0 | mgN/L |
| Non-Degradable Fraction of Volatile Suspended Solids (VSS) | 48 | % |
| Biodegradable VSS | 52 | % |
| Average Summer[a] | 23 | deg C |
| Average Winter[a] | 10 | deg C |

[a] Applicable only for the AeMBR system.

The AnMBR model varies slightly, based on available pilot scale research for modeling these systems. The average influent temperature for the AnMBR is assumed to be 20˚C and the average ambient temperature is assumed to be 21.5˚C (Feickert et al., 2012). Since this study investigates a transitional system using sewer mining concepts, diurnal and seasonal variation in influent water quantity is not considered in the baseline results. However, modeling of different ambient and influent temperatures for the AnMBR is conducted in the sensitivity analyses in Section 5.0. The amount of water withdrawn from the sewer would be controlled such that any water flow in the sewer beyond the capacity of the MBR treatment facility would bypass the MBR facility and continue down the sewer to the centralized WWTP. One additional MBR treatment train is included in each scenario to allow for operation at full capacity during periodic cleanings of each MBR treatment train.

## 3.2 Membrane Bioreactor Model

The modules used to build the AeMBR and AnMBR LCI are provided in this section.

### 3.2.1 Aerobic MBR

The aerobic MBR model is primarily based on modeling simulations in CAPDETWorks™ design and costing software, with the sub processes of AeMBR identified in Figure 3-1. A general description of coarse screening, grit removal, fine screening, and chlorination steps is found in Section 2.2, and detailed modeling methodology for these processes is provided in Section 3.3. This section focuses on the modeling for the membrane bioreactor with a plug flow activated sludge diffused aeration reactor (PFAS).

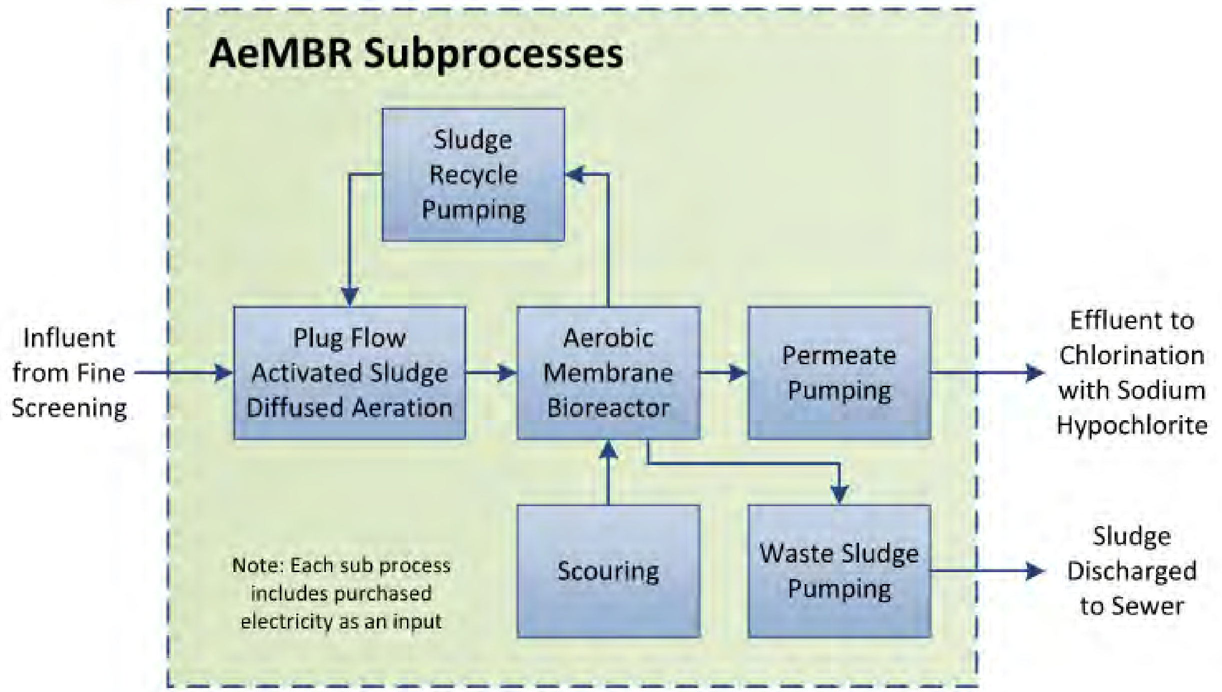


**Figure 3-1. AeMBR Sub Processes**

It is assumed the membrane technology used is the GE ZeeWeed® 500D hollow fiber membranes using LEAPmbr Aeration Technology. Table 3-2 lists the primary unit processes and related sub-processes and Table 3-3 through Table 3-7 show the LCI data for AeMBR operation, excluding pre- and post-treatment steps (the modeling of these steps is shown in Section 3.3). Life cycle costs are based on CAPDETWorks modeling unless otherwise noted.

**Table 3-2. Primary Unit Processes and Sub-Processes in AeMBR Operation**

| Unit Process | Sub-Process |
|---|---|
| Plug Flow Activated Sludge with MBR | Aeration |
| Plug Flow Activated Sludge with MBR | Sludge Recycle Pumping |
| Membrane Bioreactor | Scouring |
| Membrane Bioreactor | Permeate Pumping |
| Membrane Bioreactor | Waste Sludge Pumping |

The PFAS model used CADPETWorks default input parameters except for process design choice of carbon removal only instead of carbon removal plus nitrification, since nutrient removal is not included in this study. Nutrient removal is not included in order to focus on MBR technology differences and because nutrient removal is not always required for end uses or recycled water considered in this study. The CAPDETWorks model estimated the same amount of annual electricity required for the 0.05 MGD PFAS as the 0.1 MGD PFAS. The linear least squares method was used to find a best-fit line for electricity demand for the 0.1-10 MGD systems and to extrapolate electricity use per year for the 0.05 MGD PFAS.

**Table 3-3. Life Cycle Inventory Operational Data for Aeration (AeMBR)**

| | Water Output (MGD) | Electricity (kWh/yr.) |
|---|---|---|
| 0.05 MGD | 0.050 | 55,100 |
| 0.1 MGD | 0.10 | 69,300 |
| 1 MGD | 1.00 | 277,000 |
| 5 MGD | 5.00 | 1,390,000 |
| 10 MGD | 10.0 | 2,630,000 |

**Table 3-4. Life Cycle Inventory Operational Data for Sludge Recycle Pumping (AeMBR)**

| | Water Output (MGD) | Electricity (kWh/yr.) |
|---|---|---|
| 0.05 MGD | 0.050 | 5,050 |
| 0.1 MGD | 0.10 | 10,100 |
| 1 MGD | 1.00 | 100,000 |
| 5 MGD | 5.00 | 499,000 |
| 10 MGD | 10.0 | 997,000 |

The following modifications were made to the default CAPDETWorks input parameters to model the membrane bioreactor as representative of GE ZeeWeed 500D hollow fiber membranes with LEAPmbr Aeration Technology:

- Specific scour air demand – changed from 0.30 to 0.15 $Nm^3/(m^2hr)$ based on GE documentation reporting that a switch from 10/10 sequential aeration (default settings in CAPDETWorks) to 10/30 eco-aeration could reduce air demand by up to 50% and an upgrade from 10/30 sequential aeration to LEAPmbr aeration can reduce air demand by an additional 30% (Kicsi, 2014). A study by GE found an average air scouring flow rate of 0.12 $Nm^3/(m^2hr)$ using the ZeeWeed 500D membranes as of 2010 (Cote et al. 2012). Brochures and presentations published by the manufacturer suggest a 30-70% reduction in air and associated energy required for aeration as compared to the 10/10 sequential aeration used as the default in CAPDETWorks MBR model (GE Power and Water, 2014; Kicsi, 2014). A specific air demand of 0.15 $Nm^3/(m^2hr)$ was chosen for the CAPDETWorks input parameter (50% of the default setting) as it is the middle of the range of expected reductions in air demand between 10/10 sequential aeration and LEAPmbr aeration technology.
- Physical cleaning interval – changed from 9 minutes to 10 minutes of membrane relaxation (Graham Best, GE Power, and Water Regional Sales Manager, personal communication, February 27, 2015).
- Physical cleaning duration – changed from 60 seconds to 45 seconds (Graham Best, GE Power, and Water Regional Sales Manager, personal communication, February 27, 2015).

- Chemical cleaning interval – changed from 168 hours to 84 hours for biweekly membrane cleaning with sodium hypochlorite only (Graham Best, GE Power, and Water Regional Sales Manager, personal communication, February 27, 2015).
- Backflush flow factor – changed from 1.25 to 0 since membrane relaxation instead of backflushing with permeate is typically sufficient for municipal strength wastewater (Graham Best, GE Power and Water Regional Sales Manager, personal communication, February 27, 2015).

**Table 3-5. Life Cycle Inventory Operational Data for Scouring (AeMBR)**

| | Water Output (MGD) | Electricity (kWh/yr.) | NaOCl (kg/yr.) |
|---|---|---|---|
| 0.05 MGD | 0.05 | 6730 | 49.3 |
| 0.1 MGD | 0.10 | 13500 | 95.8 |
| 1 MGD | 0.98 | 135,000 | 942 |
| 5 MGD | 4.88 | 598,000 | 4,191 |
| 10 MGD | 9.77 | 1,200,000 | 8,363 |

**Table 3-6. Life Cycle Inventory Operational Data for Permeate Pumping (AeMBR)**

| | Water Output (MGD) | Electricity (kWh/yr.) |
|---|---|---|
| 0.05 MGD | 0.049 | 1,570 |
| 0.1 MGD | 0.10 | 3,140 |
| 1 MGD | 0.98 | 31,200 |
| 5 MGD | 4.88 | 156,000 |
| 10 MGD | 9.77 | 311,000 |

**Table 3-7. Life Cycle Inventory Operational Data for Waste Sludge Pumping (AeMBR)**

| | Electricity (kWh/yr.) | Sludge Output (MGD) |
|---|---|---|
| 0.05 MGD | 39.6 | 0.0012 |
| 0.1 MGD | 79.0 | 0.0023 |
| 1 MGD | 786 | 0.023 |
| 5 MGD | 3,910 | 0.12 |
| 10 MGD | 7,810 | 0.23 |

The quantity of sodium hypochlorite needed for cleaning the membranes was calculated separately from the CAPDETWorks model because the CAPDETWorks model assumes cleaning with both sodium hypochlorite and citric acid, and not enough information is provided to determine the quantity of each as calculated by CAPDETWorks. According to GE, cleaning with citric acid is not necessary since nutrient removal using a coagulant is not included in this analysis of MBR systems (Graham Best, GE Power, and Water Regional Sales Manager, personal communication, February 27, 2015). Sodium hypochlorite consumption is estimated to be 900 L of a 12.5% solution per year per 370 square feet of membrane surface area (GE Power & Water, 2014). The cost of sodium hypochlorite was calculated using the unit cost of \$2/kg NaOCl derived from the cost of 14% by weight hypochlorite solution (\$10/cu ft. 14% NaOCl) provided in CAPDETWorks.

CAPDETWorks models sludge wasted from the AeMBR tank using a mixed liquor suspended solids concentration of 12 g/L. The quantity of wasted sludge per day is shown in Table 3-7.

#### 3.2.1.1 Infrastructure

LCI infrastructure data for each sub process of the PFAS unit process were developed using CAPDETWorks modeling software and are displayed in Table 3-8 and Table 3-9.

**Table 3-8. Life Cycle Inventory Infrastructure Data for Aeration (AeMBR)**

| | Earthworks (cu ft.)[a] | Concrete (cu ft.) |
|---|---|---|
| 0.05 MGD | 13,500 | 5,610 |
| 0.1 MGD | 13,500 | 5,610 |
| 1 MGD | 18,900 | 7,590 |
| 5 MGD | 54,100 | 50,200 |
| 10 MGD | 83,800 | 63,600 |

[a] Earthworks models energy requirements for removal of soil associated with construction activities.

**Table 3-9. Life Cycle Inventory Infrastructure Data for Sludge Recycle Pumping (AeMBR)**

| | Earthworks (cu ft.) |
|---|---|
| 0.05 MGD | 1,650 |
| 0.1 MGD | 1,690 |
| 1 MGD | 2,550 |
| 5 MGD | 6,330 |
| 10 MGD | 11,100 |

LCI infrastructure data for each sub process of the MBR unit process are shown in Table 3-11 through Table 3-13. The hollow fiber membrane is made of polyvinylidene fluoride (PVDF) (Cote et al., 2012). The quantity of PVDF used in the membrane was calculated based on CAPDETWorks results for the total surface area of membrane required for each size system and manufacturer specifications for the inner and outer diameter of a hollow fiber (GE Power & Water, 2013). An Ecoinvent dataset for polyvinyl fluoride was used as a proxy to model PVDF. Manufacture of MBR cassettes was not included in the model as data were not available, and infrastructure typically is a small impact in LCAs when amortized over the equipment lifetime and compared to daily operational requirements. Membrane lifetime was estimated to be 10 years (Cote et al., 2012). Because initial CAPDETWorks model calculations resulted in larger MBR tanks than required by the GE ZeeWeed 500D LEAPmbr systems, total membrane surface area was used to derive the number of cassettes needed per train from which the tank sizes were calculated. Tank sizes, presented in Table 3-10 were modeled based on a GE factsheet (GE Power & Water, 2014). A separate CAPDETWorks modeling run was carried out with the tank length, width, and height specified in the input parameters to determine the amount of earthwork and concrete required and construction costs associated with the tank infrastructure. An Ecoinvent dataset for excavation using a hydraulic digger was used to model earthworks. The hydraulic digger consumes 0.131 kg of diesel per cubic meter of earth moved.

**Table 3-10. Aerobic Membrane Bioreactor Tank Dimensions**

| | 0.05 MGD | 0.1 MGD | 1 MGD | 5 MGD | 10 MGD |
|---|---|---|---|---|---|
| Membrane Surface Area ($m^2$) | 591 | 1,180 | 11,800 | 52,600 | 105,000 |
| Number of Trains (Including Standby) | 2 | 2 | 3 | 4 | 4 |
| Number of Cassettes per Train | 1 | 2 | 3 | 8 | 16 |
| Number of Modules per Cassette | 16 | 16 | 48 | 48 | 48 |
| Length of Tanks (m) | 1.52 | 2.44 | 6.60 | 16.8 | 33.0 |
| Width of Tanks (m) | 2.74 | 2.74 | 2.74 | 2.74 | 2.74 |
| Height of Tanks (m) | 3.66 | 3.66 | 3.66 | 3.66 | 3.66 |

**Table 3-11. Life Cycle Inventory Infrastructure Data for Scouring (AeMBR)**

| | Earthwork (cu ft.) | Concrete (cu ft.) | Membrane PVDF (kg/10 yrs.) |
|---|---|---|---|
| 0.05 MGD | 6,700 | 2,290 | 409 |
| 0.1 MGD | 7,460 | 2,710 | 816 |
| 1 MGD | 13,700 | 6,160 | 8,162 |
| 5 MGD | 29,100 | 28,200 | 36,383 |
| 10 MGD | 49,400 | 41,900 | 72,628 |

**Table 3-12. Life Cycle Inventory Infrastructure Data for Permeate Pumping (AeMBR)**

| | Earthwork (cu ft.) |
|---|---|
| 0.05 MGD | 1,600 |
| 0.1 MGD | 1,610 |
| 1 MGD | 1,680 |
| 5 MGD | 1,880 |
| 10 MGD | 2,170 |

**Table 3-13. Life Cycle Inventory Infrastructure Data for Waste Sludge Pumping (AeMBR)**

| | Earthwork (cu ft.) |
|---|---|
| 0.05 MGD | 1,600 |
| 0.1 MGD | 1,600 |
| 1 MGD | 1,600 |
| 5 MGD | 1,620 |
| 10 MGD | 1,640 |

### 3.2.2 Anaerobic MBR

While AeMBRs are largely commercialized at the scales investigated, the data behind the AnMBR model is based on bench-scale and pilot scale systems. The energy balance calculations for the AnMBR were conducted based on the work by Feickert et al. (2012). While this study modeled a system treating 130 $m^3$ of wastewater per day, the model was able to be parametrized to theoretically increase the scale to 10 MGD. The following AnMBR sub processes are incorporated, as displayed by Figure 3-2:

- Heating of influent for the bioreactor, using heat supplied by a heat exchanger extracting heat from the resulting effluent and natural gas if additional heat is necessary. For the sensitivity analysis, captured waste heat from electricity generation displaces natural gas if the scenario includes CHP operations;
- Heat loss control for the anaerobic reactor and MBR tanks, assuming insulation is used if reactor temperature is greater than ambient temperature;[4]
- Generation of methane from AnMBR headspace and utilization of that methane for production of electricity (capture of waste heat is not modeled for the baseline scenario but is included in selected scenarios in the sensitivity analysis);
- Effluent vacuum pump requiring purchased electricity or electricity generated from the recovered methane of anaerobic process;
- Biogas recirculation pump requiring purchased electricity or electricity generated from the recovered methane of anaerobic process;
- Dissolved methane recovery from the permeate (incorporated only in a sensitivity analysis);
- Heat exchanger which uses heat from the effluent to heat the influent; and
- Sludge discharged to the sewer, which leaves LCA system boundaries.

[4] Data from CAPDETWorks is used to calculate the surface area of the anaerobic digester(s) (i.e., reactor) and AnMBR tanks. For a more conservative estimate of heat loss, the same convective heat loss formula for vertical surfaces without insulation was used for horizontal surfaces exposed to the air. However, no heat loss was assumed from the bottom of tanks in contact with the ground.

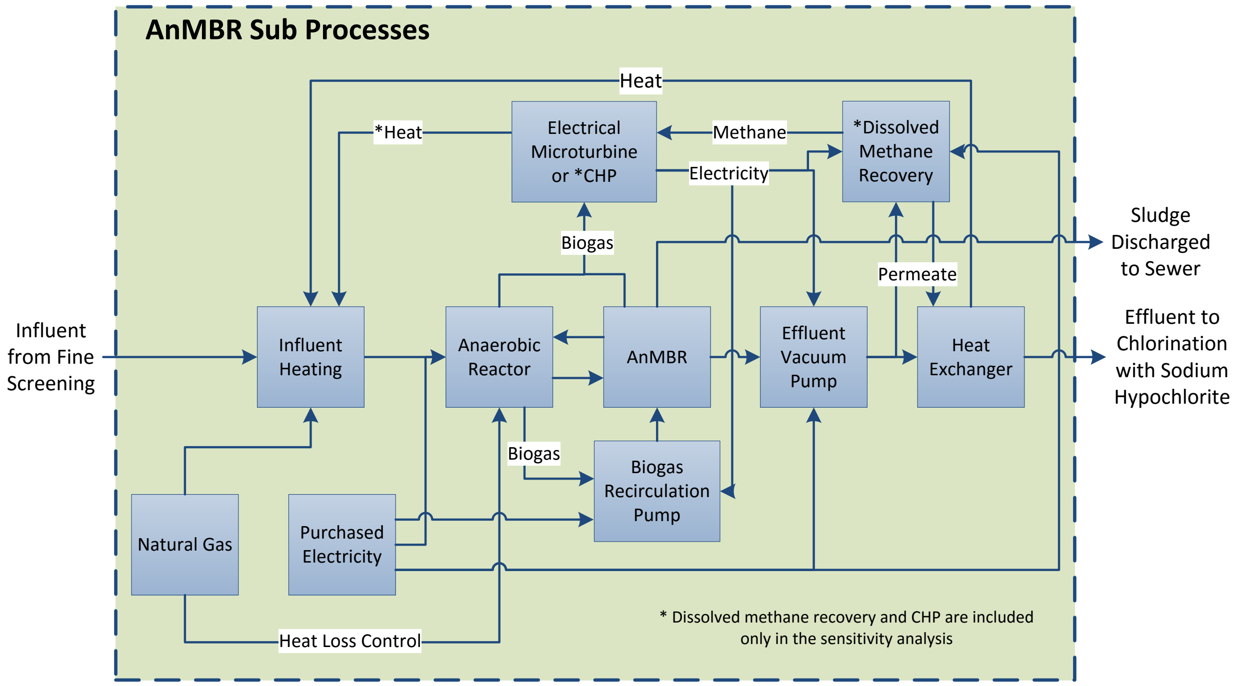


**Figure 3-2. AnMBR Sub Processes (Adapted from Feickert et al. 2012)**

This study investigated the operation of AnMBR WWT at 35˚C, representative of a mesophilic AnMBR system, and at 20˚C, representative of a psychrophilic AnMBR system. LCI operational data for the AnMBR process at 35˚C and 20˚C are displayed in Table 3-14 and Table 3-15, respectively. These LCI results were developed based on the methodology described in Sections 3.2.2.1 through 3.2.2.4. Negative net electricity values mean the system produces more electricity than it consumes so there is a net electricity displacement credit. The cost of purchased energy was calculated using the cost factors for electricity, $0.10/kWh, and natural gas, $15.50/1000 cubic feet, provided by CAPDETWorks. No cost is assigned to the energy in the form of biogas or electricity generated on-site; however, a credit is received based on the market cost of purchased electricity when the AnMBR system is a net electricity producer.

**Table 3-14. Life Cycle Inventory Operational Data for AnMBR at 35˚C**

| | Water Output (MGD) | Net Electricity (kWh/yr.) | Net Natural Gas ($m^3$/yr.) | NaOCl (kg/yr.) | Sludge Output (MGD) |
|---|---|---|---|---|---|
| 0.05 MGD | 0.049 | -20,871 | 25,504 | 170 | 0.0006 |
| 0.1 MGD | 0.099 | -41,952 | 35,022 | 339 | 0.001 |
| 1 MGD | 0.99 | -420,506 | 346,910 | 2,513 | 0.008 |
| 5 MGD | 4.96 | -2,102,970 | 1,731,625 | 10,471 | 0.04 |
| 10 MGD | 9.92 | -4,206,050 | 3,461,430 | 18,848 | 0.08 |

**Table 3-15. Life Cycle Inventory Operational Data for AnMBR at 20˚C**

| | Water Output (MGD) | Net Electricity (kWh/yr.) | Net Natural Gas ($m^3$/yr.) | NaOCl (kg/yr.) | Sludge Output (MGD) |
|---|---|---|---|---|---|
| 0.05 MGD | 0.049 | -18,263 | 0 | 170 | 0.0006 |
| 0.1 MGD | 0.099 | -36,737 | 0 | 339 | 0.001 |
| 1 MGD | 0.99 | -368,355 | 0 | 2,513 | 0.008 |
| 5 MGD | 4.96 | -1,842,212 | 0 | 10,471 | 0.04 |
| 10 MGD | 9.92 | -3,684,533 | 0 | 18,848 | 0.08 |

### 3.2.2.1 Biogas Production

Anaerobic treatment of the wastewater leads to formation of biogas. Typical biogas has a methane content of 55% to 70% (this study uses a value of 65%) and most of the remaining content is carbon dioxide (Metcalf and Eddy, 2014; Smith et al., 2012). Methane produced is largely a function of the influent COD strength, with biogas production expressed commonly as volume of $CH_4$ per mass unit of COD. An overview of the methane production results for AnMBR municipal water treatment scenarios in literature is shown in Table 3-16. This is representative of biogas in the headspace of the reactor. Methane production increases with an increase in the reactor temperature. For the purposes of this study, we have assumed an overall methane production rate of 0.24 $m^3 CH_4$/kg COD at 20˚C and 0.27 $m^3 CH_4$/kg COD at 35˚C (Martinez-Sosa et al., 2011). This range is within that reported by other sources in Table 3-16.

**Table 3-16. AnMBR Parameters Influencing Methane Generation for Municipal Wastewater**

| Source | Influent COD Strength (mg/L) | COD Removal (%) | Reactor Temperature (ºC) | HRT (day) | Reactor Volume ($m^3$) | Biogas production ($m^3$ $CH_4$/kg COD) |
|---|---|---|---|---|---|---|
| *Baek et al., 2010* | - | 64 | - | 0.5-2 | 0.01 | - |
| *Berube et al., 2006* | - | 70-90 | 11-32 | - | - | - |
| *Chang, 2014* | 342-600 | 90 | 20-30 | 1-25 | 0.06-0.35 | 0.25-0.35 |
| *Chu et al., 2005* | 383-849 | - | - | 6.04 | - | - |
| *Gao et al., 2010* | 500 | - | - | 2.08 | - | - |
| *Giménez et al., 2011* | 445 ± 95 | 86.9 ± 3.4 | 33.3±0.2 | 0.25-0.875 | 1.3 | 0.294 ± 0.04 |
| *Ho & Sung et al., 2009* | 500 | 90 | 25 | 0.25-0.5 | 0.004 | 0.21-0.22 |
| *Ho & Sung et al., 2010* | 500 | 85->95 | 15-25 | 3.75-15 | 0.004 | - |
| *Hu & Stuckey, 2006* | 460±20 | >90 | 35 | 2.0 | 0.003 | 0.22-0.33 |
| *Huang et al., 2011* | 550 | >97 | 25-30 | 1.25-2.5 | 0.006 | 0.138-0.25 |
| *Kim et al., 2011* | 513 | 99 | 35 | 0.175-0.246 | 0.003 | - |
| *Lew et al., 2009* | 540 | 88 | 25 | 0.25 | 0.18 | - |
| *Lin et al., 2011* | 425 | 90 | 30 | 0.42 | 0.08 | 0.24 |
| *Martin et al., 2011* | 400-500 | - | 35 | 0.33-.58 | - | 0.29-0.33 |
| *Martinez-Sosa et al., 2011* | 402±73 | 84-94 | 20-35 | 1.5-0.67 | 0.35 | 0.24-0.27 |
| *Saddoud et al., 2007* | 685 | 88 | 37 | 0.625-2.5 | - | - |
| *Salazar-Pelaez et al., 2011* | 350 | 80 | - | 0.16-0.50 | - | - |
| *Smith et al., 2011* | 440 | 92 | 15 | 0.67 | - | |
| *Smith et al., 2014* | 430 | 85-90 | 15-25 | 0.33 | - | 0.35 |
| *Wen et al., 1999* | 100-2600 | 97 | 12-25 | 0.16-0.25 | - | - |

Notes: COD = Chemical Oxygen Demand; HRT = Hydraulic Retention Time; SRT = Solids Retention Time

The recovered methane from the headspace is assumed to be converted to electricity for operating the pumps in the treatment system. Biogas cleaning and compression is not included in this model due to lack of available data. The destruction efficiency associated with burning the biogas in an energy/thermal device (e.g., combined heat and power (CHP), biogas flare) is modeled as 0.99 (IPCC, 2006), with one percent of the biogas produced escaping as fugitive emissions rather than recovered for electricity. Conversion of methane to electricity is calculated using Equation 1 and multiplying by the operation time (Feickert et al., 2012). The baseline model assumes methane combustion energy not converted to electricity is lost as waste heat through the exhaust stream.

$$EP_{CH4} = (PR_{CH4} * LHV_{CH4}) * DG\_eff \qquad \text{(Eqn. 1)}$$

Where:

| | | |
|---|---|---|
| $EP_{CH4}$ | = | Electric power from recovered headspace methane in kW |
| $PR_{CH4}$ | = | Methane production rate (grams CH4/second) |
| $LHV_{CH4}$ | = | Lower heating value methane (modeled as 50 kJ/g) |
| DG_eff | = | Overall efficiency power diesel engine for electric generator (modeled as 32.4%) |

While the baseline model assumes the recovered methane is used to produce only electricity, sensitivity analyses in Section 5.0 include scenarios with biogas flaring and recovery with CHP. With CHP, the additional waste heat is captured with a heat exchanger and used to heat incoming water. Appendix E lists the parameters used to develop the inventory data for biogas flaring and recovery of methane with CHP.

A portion of methane produced is dissolved in solution and leaves the system in the permeate (Smith et al., 2012). While supersaturation of dissolved methane occurs in some types of anaerobic reactors, this has not been found in AnMBR systems (Cookney et al., 2016). Thus, the amount of methane per liter of permeate was calculated based on Henry's Law and the van't Hoff-Arrhenius relationship along with coefficients for methane used to calculate Henry's constant for methane.

Van't Hoff Arrhenius Relationship, solved for Henry's Constant (Metcalf and Eddy, 2014):

$$\mathrm{H}_{\mathrm{CH}_4} = 10^{\left(-A/_{T}+B\right)} \qquad \text{(Eqn. 2)}$$

Where:

| | | |
|---|---|---|
| $H_{CH_4}$ | = | Henry's constant for methane at a given reactor temperature |
| A | = | 675.75 |
| B | = | 6.880 |
| T | = | reactor temperature in Kelvin |

Henry's Law (adapted from Smith et al., 2014):

$$CH_{4,dissolved} = \left({P_{CH_4}}\Big/{H_{CH_4}}\right)(M)\left(MW_{CH_4}\right) \quad \text{(Eqn. 3)}$$

Where:

| | | |
|---|---|---|
| $CH_{4,\ dissolved}$ | = | concentration of dissolved methane in solution (g/liter) |
| $P_{CH_4}$ | = | 0.65 atm, the partial pressure of methane in biogas |
| $H_{CH_4}$ | = | Henry's constant, as calculated for a given reactor temperature |
| M | = | 55.5 mol/liter, the molarity of water |
| $MW_{CH_4}$ | = | 16.04 g/mol, the molecular weight of methane |

The concentration of methane dissolved in permeate varies based on the temperature of the reactor. The same equations and coefficients were used to calculate the amount of methane per liter of permeate that would remain in solution once the permeate was exposed to the atmosphere, assuming normal temperature (20°C) and pressure (1 atm) in all scenarios and 1822.5 parts per billion methane in the atmosphere (Dlugokencky, 2015).

Based on previous literature, the baseline assumption for this study is a 0% recovery rate of methane dissolved in permeate (Smith et al., 2014). Therefore, the amount of methane emitted per liter of permeate is the difference between the total amount of dissolved methane and the dissolved methane that remains in solution when discharged. Future advancements, however, could lead to significant recovery of methane left in the permeate (Hu & Stuckey, 2006; Dagnew et al., 2011; Giménez et al., 2011; Kim et al., 2011; Smith et al., 2012; and Bandara et al., 2011). Section 5 investigates sensitivity analysis results when including recovery of methane from the permeate.

#### 3.2.2.2 Recovery of Dissolved Methane in Permeate

The sensitivity analysis models several scenarios with recovery of dissolved methane in the permeate for conversion to electricity. Membrane separation was selected as the methane recovery method based on its simplicity of operation and maintenance, no hazardous chemical use, and its good economic performance in low gas flow situations (Makaruk et al., 2010). Equations calculating energy use for adiabatic compression have been found to provide a good estimate for energy use for polytropic compression involved in membrane separation and were used in this model to calculate electricity demand (Perry and Green, 1997).

$$W_{ad} = \frac{kWRT}{k-1}\left[\left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} - 1\right] \quad \text{(Eqn. 4)}$$

Where:

| | | |
|---|---|---|
| $W_{ad}$ | = | power required for the compressor (Watts) |
| k | = | 1.295, the heat capacity ratio |
| W | = | molar flow rate of methane (mol/s) |
| R | = | 8.314 J/mol·K, the universal gas constant |
| T | = | inlet gas temperature (K), assumed same temperature as reactor |
| $P_{out}$ | = | 101.325 kPa, absolute discharge pressure |
| $P_{in}$ | = | 21.325 kPa, absolute inlet pressure |

The sensitivity analysis model assumes an 80% recovery of methane dissolved in the permeate (Makaruk et al., 2010). The capital cost of membrane separation technology was determined using an engineering equation from Chemical Process Equipment (Walas, 1990) based on the power requirement in kW for a screw-type compressor in 1985 and adjusted for current cost using the Chemical Engineering Plant Cost Index (CEPCI) for 1985 and December 2014 (Bailey, 1986 and 2015).

$$Cost = \left(\frac{CEPCI_{2014}}{CEPCI_{1985}}\right)(1830)(Power)^{0.71} \qquad \text{(Eqn. 5)}$$

Where:

| | | |
|---|---|---|
| Cost | = | present cost in dollars of compressor for membrane separation |
| $CEPCI_{2014}$ | = | 575.7, Chemical Engineering Plant Cost Index for Dec. 2014 |
| $CEPCI_{1985}$ | = | 325.3, Chemical Engineering Plant Cost Index for 1985 |
| Power | = | power requirement (kW) for compressor as found in Eqn. 4 |

#### 3.2.2.3 Membrane Fouling and Sludge Output

Requirements for preventing membrane fouling, as indicated by previous work, were assumed independent of wastewater strength (Smith et al., 2014). As for the AeMBR systems, sodium hypochlorite consumption (see Table 3-14 and Table 3-15) is estimated using a factor of 900 L 12.5% NaOCl per year per 370 square feet of membrane surface area (GE Power & Water, 2014). Cost of sodium hypochlorite was calculated using the same method as for the AeMBR. Membrane surface area required for each AnMBR system is listed in Table 3-22.

The amount of sludge returned to the main sewer system to be treated downstream at the centralized WWTP was derived from the following equation from Metcalf and Eddy (2014) for calculating solids retention time (SRT) for aerobic MBR systems and adapted for use with the AnMBR systems. Solving for Q obtains the volume of sludge wasted per day. See Section 3.2.2.4 for a discussion of the solids concentration and Table 3-18 for tank volumes.

$$SRT = \frac{X_A V_A + X_M V_M}{Q_W X_M} \qquad \text{(Eqn. 6)}$$

Where:

| | | |
|---|---|---|
| $V_A$ | = | volume of anaerobic reactor ($m^3$) |
| $V_M$ | = | volume of membrane separation tank ($m^3$) |
| $X_A$ | = | solids concentration in the anaerobic reactor (mg/L) |
| $X_M$ | = | solids concentration in the membrane separation tank (mg/L) |
| $Q_W$ | = | waste sludge flow rate ($m^3$/day) |

Sludge output is shown in Table 3-14 and Table 3-15 for the AnMBR systems operating at 35˚C and 20 ˚C, respectively. The remaining volume was assumed to be MBR permeate that would then be pumped to the chlorination tanks for disinfection.

#### 3.2.2.4 Infrastructure

LCI infrastructure data for the anaerobic reactor unit process were developed using CAPDETWorks modeling software and are displayed in Table 3-17.

**Table 3-17. Life Cycle Inventory Infrastructure Data for Anaerobic Reactor**

| | Earthworks (cu ft.) | Concrete (cu ft.) |
|---|---|---|
| 0.05 MGD | 3,320 | 1,728 |
| 0.1 MGD | 6,240 | 2,512 |
| 1 MGD | 51,800 | 9,700 |
| 5 MGD | 237,000 | 34,620 |
| 10 MGD | 513,000 | 61,000 |

An AnMBR process engineer at GE stated that for AnMBR systems treating municipal wastewater the HRT is typically around 8 hours, the SRT is between 40-80 days, and the mixed-liquor suspended solids (MLSS) concentration is between 10 and 14 g/liter. This study uses an SRT of 60 days and a MLSS of 12 g/L, the midpoints of the ranges provided by GE. The HRT, SRT, and influent suspended solids concentrations were used to estimate the total tank volume required for the anaerobic reactors. CAPDETWorks technical manual Section 2.19.6.3.3.1 was used as guidance for the number of reactor tanks needed for each system based on the average daily flow (Harris et al., eds. 1982). Typical tank configurations, including diameter and sidewater depth, were based on figure 2.19-9 in the CAPDETWorks technical reference for system sizes 1 MGD and greater and on CAPDETWorks equation 2.19.6.3.4.3 for 0.05 MGD and 0.1 MGD systems (Harris et al., eds. 1982). The number of tanks, tank diameter, and tank sidewall depth, as shown in Table 3-18, were used as input parameters to model anaerobic reactor infrastructure quantities and cost using CAPDETWorks. The reactor tank is modeled with a floating cover, which can adjust the volume of the tank to some degree.

**Table 3-18. Anaerobic Reactor Tank Dimensions**

| | 0.05 MGD | 0.1 MGD | 1 MGD | 5 MGD | 10 MGD |
|---|---|---|---|---|---|
| Number of Tanks | 1 | 1 | 1 | 2 | 2 |
| Diameter (ft.) | 15 | 20 | 50 | 70 | 95 |
| Sidewall Depth (ft.) | 18.2 | 19.1 | 24.4 | 28.0 | 32.4 |
| Total Volume (cu ft.) | 3,317 | 6,240 | 51,848 | 236,817 | 513,477 |

LCI infrastructure data for each sub process of the MBR unit process are shown in Table 3-19 through Table 3-21. Infrastructure data were taken from CAPDETWorks modeling results unless otherwise noted.

**Table 3-19. Life Cycle Inventory Infrastructure Data for MBR Tanks (AnMBR)**

| | Earthwork (cu ft.) | Concrete (cu ft.) | Membrane PVDF (kg/10 yrs.) |
|---|---|---|---|
| 0.05 MGD | 6,700 | 2,290 | 1,474 |
| 0.1 MGD | 7,460 | 2,710 | 2,948 |
| 1 MGD | 13,700 | 6,160 | 21,826 |
| 5 MGD | 29,100 | 28,200 | 90,942 |
| 10 MGD | 49,400 | 41,900 | 163,696 |

**Table 3-20. Life Cycle Inventory Infrastructure Data for Permeate Pumping (AnMBR)**

| | Earthwork (cu ft.) |
|---|---|
| 0.05 MGD | 1,600 |
| 0.1 MGD | 1,610 |
| 1 MGD | 1,680 |
| 5 MGD | 1,880 |
| 10 MGD | 2,170 |

**Table 3-21. Life Cycle Inventory Infrastructure Data for Waste Sludge Pumping (AnMBR)**

| | Earthwork (cu ft.) |
|---|---|
| 0.05 MGD | 1,600 |
| 0.1 MGD | 1,600 |
| 1 MGD | 1,600 |
| 5 MGD | 1,620 |
| 10 MGD | 1,640 |

Membrane surface area was determined by dividing the average daily flow by the average net flux of 7.5 liters/m$^2$/hour reported in a literature review by Chang (2014) for AnMBR systems and confirmed through personal communication with a GE AnMBR product manager (Nelson Fonseca, GE Power and Water Lead Product Manager for Anaerobic MBR, August 18, 2015). Note that flux was assumed the same for both 35˚C and 20˚C operating temperatures, so the potential increase in flux due to decreased viscosity of permeate at the higher temperature was not taken into account. Table 3-22 displays membrane surface area required for each AnMBR scale as well as MBR tank dimensions. Tank dimensions were derived from membrane surface area requirements and GE guidelines for tank sizes as described in the Aerobic MBR Infrastructure section of this report.

**Table 3-22. Anaerobic Membrane Bioreactor Tank Dimensions**

| | 0.05 MGD | 0.1 MGD | 1 MGD | 5 MGD | 10 MGD |
|---|---|---|---|---|---|
| Membrane Surface Area (m2) | 1,051 | 2,103 | 21,029 | 105,146 | 210,293 |
| Number of Trains (Including Standby) | 2 | 2 | 3 | 5 | 9 |
| Number of Cassettes per Train | 2 | 2 | 7 | 16 | 16 |
| Number of Modules per Cassette | 16 | 48 | 48 | 48 | 48 |
| Length of Tanks (m) | 2.43 | 4.57 | 14.7 | 33.0 | 33.0 |
| Width of Tanks (m) | 2.74 | 2.74 | 2.74 | 2.74 | 2.74 |
| Height of Tanks (m) | 3.66 | 3.66 | 3.66 | 3.66 | 3.66 |

Costs for infrastructure associated with the anaerobic MBR unit process were largely derived from CAPDETWorks modeling results for the aerobic MBR unit process using tank dimension input parameters as specified in Table 3-22 since CAPDETWorks software does not include a unit process for AnMBR. Insulation costs for the AnMBR system operating at 35°C were estimated using surface area calculations for the sides and top of the reactor and AnMBR tanks based on anaerobic digester dimensions from CAPDETWorks. The insulation was assumed to be 1-foot-thick and composed of equal volumes of expanded polystyrene (EPS) insulation board and foil-faced fiberglass batts (Feickert et al., 2012). RSMeansOnline square foot estimator provided cost factors of $1.59/sq. ft. of 12-inch-thick foil-faced fiberglass and $6.12/ sq. ft. of 12-inch-thick EPS ($1.53/sq. ft. for 3 inch EPS board multiplied by 4 for an equivalent 12-inch thickness) (The Gordian Group 2016). The capital cost for the microturbine units used to generate electricity in the baseline scenarios was modeled using a factor of $1,660/kW of electricity generated, the midpoint of a range found in three sources (Capehart, 2014) (NREL FEMP, 2002) (Van Holde et al., 2002). For the sensitivity analysis in Chapter 5, capital cost for the combined heat and power unit was calculated using a factor of $2,030/kW of electricity generated, the midpoint of a range found in several reports (Capehart, 2014; Chambers and Potter, 2002; NREL FEMP, 2002; U.S. EPA CHPP, 2011; Van Holde et al., 2002). The cost of a flare, estimated by CAPDETWorks, is included in all AnMBR scenarios, as a flare is required as a safety measure to burn excess methane.

## 3.3 Pre and Post Treatment Model

Life cycle environmental inventory and cost data for pre and post treatment modeling for both the AnMBR and AeMBR were primarily derived from CAPDETWorks simulations as illustrated in Figure 3-1. As discussed in Section 2.2, pre-treatment includes screening and grit removal followed by fine screening. Post treatment includes disinfection with sodium hypochlorite prior to the recycled water delivery to end users.

### 3.3.1 Preliminary Treatment (Screening and Grit Removal)

The screening and grit removal step is assumed equivalent for the AeMBR and AnMBR model. CAPDETWorks default settings were used for input parameters to calculate the infrastructure and energy requirements as well as grit landfilled after collection from a mechanically cleaned bar screen and a horizontal grit removal unit. The CAPDETWorks model assumes negligible water loss from screening and grit removal processes. The operational LCI data for this work are displayed in Table 3-23.

**Table 3-23. Life Cycle Inventory Operational Data for Preliminary Treatment**

| | Water Output (MGD) | Electricity (kWh/yr.) | Grit Disposed (kg/yr.) |
|---|---|---|---|
| 0.05 MGD | 0.050 | 4,000 | 5.48 |
| 0.1 MGD | 0.10 | 5,510 | 11.0 |
| 1 MGD | 1.00 | 16,000 | 110 |
| 5 MGD | 5.00 | 33,700 | 548 |
| 10 MGD | 10.0 | 46,500 | 1,096 |

**Table 3-24. Life Cycle Inventory Infrastructure Data for Preliminary Treatment**

| | Earthworks (cu ft.) | Concrete (cu ft.) |
|---|---|---|
| 0.05 MGD | 1,655 | 547 |
| 0.1 MGD | 1,748 | 595 |
| 1 MGD | 2,515 | 947 |
| 5 MGD | 4,256 | 1,586 |
| 10 MGD | 5,847 | 2,061 |

Earthworks and concrete quantities required for construction of the grit channel were derived from CAPDETWorks outputs of the length, width, and depth of the grit channel. The calculation assumed these channel measurements describe the inner dimensions of the channel, and used a conservative assumption that the two side walls and bottom wall were one-foot-thick concrete. Required earth work was assumed to be 1 foot wider on either side of the two concrete side walls and 1 foot below the concrete slab forming the bottom of the channel. The LCI infrastructure data is shown in Table 3-24. Costs for preliminary treatment earthwork and concrete were calculated using cost factors per unit of earthwork and concrete provided in CAPDETWorks.

### 3.3.2 Fine Screening

The fine screening step is assumed equivalent for the AeMBR and AnMBR model. The operational LCI data for this work are displayed in Table 3-25, and the infrastructure LCI data are shown in Table 3-26.

**Table 3-25. Life Cycle Inventory Operational Data for Fine Screening**

| | Water Output (MGD) | Electricity (kWh/yr.) |
|---|---|---|
| 0.05 MGD | 0.050 | 100 |
| 0.1 MGD | 0.10 | 200 |
| 1 MGD | 1.00 | 2,070 |
| 5 MGD | 5.00 | 10,360 |
| 10 MGD | 10.0 | 20,720 |

**Table 3-26. Life Cycle Inventory Infrastructure Data for Fine Screening**

| | Earthworks (cu ft.) |
|---|---|
| 0.05 MGD | 32.6 |
| 0.1 MGD | 65.2 |
| 1 MGD | 652 |
| 5 MGD | 3,260 |
| 10 MGD | 6,521 |

Since CAPDETWorks does not include a fine screening module, manufacturer equipment specifications were used to calculate electricity demand for operating fine screening equipment. Huber Technology states energy consumption of screens, screening conveyors and wash-presses ranges from 0.5 to 1.5 Wh per $m^3$ of wastewater processed (Huber Technology, 2015). Since an estimate of energy use for ancillary equipment was not readily available, the maximum of the range provided by Huber Technology was used to calculate electricity consumption. As for preliminary treatment, the fine screening process was assumed to result in negligible water loss.

Data on fine screening cost of construction and equipment installation as well as yearly operation and maintenance costs were drawn from a Wastewater Technology Factsheet published by the U.S. EPA Office of Water (U.S. EPA, 2003). The factsheet provided a cost curve for horizontal shaft rotary screens for systems between 0.1 and 100 MGD. Linear extrapolation was used to estimate these costs for the 0.05 MGD system. The cost of energy was calculated using the electricity consumption for each system and an average U.S. cost of electricity of 10 cents per kWh (as assumed by CAPDETWorks).

Earthworks required for installation of the fine screening equipment was based on excavation dimensions for fine screening facilities associated with an MBR WWTP under construction in Riverside, California (City of Riverside, 2013). The reported earthworks for the Riverside fine screening facility was normalized to a volume of earthworks per million gallons of wastewater treated and then extrapolated based on the daily flow for each WWTP scale considered (City of Riverside, 2012). The cost of earthworks for fine screening was calculated using the cost factor per unit of earthwork provided in CAPDETWorks.

### 3.3.3 Chlorination

The LCI data for the chlorination stage is assumed equivalent for the AeMBR and AnMBR model. The operational LCI data for this work are presented in Table 3-27 and LCI data for infrastructure are shown in Table 3-28. Cost data for the chlorination unit process were taken directly from CAPDETWorks results except as noted below. Water output from chlorination is higher for AnMBR than AeMBR because the AnMBR system operates with a longer SRT and therefore treats more water per unit of sludge sent back into the main sewer line (Table 3-6 vs Table 3-14 and Table 3-15). Water output volume from chlorination is assumed to be the same as input volume.

**Table 3-27. Life Cycle Inventory Operational Data for Chlorination**

| | Water Output – AeMBR/AnMBR (MGD) | Electricity (kWh/yr.) | NaOCl (kg/yr.) |
|---|---|---|---|
| 0.05 MGD | 0.049 / 0.049 | 45,713 | 283 |
| 0.1 MGD | 0.10 / 0.10 | 52,478 | 567 |
| 1 MGD | 0.98 / 0.99 | 83,000 | 5,667 |
| 5 MGD | 4.88 / 4.96 | 114,352 | 28,334 |
| 10 MGD | 9.77 / 9.92 | 131,000 | 56,668 |

**Table 3-28. Life Cycle Inventory Infrastructure Data for Chlorination**

| | Earthworks (cu ft.) | Concrete (cu ft.) |
|---|---|---|
| 0.05 MGD | 58 | 1,824 |
| 0.1 MGD | 116 | 1,847 |
| 1 MGD | 1,160 | 2,383 |
| 5 MGD | 5,810 | 4,720 |
| 10 MGD | 11,600 | 7,640 |

In order to reuse the treated water, water quality standards must be met. The regulations for water reuse are set by each state. However, U.S. EPA developed a set of guidelines for a range of water reuse categories, which are used in this study (U.S. EPA, 2012). The water quality standards are shown in Table 3-29.

**Table 3-29. U.S. EPA Guidelines for Water Quality Standards for Unrestricted and Restricted Urban Reuse**

| | Urban Reuse – Unrestricted | Urban Reuse – Restricted | Units |
|---|---|---|---|
| BOD | ≤10 | ≤30 | mg/l |
| Total Suspended Solids | | ≤30 | mg TSS/l |
| Turbidity | ≤2 | | NTU |
| Fecal coliform | ND | ≤200 | #/100 ml |
| pH | 6.0-9.0 | 6.0-9.0 | |
| Chlorine Residual | ≥1 | ≥1 | mg/l |

In general, aerobic MBR systems are expected to produce effluents with E. coli levels at or below 100 count per 100 mL (Metcalf and Eddy, 2014), and a survey of 38 small water recycling facilities found that 90% had turbidity levels less than 0.7 Nephelometric Turbidity Units (NTU) (Hirani et al., 2013). CAPDETWorks modeling results showed AeMBR effluent BOD concentrations less than 5 mg/L. Recent research reported that, under normal operating conditions of an AeMBR system, a free chlorine contact time of 10 mg-min/L was sufficient to achieve 5-log removal of a virus and reduce total coliform count to below detection levels of 2 colony forming units (CFU) per 100ml (Hirani et al., 2014). EPA guidelines for water reuse recommend a 30-minute contact time during chlorination and a 1 mg/L chlorine residual at a minimum (U.S. EPA, 2012). Therefore, an influent coliform count of 100/100 mL, a 2 mg/liter chlorine dosage, and the default 30-minute contact time were chosen as input parameters to the CAPDETWorks chlorination model for AeMBR. The input parameters are conservative in comparison with the 10 mg-min/L shown to be sufficient disinfection for AeMBR effluent to meet the restricted and unrestricted urban U.S. EPA water reuse guidelines, but allow for some variability in effluent quality and ensures there would still be at least 1 mg/l of chlorine residual. Given that a study of a bench-scale AnMBR system with 60 day SRT found that AnMBR effluent had no detectable fecal coliform and total suspended solids concentration less than 1 mg/L, the same contact time and dosage level was modeled for the AnMBR as well (Herrera-Robledo et al., 2010).

Since CAPDETWorks only models chlorination with chlorine gas, a stoichiometric conversion was made to calculate sodium hypochlorite consumption required from the CAPDETWorks output of average chlorine required per day. All infrastructure data were taken from the CAPDETWorks modeling results. The cost of sodium hypochlorite was calculated using the unit cost of \$2/kg NaOCl derived from the cost of 14% by weight hypochlorite solution (\$10/cu ft. 14% NaOCl) provided in CAPDETWorks. CAPDETWorks assumes that all chlorination systems with average influent flows of 5 MGD or less use 118,000 kWh of electricity per year. This assumption did not seem reasonable for the WWT systems as small as 0.05 MGD. CAPDETWorks technical manual provides equation number 2.13.6.12.2 to calculate the annual electrical demand for chlorination units for systems larger than 5 MGD (Harris et al., eds. 1982). This equation was used to manually calculate electricity demand for chlorination for the 0.05, 0.1, 1, and 5 MGD systems (see Table 3-27).

$$kWh = (83{,}000)\,(Q_{avg})^{0.1991} \qquad \text{(Eqn. 7)}$$

Where:

$Q_{avg}$ = average daily flow in MGD

kWh = annual electricity consumption to operate the chlorinator and evaporator

The cost of energy was calculated using the average cost of electricity per kWh provided by CAPDETWorks.

## 3.4 Wastewater Collection System Model

This section covers the wastewater collection system operational and infrastructure requirements for the different population density scenarios investigated. It is assumed the wastewater collection system infrastructure has been in place prior to establishment of the plug-in MBR systems. Infrastructure requirements are included in the scope of the LCA model, since these impacts are amortized over the lifetime of the pipe system. However, infrastructure for the collection system is not included in the cost analysis since all costs were incurred prior to establishment of the decentralized MBR systems.

### 3.4.1 Infrastructure Calculations

The collection system pipe composition and pipe lifetime are displayed in Table 3-30 and Table 3-31 respectively.

**Table 3-30. Collection System Pipe Material by Diameter**

| | % of Collection System | | | | |
|---|---|---|---|---|---|
| Diameter of Pipe (inches) | PVC | Vitrified Clay | Concrete | Reinforced Concrete | Cement-Lined Ductile Iron |
| 8 | 7.1% | 31.8% | 33.1% | 7.0% | 1.1% |
| 10 to 12 | 0.9% | 4.0% | 4.1% | 0.9% | 0.1% |
| 15 to 21 | 0.4% | 2.0% | 2.1% | 0.4% | 0.1% |
| 24 and larger | 0.4% | 2.0% | 2.1% | 0.4% | 0.1% |

Source:
Rowlett, T. 2015. Personal communication with T. Rowlett, Water Infrastructure Expert at PG Environmental, LLC, 4 March 2015.

**Table 3-31. Collection System Pipe Lifetimes by Material Type**

| | Pipe Material | | | | |
|---|---|---|---|---|---|
| | PVC | Vitrified Clay | Concrete | Reinforced Concrete | Cement-Lined Ductile Iron |
| Lifetime (Years) | 55 | 100 | 105 | 105 | 97.5 |

Source:
American Water Works Association. 2012. Buried No Longer: Confronting America's Water Infrastructure Challenge

The total length of pipe calculated per scenario is illustrated in Figure 3-3 and Figure 3-4 (Rowlett, 2015).

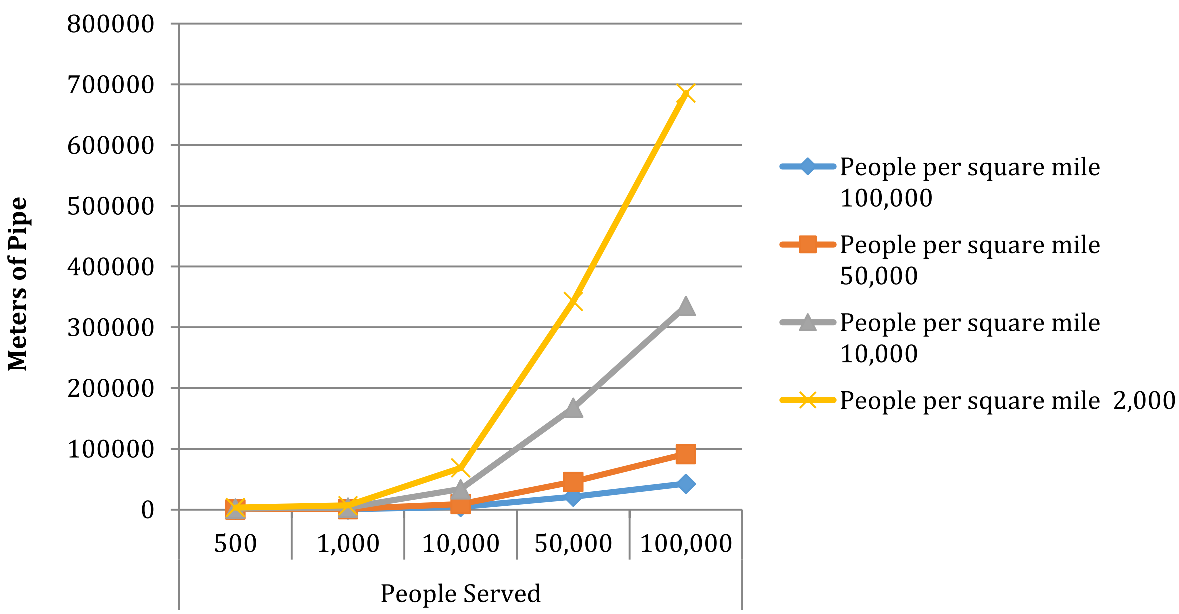


**Figure 3-3. Total Meters of Sewer Pipe by Scenario on the Basis of People Served**

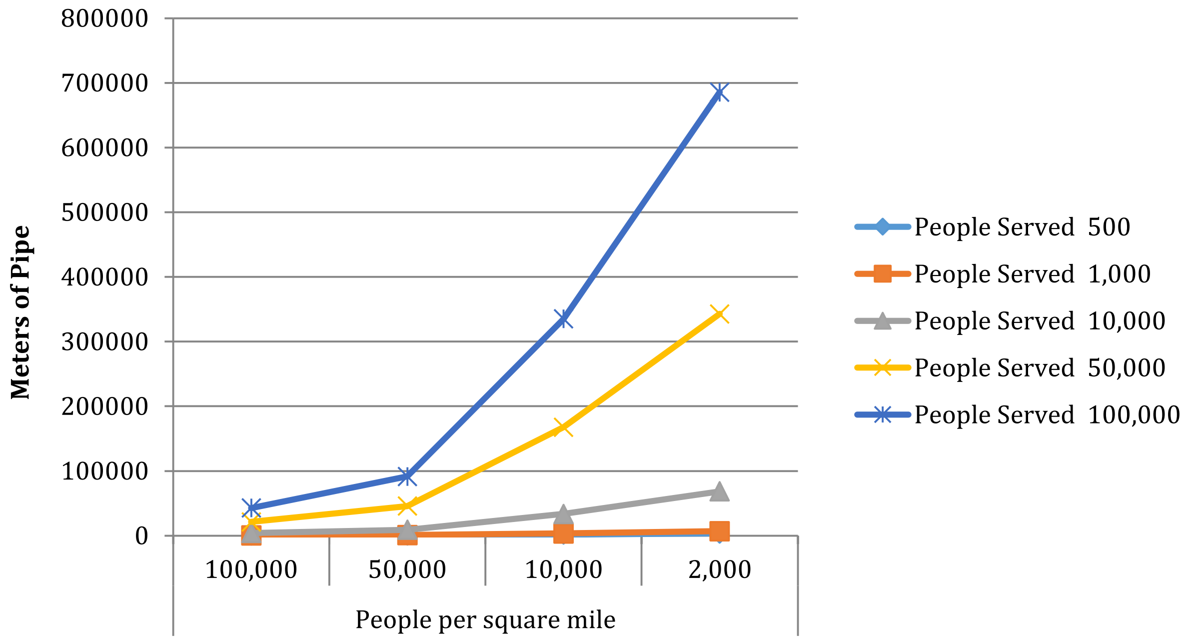


**Figure 3-4. Total Meters of Sewer Pipe by Scenario on the Basis of People per Square Mile**

When normalized to cubic meters of water treated, then meters of sewer pipe required stays constant throughout the same population densities, as evident in Figure 3-5. The meters of pipe required increases as the population density decreases (Figure 3-6).

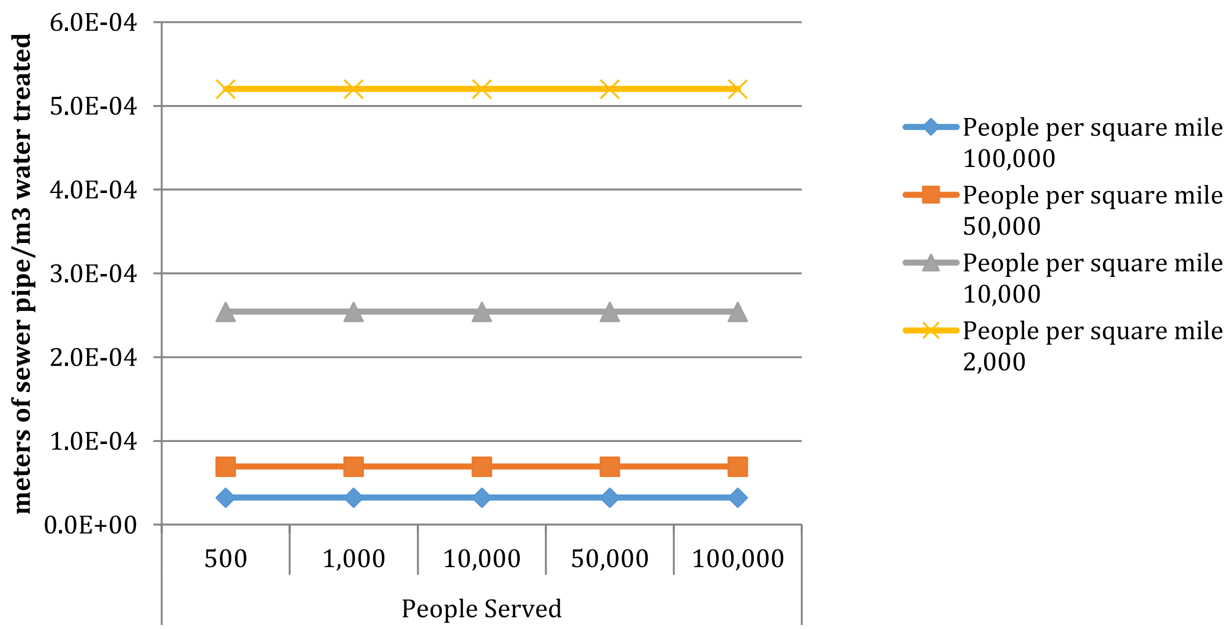


**Figure 3-5. Meters of Sewer Pipe by Scenario Normalized to Cubic Meters of Water Treated and on the Basis of People Served**

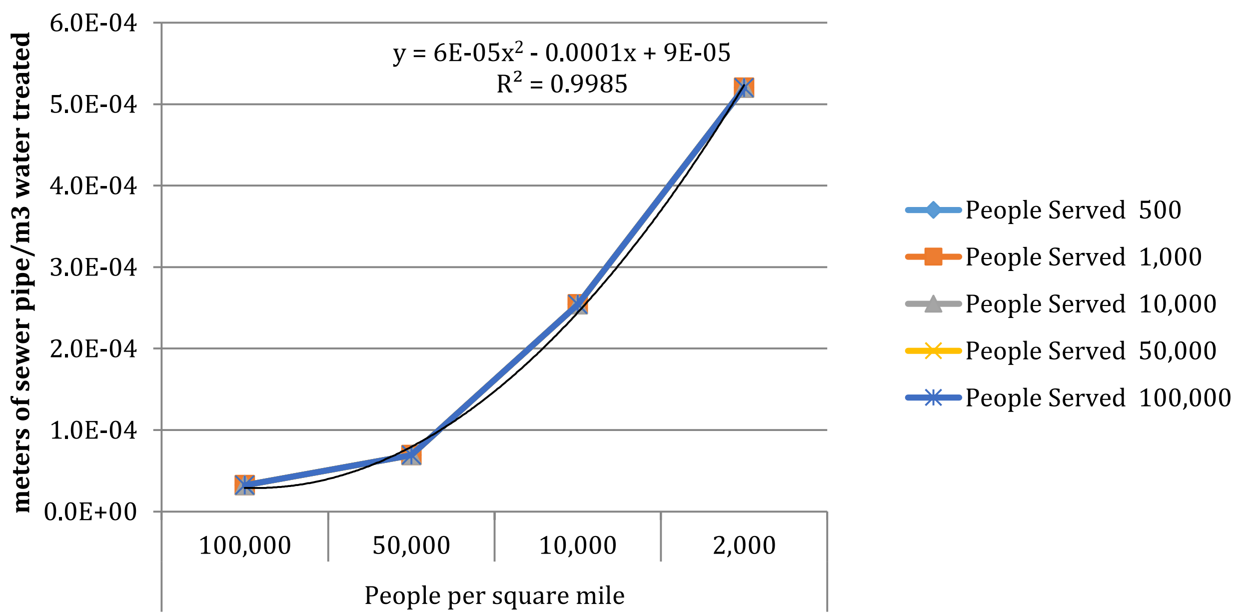


**Figure 3-6. Meters of Sewer Pipe by Scenario Normalized to Cubic Meters of Water Treated and on the Basis of People per Square Mile**

### 3.4.2 Operational Requirements

The operational requirements for delivery of the wastewater from the user to the treatment facility is displayed in Table 3-32 and normalized to a cubic meter of wastewater treated. Since the model considers a gravity collection system, the study makes the simplifying assumption the volume of wastewater drives the overall energy requirements for operation.

**Table 3-32. Collection System Operational Requirements per Cubic Meter of Wastewater Treated**

| *Input* | *Unit* | *Value* |
|---|---|---|
| Wastewater treated | $m^3$ | 1.0 |
| Purchased electricity | kWh | 0.0067 |
| Natural gas | $m^3$ | 0.00034 |
| Diesel | l | 0.0018 |
| Gasoline | l | 0.0015 |

Source: Cashman, S., A. Gaglione, J. Mosley, L. Weiss, N. Ashbolt, T. Hawkins, J. Cashdollar, X. Xue, C, Ma, AND S. Arden. Environmental and cost life cycle assessment of disinfection options for municipal wastewater treatment. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/377, 2014.

## 3.5 Recycled Water Delivery System

This section covers the recycled water delivery system operational and infrastructure requirements for the different population density scenarios investigated. It is assumed the recycled water delivery infrastructure is installed with establishment of the MBR systems. The recycled water delivery model covers the displacement of potable water, as described in Section 3.5.3.

### 3.5.1 Infrastructure Calculations

The pipe material and diameter composition modeled for recycled water delivery pipe are displayed in Table 3-33, with associated pipe material lifetimes displayed in Table 3-34. Overall impacts of pipe materials are amortized over their useful lifetimes.

**Table 3-33. Recycled Water Delivery System Pipe Material by Diameter**

| | % of Recycled Water Delivery System | | | |
|---|---|---|---|---|
| **Diameter of Pipe (inches)** | **PVC** | **Ductile Iron** | **Steel** | **Concrete** |
| **6** | 36.0% | 44.0% | 0.0% | 0.0% |
| **8** | 4.5% | 5.5% | 0.0% | 0.0% |
| **10 to 12** | 0.0% | 3.0% | 0.8% | 1.3% |
| **14-inch and larger** | 0.0% | 3.0% | 0.8% | 1.3% |

Source:
[1] American Water Works Association. 2012. Buried No Longer: Confronting America's Water Infrastructure Challenge
[2] Rowlett, T. 2015. Personal communication with T. Rowlett, Water Infrastructure Expert at PG Environmental, LLC, 4 March 2015.

**Table 3-34. Recycled Water Delivery System Pipe Lifetimes by Material Type**

| | Pipe Material | | | |
|---|---|---|---|---|
| | PVC | Ductile Iron | Steel | Concrete |
| **Lifetime (Years)** | 55 | 110 | 80 | 105 |

Source:
American Water Works Association. 2012. Buried No Longer: Confronting America's Water Infrastructure Challenge

The pipe length for the recycled water delivery system is similar to that of the collection system, as this study assumes all recycled water is delivered back to the original user. Some additional piping is, however, required for the recycled water to loop the distribution system. The total pipe modeled for the recycled water delivery system is provided in Table 3-35.

**Table 3-35. Total Meters of Recycled Water Delivery Pipe per Scenario**

| | | People Served | | | | |
|---|---|---|---|---|---|---|
| | | **500** | **1,000** | **10,000** | **50,000** | **100,000** |
| **People per square mile** | **100,000** | 240 | 480 | 4,801 | 24,003 | 48,006 |
| | **50,000** | 514 | 1,029 | 10,287 | 51,435 | 102,870 |
| | **10,000** | 1,886 | 3,772 | 37,719 | 188,595 | 377,189 |
| | **2,000** | 3,858 | 7,715 | 77,152 | N/A | N/A |

### 3.5.2 Operational Requirements

For distribution of the recycled water from the decentralized wastewater treatment facility back to the end user, the pumping energy required for water delivery is affected by changes in elevation throughout the pipe network as well as head losses due to friction inside the pipe. Changes in elevation throughout the distribution network can vary greatly depending on the geographic location being modeled and therefore are not included in the pumping energy calculations in this analysis. Frictional head losses are influenced by the inside diameter of the pipe, the flow rate through the pipe, and the smoothness of the interior pipe wall (DIPRA, 2006). The Hazen-Williams coefficient is an indicator of the smoothness of the pipe interior. The higher the coefficient, the smoother the surface and the lower the frictional head loss. The Hazen-Williams coefficient values used in the analysis are shown in Table 3-36.

**Table 3-36. Hazen-Williams Coefficients by Pipe Material**

| Pipe Material | Hazen-Williams Coefficients |
|---|---|
| PVC | 150 |
| Ductile Iron | 140 |
| Steel | 140 |
| Concrete | 140 |

Source: Ductile Iron Pipe Research Association (DIPRA). Hydraulic Analysis of Ductile Iron Pipe. Table 2.

Frictional losses and associated pumping energy increase with increasing distance that water travels through the pipe. Pumping distance per customer served decreases with increasing population density. The previously displayed Table 3-35 shows the length of water distribution pipe modeled for the population scenarios evaluated. The mix of pipe sizes and types used for recycled water distribution was previously presented in Table 3-33.

Pumping energy to overcome frictional head losses was calculated for each pipe type and diameter for a representative flow velocity of 2 feet/second (Uni-Bell PVC Pipe Association, 2015) using the following equations:

Volumetric flow rate "q" in gal/min per foot of pipe: $\pi\ (d_h/2)^2\ l/(231\ in^3/gal^{)}*v*60$ sec/min (Eqn. 8)

Where

$d_h$ = hydraulic diameter in inches (inside diameter of pipe)

l = length of pipe in inches (12 inches when calculating gal/min/foot of pipe)

v = flow velocity in feet/sec

Head loss "H" (in feet/100 feet of pipe): $0.2083\ (100/c)^{1.852}\ q^{1.852}\ /\ d_h^{4.8655}$ (Eqn. 9)

Where

c = Hazen-Williams coefficient

q = flow rate in gal/min (from equation above)

dh = hydraulic diameter in inches

$$\text{Pumping energy (kwh/yr.)} = 1.65*H*q/E*l \qquad \text{(Eqn. 10)}$$

Where

| | | |
|---|---|---|
| c | = | Hazen-Williams coefficient |
| H | = | head loss (from previous equation, in feet/100 feet of pipe) |
| q | = | flow rate in gal/min (from first equation) |
| E | = | pump efficiency (80% used in this study) |
| l | = | hundred feet of pipe evaluated (dependent on customers served and population density; see table above) |

A weighted average pumping energy was then compiled based on the values for the individual pipe sizes and types and their percentage of the distribution system shown in the table above. This pumping energy is presented in kWh per year for each scale and population density scenario in Table 3-37.

**Table 3-37. Recycled Water Delivery Electricity Consumption per Scenario**

| | kWh/yr. | | | | |
|---|---|---|---|---|---|
| **MGD** | **0.05** | **0.1** | **1** | **5** | **10** |
| 100,000 #ppl/sqmi | 983 | 1,226 | 5,586 | 24,963 | 49,186 |
| 50,000 #ppl/sqmi | 1,260 | 1,780 | 11,122 | 52,646 | 104,551 |
| 10,000 #ppl/sqmi | 2,644 | 4,548 | 38,805 | 191,058 | 381,376 |
| 2,000 #ppl/sqmi | 4,634 | 8,527 | 78,599 | | |

sqm = square mile; ppl = people; MGD = million gallons per day

### 3.5.3 Displacement of Drinking Water

The use of recycled water is assumed to replace the equivalent quantity of drinking water produced in Cincinnati (Cashman et al., 2014a). Based on the recycled water produced under the AeMBR and AnMBR decentralized treatment described in Table 3-6, Table 3-13, and Table 3-14 and an assumption of 19% water loss during recycled water distribution (Cashman et al., 2014a), the volume of potable water displaced can be calculated using the following equation.

Volume of displaced potable water = volume of water treated - volume of water treated * % water lost to sludge-volume of water treated*(1-% water lost to sludge) * % water loss during distribution (Eqn. 11)

Table 3-38 displays the recycled water produced and delivered by each scenario scale per year. In the LCA model, it is assumed that each cubic meter of recycled water delivered to the user displaces one cubic meter of potable water.

**Table 3-38. Recycled Water Delivered per Year and Associated Parameters by Scenario Scale**

| | *AeMBR - per year* | | | | |
|---|---|---|---|---|---|
| | **Water treated (m3)** | **Permeate produced (m3)** | **Recycled water delivered (m3)** | **Water loss to sludge** | **Water loss during distribution** |
| **0.05 MGD** | 69,130 | 67,526 | 54,696 | 2.32% | 19% |
| **0.1 MGD** | 138,259 | 135,051 | 109,392 | 2.32% | 19% |
| **1 MGD** | 1,382,591 | 1,350,515 | 1,093,917 | 2.32% | 19% |
| **5 MGD** | 6,912,954 | 6,752,573 | 5,469,584 | 2.32% | 19% |
| **10 MGD** | 13,825,907 | 13,505,146 | 10,939,168 | 2.32% | 19% |
| | *AnMBR - per year* | | | | |
| | **Water treated (m3)** | **Permeate produced (m3)** | **Recycled water delivered (m3)** | **Water loss to sludge** | **Water loss during distribution** |
| **0.05 MGD** | 69,130 | 68,252 | 55,284 | 1.27% | 19% |
| **0.1 MGD** | 138,259 | 136,622 | 110,664 | 1.18% | 19% |
| **1 MGD** | 1,382,591 | 1,370,977 | 1,110,491 | 0.84% | 19% |
| **5 MGD** | 6,912,954 | 6,861,798 | 5,558,056 | 0.74% | 19% |
| **10 MGD** | 13,825,907 | 13,719,448 | 11,112,753 | 0.77% | 19% |

The system boundaries for the production of drinking water are displayed in Figure 3-7. The overall impacts from drinking water production, which are displaced in this study, are provided in Table 3-39 (Cashman et al., 2014a). The baseline water treatment system is based on the GCWW Richard Miller Treatment Plant. The data in the GCWW model is representative of the year 2011, in which 106 MGD of potable water were produced. The population density for this drinking water is representative, therefore, of the greater Cincinnati region. The system boundaries for drinking water include water losses during distribution to the consumer. A sensitivity analysis is included in Section 5.3 assessing the relative change in global warming potential using other reported literature values for electricity consumption during drinking water treatment and distribution.

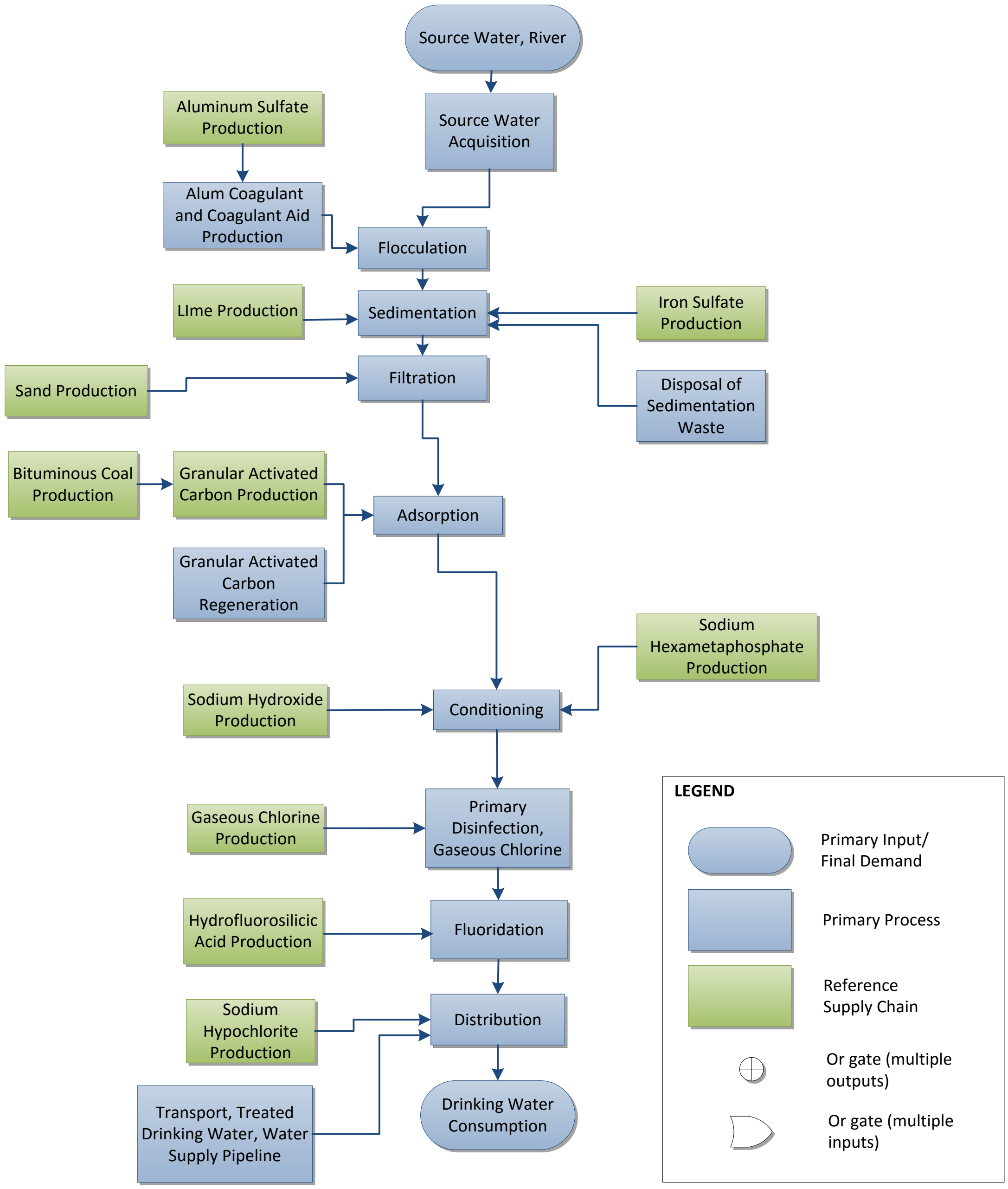


**Figure 3-7. System Boundaries of Drinking Water Treatment**

Drinking water treatment operations along with infrastructure raw material extraction and construction are within the system boundaries. End-of-life of infrastructure is excluded due to lack of available data.

**Table 3-39. Displaced Drinking Water Treatment Impacts**

| Results Category | Unit | Impact/m$^3$ Drinking Water Delivered |
|---|---|---|
| Global Warming | *kg $CO_2$ eq* | 1.08 |
| Energy Demand | *MJ* | 20.3 |
| Fossil Depletion | *kg oil eq* | 0.37 |
| Acidification | *kg H+ mole eq* | 0.48 |
| Eutrophication | *kg N eq* | 9.7E-04 |
| Blue Water Use | *$m^3$* | 1.20 |
| Smog | *kg $O_3$ eq* | 0.068 |
| Ozone Depletion | *kg CFC-11 eq* | 2.8E-08 |
| Human Health, Cancer, Total | *CTU* | 2.9E-11 |
| Human Health, NonCancer, Total | *CTU* | 3.2E-11 |
| Human Health, Criteria | *kg PM10 eq* | 0.0015 |
| Ecotoxicity, Total | *CTU* | 4.5E-04 |

## 3.6 Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Water and Wastewater Treatment Options for Sustainability: Influence of Scale on Membrane Bioreactor Systems* approved by EPA on April 21, 2016 (ERG, 2016), ERG collected existing data[5] to develop the LCA and cost estimates for the AeMBR and AnMBR systems investigated in this study. As discussed in Section 3.1 through Section 3.5, the life cycle inventory and cost estimate data sources include CAPDETWorks Version 3.0 (Hydromantis, 2014), EPA reports, peer-reviewed literature, publicly available equipment specifications from communication with technology vendors, and industry-accepted construction cost data and indices. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date, accuracy/reliability, and costs completeness when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the LCA and costing methodology and calculations for this study.

Table 3-40 presents the data quality criteria ERG used when evaluating collected cost data. ERG documented the data quality for each data source for each criterion in a spreadsheet for EPA's use in determining whether the cost data are acceptable for use. All of the references used to develop the costs met all of the data quality criteria with the exception of infrastructure and labor costs for the AnMBR unit process which is estimated using CAPDETWorks data for conventional anaerobic digestion. Since AnMBR is currently only operating at pilot-scales, costing data on construction and labor for operating and maintaining AnMBR reactors at full-scale plants are not yet available.

[5] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

**Table 3-40. Cost Data Quality Criteria**

| Quality Criterion: Cost Data | Description/Definition | Acceptance Specifications |
|---|---|---|
| Current | Report the time period of the data. | Costs are converted to a standard year using RSMeans Construction Index or other standard cost index. |
| Complete | Ensure all aspects of the technology costs are reported. | Cost estimates are completed using all input costs for energy, labor, chemicals, and waste disposal. |
| Representative | Report if the costs used are representative of the technology studied. | Costs are based on data from peer reviewed literature, vendor information and engineering software specific to the technologies studied. |
| Accurate/Reliable | Document the sources of the data. Confirm calculations are based on sound methodology and technically correct. | Data sources and calculations were documented and reviewed. |

Table 3-41 presents the data quality criteria ERG used when evaluating collected life cycle inventory data. ERG documented qualitative descriptions of the source reliability, completeness, temporal correlation, geographical correlation, and technological correlation in a spreadsheet for EPA's use in determining whether the life cycle inventory data are acceptable for use. Table 3-41 also lists the approximate overall data quality score achieved for the AeMBR and AnMBR LCI model. Because the life cycle inventory model uses data from existing peer reviewed literature, information from technology vendors, and engineering design software to approximate average conditions in the U.S., a data quality score higher than 3 is difficult achieve for all criteria with the exception of technological correlation. However, in all cases, the best available existing data identified during the comprehensive literature review were used. For technological correlation, only data from the technology (e.g., GE ZeeWeed® 500D hollow fiber membranes using LEAPmbr Aeration Technology for MBR step), process, or material being studied were considered.

## Table 3-41. Life Cycle Inventory Data Quality Criteria

| Indicator | Reporting Criteria | Score | AeMBR Overall Result* | AnMBR Overall Result* |
|---|---|---|---|---|
| **Source Reliability** | Data verified based on measurements. | **1** | Data verified with many assumptions, or non-verified but from quality source (score = 3). | Data verified with many assumptions, or non-verified but from quality source (score = 3). |
| | Data verified based on some assumptions and/or standard science and engineering calculations. | **2** | | |
| | Data verified with many assumptions, or non-verified but from quality source. | **3** | | |
| | Qualified estimate. | **4** | | |
| | Non-qualified estimate. | **5** | | |
| **Completeness** | Representative data from a sufficient sample of sites over an adequate period of time. | **1** | Representativeness unknown or incomplete data sets (score = 5). | Representativeness unknown or incomplete data sets (score = 5). |
| | Smaller number of sites, but an adequate period of time. | **2** | | |
| | Sufficient number of sites, but a less adequate period of time. | **3** | | |
| | Smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods. | **4** | | |
| | Representativeness unknown or incomplete data sets. | **5** | | |
| **Temporal Correlation** | Less than 3 years of difference to year of study/current year. | **1** | Less than 10 years of difference (score = 3). | Less than 10 years of difference (score = 3). |
| | Less than 6 years of difference. | **2** | | |
| | Less than 10 years of difference. | **3** | | |
| | Less than 15 years of difference. | **4** | | |
| | Age of data unknown or more than 15 years of difference. | **5** | | |
| **Geographical Correlation** | Data from area under study. | **1** | Data from area with similar production conditions (score = 3). | Data from area with similar production conditions (score = 3). |
| | Average data from larger area or specific data from a close area. | **2** | | |
| | Data from area with similar production conditions. | **3** | | |
| | Data from area with slightly similar production conditions. | **4** | | |
| | Data from unknown area or area with very different production conditions. | **5** | | |
| **Technological Correlation** | Data from technology, process, or materials being studied. | **1** | Data from technology, process, or materials being studied (score = 1). | Data from technology, process, or materials being studied (score = 1). |
| | Data from a different technology using the same process and/or materials. | **2** | | |
| | | **3** | | |
| | Data on related process or material using the same technology. | **4** | | |
| | Data or related process or material using a different technology. | **5** | | |

*Approximate score based on average of LCI unit process scores.

ERG developed the CAPDETWorks input files containing all the necessary information and data required for the tool to execute the AeMBR designs and engineering costing. All CAPDETWorks input files were reviewed by a team member knowledgeable of the project, but who did not develop the input files. The reviewer ensured the accuracy of the data transcribed into the input files, the technical soundness of methods and approaches used (i.e., included all of the cost components and LCA inputs) and the accuracy of the calculations (i.e., used the methodology in Section 3.1 through Section 3.5 to calculate the costs).

ERG developed the supplemental cost and life cycle inventory estimates for the AnMBR and other unit process not covered in CAPDETWorks an Excel® Workbook. A team member knowledgeable of the project, but who did not develop the Excel® workbook, reviewed the workbook to ensure the accuracy of the data transcribed into the workbook, the technical soundness of methods and approaches used, and the accuracy of calculations.

ERG input all life cycle inventory data developed into the openLCA software (GreenDelta, 2015). A team member knowledgeable of the project, but who did not develop the model, reviewed the openLCA model to ensure the accuracy of the data transcribed into the software.

# 4.0 BASELINE RESULTS

The focus of the baseline results is energy demand, global warming potential, and costs. However, the LCA model was constructed to cover a comprehensive suite of environmental impact categories. The full LCIA results are provided in Appendix B of this report. Additional findings on net water savings are provided in this Section.

## 4.1 Detailed AeMBR Energy Results

The cumulative energy demand results for all AeMBR scenarios are presented in Figure 4-1 on an annual basis. Similar results are illustrated in Figure 4-2, but on a basis of $m^3$ wastewater treated. Energy demand impacts decrease comparatively as the population density increases and the scale of the system increases. Net energy demand benefits are realized for 1 MGD systems and above. Detailed cumulative energy demand results for all AeMBR scenarios on an annual basis are presented in Appendix A (Table A-1 through Table A-5). These tables show the relative breakout of impacts for infrastructure, energy for operation, and chemical consumption. Infrastructure, including collection system and recycled water delivery piping, contributes to 0.2% to 1.6% of the overall energy demand impacts for the AeMBR (excluding the credit for displaced drinking water). The highest infrastructure burdens are seen in the semi-rural single family land use type. Operational impacts are overwhelmingly higher than infrastructure impacts with the largest energy demand required for aeration followed by chlorination and scouring. Operational impacts are dominated by on-site electricity usage, which accounts for approximately 90% of operational energy demand burdens of the AeMBR. Production of chemicals for consumption contributes the remaining 10% to total operational energy demand for the AeMBR. There are significant net energy benefits from recycled water displacement of drinking water.

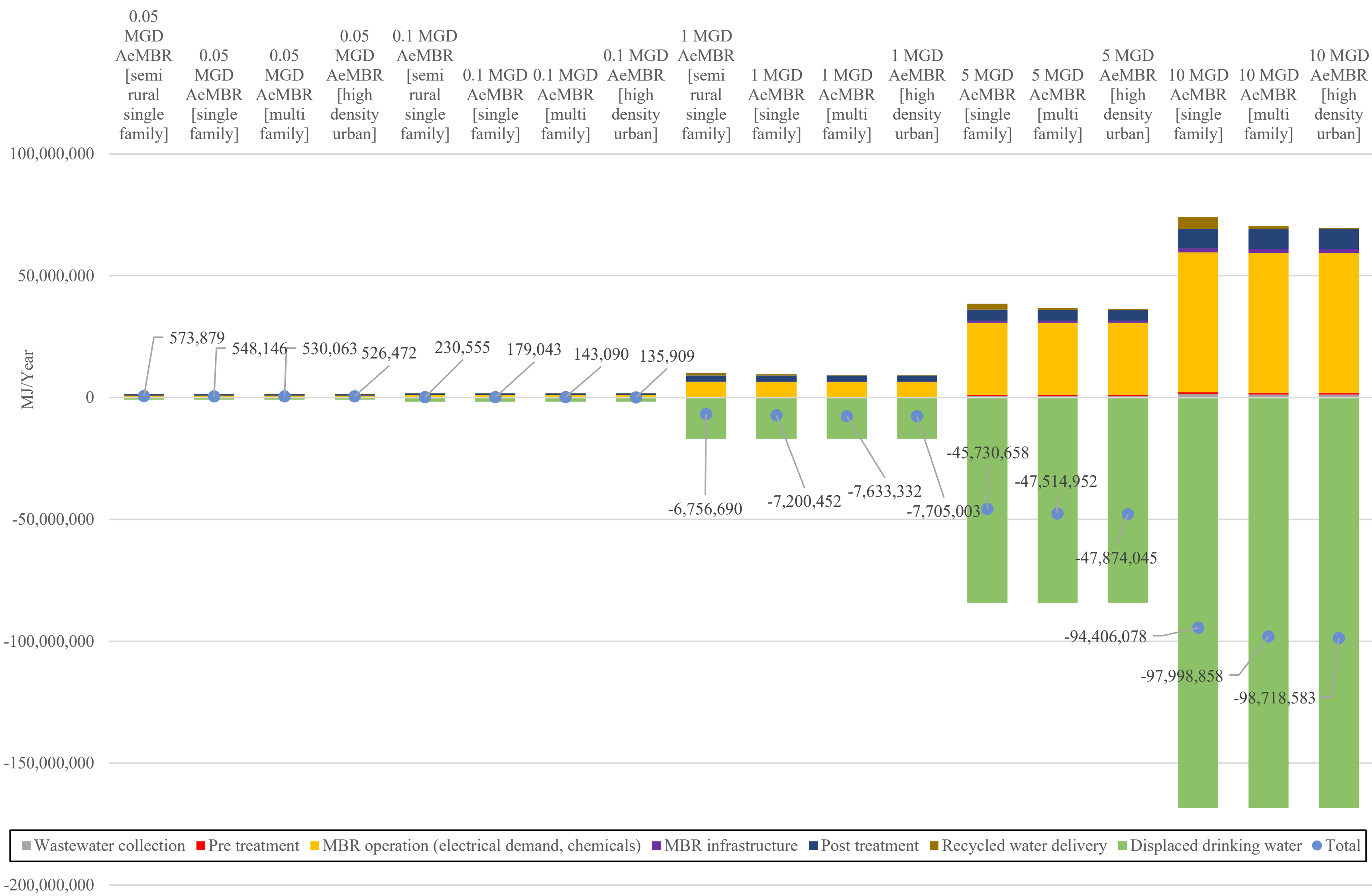


**Figure 4-1. AeMBR Cumulative Energy Demand Results (MJ/Year)**

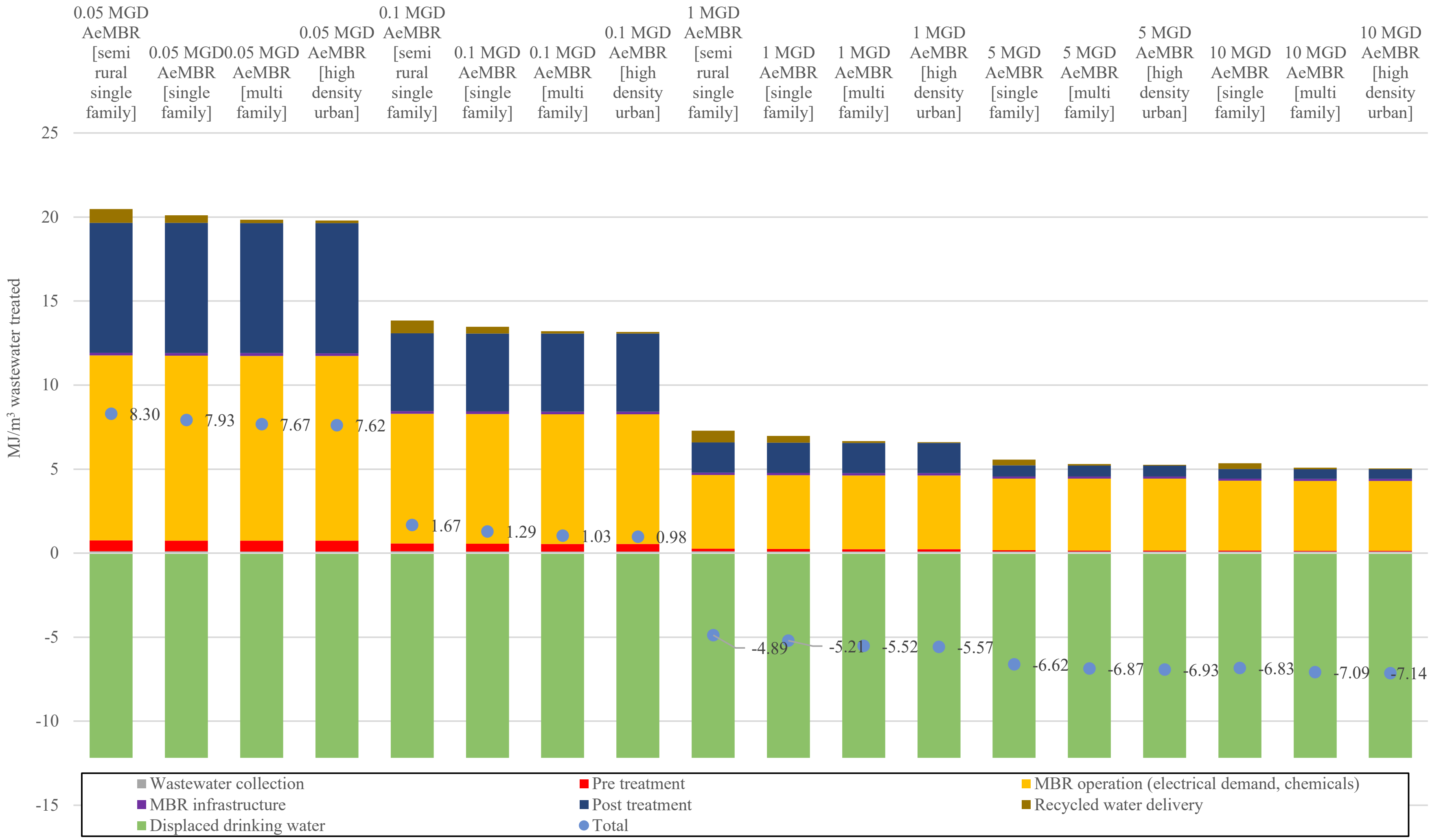


**Figure 4-2. AeMBR Cumulative Energy Demand Results (MJ/m³ Wastewater Treated)**

## 4.2 Detailed AnMBR Energy Results

Based on preliminary model findings, it was determined that reactor temperature is a significant parameter in the overall environmental impacts for the AnMBR system. Therefore, as discussed in Section 3, results are modeled for a high [mesophilic (35˚C)] and low [psychrophilic (20˚C)] temperature. Less methane is produced, and thus recovered, under lower temperature scenario. However, less natural gas is required to keep the wastewater at a higher overall temperature in the 20˚C scenario. The next sections cover the energy demand results for each of these temperature scenarios.

### 4.2.1 AnMBR Energy Results, 35˚C Reactor Temperature

Figure 4-3 displays the AnMBR cumulative energy demand impacts on an annual basis with the reactor operating at 35˚C, while Figure 4-4 illustrates the same results per $m^3$ wastewater treated basis. Detailed cumulative energy demand results for all AnMBR scenarios operating at 35˚C on an annual basis are presented in Appendix A (Table A-6 through Table A-10).

For the AnMBR operating at 35˚C, net benefits are not realized until the 5 MGD scale. The driver for AnMBR operational impacts under this scenario is the heating of the influent by natural gas, even when considering the heat recovery from the effluent. Because all water must be heated from 20˚C to 35˚C regardless of the flow, no economies of scale are realized for this step. That is, the heating of the influent is linear across scales. The relative savings from the biogas recovery are overshadowed by the impact for heating the influent.

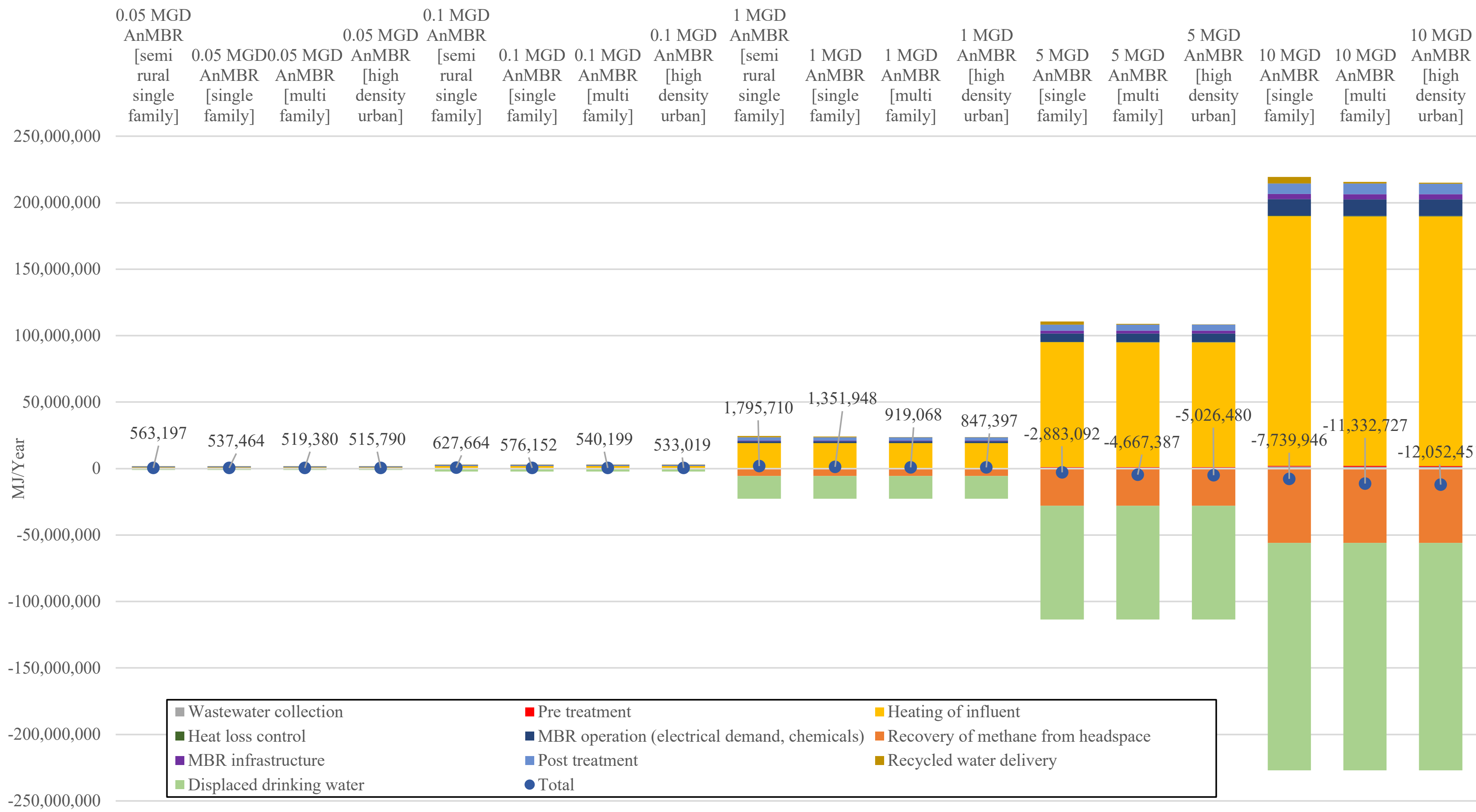


**Figure 4-3. AnMBR, 35˚C Reactor Temperature, Cumulative Energy Demand Results (MJ/Year)**

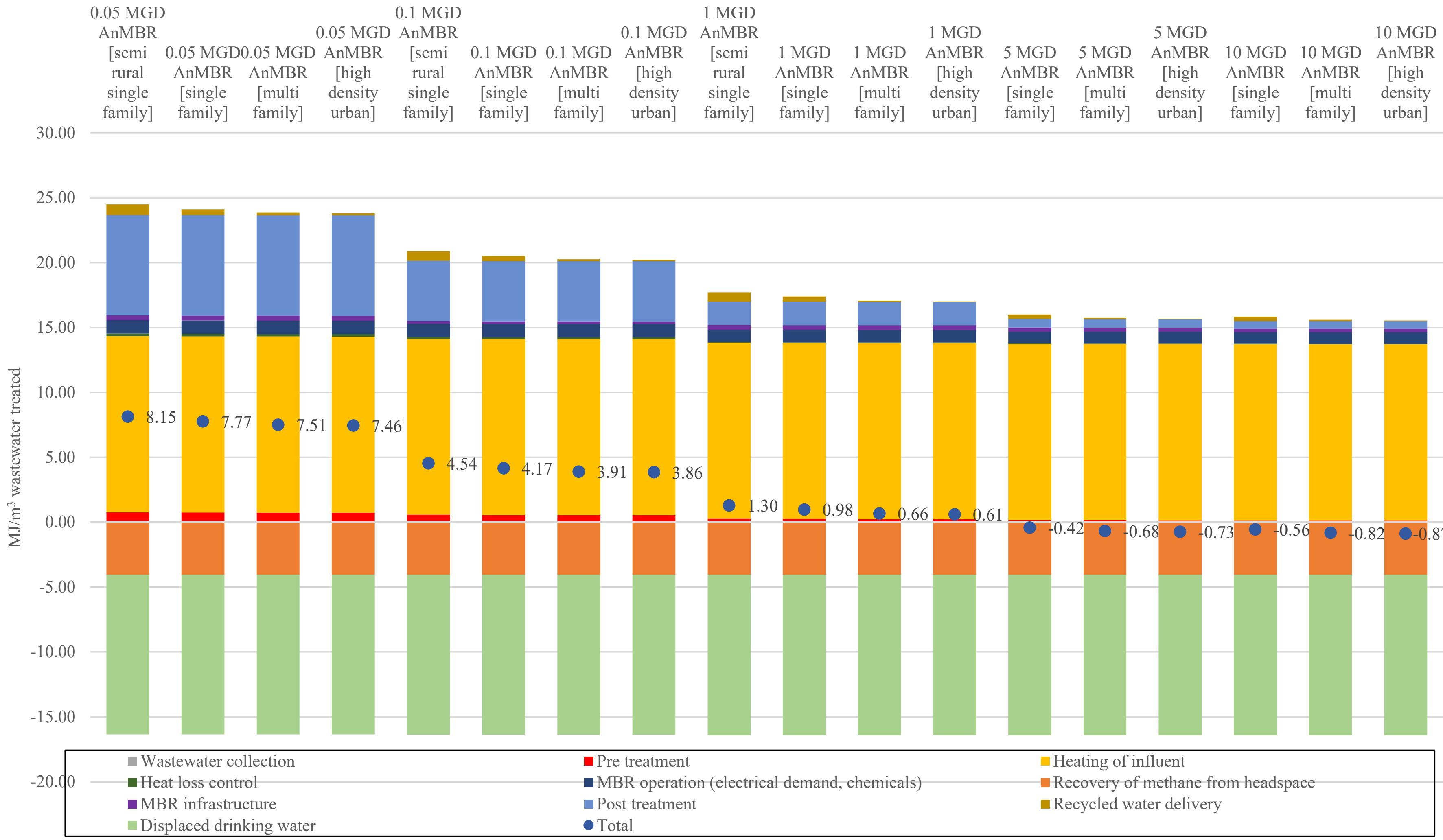


**Figure 4-4. AnMBR, 35˚C Reactor Temperature, Cumulative Energy Demand Results (MJ/m$^3$ Wastewater Treated)**

### 4.2.2 AnMBR Energy Results, 20˚C Reactor Temperature

Figure 4-5 displays the AnMBR cumulative energy demand impacts on an annual basis with the reactor operating at 20˚C, while Figure 4-6 illustrates the same results per $m^3$ wastewater treated basis. For the AnMBR operating at a lower reactor temperature, net energy demand benefits are seen for all investigated scenarios. This scenario models an influent temperature equivalent to the reactor temperature (20˚C). Because of the lack of temperature differential between the influent and reactor, no natural gas is required for heating the influent or controlling heat loss. Electricity is still required for operating the pumps, but this is more than offset by the recovery of biogas from the headspace of the reactor. This is the case even though a lower quantity of biogas is produced at a lower reactor temperature. Detailed cumulative energy demand results for all AnMBR scenarios operating at 20˚C on an annual basis are presented in Appendix A (Table A-11 through Table A-15).

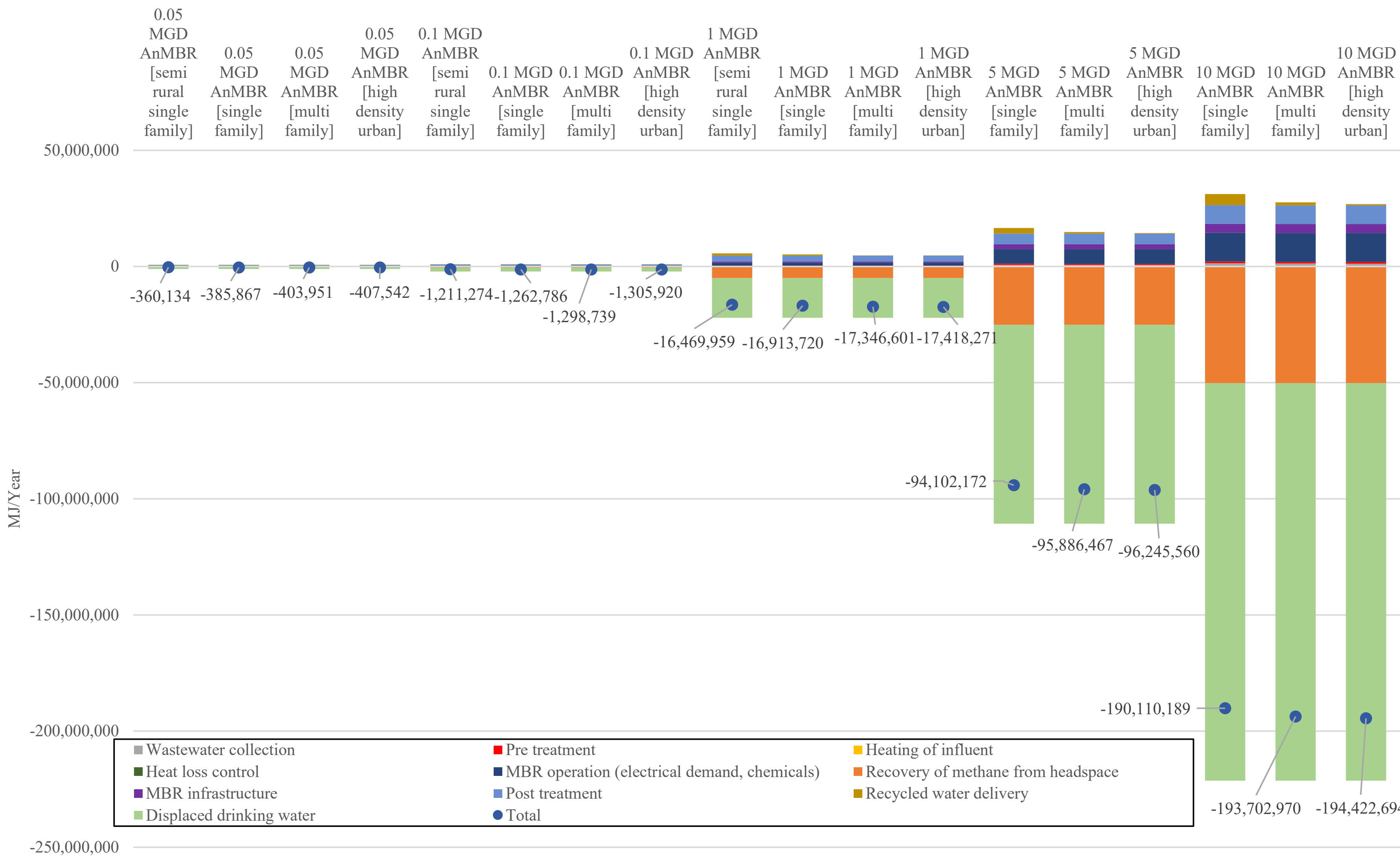


**Figure 4-5. AnMBR, 20˚C Reactor Temperature, Cumulative Energy Demand Results (MJ/Year)**

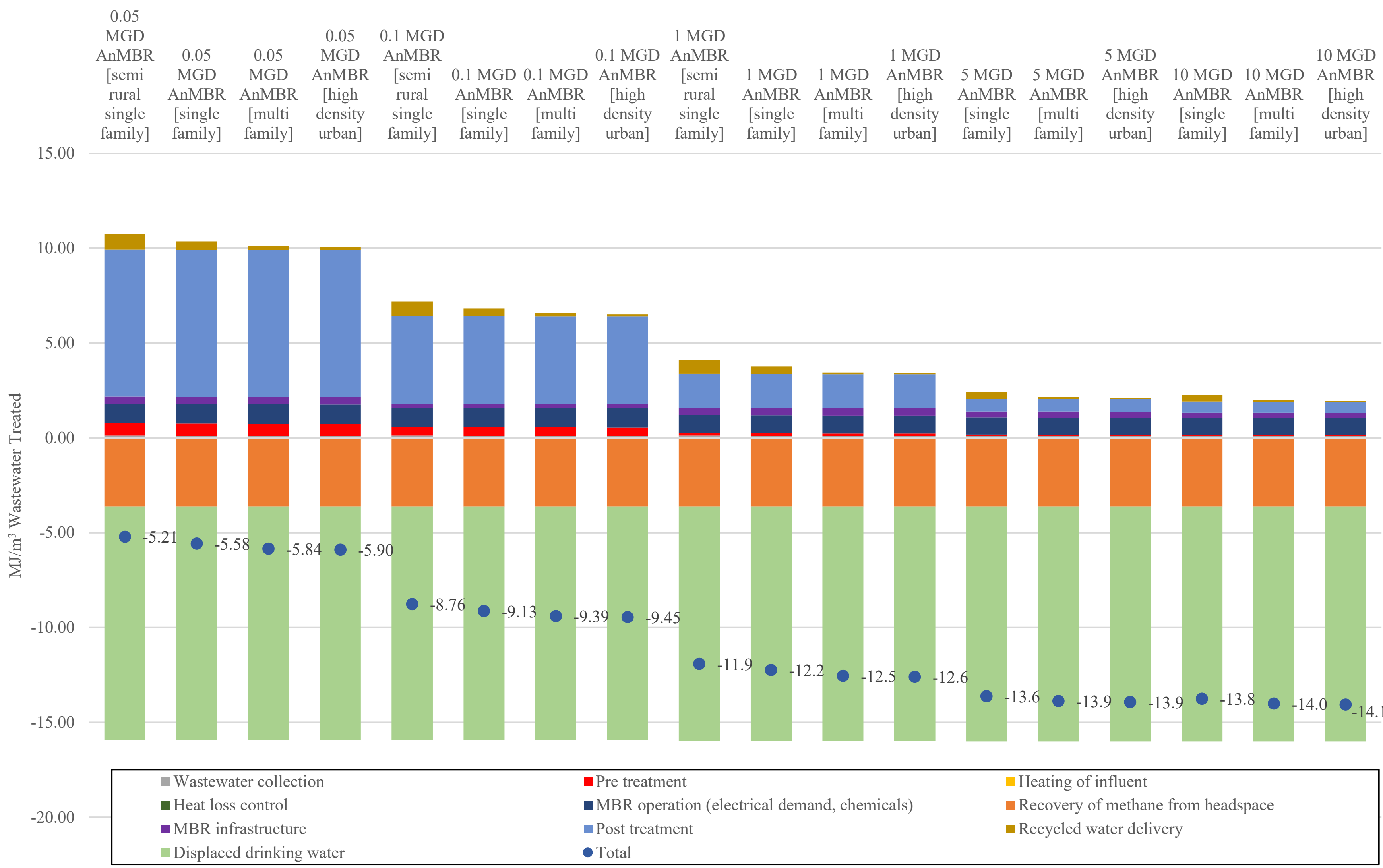


**Figure 4-6. AnMBR, 20˚C Reactor Temperature, Cumulative Energy Demand Results (MJ/m$^3$ Wastewater Treated)**

## 4.3 AeMBR Global Warming Potential Results

Global warming potential results for the AeMBR scenarios are displayed on an annual basis and on $m^3$ wastewater treated basis in Figure 4-7 and Figure 4-8, respectively. As the primary greenhouse gases modeled in the system boundaries are related to energy usage in the treatment system and upstream energy usage for production of cleaning chemicals, the global warming potential results for the AeMBR scenarios follow the same trends as seen in the cumulative energy demand analysis. Detailed global warming potential results for all AeMBR scenarios on an annual basis are presented in Appendix A (Table A-16 through Table A-20).

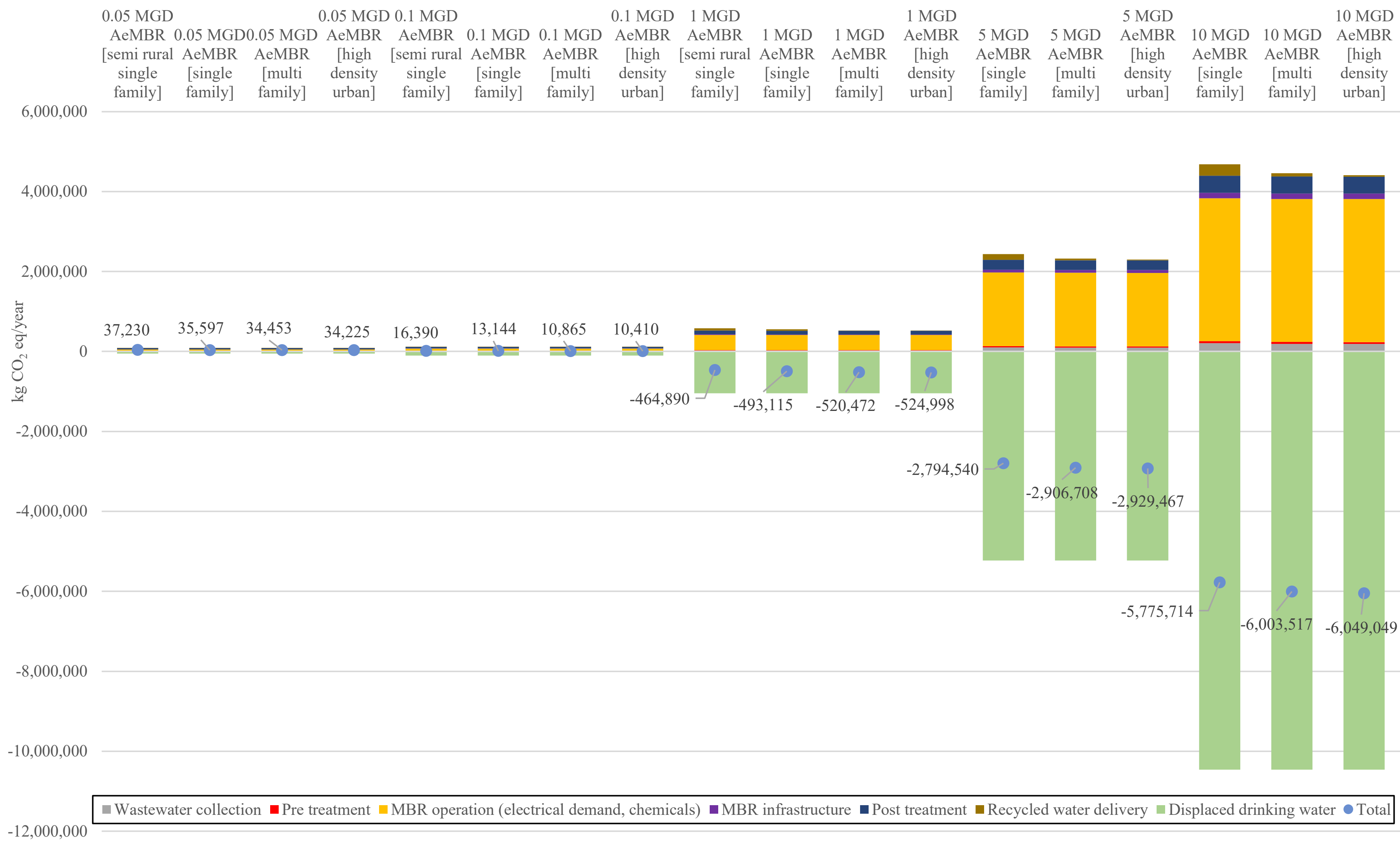


**Figure 4-7. AeMBR Global Warming Potential Results (kg $CO_2$ eq/Year)**

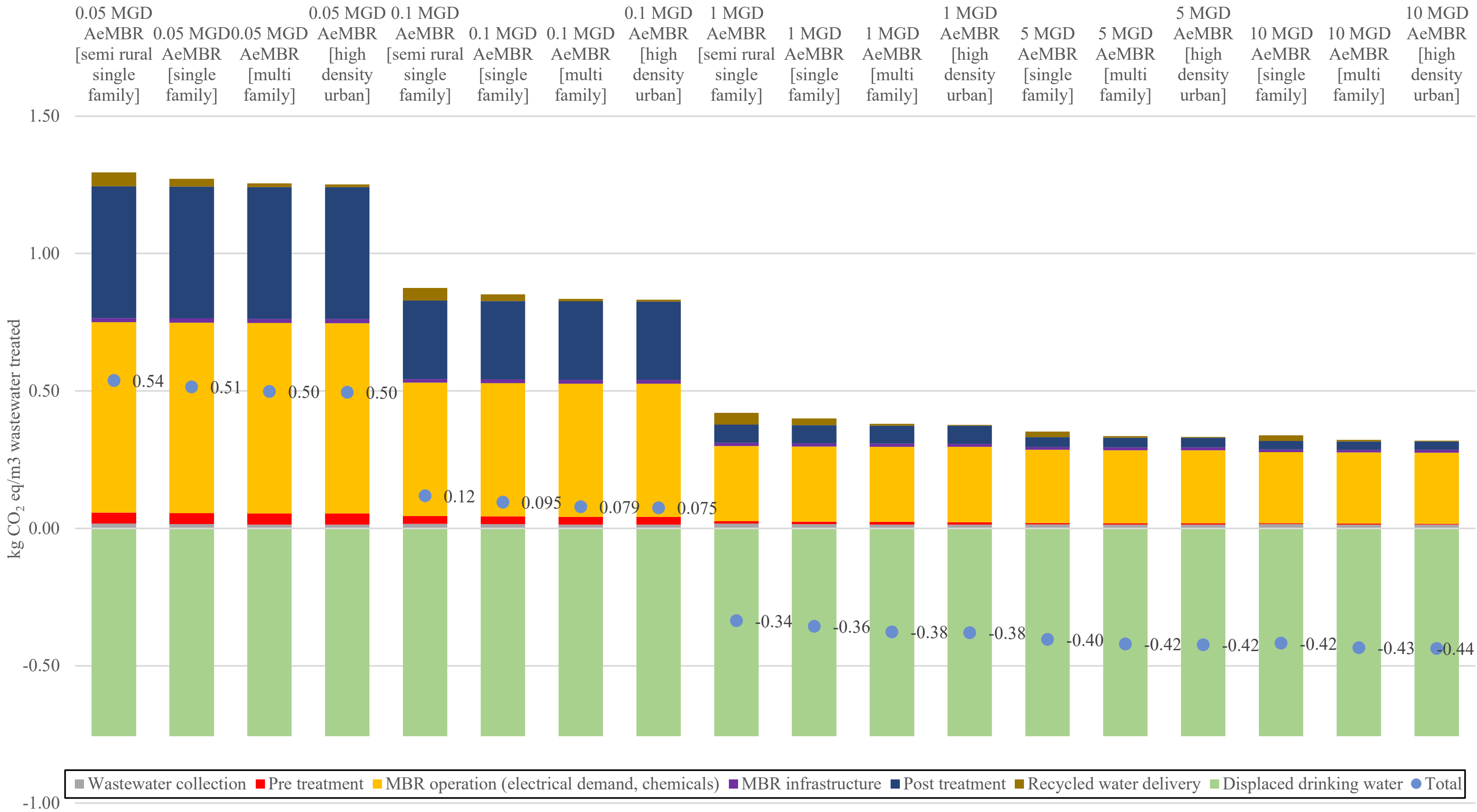


**Figure 4-8. AeMBR Global Warming Potential Results (kg $CO_2$ eq/$m^3$ Wastewater Treated)**

## 4.4 AnMBR Global Warming Potential Results

Figure 4-9 and Figure 4-10 display the AnMBR global warming potential results on a yearly basis for a reactor operating at 35˚C and 20˚C, respectively. Similar results are shown per $m^3$ wastewater treated basis in Figure 4-11 and Figure 4-12. As the primary greenhouse gases modeled in the system boundaries are related to energy usage in the treatment system and upstream energy usage for production of cleaning chemicals, the global warming potential results for the AnMBR scenarios (similar to the AeMBR scenarios) follow the same trends as seen in the cumulative energy demand analysis. The one exception to this is the methane emissions from permeate. Detailed global warming potential results for all AnMBR scenarios on an annual basis are presented in Appendix A (Table A-21 through Table A-30).

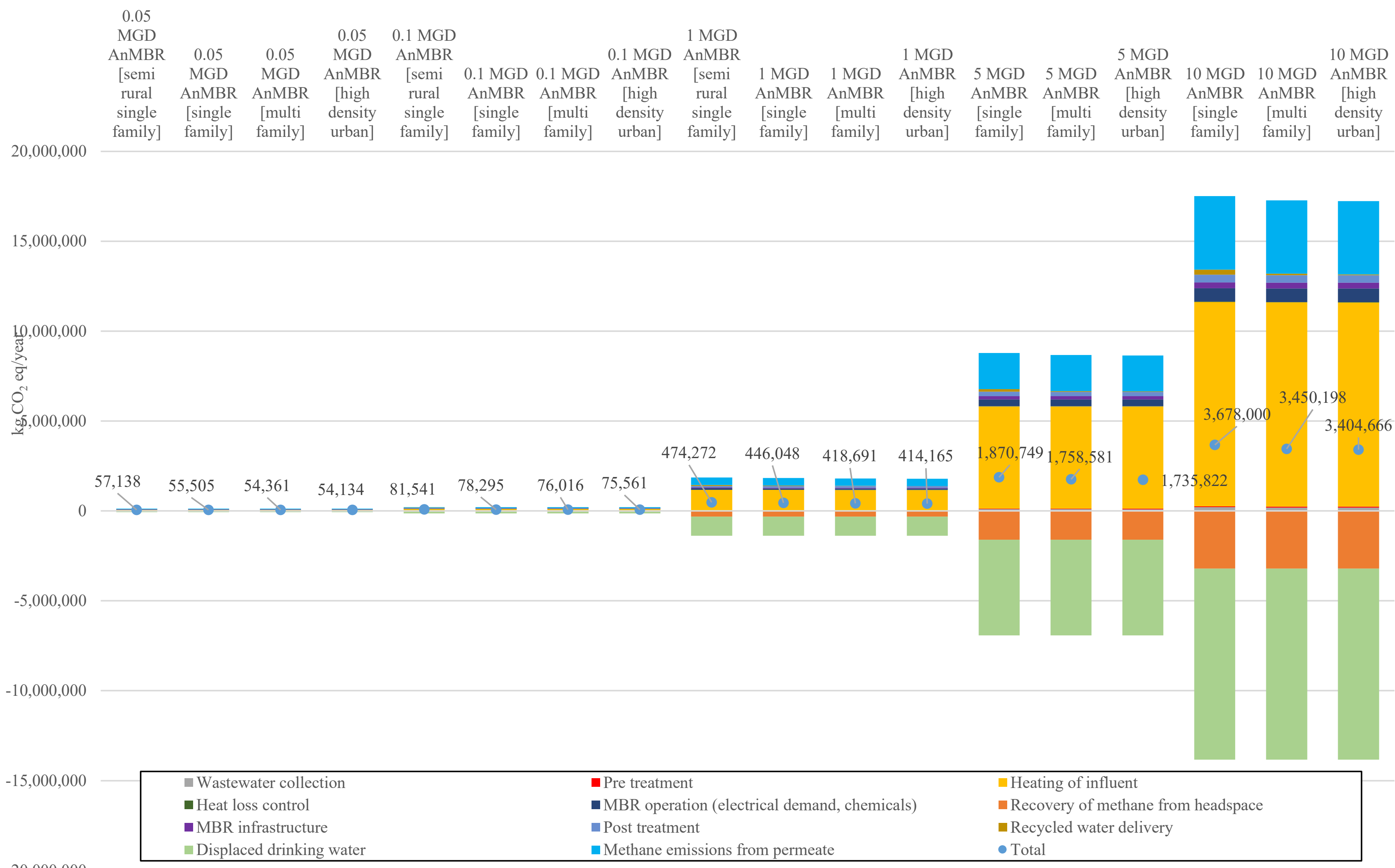


**Figure 4-9. AnMBR, 35˚C Reactor Temperature, Global Warming Potential Results (kg $CO_2$ eq/Year)**

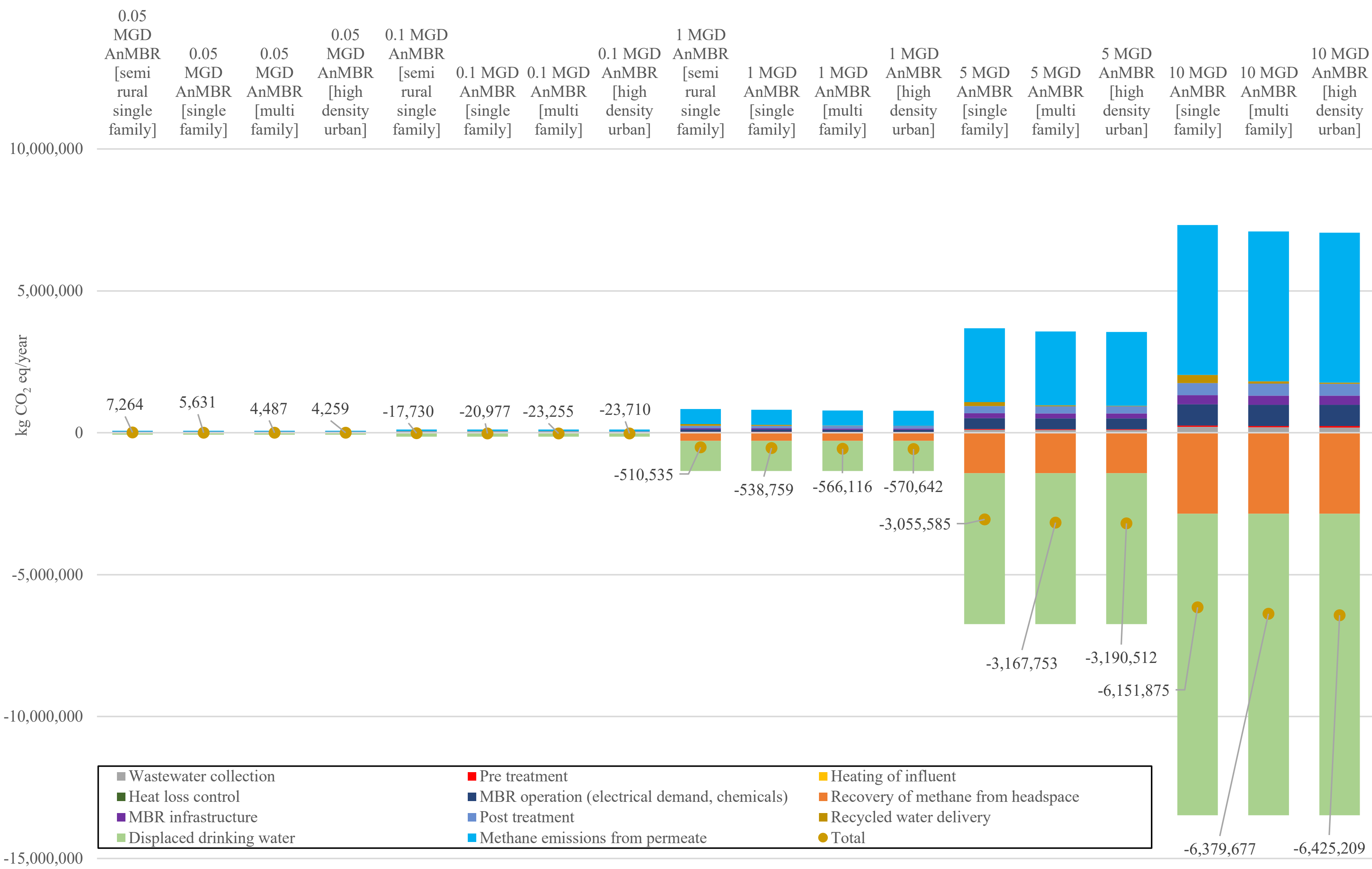


**Figure 4-10. AnMBR, 20˚C Reactor Temperature, Global Warming Potential Results (kg $CO_2$ eq/Year)**

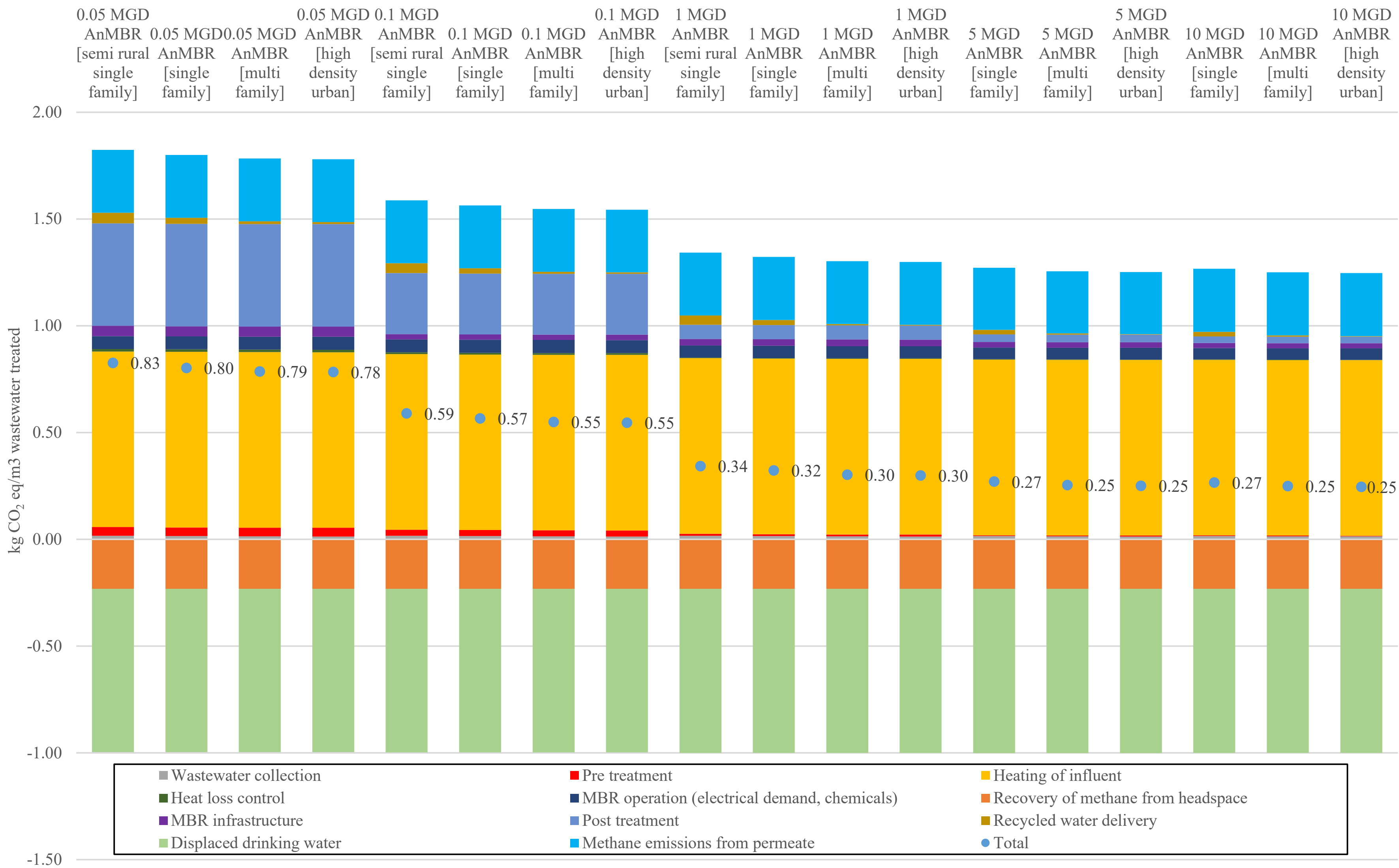


**Figure 4-11. AnMBR, 35˚C Reactor Temperature, Global Warming Potential Results (kg $CO_2$ eq/ $m^3$ Wastewater Treated)**

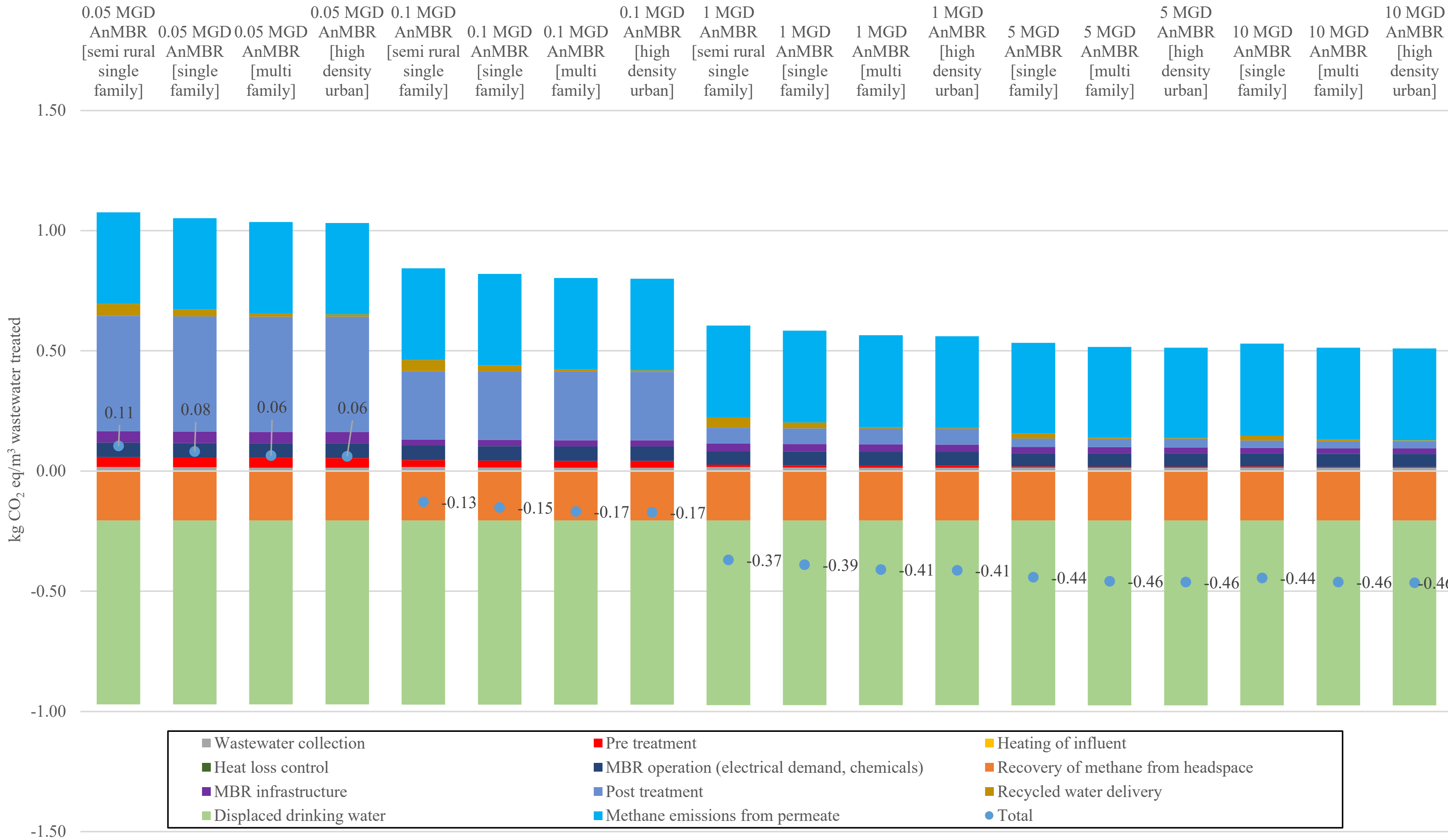


**Figure 4-12. AnMBR, 20˚C Reactor Temperature, Global Warming Potential Results (kg $CO_2$ eq/ m$^3$ Wastewater Treated)**

## 4.5 Energy Demand and Global Warming Potential Comparative Scenario Analysis

Comparative energy demand results for the AeMBR and the AnMBR run at both 35˚C and 20˚C for the multi family land use scenario are illustrated in Figure 4-13 and Figure 4-14 on the basis of a year of operation and a cubic meter of wastewater treated respectively. In all cases, the AnMBR operated at 20˚C results in the lowest energy demand impacts followed by the AeMBR, and then the AnMBR operated at 35˚C. Net energy benefits, considering the displaced drinking water by the delivered recycled water, start at the 1 MGD scale for the AeMBR and at the 5 MGD scale for the AnMBR operated at 35˚C. For all scales investigated, the AnMBR reactor operated at 20˚C results in the most net energy benefits due to no heating of influent and the ability to recovery biogas for operation. When examining the energy demand results normalized to a cubic meter of water treated, all energy demand impacts decrease as the scale increases.

As discussed in Section 4.3 and Section 4.4, the global warming potential results follow the same trends as the energy demand results, with the exception of methane emissions from the permeate. Figure 4-15 and Figure 4-16 display the comparative global warming potential results for the AeMBR and the AnMBR run at both 35˚C and 20˚C for the multi family land use scenario on the basis of a year of operation and a cubic meter of wastewater treated respectively.

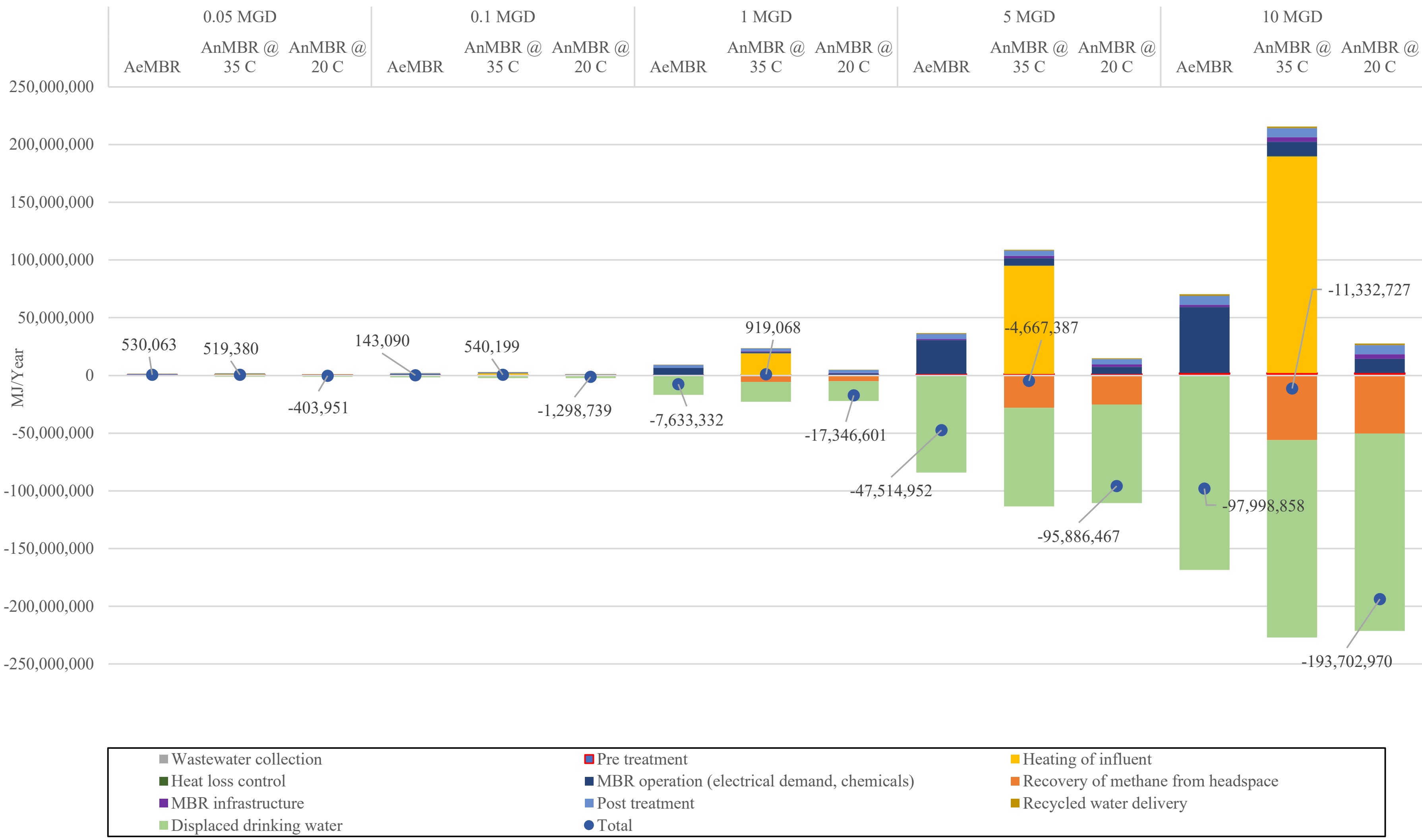


**Figure 4-13. AeMBR and AnMBR Energy Demand Comparison for Multi Family Land Use (MJ/Year)**

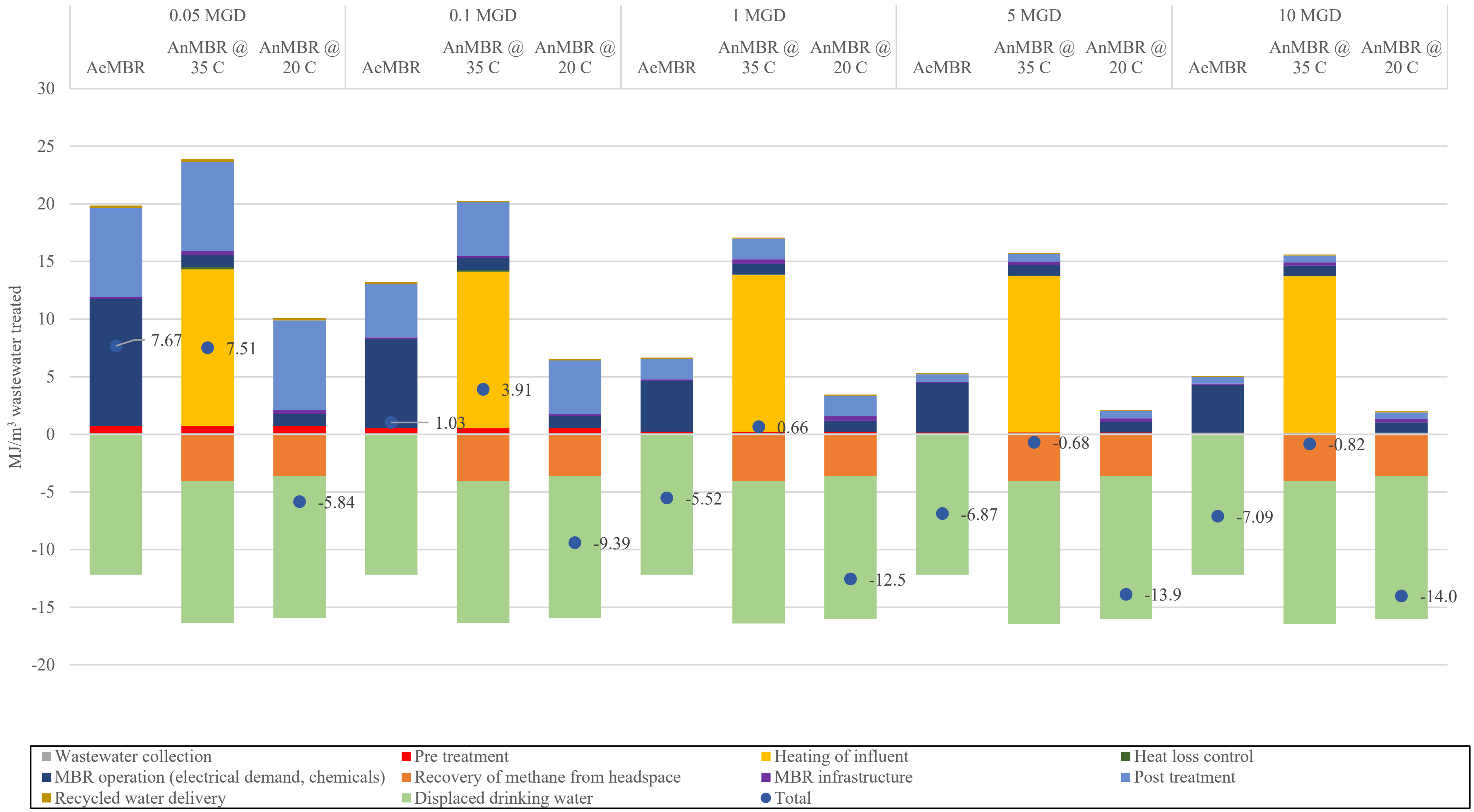


**Figure 4-14. AeMBR and AnMBR Energy Demand Comparison for Multi Family Land Use (MJ/m$^3$ Wastewater Treated)**

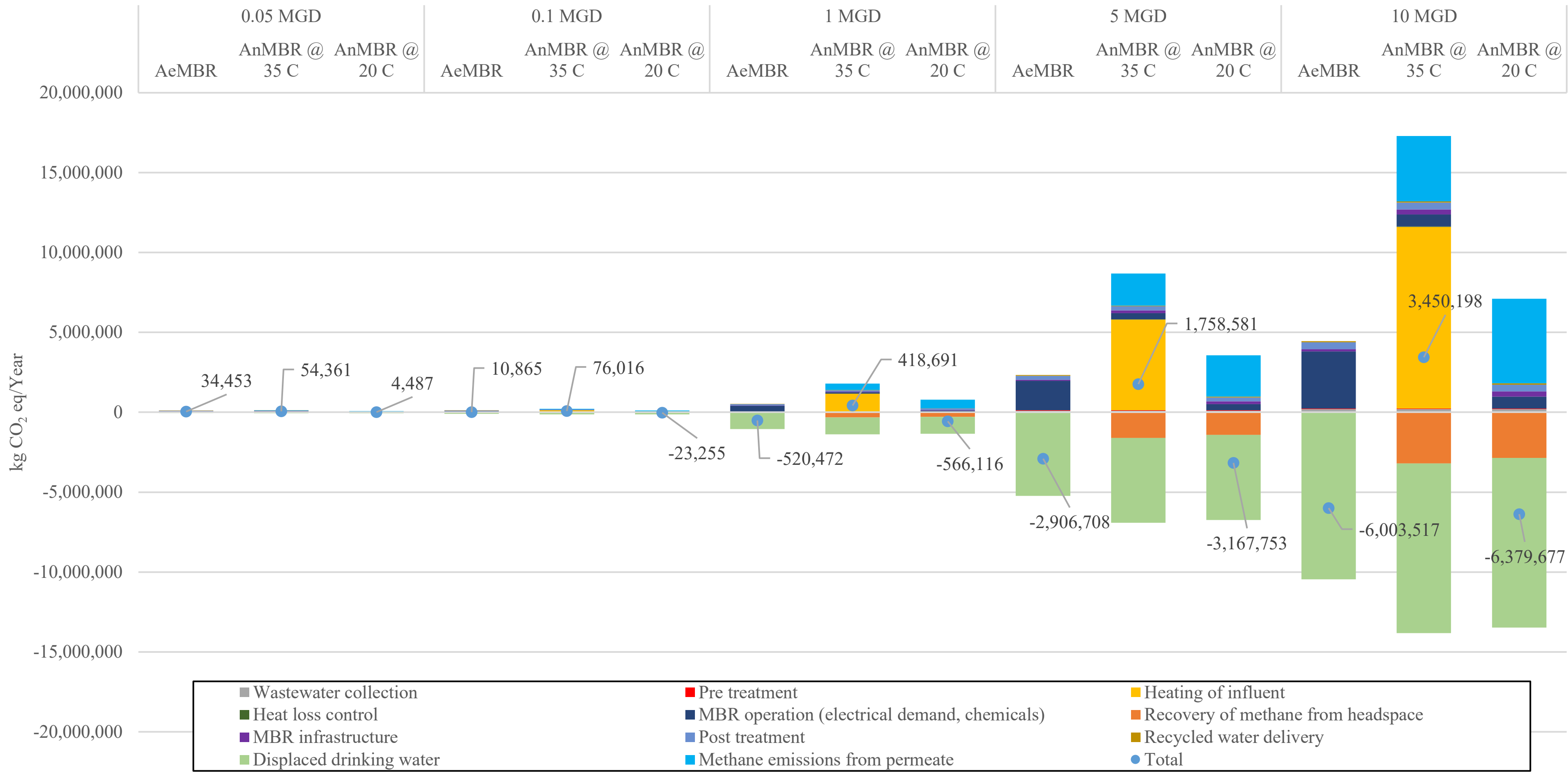


**Figure 4-15. AeMBR and AnMBR Global Warming Potential Comparison for Multi Family Land Use (kg $CO_2$ eq/Year)**

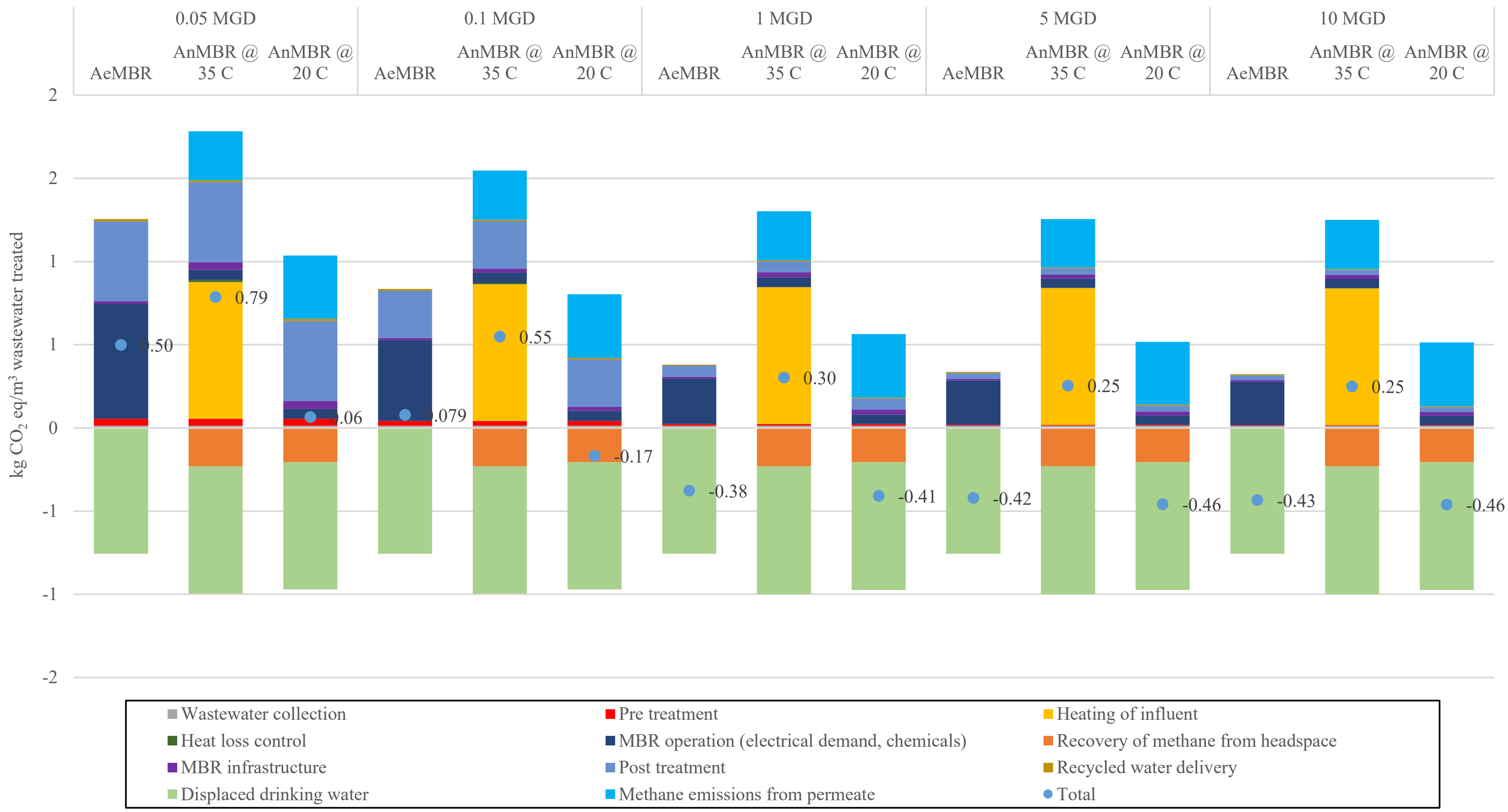


**Figure 4-16. AeMBR and AnMBR Global Warming Potential Comparison for Multi Family Land Use (kg $CO_2$ eq/m$^3$ Wastewater Treated)**

## 4.6 Net Water Savings and other Potential Benefits

While this study focuses on energy demand and GHG impacts of the decentralized MBR systems, there is a potential significant water savings from using recycled wastewater. This study found that use of recycled water from decentralized MBR scenarios avoids 0.94 to 0.96 cubic meters of fresh water per cubic meter of wastewater treated by MBR as displayed in Table 4-1. Results are not shown by life cycle stage or by scale scenario since, as can be seen in the first row of Table 4-1, the recycled water displacement of potable water dwarfs the operational impacts.

**Table 4-1. Water Savings ($m^3$ Water Consumed/$m^3$ Wastewater Treated)**

| | AeMBR | AnMBR |
|---|---|---|
| Displaced drinking water | -0.95 | -0.96 |
| Operational/infrastructure requirements* | 0.002 to 0.0077 | 0.0004 to 0.0029 |
| **Net total** | **-0.94** | **-0.95 to -0.96** |

*Varies by scale.

Not all benefits that are possible with a centralized or fully decentralized resource recovery system can be captured when modeling transitional AnMBR WWT and recycled water systems. While the transitional systems can capture the benefits of water reuse and, in case of AnMBR, energy recovery, returning the sludge for treatment at the downstream centralized WWTP removes the possibility of nutrient recovery from sludge for use as fertilizer. In addition, because final solids handling is carried out at the centralized WWTP where any change in sludge received due to the operation of the transitional systems is assumed to have a negligible impact on the centralized WWTP's operations, it is not possible to assess the potential benefits of lower sludge production by the AnMBR system compared to the AeMBR system (see Table 4-2) or in comparison to conventional aerobic activated sludge treatment.

**Table 4-2. Comparison of Sludge Output by AeMBR and AnMBR systems**

| | AeMBR Sludge Output (MGD) | AnMBR Sludge Output (MGD) |
|---|---:|---:|
| 0.05 MGD | 0.0012 | 0.00063 |
| 0.1 MGD | 0.0023 | 0.0012 |
| 1 MGD | 0.023 | 0.0084 |
| 5 MGD | 0.12 | 0.037 |
| 10 MGD | 0.23 | 0.077 |

## 4.7 Cost Analysis Results

The cost analysis results are presented in the following sections, with results shown separately for the AeMBR WWTP, the 20˚C AnMBR WWTP, the 35˚C AnMBR WWTP, the recycled water delivery system, and the avoided costs for drinking water treatment and distribution for each scale and density. The last two sections provide total costs for the combined WWTP, recycled water delivery, and avoided DWT costs for each scale and density. Detailed results tables corresponding to each figure are provided in Appendix C.

### 4.7.1 Cost Analysis Results for Aerobic MBR Wastewater Treatment Plant

The yearly expenses for plant construction and operation of the AeMBR at the different scales examined are displayed in Figure 4-17. The same expenses are presented in Figure 4-18 on a per cubic meter ($m^3$) of treated wastewater basis. In terms of the impact of scale, the relationship between yearly expenses and expenses per $m^3$ treated wastewater are inversely proportional. The 10 MGD system has the highest overall yearly costs, but the lowest costs on a MGD basis. In all cases, the greatest portion of the cost, ranging from 40% for the 0.05 MGD system to 63% for the 10 MGD system, is the amortized value of the construction and equipment installation costs. The cost of labor for operating the plant is high, accounting for 40% of total annual cost for the 0.05 MGD plant but only 20% for the 10 MGD plant. Maintenance, purchased energy, materials, and chemicals are each 10% or less of total costs, regardless of the scale considered.

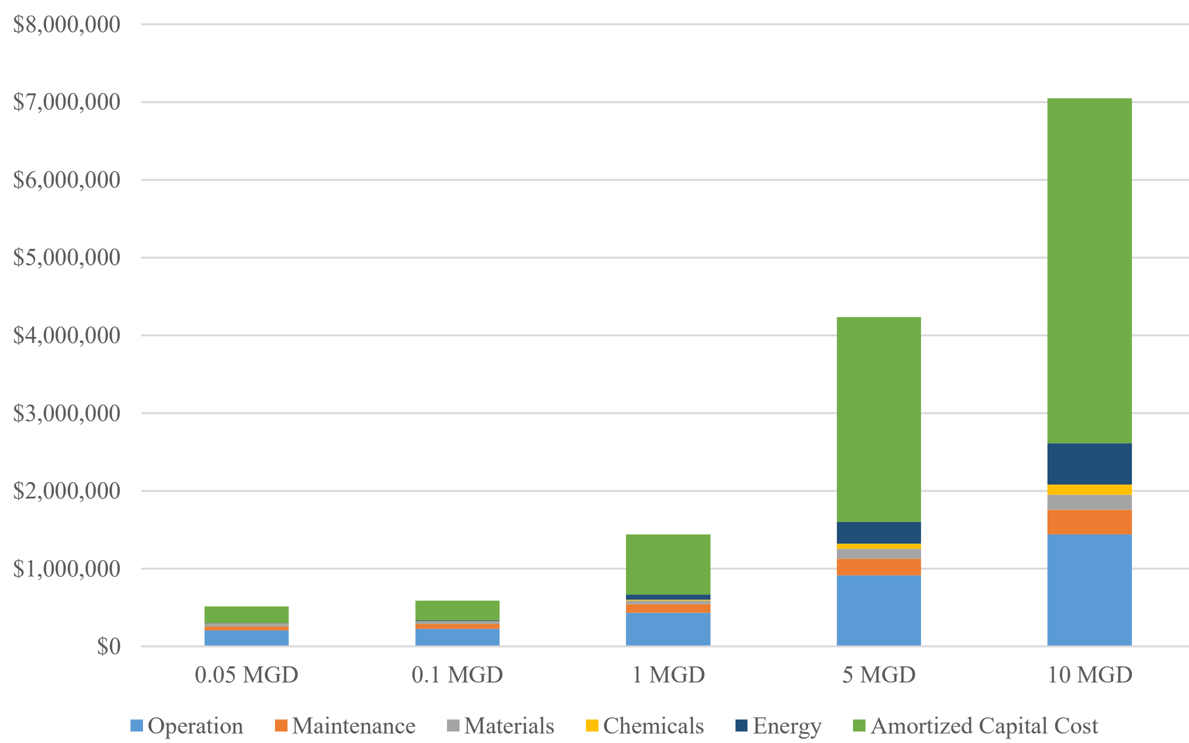


**Figure 4-17. Yearly Expenses for AeMBR Facility by Scale**

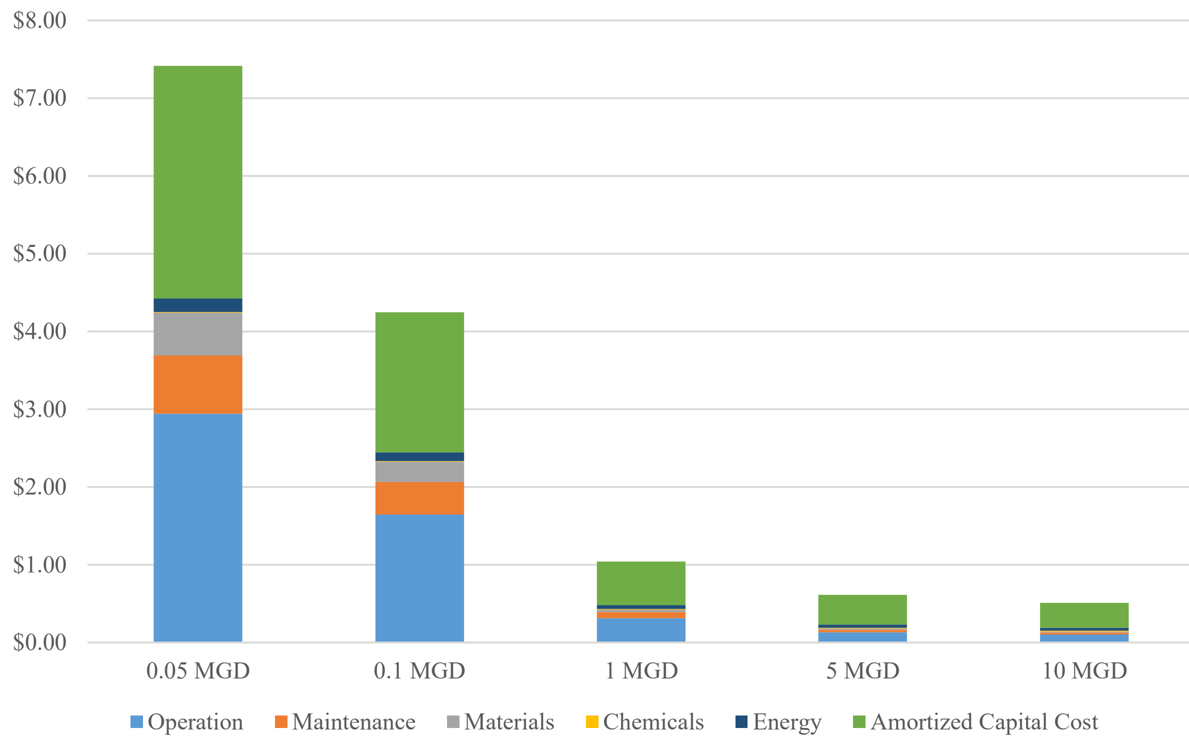


**Figure 4-18. Expenses for AeMBR Facility by Scale per m³ Wastewater Treated**

### 4.7.2 Cost Analysis Results for Anaerobic MBR Wastewater Treatment Plant

The yearly expenses for plant construction and operation of the AnMBR operating at 35˚C and 20˚C at the different scales examined are displayed in Figure 4-19 and Figure 4-20, respectively. The same expenses per m³ treated wastewater basis are provided in Figure 4-21 and Figure 4-22. As for the AeMBR cost analysis results, the relationship between yearly expenses and expenses on per m³ treated wastewater basis are inversely proportional. The 10 MGD system has the highest overall yearly costs, but the lowest costs on a MGD basis. Operation labor and amortized capital costs contribute a roughly equal share, 30-40% each, of the total cost for the AnMBR WWTPs. The percent contribution of operation labor and capital costs drop slightly for scales 1 MGD and greater. For the 35°C operating scenario, purchased energy makes up a larger portion of the total costs compared to energy costs for the AeMBR WWTPs. However, this percentage is lower for the 20°C operating scenario since purchase of natural gas is not necessary. Some cost benefits are realized from electricity generation for both 35°C and 20°C operating scenarios. The net energy cost differential between the AnMBR operating at 35°C and at 20°C is illustrated in Table 4-3.

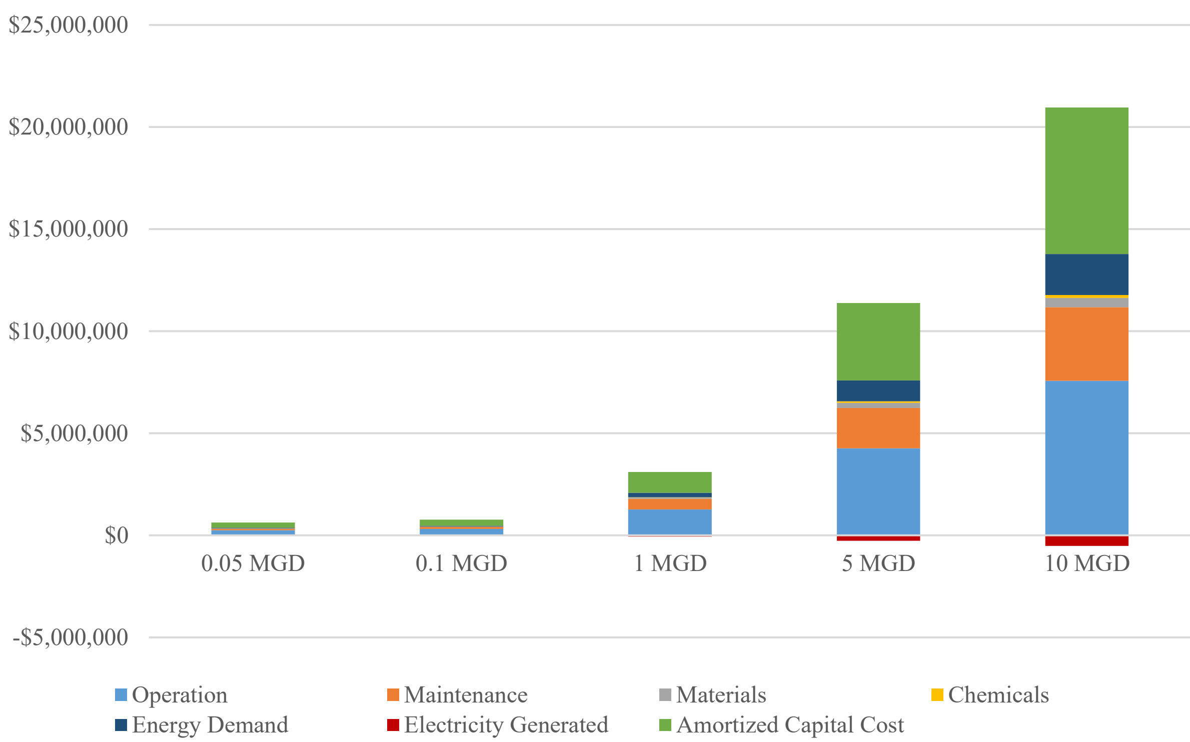


**Figure 4-19. Yearly Expenses for the 35˚C AnMBR Facility by Scale**

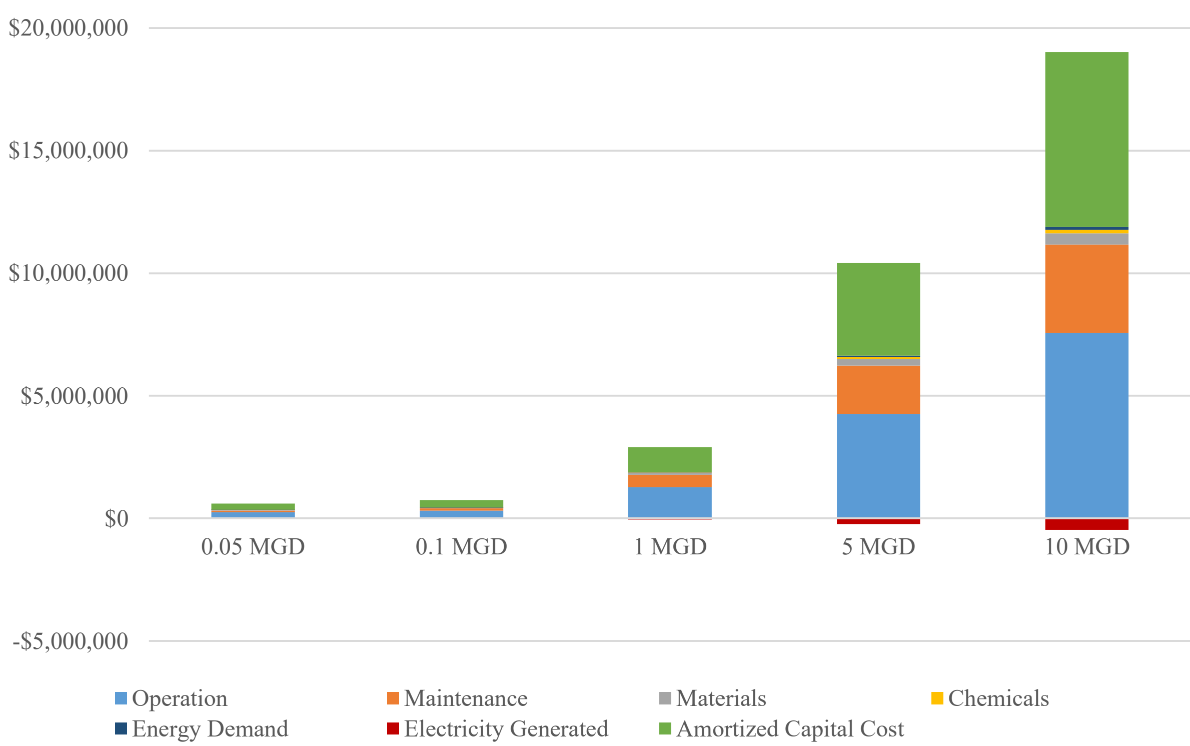


**Figure 4-20. Yearly Expenses for the 20˚C AnMBR Facility by Scale**

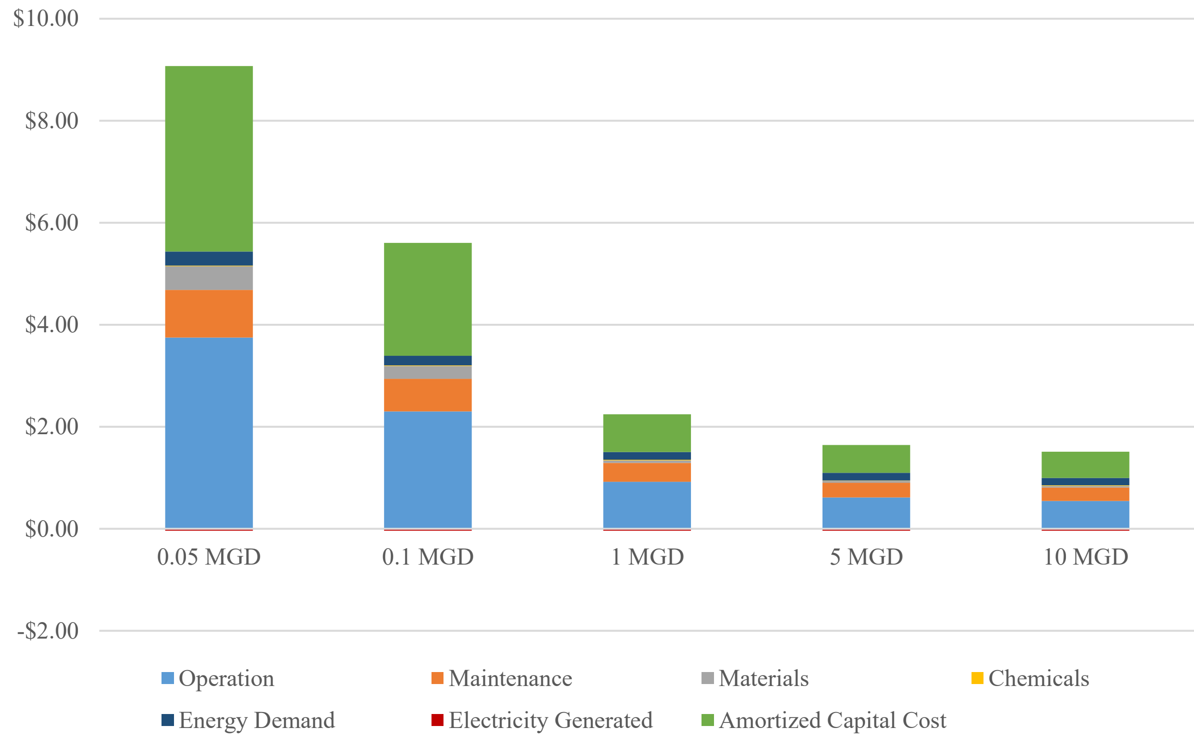


**Figure 4-21. Expenses for the 35˚C AnMBR Facility by Scale per m³ Wastewater Treated**

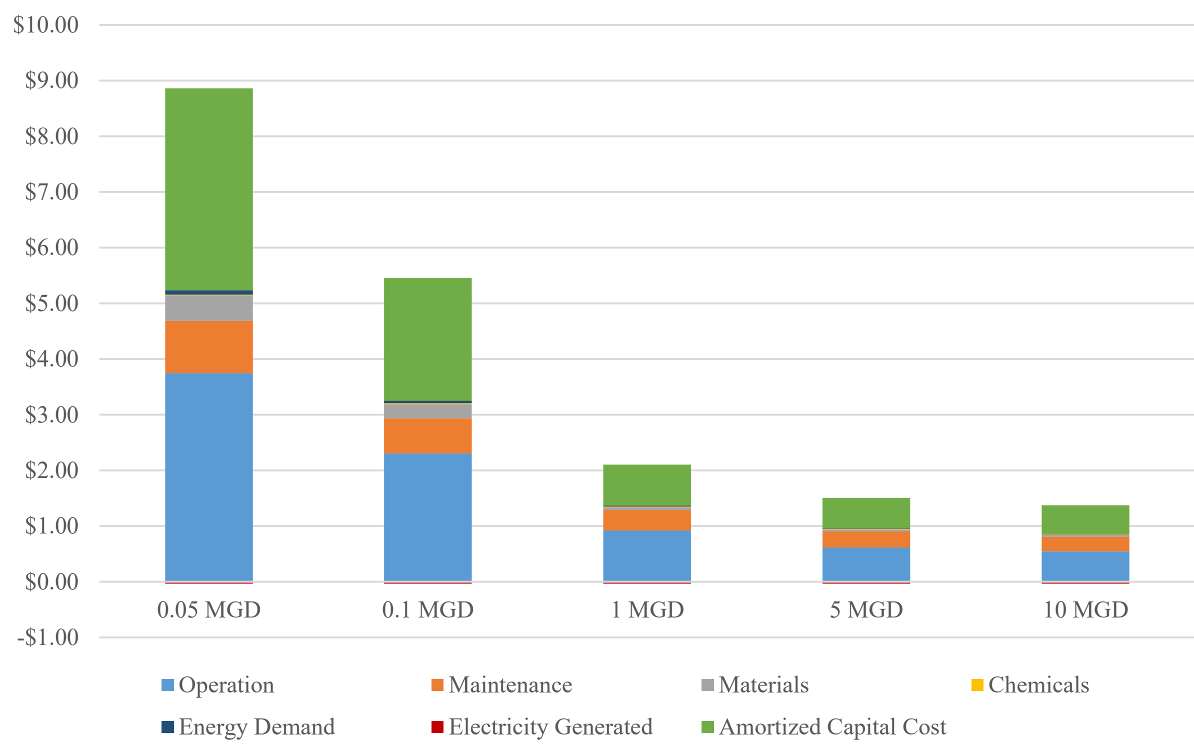


**Figure 4-22. Expenses for the 20˚C AnMBR Facility by Scale per m$^3$ Wastewater Treated**

**Table 4-3. AnMBR Annual Energy Cost Differential between Operating at 35˚C and 20˚C**

| | **0.05 MGD** | **0.1 MGD** | **1 MGD** | **5 MGD** | **10 MGD** |
|---|---|---|---|---|---|
| @ 35 C | 16,855 | 20,795 | 157,948 | 753,397 | 1,493,928 |
| @ 20 C | 3,155 | 2,146 | -26,728 | -168,380 | -348,631 |
| *Percent Decrease* | *-81%* | *-90%* | *-117%* | *-122%* | *-123%* |

### 4.7.3 Cost Analysis Results for Recycled Water Distribution System

Figure 4-23 and Figure 4-24 show the yearly costs for constructing and operating the recycled water distribution system. As expected, the greater the amount of water delivered, the greater the costs. In addition, when holding the amount of people served constant, distribution system costs increase as the density of the service area decreases.

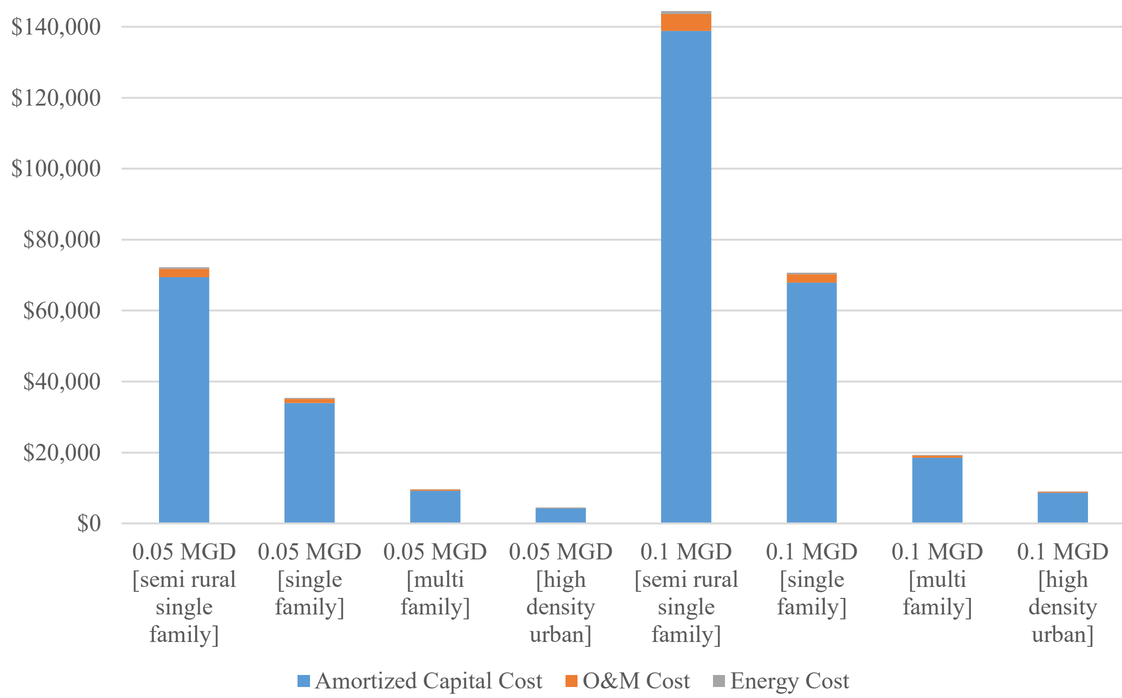


**Figure 4-23. Yearly Life Cycle Costs for Recycled Water Delivery System for Each Density Scenario Associated with the 0.05 and 0.1 MGD Scales**

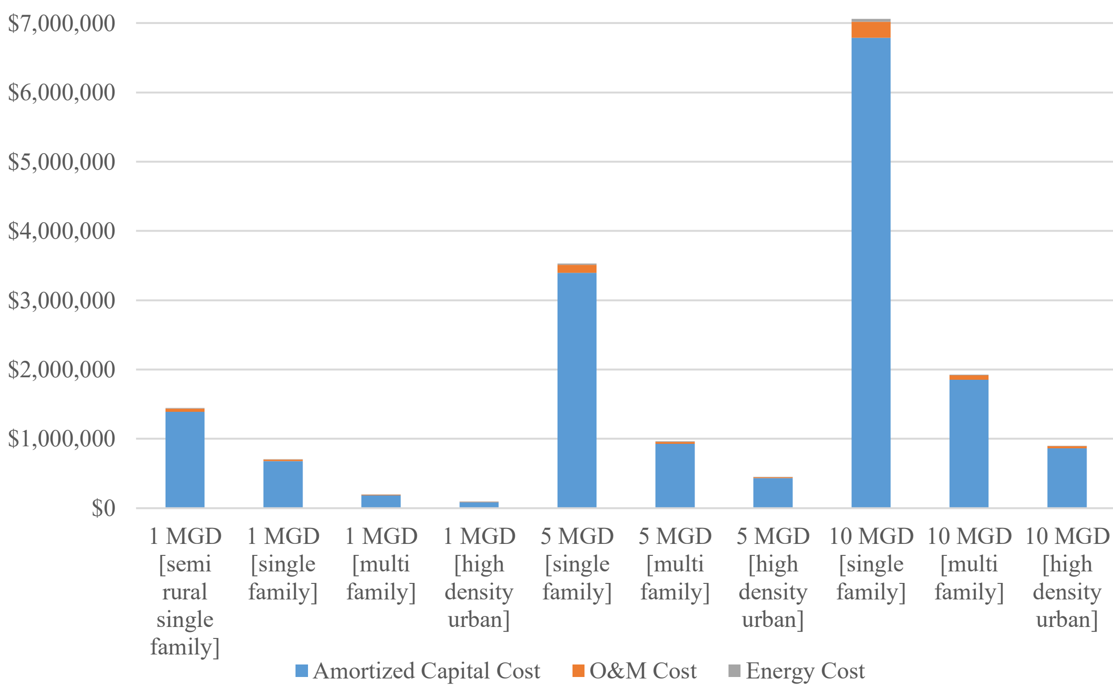


**Figure 4-24. Yearly Life Cycle Costs for Recycled Water Delivery System for Each Density Scenario Associated with the 1, 5, and 10 MGD Scales**

### 4.7.4 Avoided Costs from Drinking Water Treatment and Distribution

This cost analysis includes the savings that result from reducing the amount of water that must be treated at the centralized drinking water treatment facility and then distributed for use by displacing drinking water with recycled water. Avoided amortized capital, O&M, and energy costs for each scale are based on an EPA life cycle cost analysis of Greater Cincinnati Water Works and are summarized in Table 4-4 and Table 4-5 for the AeMBR and AnMBR WWT systems, respectively (Cashman et al., 2014a). Avoided costs are greater for the AnMBR systems since a greater quantity of influent wastewater is recovered and recycled. Note the avoided costs for the drinking water treatment and distribution include ongoing maintenance and labor but do not include expenditures on previously purchased capital goods since those are sunk costs.

**Table 4-4. Drinking Water Treatment and Distribution Costs Avoided by AeMBR WWT and Recycled Water Delivery System**

| | 0.05 MGD | 0.1 MGD | 1 MGD | 5 MGD | 10 MGD |
|---|---|---|---|---|---|
| Amortized Capital Cost | -2 | -4 | -37 | -186 | -372 |
| O&M Cost | -2,558 | -5,116 | -51,159 | -255,795 | -511,590 |
| Energy Cost | -1,863 | -3,726 | -37,264 | -186,322 | -372,644 |
| *Total* | *-4,423* | *-8,846* | *-88,461* | *-442,303* | *-884,606* |

**Table 4-5. Drinking Water Treatment and Distribution Costs Avoided by AnMBR WWT and Recycled Water Delivery System**

| | 0.05 MGD | 0.1 MGD | 1 MGD | 5 MGD | 10 MGD |
|---|---|---|---|---|---|
| Amortized Capital Cost | -2 | -4 | -38 | -189 | -378 |
| O&M Cost | -2,585 | -5,175 | -51,934 | -259,933 | -519,708 |
| Energy Cost | -1,883 | -3,770 | -37,829 | -189,336 | -378,557 |
| *Total* | *-4,471* | *-8,949* | *-89,801* | *-449,457* | *-898,643* |

### 4.7.5 Combined AeMBR WWTP, Recycled Water Delivery System, and Avoided DWT Cost Analysis Results

The combined annual costs for constructing and operating the AeMBR WWTP and recycled water distribution system as well as avoided drinking water treatment and delivery costs for all scale and density scenarios are presented in Figure 4-25 and Figure 4-26. Across all of the scenarios, O&M and capital costs combined are responsible for roughly 90% or more of the overall cost of the system. The share of expenses due to O&M decreases with increasing scale, while the share for capital costs increase. In all cases, the total cost for a system of a particular scale will be less than the total cost for a larger scale, regardless of the density of the service area. Scenarios with lower density service areas are costlier than scenarios of the same scale with higher density service areas due to increased infrastructure to deliver recycled water over greater distances. Figure 4-27 highlights how cost effectiveness improves dramatically as the system scale increases from 0.05 MGD to 0.1 MGD and from 0.1 MGD to 1 MGD, mainly due to economies of scale achieved for the WWTP O&M labor and capital costs, but cost effectiveness improvements are small between the 1 MGD, 5 MGD, and 10 MGD systems. Because wastewater treatment contributes a much smaller portion of overall costs at scales of 1 MGD and larger, a change in service area density has a greater impact on overall system cost. For example, overall cost per cubic meter of treated wastewater for a 10 MGD system serving single family homes is higher than for a 5 MGD system serving high-density urban or multi family homes.

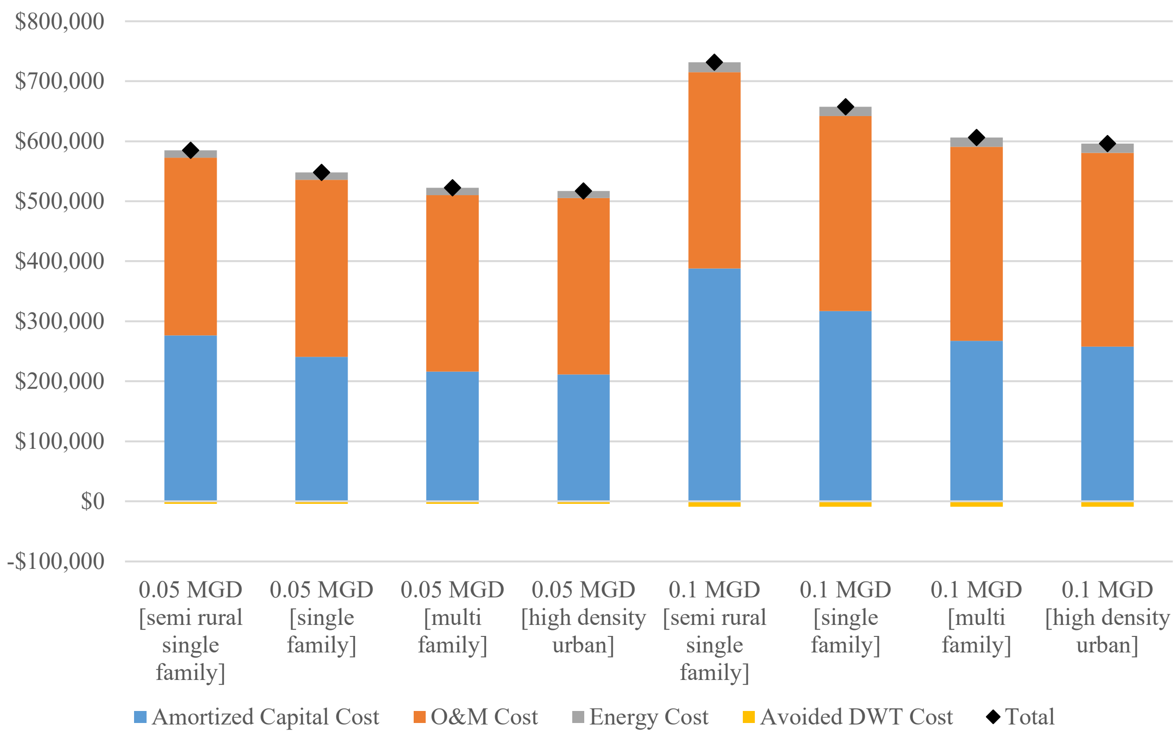


**Figure 4-25. Combined Annual AeMBR, Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 0.05 and 0.1 MGD Scales**

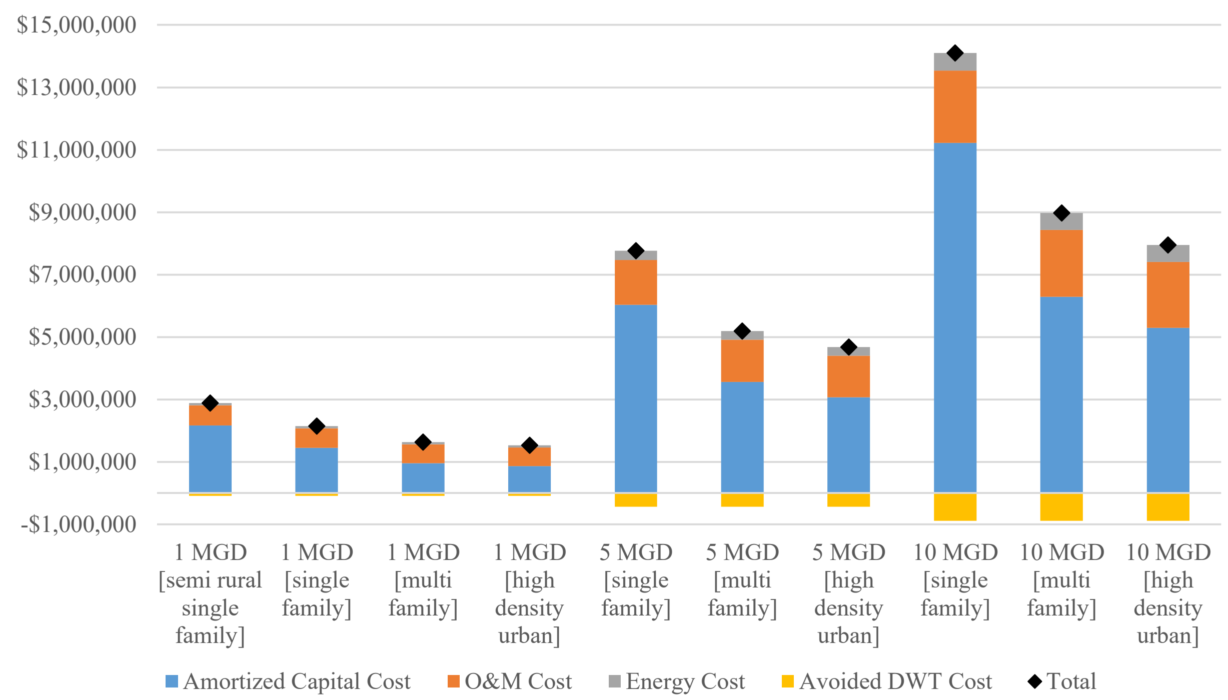


**Figure 4-26. Combined Annual AeMBR, Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 1, 5, and 10 MGD Scales**

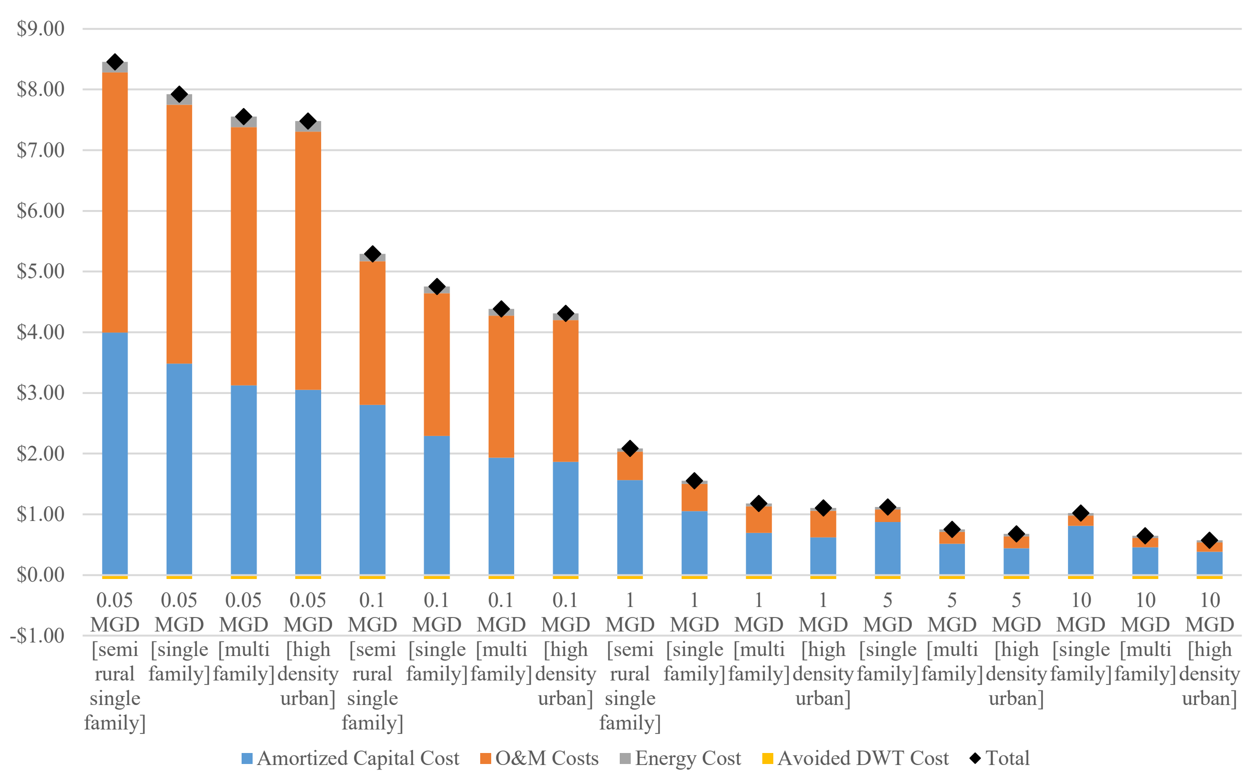


**Figure 4-27. Combined AeMBR, Recycled Water Delivery, and Avoided DWT Costs for Each Density and Scale Scenario per m$^3$ of Treated Wastewater**

### 4.7.6 Combined AnMBR WWTP and Recycled Distribution System Cost Analysis Results

The yearly costs for constructing and operating the AnMBR WWTP, recycled water distribution system, and the avoided drinking water treatment and distribution costs for all scale and density scenarios are presented in Figure 4-28 and Figure 4-29 for the AnMBR operating at 35 °C and in Figure 4-31 and Figure 4-32 for the AnMBR operating at 20 °C. As shown in the figures, operation and maintenance and capital costs are the biggest contributors to the overall cost of the system. Even though a system installed in a lower density area would be more expensive, the wastewater treatment facility is the main driver of overall costs, meaning the larger the scale, the greater the cost, regardless of the density of the service area. In general, the overall costs for AnMBR systems are more expensive than the AeMBR systems. This is largely due to the cost of increased labor required to operate the anaerobic reactor system as well as the high quantity of membrane required since AnMBR operates at a much lower average net flux than the AeMBR. Combined cost results are shown on a per $m^3$ of treated wastewater basis in Figure 4-30 for scenarios with a 35 °C AnMBR and in Figure 4-33 for scenarios with a 20 °C AnMBR. Both of these figures follow the same pattern observed for the AeMBR results on a per $m^3$ treated wastewater basis.

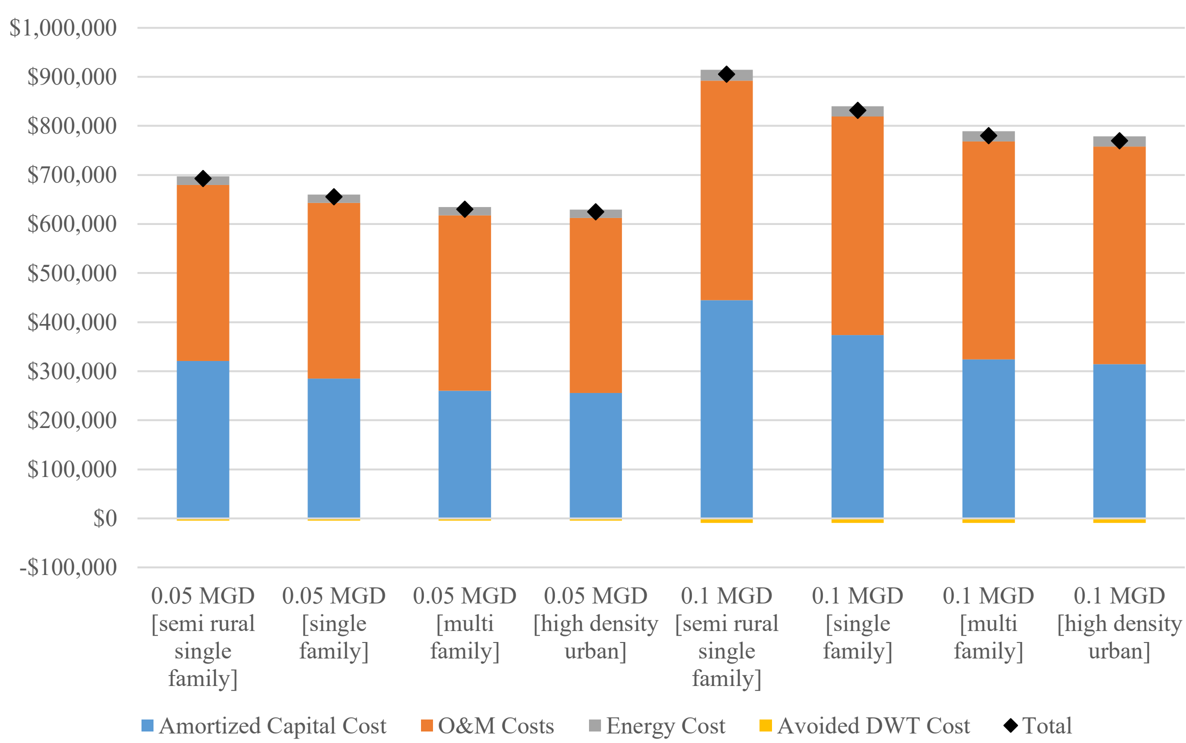


**Figure 4-28. Combined Annual AnMBR (35 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 0.05 and 0.1 MGD Scales**

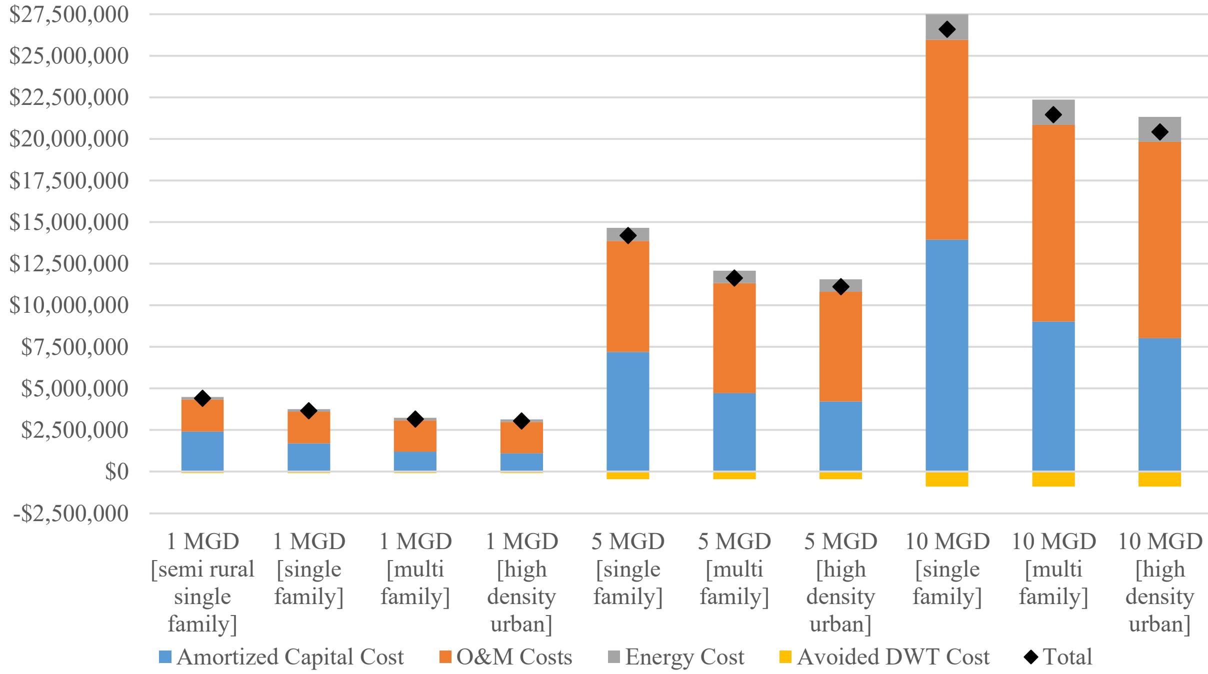


**Figure 4-29. Combined Annual AnMBR (35 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 1, 5, and 10 MGD Scales**

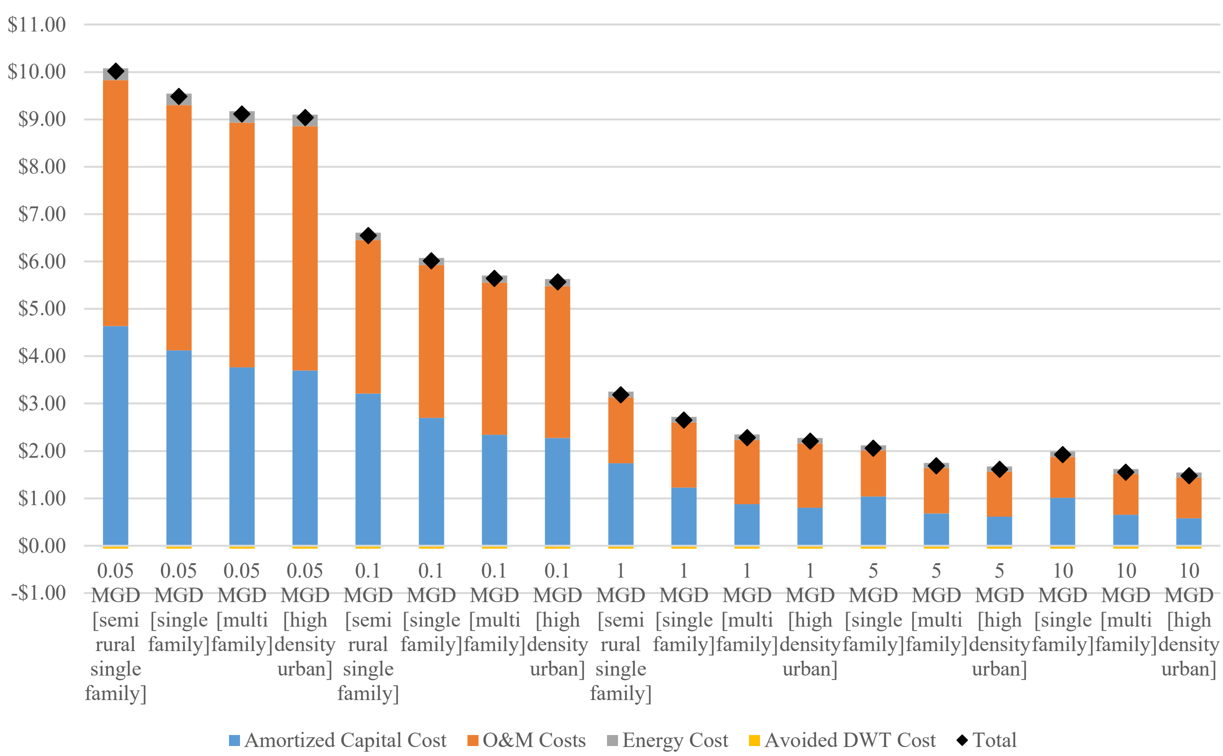


**Figure 4-30. Combined AnMBR (35 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density and Scale Scenario per m³ of Treated Wastewater**

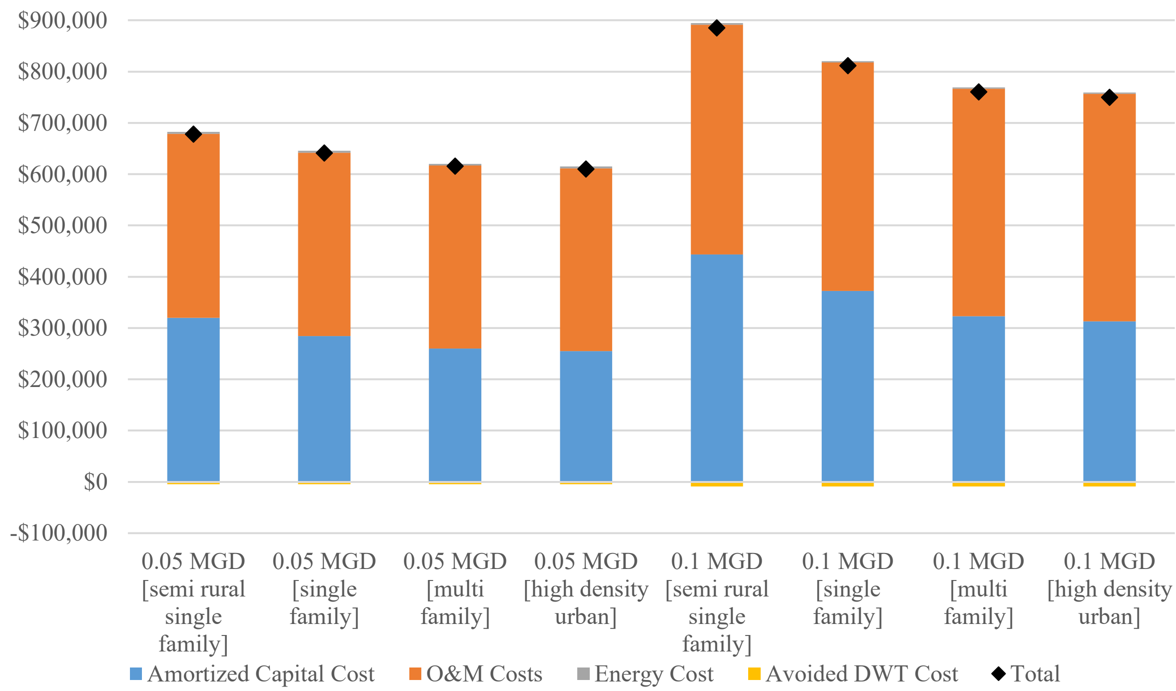


**Figure 4-31. Combined AnMBR (20 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 0.05 and 0.1 MGD Scales**

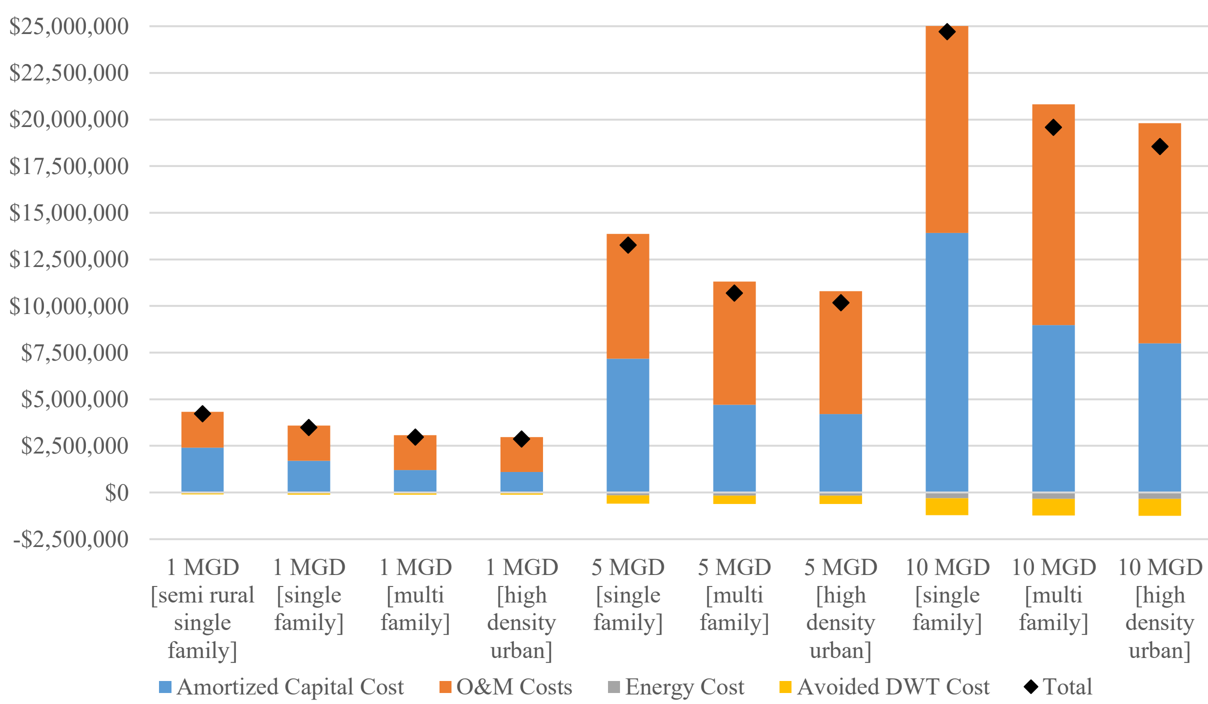


**Figure 4-32. Combined AnMBR (20 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density Scenario Associated with the 1, 5, and 10 MGD Scales**

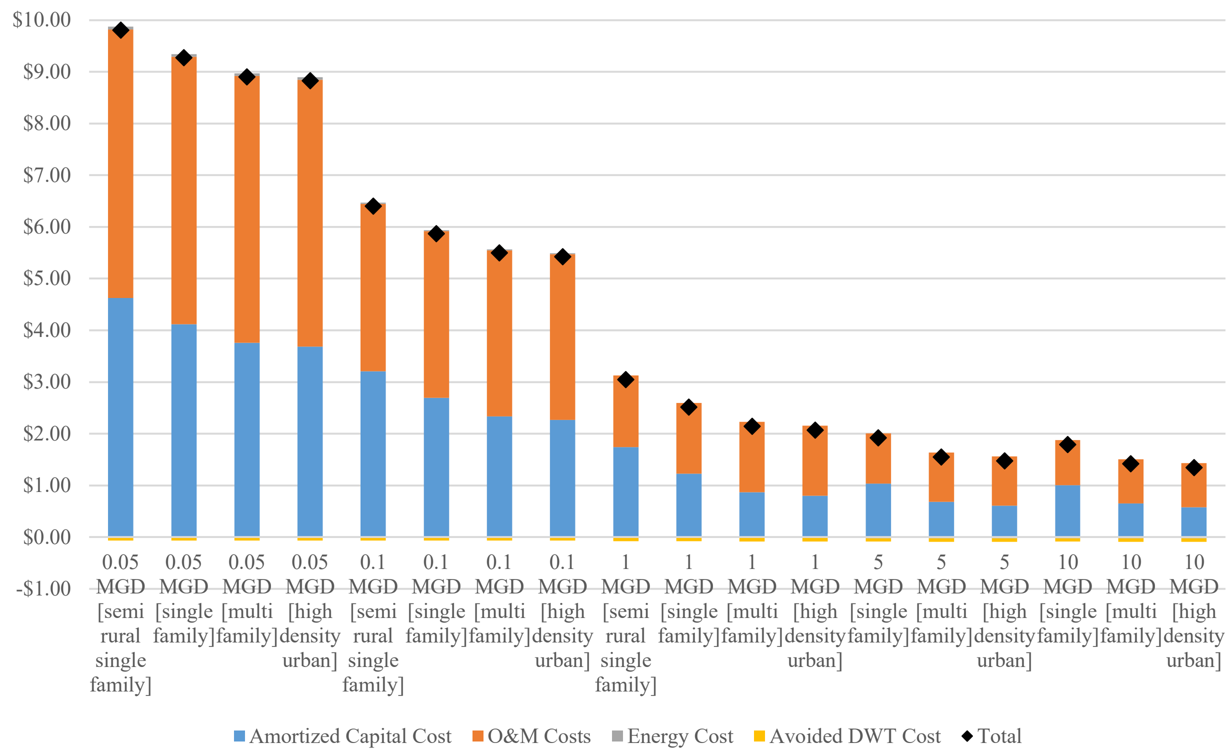


**Figure 4-33. Combined AnMBR (20 °C), Recycled Water Delivery, and Avoided DWT Costs for Each Density and Scale Scenario per m³ of Treated Wastewater**

### 4.7.7 Cost Comparative Scenario Analysis

Comparative AeMBR and AnMBR costs are shown for the multi family land use scenario on an annual basis in Figure 4-34 and on a per cubic meter of wastewater treated in Figure 4-35. These figures include WWTP operation, recycled water delivery, and avoided drinking water costs. AnMBR costs are notably higher than the AeMBR costs. This is primarily from differences in O&M costs between the AeMBR and AnMBR systems. The driver for this is the increase in O&M labor needed to operate the anaerobic reactor system.

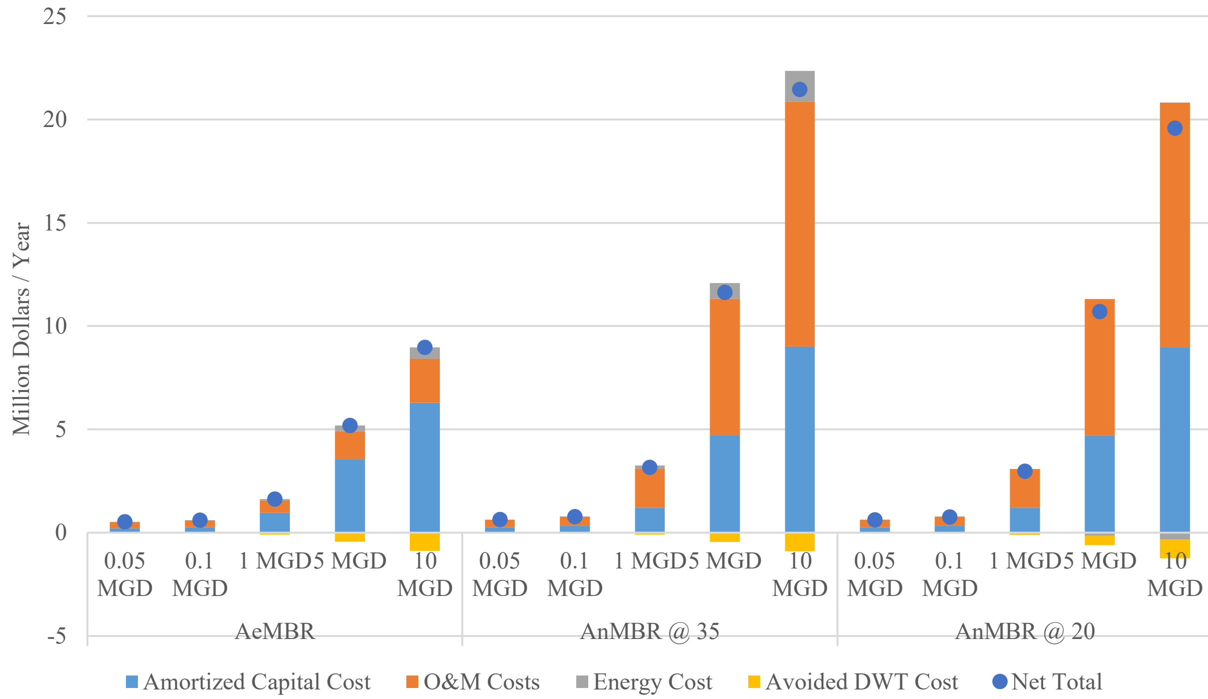


**Figure 4-34. Comparative Yearly MBR Costs for Multi Family Land Use Scenario**

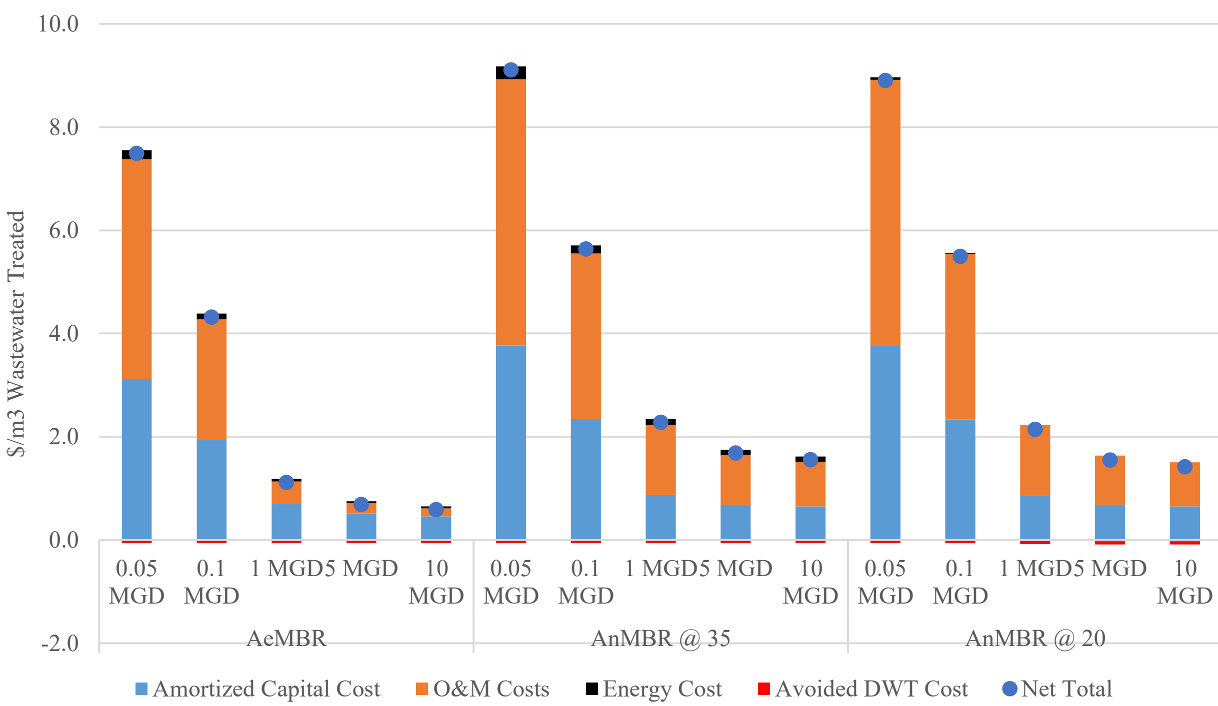


**Figure 4-35. Comparative MBR Costs per m$^3$ of Treated Wastewater for Multi Family Land Use Scenario**

# 5.0 SENSITIVITY ANALYSES

Sensitivity analysis is an important component in the production of robust LCA study results. As with any modeling process, the construction and analysis of an LCA model and results requires making and documenting many assumptions. Many individual assumptions are known to have only an insignificant effect on the final impact results calculated for a given functional unit, but the effects of other assumptions are uncertain or are known to be significant. In the latter two cases, sensitivity analysis is employed to quantify the effect of modeling choices on LCA results. To increase the robustness of the study, the following sensitivity analyses were conducted on parameters determined to be important after reviewing the baseline findings.

- Inclusion of CHP unit for the AnMBR;
- Flaring of biogas rather than recovery for methane for AnMBR;
- Inclusion of two climate scenarios for psychrophilic AnMBR:
  - — Variability in both the ambient air temperature, reactor temperature and influent wastewater temperature.
  - — Calculations with and without reactor insulation for each climate scenario.
  - — Examination of dissolved methane in the permeate and the potential impacts and benefits of recovering this methane within different climates.
- Incorporation of a range of displaced potable water scenarios based on a literature review (both aerobic MBR and AnMBR scenarios); and
- Incorporation of different regional electrical grid mixes for both MBR operation and the treatment and delivery of displaced potable water.

## 5.1 Climate and Methane Recovery Scenarios

Table 5-1 provides detailed descriptions of the scenario abbreviations used in the climate and methane recovery sensitivity analysis results' display. Two specific climate scenarios are run under multiple conditions. AnMBR operation is considered in the winter time in a cold climate Cincinnati, Ohio (abbreviated CN) and for the annual average in a warm climate Miami, Florida (abbreviated MIA). These scenario analyses have only been conducted for the psychrophilic AnMBR, as the psychrophilic AnMBR showed the most promise in the baseline results from an energy and global warming potential perspective. Key differentiating parameters for the scenarios are indicated Table 5-1. These differentiating parameters include the ambient temperature, influent wastewater temperature, reactor temperature, whether reactor surface insulation is included, whether methane is recovered from the permeate, and whether methane recovered from permeate/headspace is flared, converted to electricity only, or converted to both electricity and heat via CHP. A discussion of the ambient and influent temperatures used is provided in Appendix D.

**Table 5-1. Full and Abbreviated Names of Climate and Methane Recovery Scenarios and Associated Differentiating Parameters**

| | | | | | | Methane Recovery Option | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Scenario Abbreviations*** | ***Scenario Full Name*** | **Ambient T (˚C)** | **Influent T (˚C)** | **Reactor T (˚C)** | **Reactor Insulation** | **Flared** | **Converted to Electricity Only** | **CHP** | **Methane Permeate Recovery** |
| CN winter no insulation; biogas flare; no methane biogas recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas is flared; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | | √ | | | |
| CN winter w/ insulation; biogas flare; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is flared; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | √ | | | |
| CN winter no insulation; elect; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas is converted to electricity; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | | | √ | | |
| CN winter w/ insulation; elect; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is converted to electricity; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | | √ | | |
| CN winter no insulation; CHP; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas is converted to electricity and heat via CHP; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | | | | √ | |
| CN winter no insulation; biogas flare; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas | 6.0 | 17.9 | 20.0 | | √ | | | √ |

**Table 5-1. Full and Abbreviated Names of Climate and Methane Recovery Scenarios and Associated Differentiating Parameters**

| | | | | | | Methane Recovery Option | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Scenario Abbreviations*** | ***Scenario Full Name*** | **Ambient T (˚C)** | **Influent T (˚C)** | **Reactor T (˚C)** | **Reactor Insulation** | **Flared** | **Converted to Electricity Only** | **CHP** | **Methane Permeate Recovery** |
| | is flared; recovery of methane from permeate | | | | | | | | |
| CN winter w/ insulation; CHP; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is converted to electricity and heat via CHP; no recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | | | √ | |
| CN winter w/ insulation; biogas flare; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is flared; recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | √ | | | √ |
| CN winter no insulation; elect; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas is converted to electricity; recovery of methane from permeate | 6.0 | 17.9 | 20.0 | | | √ | | √ |
| CN winter w/ insulation; elect; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is converted to electricity; recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | | √ | | √ |
| CN winter no insulation; CHP; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; no reactor insulation; recovered biogas is converted to electricity and heat via CHP; recovery of methane from permeate | 6.0 | 17.9 | 20.0 | | | | √ | √ |

**Table 5-1. Full and Abbreviated Names of Climate and Methane Recovery Scenarios and Associated Differentiating Parameters**

| | | | | | | Methane Recovery Option | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Scenario Abbreviations*** | ***Scenario Full Name*** | **Ambient T (˚C)** | **Influent T (˚C)** | **Reactor T (˚C)** | **Reactor Insulation** | **Flared** | **Converted to Electricity Only** | **CHP** | **Methane Permeate Recovery** |
| CN winter w/ insulation; CHP; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Cincinnati, OH winter conditions; with insulation on reactor surface; recovered biogas is converted to electricity and heat via CHP; recovery of methane from permeate | 6.0 | 17.9 | 20.0 | √ | | | √ | √ |
| MIA; biogas flare; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Miami, FL annual conditions; recovered biogas is flared; no recovery of methane from permeate | 26.4 | 26.4 | 26.4 | | √ | | | |
| MIA; elect; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Miami, FL annual conditions; recovered biogas is converted to electricity; no recovery of methane from permeate | 26.4 | 26.4 | 26.4 | | | √ | | |
| MIA; biogas flare; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Miami, FL annual conditions; recovered biogas is flared; recovery of methane from permeate | 26.4 | 26.4 | 26.4 | | √ | | | √ |
| MIA; CHP; no permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Miami, FL annual conditions; recovered biogas is converted to electricity and heat via CHP; no recovery of methane from permeate | 26.4 | 26.4 | 26.4 | | | | √ | |
| MIA; elect; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; Miami, FL annual conditions; recovered biogas is converted to electricity; recovery of methane from permeate | 26.4 | 26.4 | 26.4 | | | √ | | √ |
| MIA; CHP; permeate methane recovery | 1 MGD AnMBR serving 10,000 people at 50,000 people/sq. mi; | 26.4 | 26.4 | 26.4 | | | | √ | √ |

**Table 5-1. Full and Abbreviated Names of Climate and Methane Recovery Scenarios and Associated Differentiating Parameters**

| | | | | | | Methane Recovery Option | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Scenario Abbreviations*** | ***Scenario Full Name*** | **Ambient T (˚C)** | **Influent T (˚C)** | **Reactor T (˚C)** | **Reactor Insulation** | **Flared** | **Converted to Electricity Only** | **CHP** | **Methane Permeate Recovery** |
| | Miami, FL annual conditions; recovered biogas is converted to electricity and heat via CHP; recovery of methane from permeate | | | | | | | | |
| | | | | | | | | | |

CN = Cincinnati, MIA = Miami

### 5.1.1 Cumulative Energy Demand Results for Climate and Methane Recovery Scenarios

Figure 5-1 displays the detailed cumulative energy demand results for AnMBR climate scenarios. Scenarios are ordered by highest to lowest net energy demand. As can be seen in this figure, net cumulative energy demand benefits are realized for all scenarios except Cincinnati winter scenarios with only biogas flare and no reactor surface insulation. The largest cumulative energy demand benefits are from displaced potable water and recovery of methane in headspace. Less key cumulative energy demand benefits are for inclusion of reactor surface insulation and recovery of methane from permeates. The most burdensome energy impact is for heating of influent under Cincinnati winter conditions. The optimal scenario investigated from an energy perspective is the psychrophilic AnMBR operated in warm climate (e.g., Miami, FL) with methane recovery via CHP and both headspace and permeate methane recovery.

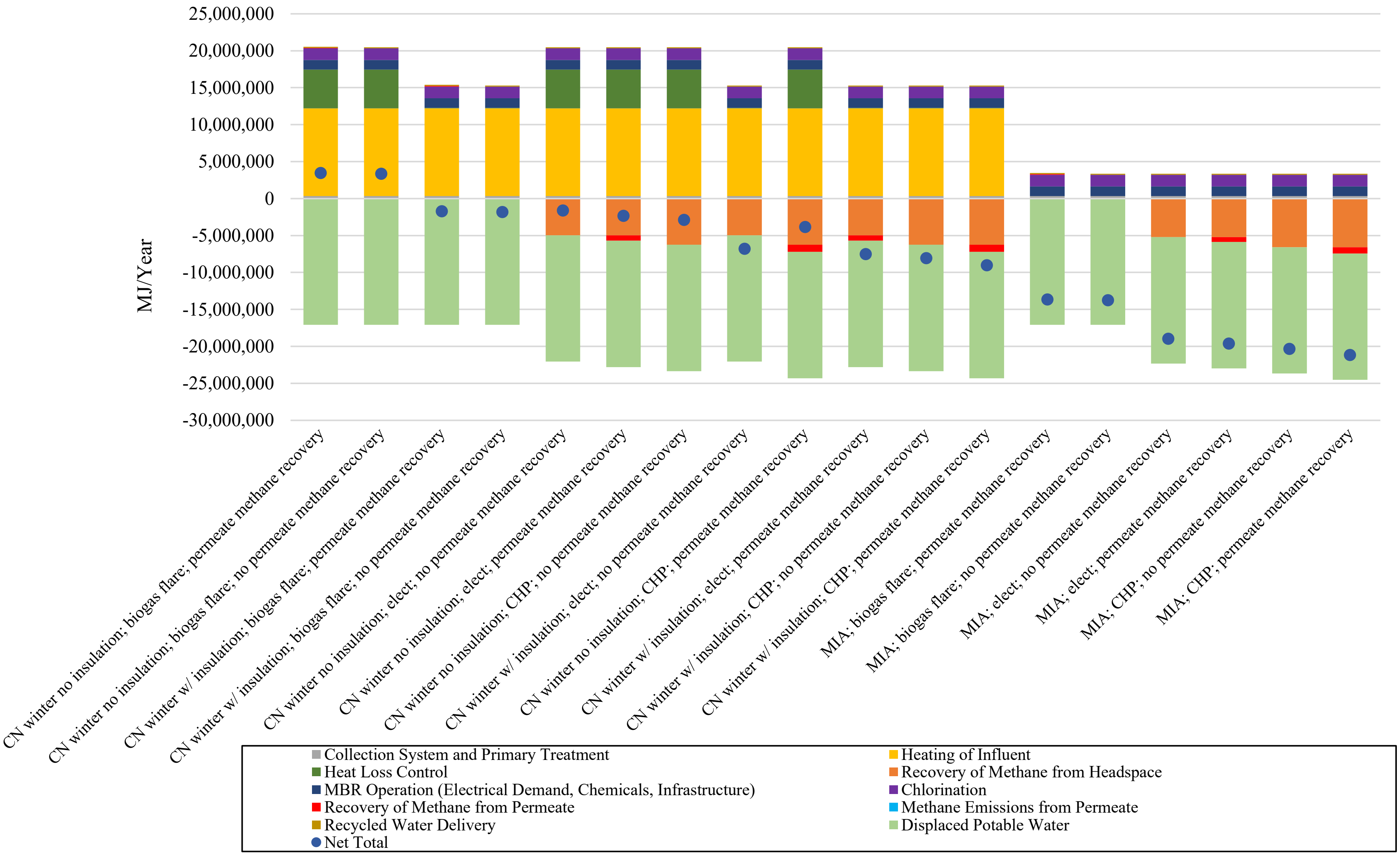


**Figure 5-1. Detailed Cumulative Energy Demand Results for AnMBR Climate and Methane Recovery Scenarios**

### 5.1.2 Global Warming Potential Results for Climate and Methane Recovery Scenarios

Figure 5-2 presents the detailed global warming potential results for AnMBR climate scenarios. Results are similar to those seen for the energy demand with the exception of permeates methane emissions. Inclusion of permeate methane recovery avoids 80% of the permeate methane emissions. Some key findings for this sensitivity analysis include:

- Net global warming potential benefits realized for all Miami, FL (warm climate) scenarios;
- Net global warming potential benefits are only seen for cold climate scenario only when dissolved methane in permeate is recovered, and methane in headspace/permeate is converted to electricity or electricity in heat (i.e., methane is not flared);
- For global warming potential, heating of influent (for cold climate) and methane emissions from permeate are the most impactful stages;
- For global warming potential, displaced potable water and recovery of methane from headspace are the most beneficial life cycle stages. Recovery of methane in permeate (to avoid emissions from permeate) is key; and
- Incremental global warming potential benefits are seen for inclusion of insulation on surface of the reactor and recovery of methane for CHP rather than just for electricity.

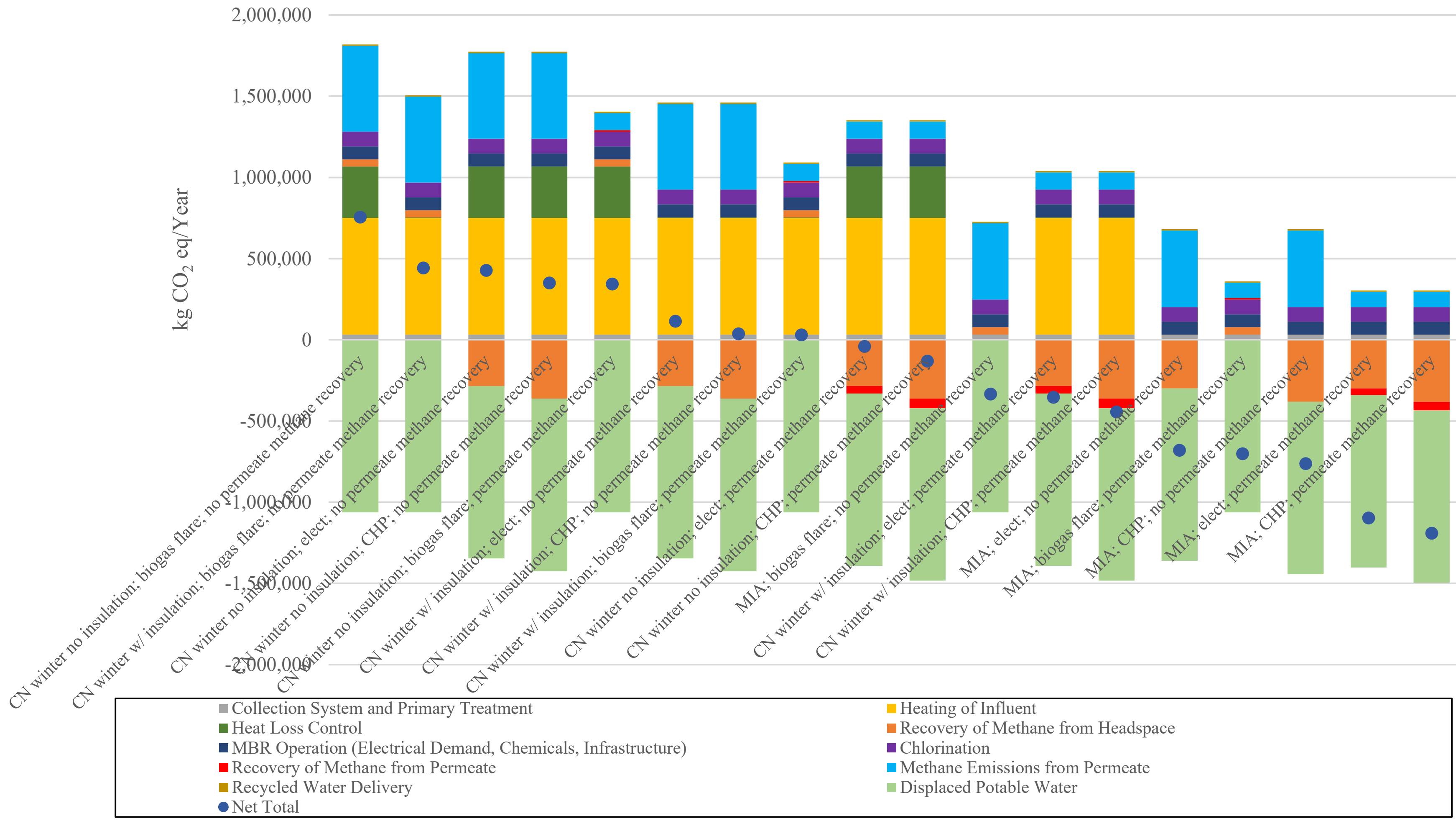


**Figure 5-2. Detailed Global Warming Potential Results for AnMBR Climate and Methane Recovery Scenarios**

### 5.1.3 Cost Results for Climate and Methane Recovery Scenarios

Figure 5-3 displays the detailed cost results for the AnMBR climate and methane recovery scenarios. Scenarios are ordered by highest to lowest net cost. Overall, the sensitivity analyses found very little variation between the different scenarios. This is mainly due to the fact that changes associated with the chosen scenarios mostly impact net energy use and do not affect O&M labor costs, 55-60% of total cost, or the key contributors to capital costs, 35-40% of total expenses, such as the anaerobic reactor and MBR infrastructure and installation.[6] In all cases, the AnMBR and recycled water delivery systems are more expensive to construct and operate in Cincinnati's winter climate than in Miami. The largest difference is the cost of natural gas needed to heat the influent wastewater and reactor in Cincinnati while no heating is necessary for the Miami scenarios. Because of the high cost of heating wastewater during Cincinnati winters, inclusion of insulation has the greatest effect on differences in cost for the Cincinnati scenarios. All Cincinnati scenarios with insulation are less expensive than any of the scenarios without insulation. Including dissolved methane recovery from permeate reduces costs as long as the methane is used to generate electricity, regardless of whether heat recovery is included. CHP is the most cost effective use of biogas as it captures the value of the electricity and heat produces, while scenarios with biogas flaring are costlier than either CHP or electricity generation only. The highest cost scenario is Cincinnati in the winter with no insulation, biogas flaring, and dissolved methane recovery from the permeate. The lowest cost scenario is the system in Miami with a CHP and dissolved methane recovery from the permeate.

[6] Percent contribution ranges for O&M and amortized capital cost are provided for total costs, not including avoided DWT costs.

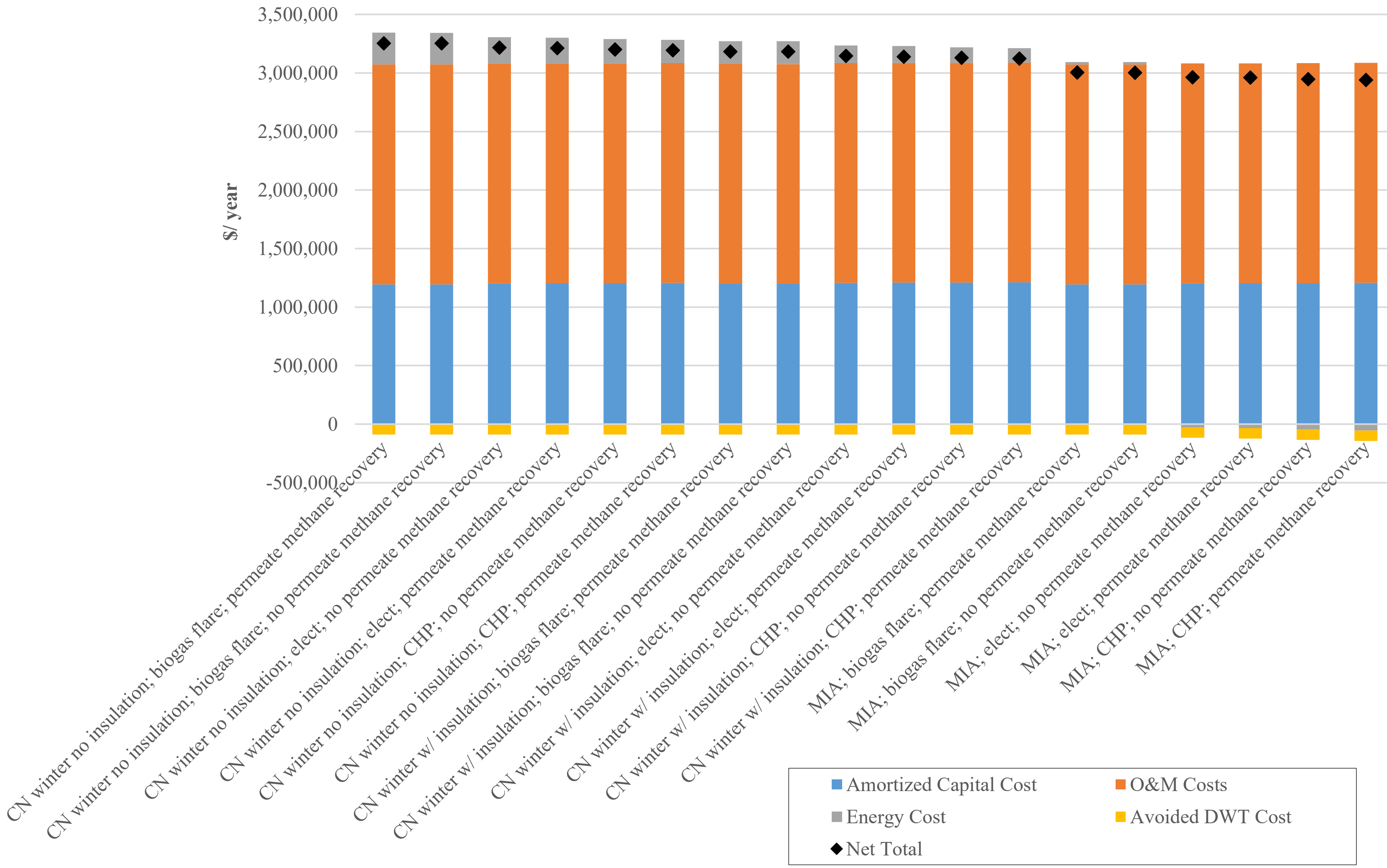


**Figure 5-3. Detailed Cost Results for AnMBR Climate and Methane Recovery Scenarios**

## 5.2 Electrical Grid Mix

Electricity plays a large role in the operational requirements of the MBR systems as well as the displaced drinking water. In the baseline LCA model, we assume the average U.S. electrical grid mix. Here, we examine scenarios with different fuel grid mixes representative of eGRID sub regions in Cincinnati, Ohio and Miami, Florida. Table 5-2 provides more information on the fuel mix for all electrical grids considered.

**Table 5-2. eGRID 2012 Resource Mix by Subregion**

| | Average U.S. | RFCW[1] | FRCC[2] |
|---|---|---|---|
| Coal | 37.4% | 58.7% | 19.4% |
| Oil | 0.7% | 0.5% | 0.6% |
| Natural Gas | 30.3% | 11.1% | 68.1% |
| Nuclear | 19.0% | 25.7% | 8.5% |
| Hydro | 6.7% | 0.7% | 0.1% |
| Biomass | 1.4% | 0.5% | 1.8% |
| Wind | 3.4% | 2.1% | 0.0% |
| Solar | 0.1% | 0.0% | 0.1% |
| Geothermal | 0.4% | 0.0% | 0.0% |
| Other | 0.5% | 0.7% | 1.5% |
| *Total* | *100%* | *100%* | *100%* |

[1]RFCW = Reliability First Corporation/west eGRID sub region. Applicable for Cincinnati, OH.
[2]FRCC = Florida Reliability Coordinating Council eGRID sub region. Applicable for Miami, FL.

Table 5-3 displays the global warming potential results of this sensitivity analysis for the multi family land use type. Baseline scenarios include the change from applying both the RFCW electrical grid and the FRCC electrical grid. Results are shown for the climate scenarios. Only the applicable regional electrical grids are applied to these scenarios (i.e., sensitivity analysis run with RFCW electrical grid for Cincinnati, OH scenarios and sensitivity analysis run with FRCC electrical grid for Miami, FL scenarios). Figure 5-4 displays these results for the baseline scenarios only.

In all cases, application of the RFCW electrical grid increases global warming potential impacts, and application of the FRCC electrical grid decreases global warming potential impacts. This is largely driven by the higher reliance of coal resources in the RFCW electrical grid compared to the U.S. average electrical grid and the lower reliance on coal in the FRCC electrical grid compared to the U.S. average electrical grid.

**Table 5-3. Global Warming Potential Results for Electrical Grid Sensitivity Analysis (kg CO2 eq per Year)**

| | | GWP (kg $CO_2$ eq/Yr.) | | | | |
|---|---|---|---|---|---|---|
| | | U.S. Ave | RFCW[1] | RFCW[1] % Change | FRCC[2] | FRCC[2] % Change |
| **Baseline** | 1 MGD AeMBR; multi family | -520,472 | -444,985 | *15%* | -748,959 | *-44%* |
| | 1 MGD AnMBR @ 35 degrees; multi family | 418,691 | 548,800 | *31%* | -137,990 | *-133%* |
| | 1 MGD AnMBR @ 20 degrees; multi family | -566,116 | -441,546 | *22%* | -1,106,250 | *-95%* |
| **Climate Sensitivity (All 1 MGD AnMBR ambient; multi family)** | CN winter no insulation; biogas flare; no permeate methane recovery | 756,043 | 878,624 | *16%* | | |
| | CN winter w/ insulation; biogas flare; no permeate methane recovery | 442,878 | 565,459 | *28%* | | |
| | CN winter no insulation; elect; no permeate methane recovery | 427,500 | 594,437 | *39%* | | |
| | CN winter w/ insulation; elect; no permeate methane recovery | 114,335 | 281,272 | *146%* | | |
| | CN winter no insulation; CHP; no permeate methane recovery | 349,576 | 516,513 | *48%* | | |
| | CN winter no insulation; biogas flare; permeate methane recovery | 342,877 | 464,670 | *36%* | | |
| | CN winter w/ insulation; CHP; no permeate methane recovery | 36,411 | 203,348 | *458%* | | |
| | CN winter w/ insulation; biogas flare; permeate methane recovery | 29,712 | 151,505 | *410%* | | |
| | CN winter no insulation; elect; permeate methane recovery | -40,822 | 132,460 | *424%* | | |
| | CN winter w/ insulation; elect; permeate methane recovery | -353,987 | -180,705 | *49%* | | |
| | CN winter no insulation; CHP; permeate methane recovery | -131,789 | 41,494 | *131%* | | |
| | CN winter w/ insulation; CHP; permeate methane recovery | -444,954 | -271,671 | *39%* | | |
| | MIA; biogas flare; no permeate methane recovery | -333,883 | | | -699,318 | *-109%* |
| | MIA; elect; no permeate methane recovery | -679,833 | | | -1,184,630 | *-74%* |

**Table 5-3. Global Warming Potential Results for Electrical Grid Sensitivity Analysis (kg CO2 eq per Year)**

| | | GWP (kg $CO_2$ eq/Yr.) | | | | |
|---|---|---|---|---|---|---|
| | | U.S. Ave | RFCW[1] | RFCW[1] % Change | FRCC[2] | FRCC[2] % Change |
| | MIA; biogas flare; permeate methane recovery | -702,293 | | | -1,065,180 | -52% |
| | MIA; CHP; no permeate methane recovery | -761,886 | | | -1,266,690 | -66% |
| | MIA; elect; permeate methane recovery | -1,097,521 | | | -1,619,830 | -48% |
| | MIA; CHP; permeate methane recovery | -1,191,226 | | | -1,713,530 | -44% |

[1]RFCW = Reliability First Corporation/west eGRID sub region.
[2]FRCC = Florida Reliability Coordinating Council eGRID sub region.

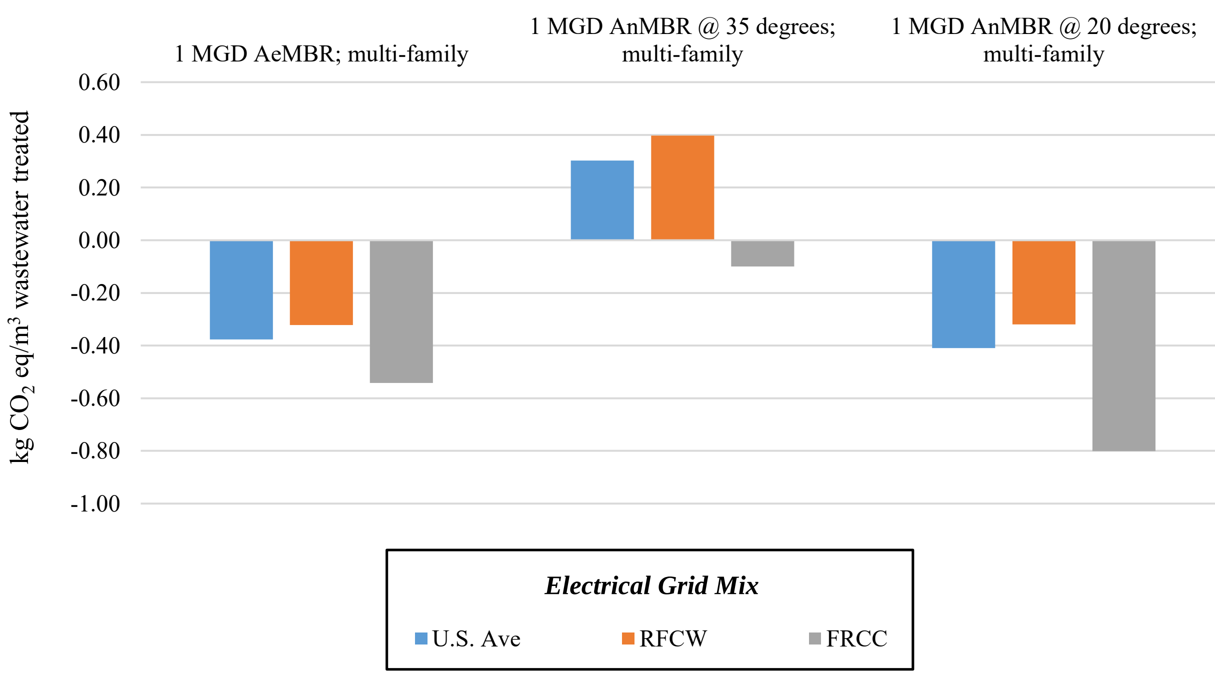


**Figure 5-4. Global Warming Potential Results for Electrical Grid Sensitivity Analysis (kg $CO_2$ eq per $m^3$ Wastewater Treated)**

## 5.3 Displaced Drinking Water

Based on a literature review of studies reporting energy consumption for drinking water treatment and distribution, it was determined the energy consumption for the displaced drinking water considered in the baseline results is relatively high. Table 5-4 lists reported literature values (in kWh per cubic meter of drinking water delivered) for raw water pumping/treatment at plant and finished water pumping, with the baseline value used in this study from the Cashman et al. (2014) study. While the baseline kWh for treatment is within the range of reported literature values, the baseline kWh for finished water pumping is considered high compared to other reported values. This is likely because of the large scale and hilly terrain of the Cincinnati distribution network. Ranges for electricity consumption by drinking water treatment stage are shown visually in Figure 5-5.

**Table 5-4. Literature Values for Electricity Consumption for Drinking Water Production and Delivery**

| | ***kWh/m³ Drinking Water Delivered*** | | |
|---|---|---|---|
| **Source** | **Raw Water Pumping, Surface Plant/Treatment** | **Finished Water Pumping** | **Total Drinking Water Treatment and Supply** |
| Cincinnati Study (Cashman et al., 2014a) | 0.27 | 0.52 | **0.79** |
| EPRI, 1996 | 0.055 | 0.31 | **0.37** |
| U.S. EPA, 2008 | 0.40 | N/A | **N/A** |
| Energy Center of Wisconsin, 2003 | 0.50 | N/A | **N/A** |
| WaterRF, 2007 | 0.39 | 0.070 | **0.50** |
| U.S. Geological Survey, 2005 | 0.213 | 0.30 | **0.51** |
| Iowa Association of Municipal Utilities, 2002 | 0.63 | 0.10 | **0.73** |
| EPRI/WERF 2013 | N/A | N/A | **0.42** |
| deMonsabert et al., 2008 | 0.37 | 0.26 | **0.63** |
| Maas, 2009 | 0.41 | 0.17 | **0.58** |
| deMonsabert and Liner, 1998 | N/A | N/A | **0.11-0.44** |
| Amores et al., 2013 | 0.55 | 0.29 | **0.85** |
| Lassaux et al., 2007 | 0.21 | 0.18 | **0.39** |
| Burton 1996 (from Arpke and Hutzler 2006) | 0.37 | N/A | **N/A** |
| Jeong et al., 2015 | N/A | N/A | **0.62** |
| Lundie et al., 2004 | 0.086 | 0.28 | **0.37** |

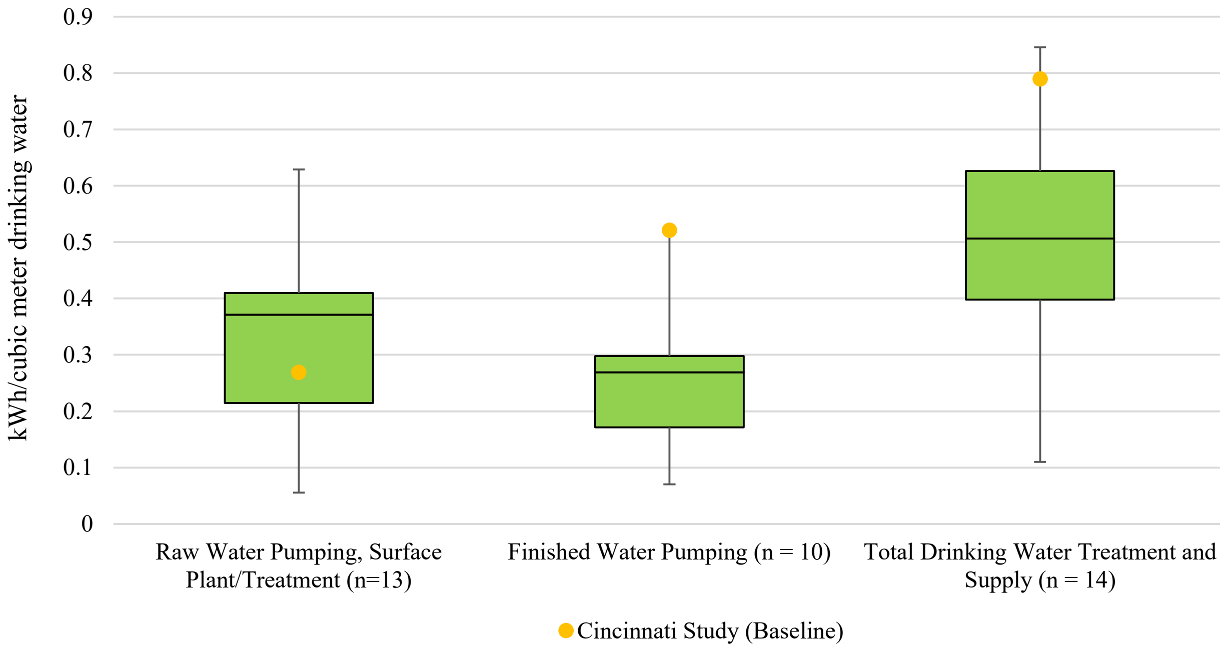


**Figure 5-5. Range of Electricity Consumption Reported in Literature for Drinking Water Treatment Stages**

A sensitivity analysis is conducted for global warming potential results by taking the minimum kWh for total drinking water treatment and supply as well as the maximum from total drinking water treatment and supply (Figure 5-6). For all scenarios, the total GWP savings by displacing drinking water decreases when assuming that less electricity would be required to produce and deliver the drinking water from a centralized plant. While the overall GWP trends for all scenarios do not change in this sensitivity analysis, it is clear the relative GWP benefit of recycling wastewater is dependent on the assumption of energy use for the avoided potable water.

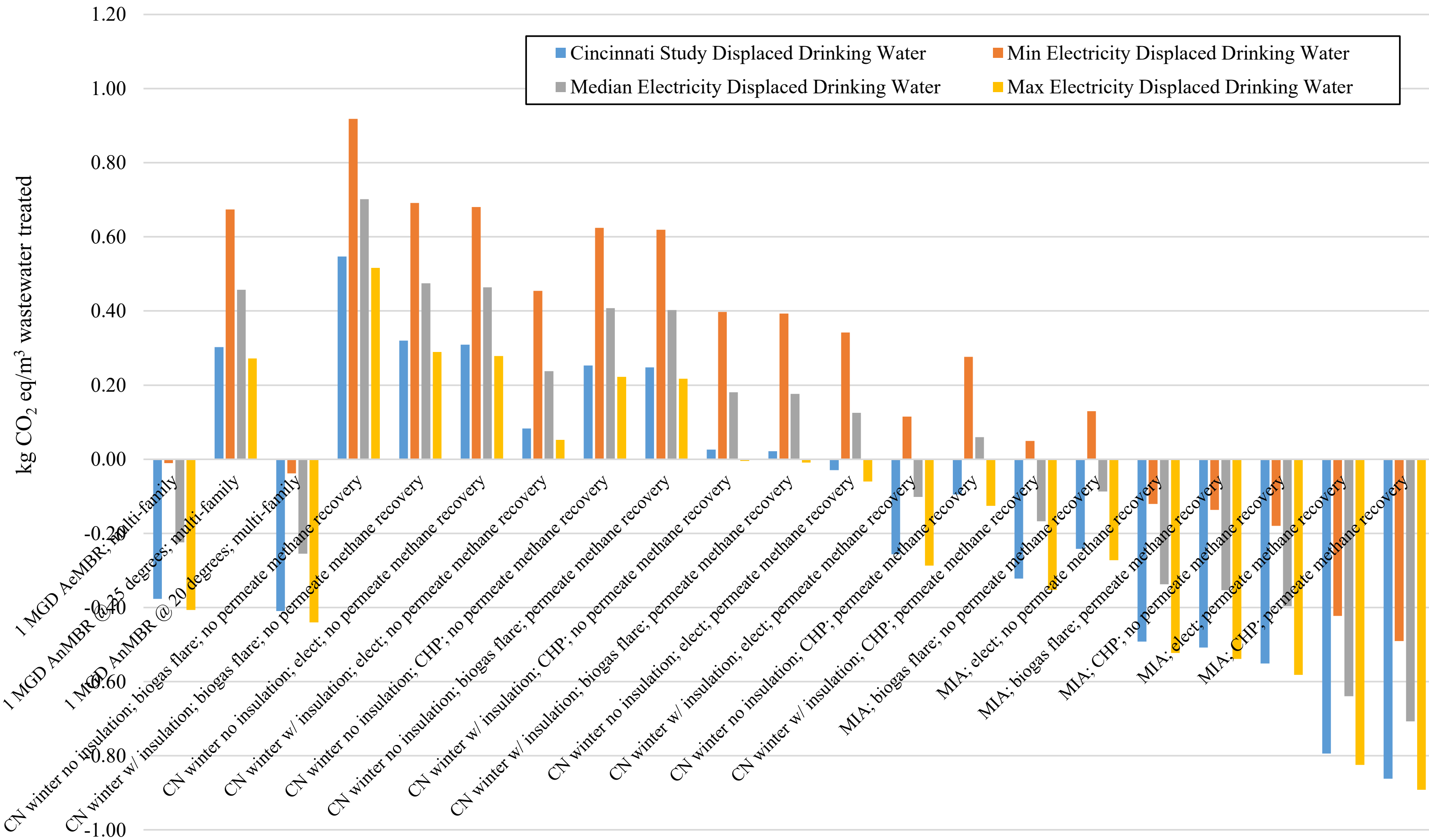


**Figure 5-6. Global Warming Potential Results for Displaced Drinking Water Treatment Sensitivity Analysis for all Considered Scenarios**

# 6.0 CONCLUSIONS AND NEXT STEPS

This report investigated the baseline LCA and cost analysis results for 18 population density and scale scenarios for MBRs. Both AeMBRs and AnMBRs were explored. Additionally, the study examined the operation of AnMBR WWT at 35˚C, representative of a mesophilic AnMBR system, and at 20˚C, representative of a psychrophilic AnMBR system. The results focused on the energy demand and associated greenhouse gases for the scenarios examined. However, a full suite of life cycle impact assessment results was calculated. Net energy benefits, considering the displaced drinking water by the delivered recycled water, started at the 1 MGD scale for the AeMBR and at the 5 MGD scale for the AnMBR operated at 35˚C. For all scales investigated, the AnMBR reactor operated at 20˚C resulted in the most net energy benefits compared to the other investigated systems. This study supports the findings that AnMBRs operated at lower reactor temperatures represent a promising technology for decreasing the environmental impacts of wastewater treatment systems. Potential energy demand and global warming potential benefits of the psychrophilic AnMBR increase when operating in warm climates and when the dissolved methane in the permeate is recovered. When examining the energy demand results normalized to a cubic meter of water treated, all energy demand impacts decrease as the scale increases. While the AnMBR operating at ambient temperature resulted in notable energy and GHG benefits, the AnMBR costs remained higher than the AeMBR under all scenarios. The driver for this was the increased operation and maintenance costs associated with the greater labor infrastructure needs of maintaining the anaerobic reactor relative to the AeMBR. The study found that all impacts decrease comparatively as the population density increases, with the highest burdens realized for the semi-rural single family land use and the lowest overall burdens seen for the high-density urban land use. While this study focused primarily on energy demand and GHG impacts of the decentralized MBR systems, there is a potential significant water savings from using recycled wastewater. This study found that use of recycled water from all decentralized MBR scenarios avoids 0.94 to 0.96 cubic meters of fresh water per cubic meter of wastewater treated by MBR.

The study found that overall energy demand and GHG impacts were sensitive to the assumptions regarding displaced potable water. Since displaced potable water represented a significant net energy and GHG benefit of recycled water production, case specific scenarios may need to be run to understand the relative savings of displacing regional potable water produced at centralized drinking water treatment facilities. This research built a framework model for examining the impact of scale and population density for transitional decentralized MBR wastewater treatment systems. The AnMBR model was investigated under two reactor temperatures. The differential in temperature between the influent and the reactor temperature was shown to play a large role in determining the overall energy and GHG burdens of the system. The climate scenarios investigated for the psychrophilic AnMBR provide further insight into combinations of parameters leading to more optimal results. The optimal scenario investigated from an energy and GHG perspective overall was the psychrophilic AnMBR operated in warm climate (e.g., Miami, FL) with methane recovery via CHP and both headspace and permeate methane recovery.

Overall, the LCA model and cost analysis built here can serve as the basis for future assessments of decentralized water-related technologies. While AeMBRs are largely commercialized at the scales investigated, the data behind the AnMBR model is based on bench-scale and pilot scale systems. As AnMBRs become more commercial, and operational data is better understood, the LCA model presented in this work can be continually improved upon.

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# Appendix A

# Detailed Energy and GWP Baseline Results

# Appendix A – Detailed Energy and GWP Baseline Results

## Detailed Energy Demand Baseline Results

Detailed cumulative energy demand results for all AeMBR scenarios on an annual basis are presented in Table A-1 through Table A-5. These tables show the relative break out of impacts for infrastructure, energy for operation, and chemical consumption. Similar annual energy demand results for AnMBR baseline scenarios (mesophilic and psychrophilic) are provided in Table A-6 through Table A-15.

### Table A-1. Detailed Energy Results for 0.05 MGD AeMBR (MJ/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | ***Water treated per year ($m^3$)*** | *69,130* | *69,130* | *69,130* | *69,130* |
| | | | **0.05 MGD AeMBR [semi rural single family]** | **0.05 MGD AeMBR [single family]** | **0.05 MGD AeMBR [multi family]** | **0.05 MGD AeMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 1,725 | 943 | 230 | 108 |
| | | Pipe installation | 339 | 166 | 45.2 | 21.1 |
| | | Operation | 5,998 | 5,998 | 5,998 | 5,998 |
| Pre Treatment | Preliminary treatment | Operation | 43,819 | 43,819 | 43,819 | 43,819 |
| | | Infrastructure | 0.030 | 0.030 | 0.030 | 0.030 |
| | Fine screening | Operation | 1,095 | 1,095 | 1,095 | 1,095 |
| | | Infrastructure | 0.13 | 0.13 | 0.13 | 0.13 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 603,739 | 603,739 | 603,739 | 603,739 |
| | | Infrastructure | 4,090 | 4,090 | 4,090 | 4,090 |
| | Sludge recycle pumping | Operation | 55,322 | 55,322 | 55,322 | 55,322 |
| | | Infrastructure | 6.65 | 6.65 | 6.65 | 6.65 |
| MBR operation | Scouring | Operation | 73,726 | 73,726 | 73,726 | 73,726 |
| | | Sodium hypochlorite, 15% | 5,723 | 5,723 | 5,723 | 5,723 |
| | Permeate pumping | Operation | 17,199 | 17,199 | 17,199 | 17,199 |
| | | Infrastructure | 6.45 | 6.45 | 6.45 | 6.45 |
| | Waste sludge pumping | Operation | 434 | 434 | 434 | 434 |
| | | Infrastructure | 6.45 | 6.45 | 6.45 | 6.45 |
| MBR | | Infrastructure | 11,101 | 11,101 | 11,101 | 11,101 |
| Post treatment | Chlorination | Operation | 500,775 | 500,775 | 500,775 | 500,775 |
| | | Sodium hypochlorite, 15% | 32,889 | 32,889 | 32,889 | 32,889 |
| | | Infrastructure | 1,312 | 1,312 | 1,312 | 1,312 |
| Recycled water delivery | | Operation | 50,774 | 28,972 | 13,803 | 10,773 |
| | | Pipe infrastructure | 5,751 | 2,820 | 769 | 360 |
| | | Pipe installation | 85.1 | 41.7 | 11.4 | 5.40 |
| | | Displaced drinking water | -842,037 | -842,037 | -842,037 | -842,037 |
| | | ***Net Impact*** | ***573,879*** | ***548,146*** | ***530,063*** | ***526,472*** |

## Table A-2. Detailed Energy Results for 0.1 MGD AeMBR (MJ/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *138,259* | *138,259* | *138,259* | *138,259* |
| | | | **0.1 MGD AeMBR [semi rural single family]** | **0.1 MGD AeMBR [single family]** | **0.1 MGD AeMBR [multi family]** | **0.1 MGD AeMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 3,279 | 1,687 | 460 | 206 |
| | | Pipe installation | 678 | 332 | 90.5 | 63.3 |
| | | Operation | 11,996 | 11,996 | 11,996 | 11,996 |
| Pre Treatment | Preliminary treatment | Operation | 60,361 | 60,361 | 60,361 | 60,361 |
| | | Infrastructure | 0.059 | 0.059 | 0.059 | 0.059 |
| | Fine screening | Operation | 2,191 | 2,191 | 2,191 | 2,191 |
| | | Infrastructure | 0.26 | 0.26 | 0.26 | 0.26 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 759,164 | 759,164 | 759,164 | 759,164 |
| | | Infrastructure | 4,090 | 4,090 | 4,090 | 4,090 |
| | Sludge recycle pumping | Operation | 110,643 | 110,643 | 110,643 | 110,643 |
| | | Infrastructure | 6.81 | 6.81 | 6.81 | 6.81 |
| MBR operation | Scouring | Operation | 147,889 | 147,889 | 147,889 | 147,889 |
| | | Sodium hypochlorite, 15% | 11,145 | 11,145 | 11,145 | 11,145 |
| | Permeate pumping | Operation | 34,390 | 34,390 | 34,390 | 34,390 |
| | | Infrastructure | 6.49 | 6.49 | 6.49 | 6.49 |
| | Waste sludge pumping | Operation | 865 | 865 | 865 | 865 |
| | | Infrastructure | 6.45 | 6.45 | 6.45 | 6.45 |
| MBR | | Infrastructure | 20,801 | 20,801 | 20,801 | 20,801 |
| Post treatment | Chlorination | Operation | 574,884 | 574,884 | 574,884 | 574,884 |
| | | Sodium hypochlorite, 15% | 65,789 | 65,789 | 65,789 | 65,789 |
| | | Infrastructure | 1,329 | 1,329 | 1,329 | 1,329 |
| Recycled water delivery | | Operation | 93,417 | 49,823 | 19,497 | 13,427 |
| | | Pipe infrastructure | 11,523 | 5,631 | 1,533 | 716 |
| | | Pipe installation | 171 | 83.2 | 22.7 | 10.5 |
| | | Displaced drinking water | -1,684,070 | -1,684,070 | -1,684,070 | -1,684,070 |
| | | ***Net Impact*** | ***230,555*** | ***179,043*** | ***143,090*** | ***135,909*** |

## Table A-3. Detailed Energy Results for 1 MGD AeMBR (MJ/Year)

| | | ***Water treated per year (m3)*** | *1,382,591* | *1,382,591* | *1,382,591* | *1,382,591* |
|---|---|---|---|---|---|---|
| | | | **1 MGD AeMBR [semi rural single family]** | **1 MGD AeMBR [single family]** | **1 MGD AeMBR [multi family]** | **1 MGD AeMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 34,504 | 16,869 | 4,601 | 2,147 |
| | | Pipe installation | 6,785 | 3,317 | 905 | 485 |
| | | Operation | 119,955 | 119,955 | 119,955 | 119,955 |
| Pre Treatment | Preliminary treatment | Operation | 175,276 | 175,276 | 175,276 | 175,276 |
| | | Infrastructure | 0.59 | 0.59 | 0.59 | 0.59 |
| | Fine screening | Operation | 22,676 | 22,676 | 22,676 | 22,676 |
| | | Infrastructure | 2.63 | 2.63 | 2.63 | 2.63 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 3,034,470 | 3,034,470 | 3,034,470 | 3,034,470 |
| | | Infrastructure | 5,537 | 5,537 | 5,537 | 5,537 |
| | Sludge recycle pumping | Operation | 1,095,480 | 1,095,480 | 1,095,480 | 1,095,480 |
| | | Infrastructure | 10.3 | 10.3 | 10.3 | 10.3 |
| MBR operation | Scouring | Operation | 1,478,890 | 1,478,890 | 1,478,890 | 1,478,890 |
| | | Sodium hypochlorite, 15% | 109,359 | 109,359 | 109,359 | 109,359 |
| | Permeate pumping | Operation | 341,788 | 341,788 | 341,788 | 341,788 |
| | | Infrastructure | 6.77 | 6.77 | 6.77 | 6.77 |
| | Waste sludge pumping | Operation | 8,610 | 8,610 | 8,610 | 8,610 |
| | | Infrastructure | 6.45 | 6.45 | 6.45 | 6.45 |
| MBR | | Infrastructure | 192,694 | 192,694 | 192,694 | 192,694 |
| Post treatment | Chlorination | Operation | 909,245 | 909,245 | 909,245 | 909,245 |
| | | Sodium hypochlorite, 15% | 1,568,860 | 1,568,860 | 1,568,860 | 1,568,860 |
| | | Infrastructure | 1,719 | 1,719 | 1,719 | 1,719 |
| Recycled water delivery | | Operation | 861,124 | 498,231 | 121,853 | 61,200 |
| | | Pipe infrastructure | 115,305 | 56,414 | 15,196 | 7,172 |
| | | Pipe installation | 1,706 | 832 | 227 | 107 |
| | | Displaced drinking water | -16,840,700 | -16,840,700 | -16,840,700 | -16,840,700 |
| | | ***Net Impact*** | ***-6,756,690*** | ***-7,200,452*** | ***-7,633,332*** | ***-7,705,003*** |

## Table A-4. Detailed Energy Results for 5 MGD AeMBR (MJ/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *6,912,954* | *6,912,954* | *6,912,954* |
| | | | 5 MGD AeMBR [single family] | 5 MGD AeMBR [multi family] | 5 MGD AeMBR [high density urban] |
| Wastewater collection | | Pipe infrastructure | 70,901 | 23,003 | 10,735 |
| | | Pipe installation | 16,585 | 4,523 | 2,596 |
| | | Operation | 599,775 | 599,775 | 599,775 |
| Pre Treatment | Preliminary treatment | Operation | 369,175 | 369,175 | 369,175 |
| | | Infrastructure | 2.98 | 2.98 | 2.98 |
| | Fine screening | Operation | 113,491 | 113,491 | 113,491 |
| | | Infrastructure | 13.1 | 13.1 | 13.1 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 15,227,100 | 15,227,100 | 15,227,100 |
| | | Infrastructure | 36,334 | 36,334 | 36,334 |
| | Sludge recycle pumping | Operation | 5,466,420 | 5,466,420 | 5,466,420 |
| | | Infrastructure | 25.5 | 25.5 | 25.5 |
| MBR operation | Scouring | Operation | 6,550,940 | 6,550,940 | 6,550,940 |
| | | Sodium hypochlorite, 15% | 486,542 | 486,542 | 486,542 |
| | Permeate pumping | Operation | 1,708,940 | 1,708,940 | 1,708,940 |
| | | Infrastructure | 7.58 | 7.58 | 7.58 |
| | Waste sludge pumping | Operation | 42,833 | 42,833 | 42,833 |
| | | Infrastructure | 6.53 | 6.53 | 6.53 |
| MBR | | Infrastructure | 859,360 | 859,360 | 859,360 |
| Post treatment | Chlorination | Operation | 1,252,700 | 1,252,700 | 1,252,700 |
| | | Sodium hypochlorite, 15% | 3,289,350 | 3,289,350 | 3,289,350 |
| | | Infrastructure | 3,419 | 3,419 | 3,419 |
| Recycled water delivery | | Operation | 2,093,230 | 576,786 | 273,497 |
| | | Pipe infrastructure | 281,726 | 76,865 | 35,861 |
| | | Pipe installation | 4,165 | 1,135 | 530 |
| | | Displaced drinking water | -84,203,700 | -84,203,700 | -84,203,700 |
| | | ***Net Impact*** | ***-45,730,658*** | ***-47,514,952*** | ***-47,874,045*** |

## Table A-5. Detailed Energy Results for 10 MGD AeMBR (MJ/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *13,825,907* | *13,825,907* | *13,825,907* |
| | | | 10 MGD AeMBR [single family] | 10 MGD AeMBR [multi family] | 10 MGD AeMBR [high density urban] |
| Wastewater collection | | Pipe infrastructure | 168,686 | 44,761 | 21,469 |
| | | Pipe installation | 33,170 | 13,569 | 6,818 |
| | | Operation | 1,199,550 | 1,199,550 | 1,199,550 |
| Pre Treatment | Preliminary treatment | Operation | 509,396 | 509,396 | 509,396 |
| | | Infrastructure | 5.94 | 5.94 | 5.94 |
| | Fine screening | Operation | 226,983 | 226,983 | 226,983 |
| | | Infrastructure | 26.3 | 26.3 | 26.3 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 28,811,000 | 28,811,000 | 28,811,000 |
| | | Infrastructure | 46,094 | 46,094 | 46,094 |
| | Sludge recycle pumping | Operation | 10,921,900 | 10,921,900 | 10,921,900 |
| | | Infrastructure | 44.8 | 44.8 | 44.8 |
| MBR operation | Scouring | Operation | 13,145,700 | 13,145,700 | 13,145,700 |
| | | Sodium hypochlorite, 15% | 970,878 | 970,878 | 970,878 |
| | Permeate pumping | Operation | 3,406,930 | 3,406,930 | 3,406,930 |
| | | Infrastructure | 8.75 | 8.75 | 8.75 |
| | Waste sludge pumping | Operation | 85,557 | 85,557 | 85,557 |
| | | Infrastructure | 6.61 | 6.61 | 6.61 |
| MBR | | Infrastructure | 1,705,070 | 1,705,070 | 1,705,070 |
| Post treatment | Chlorination | Operation | 1,435,070 | 1,435,070 | 1,435,070 |
| | | Sodium hypochlorite, 15% | 6,578,710 | 6,578,710 | 6,578,710 |
| | | Infrastructure | 5,543 | 5,543 | 5,543 |
| Recycled water delivery | | Operation | 4,178,340 | 1,145,450 | 538,875 |
| | | Pipe infrastructure | 563,936 | 153,616 | 71,723 |
| | | Pipe installation | 8,317 | 2,272 | 1,059 |
| | | Displaced drinking water | -168,407,000 | -168,407,000 | -168,407,000 |
| | | ***Net Impact*** | ***-94,406,078*** | ***-97,998,858*** | ***-98,718,583*** |

## Table A-6. Detailed Energy Results for 0.05 MGD AnMBR, 35˚C Reactor Temperature (MJ/Year)

| | | | 0.05 MGD AnMBR [semi rural single family] | 0.05 MGD AnMBR [single family] | 0.05 MGD AnMBR [multi family] | 0.05 MGD AnMBR [high density urban] |
|---|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *69,130* | *69,130* | *69,130* | *69,130* |
| Wastewater collection | | Pipe infrastructure | 1,725 | 943 | 230 | 108 |
| | | Pipe installation | 339 | 166 | 45.2 | 21.1 |
| | | Operation | 5,998 | 5,998 | 5,998 | 5,998 |
| Pre Treatment | Preliminary treatment | Operation | 43,819 | 43,819 | 43,819 | 43,819 |
| | | Infrastructure | 0.030 | 0.030 | 0.030 | 0.030 |
| | Fine screening | Operation | 1,095 | 1,095 | 1,095 | 1,095 |
| | | Infrastructure | 0.13 | 0.13 | 0.13 | 0.13 |
| MBR operation | | Heating of influent | 4,416,950 | 4,416,950 | 4,416,950 | 4,416,950 |
| | | MBR pump | 11,221 | 11,221 | 11,221 | 11,221 |
| | | Heat loss control | 13,476 | 13,476 | 13,476 | 13,476 |
| | | Recovery of methane | -279,690 | -279,690 | -279,690 | -279,690 |
| | | Effluent pumping out | 38,089 | 38,089 | 38,089 | 38,089 |
| | | Heat recovery from discharge water | -3,478,530 | -3,478,530 | -3,478,530 | -3,478,530 |
| | | Biogas recirculation pump | 1,748 | 1,748 | 1,748 | 1,748 |
| | | Sodium hypochlorite, 15% | 19,701 | 19,701 | 19,701 | 19,701 |
| MBR | | Infrastructure | 26,758 | 26,758 | 26,758 | 26,758 |
| Post treatment | Chlorination | Operation | 500,775 | 500,775 | 500,775 | 500,775 |
| | | Sodium hypochlorite, 15% | 32,889 | 32,889 | 32,889 | 32,889 |
| | | Infrastructure | 1,312 | 1,312 | 1,312 | 1,312 |
| Recycled water delivery | | Operation | 50,774 | 28,972 | 13,803 | 10,773 |
| | | Pipe infrastructure | 5,751 | 2,820 | 769 | 360 |
| | | Pipe installation | 85.1 | 41.7 | 11.4 | 5.40 |
| | | Displaced drinking water | -851,088 | -851,088 | -851,088 | -851,088 |
| | | ***Net Impact*** | ***563,197*** | ***537,464*** | ***519,380*** | ***515,790*** |

## Table A-7. Detailed Energy Results for 0.1 MGD AnMBR, 35˚C Reactor Temperature (MJ/Year)

| | | | 0.1 MGD AnMBR [semi rural single family] | 0.1 MGD AnMBR [single family] | 0.1 MGD AnMBR [multi family] | 0.1 MGD AnMBR [high density urban] |
|---|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *138,259* | *138,259* | *138,259* | *138,259* |
| Wastewater collection | | Pipe infrastructure | 3,279 | 1,687 | 460 | 206 |
| | | Pipe installation | 678 | 332 | 90.5 | 63.3 |
| | | Operation | 11,996 | 11,996 | 11,996 | 11,996 |
| Pre Treatment | Preliminary treatment | Operation | 60,361 | 60,361 | 60,361 | 60,361 |
| | | Infrastructure | 0.059 | 0.059 | 0.059 | 0.059 |
| | Fine screening | Operation | 2,191 | 2,191 | 2,191 | 2,191 |
| | | Infrastructure | 0.26 | 0.26 | 0.26 | 0.26 |
| MBR operation | | Heating of influent | 8,833,900 | 8,833,900 | 8,833,900 | 8,833,900 |
| | | MBR pump | 22,441 | 22,441 | 22,441 | 22,441 |
| | | Heat loss control | 19,228 | 19,228 | 19,228 | 19,228 |
| | | Recovery of methane | -559,379 | -559,379 | -559,379 | -559,379 |
| | | Effluent pumping out | 76,171 | 76,171 | 76,171 | 76,171 |
| | | Heat recovery from discharge water | -6,957,060 | -6,957,060 | -6,957,060 | -6,957,060 |
| | | Biogas recirculation pump | 3,495 | 3,495 | 3,495 | 3,495 |
| | | Sodium hypochlorite, 15% | 39,413 | 39,413 | 39,413 | 39,413 |
| MBR | | Infrastructure | 27,497 | 27,497 | 27,497 | 27,497 |
| Post treatment | Chlorination | Operation | 574,884 | 574,884 | 574,884 | 574,884 |
| | | Sodium hypochlorite, 15% | 65,789 | 65,789 | 65,789 | 65,789 |
| | | Infrastructure | 1,329 | 1,329 | 1,329 | 1,329 |
| Recycled water delivery | | Operation | 93,417 | 49,823 | 19,497 | 13,427 |
| | | Pipe infrastructure | 11,523 | 5,631 | 1,533 | 716 |
| | | Pipe installation | 171 | 83.2 | 22.7 | 10.5 |
| | | Displaced drinking water | -1,703,660 | -1,703,660 | -1,703,660 | -1,703,660 |
| | | ***Net Impact*** | ***627,664*** | ***576,152*** | ***540,199*** | ***533,019*** |

# Table A-8. Detailed Energy Results for 1 MGD AnMBR, 35˚C Reactor Temperature (MJ/Year)

| | | ***Water treated per year (m3)*** | *1,382,591* | *1,382,591* | *1,382,591* |
|---|---|---|---|---|---|
| | | | 1 MGD AnMBR [semi rural single family] | 1 MGD AnMBR [single family] | 1 MGD AnMBR [multi family] |
| Wastewater collection | | Pipe infrastructure | 34,504 | 16,869 | 4,601 |
| | | Pipe installation | 6,785 | 3,317 | 905 |
| | | Operation | 119,955 | 119,955 | 119,955 |
| Pre Treatment | Preliminary treatment | Operation | 175,276 | 175,276 | 175,276 |
| | | Infrastructure | 0.59 | 0.59 | 0.59 |
| | Fine screening | Operation | 22,676 | 22,676 | 22,676 |
| | | Infrastructure | 2.63 | 2.63 | 2.63 |
| MBR operation | | Heating of influent | 88,339,000 | 88,339,000 | 88,339,000 |
| | | MBR pump | 224,412 | 224,412 | 224,412 |
| | | Heat loss control | 68,568 | 68,568 | 68,568 |
| | | Recovery of methane | -5,593,790 | -5,593,790 | -5,593,790 |
| | | Effluent pumping out | 761,649 | 761,649 | 761,649 |
| | | Heat recovery from discharge water | -69,570,600 | -69,570,600 | -69,570,600 |
| | | Biogas recirculation pump | 34,952 | 34,952 | 34,952 |
| | | Sodium hypochlorite, 15% | 291,739 | 291,739 | 291,739 |
| MBR | | Infrastructure | 518,521 | 518,521 | 518,521 |
| Post treatment | Chlorination | Operation | 909,245 | 909,245 | 909,245 |
| | | Sodium hypochlorite, 15% | 1,568,860 | 1,568,860 | 1,568,860 |
| | | Infrastructure | 1,719 | 1,719 | 1,719 |
| Recycled water delivery | | Operation | 861,124 | 498,231 | 121,853 |
| | | Pipe infrastructure | 115,305 | 56,414 | 15,196 |
| | | Pipe installation | 1,706 | 832 | 227 |
| | | Displaced drinking water | -17,095,900 | -17,095,900 | -17,095,900 |
| | | ***Net Impact*** | ***1,795,710*** | ***1,351,948*** | ***919,068*** |

## Table A-9. Detailed Energy Results for 5 MGD AnMBR, 35˚C Reactor Temperature (MJ/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *6,912,954* | *6,912,954* | *6,912,954* |
| | | | 5 MGD AnMBR [single family] | 5 MGD AnMBR [multi family] | 5 MGD AnMBR [high density urban] |
| Wastewater collection | | Pipe infrastructure | 70,901 | 23,003 | 10,735 |
| | | Pipe installation | 16,585 | 4,523 | 2,596 |
| | | Operation | 599,775 | 599,775 | 599,775 |
| Pre Treatment | Preliminary treatment | Operation | 369,175 | 369,175 | 369,175 |
| | | Infrastructure | 2.98 | 2.98 | 2.98 |
| | Fine screening | Operation | 113,491 | 113,491 | 113,491 |
| | | Infrastructure | 13.1 | 13.1 | 13.1 |
| MBR operation | | Heating of influent | 441,695,000 | 441,695,000 | 441,695,000 |
| | | MBR pump | 1,122,060 | 1,122,060 | 1,122,060 |
| | | Heat loss control | 233,580 | 233,580 | 233,580 |
| | | Recovery of methane | -27,969,000 | -27,969,000 | -27,969,000 |
| | | Effluent pumping out | 3,808,220 | 3,808,220 | 3,808,220 |
| | | Heat recovery from discharge water | -347,853,000 | -347,853,000 | -347,853,000 |
| | | Biogas recirculation pump | 174,760 | 174,760 | 174,760 |
| | | Sodium hypochlorite, 15% | 1,215,600 | 1,215,600 | 1,215,600 |
| MBR | | Infrastructure | 2,160,855 | 2,160,855 | 2,160,855 |
| Post treatment | Chlorination | Operation | 1,252,700 | 1,252,700 | 1,252,700 |
| | | Sodium hypochlorite, 15% | 3,289,350 | 3,289,350 | 3,289,350 |
| | | Infrastructure | 3,419 | 3,419 | 3,419 |
| Recycled water delivery | | Operation | 2,093,230 | 576,786 | 273,497 |
| | | Pipe infrastructure | 281,726 | 76,865 | 35,861 |
| | | Pipe installation | 4,165 | 1,135 | 530 |
| | | Displaced drinking water | -85,565,700 | -85,565,700 | -85,565,700 |
| | | ***Net Impact*** | ***-2,883,092*** | ***-4,667,387*** | ***-5,026,480*** |

## Table A-10. Detailed Energy Results for 10 MGD AnMBR, 35˚C Reactor Temperature (MJ/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *13,825,907* | *13,825,907* | *13,825,907* |
| | | | **10 MGD AnMBR [single family]** | **10 MGD AnMBR [multi family]** | **10 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 168,686 | 44,761 | 21,469 |
| | | Pipe installation | 33,170 | 13,569 | 6,818 |
| | | Operation | 1,199,550 | 1,199,550 | 1,199,550 |
| Pre Treatment | Preliminary treatment | Operation | 509,396 | 509,396 | 509,396 |
| | | Infrastructure | 5.94 | 5.94 | 5.94 |
| | Fine screening | Operation | 226,983 | 226,983 | 226,983 |
| | | Infrastructure | 26.3 | 26.3 | 26.3 |
| MBR operation | | Heating of influent | 883,390,000 | 883,390,000 | 883,390,000 |
| | | MBR pump | 2,244,120 | 2,244,120 | 2,244,120 |
| | | Heat loss control | 399,243 | 399,243 | 399,243 |
| | | Recovery of methane | -55,937,900 | -55,937,900 | -55,937,900 |
| | | Effluent pumping out | 7,616,430 | 7,616,430 | 7,616,430 |
| | | Heat recovery from discharge water | -695,706,000 | -695,706,000 | -695,706,000 |
| | | Biogas recirculation pump | 349,522 | 349,522 | 349,522 |
| | | Sodium hypochlorite, 15% | 2,188,000 | 2,188,000 | 2,188,000 |
| MBR | | Infrastructure | 3,888,905 | 3,888,905 | 3,888,905 |
| Post treatment | Chlorination | Operation | 1,435,070 | 1,435,070 | 1,435,070 |
| | | Sodium hypochlorite, 15% | 6,578,710 | 6,578,710 | 6,578,710 |
| | | Infrastructure | 5,543 | 5,543 | 5,543 |
| Recycled water delivery | | Operation | 4,178,340 | 1,145,450 | 538,875 |
| | | Pipe infrastructure | 563,936 | 153,616 | 71,723 |
| | | Pipe installation | 8,317 | 2,272 | 1,059 |
| | | Displaced drinking water | -171,080,000 | -171,080,000 | -171,080,000 |
| | | ***Net Impact*** | ***-7,739,946*** | ***-11,332,727*** | ***-12,052,451*** |

## Table A-11. Detailed Energy Results for 0.05 MGD AnMBR, 20˚C Reactor Temperature (MJ/Year)

| | | *Water treated per year (m3)* | *69,130* | *69,130* | *69,130* | *69,130* |
|---|---|---|---|---|---|---|
| | | | **0.05 MGD AnMBR [semi rural single family]** | **0.05 MGD AnMBR [single family]** | **0.05 MGD AnMBR [multi family]** | **0.05 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 1,725 | 943 | 230 | 108 |
| | | Pipe installation | 339 | 166 | 45.2 | 21.1 |
| | | Operation | 5,998 | 5,998 | 5,998 | 5,998 |
| Pre Treatment | Preliminary treatment | Operation | 43,819 | 43,819 | 43,819 | 43,819 |
| | | Infrastructure | 0.030 | 0.030 | 0.030 | 0.030 |
| | Fine screening | Operation | 1,095 | 1,095 | 1,095 | 1,095 |
| | | Infrastructure | 0.13 | 0.13 | 0.13 | 0.13 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 11,221 | 11,221 | 11,221 | 11,221 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -251,125 | -251,125 | -251,125 | -251,125 |
| | | Effluent pumping out | 38,089 | 38,089 | 38,089 | 38,089 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 1,748 | 1,748 | 1,748 | 1,748 |
| | | Sodium hypochlorite, 15% | 19,701 | 19,701 | 19,701 | 19,701 |
| MBR | | Infrastructure | 26,758 | 26,758 | 26,758 | 26,758 |
| Post treatment | Chlorination | Operation | 500,775 | 500,775 | 500,775 | 500,775 |
| | | Sodium hypochlorite, 15% | 32,889 | 32,889 | 32,889 | 32,889 |
| | | Infrastructure | 1,312 | 1,312 | 1,312 | 1,312 |
| Recycled water delivery | | Operation | 50,774 | 28,972 | 13,803 | 10,773 |
| | | Pipe infrastructure | 5,751 | 2,820 | 769 | 360 |
| | | Pipe installation | 85.1 | 41.7 | 11.4 | 5.40 |
| | | Displaced drinking water | -851,088 | -851,088 | -851,088 | -851,088 |
| | | ***Net Impact*** | ***-360,134*** | ***-385,867*** | ***-403,951*** | ***-407,542*** |

# Table A-12. Detailed Energy Results for 0.1 MGD AnMBR, 20˚C Reactor Temperature (MJ/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *138,259* | *138,259* | *138,259* | *138,259* |
| | | | **0.1 MGD AnMBR [semi rural single family]** | **0.1 MGD AnMBR [single family]** | **0.1 MGD AnMBR [multi family]** | **0.1 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 3,279 | 1,687 | 460 | 206 |
| | | Pipe installation | 678 | 332 | 90.5 | 63.3 |
| | | Operation | 11,996 | 11,996 | 11,996 | 11,996 |
| Pre Treatment | Preliminary treatment | Operation | 60,361 | 60,361 | 60,361 | 60,361 |
| | | Infrastructure | 0.059 | 0.059 | 0.059 | 0.059 |
| | Fine screening | Operation | 2,191 | 2,191 | 2,191 | 2,191 |
| | | Infrastructure | 0.26 | 0.26 | 0.26 | 0.26 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 22,441 | 22,441 | 22,441 | 22,441 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -502,249 | -502,249 | -502,249 | -502,249 |
| | | Effluent pumping out | 76,171 | 76,171 | 76,171 | 76,171 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 3,495 | 3,495 | 3,495 | 3,495 |
| | | Sodium hypochlorite, 15% | 39,413 | 39,413 | 39,413 | 39,413 |
| MBR | | Infrastructure | 27,497 | 27,497 | 27,497 | 27,497 |
| Post treatment | Chlorination | Operation | 574,884 | 574,884 | 574,884 | 574,884 |
| | | Sodium hypochlorite, 15% | 65,789 | 65,789 | 65,789 | 65,789 |
| | | Infrastructure | 1,329 | 1,329 | 1,329 | 1,329 |
| Recycled water delivery | | Operation | 93,417 | 49,823 | 19,497 | 13,427 |
| | | Pipe infrastructure | 11,523 | 5,631 | 1,533 | 716 |
| | | Pipe installation | 171 | 83.2 | 22.7 | 10.5 |
| | | Displaced drinking water | -1,703,660 | -1,703,660 | -1,703,660 | -1,703,660 |
| | | ***Net Impact*** | ***-1,211,274*** | ***-1,262,786*** | ***-1,298,739*** | ***-1,305,920*** |

## Table A-13. Detailed Energy Results for 1 MGD AnMBR, 20˚C Reactor Temperature (MJ/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | *1,382,591* | *1,382,591* | *1,382,591* | *1,382,591* |
| | | | **1 MGD AnMBR [semi rural single family]** | **1 MGD AnMBR [single family]** | **1 MGD AnMBR [multi family]** | **1 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 34,504 | 16,869 | 4,601 | 2,147 |
| | | Pipe installation | 6,785 | 3,317 | 905 | 485 |
| | | Operation | 119,955 | 119,955 | 119,955 | 119,955 |
| Pre Treatment | Preliminary treatment | Operation | 175,276 | 175,276 | 175,276 | 175,276 |
| | | Infrastructure | 0.59 | 0.59 | 0.59 | 0.59 |
| | Fine screening | Operation | 22,676 | 22,676 | 22,676 | 22,676 |
| | | Infrastructure | 2.63 | 2.63 | 2.63 | 2.63 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 224,412 | 224,412 | 224,412 | 224,412 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -5,022,490 | -5,022,490 | -5,022,490 | -5,022,490 |
| | | Effluent pumping out | 761,649 | 761,649 | 761,649 | 761,649 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 34,952 | 34,952 | 34,952 | 34,952 |
| | | Sodium hypochlorite, 15% | 291,739 | 291,739 | 291,739 | 291,739 |
| MBR | | Infrastructure | 518,521 | 518,521 | 518,521 | 518,521 |
| Post treatment | Chlorination | Operation | 909,245 | 909,245 | 909,245 | 909,245 |
| | | Sodium hypochlorite, 15% | 1,568,860 | 1,568,860 | 1,568,860 | 1,568,860 |
| | | Infrastructure | 1,719 | 1,719 | 1,719 | 1,719 |
| Recycled water delivery | | Operation | 861,124 | 498,231 | 121,853 | 61,200 |
| | | Pipe infrastructure | 115,305 | 56,414 | 15,196 | 7,172 |
| | | Pipe installation | 1,706 | 832 | 227 | 107 |
| | | Displaced drinking water | -17,095,900 | -17,095,900 | -17,095,900 | -17,095,900 |
| | | ***Net Impact*** | ***-16,469,959*** | ***-16,913,720*** | ***-17,346,601*** | ***-17,418,271*** |

## Table A-14. Detailed Energy Results for 5 MGD AnMBR, 20˚C Reactor Temperature (MJ/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | ***Water treated per year (m3)*** | *6,912,954* | *6,912,954* | *6,912,954* |
| | | | **5 MGD AnMBR [single family]** | **5 MGD AnMBR [multi family]** | **5 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 70,901 | 23,003 | 10,735 |
| | | Pipe installation | 16,585 | 4,523 | 2,596 |
| | | Operation | 599,775 | 599,775 | 599,775 |
| Pre Treatment | Preliminary treatment | Operation | 369,175 | 369,175 | 369,175 |
| | | Infrastructure | 2.98 | 2.98 | 2.98 |
| | Fine screening | Operation | 113,491 | 113,491 | 113,491 |
| | | Infrastructure | 13.1 | 13.1 | 13.1 |
| MBR operation | | Heating of influent | 0 | 0 | 0 |
| | | MBR pump | 1,122,060 | 1,122,060 | 1,122,060 |
| | | Heat loss control | 0 | 0 | 0 |
| | | Recovery of methane | -25,112,500 | -25,112,500 | -25,112,500 |
| | | Effluent pumping out | 3,808,220 | 3,808,220 | 3,808,220 |
| | | Heat recovery from discharge water | 0 | 0 | 0 |
| | | Biogas recirculation pump | 174,760 | 174,760 | 174,760 |
| | | Sodium hypochlorite, 15% | 1,215,600 | 1,215,600 | 1,215,600 |
| MBR | | Infrastructure | 2,160,855 | 2,160,855 | 2,160,855 |
| Post treatment | Chlorination | Operation | 1,252,700 | 1,252,700 | 1,252,700 |
| | | Sodium hypochlorite, 15% | 3,289,350 | 3,289,350 | 3,289,350 |
| | | Infrastructure | 3,419 | 3,419 | 3,419 |
| Recycled water delivery | | Operation | 2,093,230 | 576,786 | 273,497 |
| | | Pipe infrastructure | 281,726 | 76,865 | 35,861 |
| | | Pipe installation | 4,165 | 1,135 | 530 |
| | | Displaced drinking water | -85,565,700 | -85,565,700 | -85,565,700 |
| | | ***Net Impact*** | ***-94,102,172*** | ***-95,886,467*** | ***-96,245,560*** |

**Table A-15. Detailed Energy Results for 10 MGD AnMBR, 20˚C Reactor Temperature (MJ/Year)**

| | | | | | |
|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | *13,825,907* | *13,825,907* | *13,825,907* |
| | | | **10 MGD AnMBR [single family]** | **10 MGD AnMBR [multi family]** | **10 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 168,686 | 44,761 | 21,469 |
| | | Pipe installation | 33,170 | 13,569 | 6,818 |
| | | Operation | 1,199,550 | 1,199,550 | 1,199,550 |
| Pre Treatment | Preliminary treatment | Operation | 509,396 | 509,396 | 509,396 |
| | | Infrastructure | 5.94 | 5.94 | 5.94 |
| | Fine screening | Operation | 226,983 | 226,983 | 226,983 |
| | | Infrastructure | 26.3 | 26.3 | 26.3 |
| MBR operation | | Heating of influent | 0 | 0 | 0 |
| | | MBR pump | 2,244,120 | 2,244,120 | 2,244,120 |
| | | Heat loss control | 0 | 0 | 0 |
| | | Recovery of methane | -50,224,900 | -50,224,900 | -50,224,900 |
| | | Effluent pumping out | 7,616,430 | 7,616,430 | 7,616,430 |
| | | Heat recovery from discharge water | 0 | 0 | 0 |
| | | Biogas recirculation pump | 349,522 | 349,522 | 349,522 |
| | | Sodium hypochlorite, 15% | 2,188,000 | 2,188,000 | 2,188,000 |
| MBR | | Infrastructure | 3,888,905 | 3,888,905 | 3,888,905 |
| Post treatment | Chlorination | Operation | 1,435,070 | 1,435,070 | 1,435,070 |
| | | Sodium hypochlorite, 15% | 6,578,710 | 6,578,710 | 6,578,710 |
| | | Infrastructure | 5,543 | 5,543 | 5,543 |
| Recycled water delivery | | Operation | 4,178,340 | 1,145,450 | 538,875 |
| | | Pipe infrastructure | 563,936 | 153,616 | 71,723 |
| | | Pipe installation | 8,317 | 2,272 | 1,059 |
| | | Displaced drinking water | -171,080,000 | -171,080,000 | -171,080,000 |
| | | ***Net Impact*** | ***-190,110,189*** | ***-193,702,970*** | ***-194,422,694*** |

## Detailed Global Warming Potential Baseline Results

Detailed global warming potential results for all AeMBR scenarios on an annual basis are presented in Table A-16 through Table A-20. Similar annual global warming potential results for AnMBR baseline scenarios (mesophilic and psychrophilic) are provided in Table A-21 through Table A-30.

# Table A-16. Detailed Global Warming Potential Results for 0.05 MGD AeMBR (kg CO2 eq/Year)

| | | | 0.05 MGD AeMBR [semi rural single family] | 0.05 MGD AeMBR [single family] | 0.05 MGD AeMBR [multi family] | 0.05 MGD AeMBR [high density urban] |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 69,130 | 69,130 | 69,130 | 69,130 |
| Wastewater collection | | Pipe infrastructure | 229 | 116 | 30.5 | 14.4 |
| | | Pipe installation | 22.3 | 10.9 | 2.98 | 1.39 |
| | | Operation | 925 | 925 | 925 | 925 |
| Pre Treatment | Preliminary treatment | Operation | 2,735 | 2,735 | 2,735 | 2,735 |
| | | Infrastructure | 0.0020 | 0.0020 | 0.0020 | 0.0020 |
| | Fine screening | Operation | 68.4 | 68.4 | 68.4 | 68.4 |
| | | Infrastructure | 0.0087 | 0.0087 | 0.0087 | 0.0087 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 37,679 | 37,679 | 37,679 | 37,679 |
| | | Infrastructure | 748 | 748 | 748 | 748 |
| | Sludge recycle pumping | Operation | 3,453 | 3,453 | 3,453 | 3,453 |
| | | Infrastructure | 0.44 | 0.44 | 0.44 | 0.44 |
| MBR operation | Scouring | Operation | 4,601 | 4,601 | 4,601 | 4,601 |
| | | Sodium hypochlorite, 15% | 291 | 291 | 291 | 291 |
| | Permeate pumping | Operation | 1,073 | 1,073 | 1,073 | 1,073 |
| | | Infrastructure | 0.42 | 0.42 | 0.42 | 0.42 |
| | Waste sludge pumping | Operation | 27.1 | 27.1 | 27.1 | 27.1 |
| | | Infrastructure | 0.42 | 0.42 | 0.42 | 0.42 |
| MBR | | Infrastructure | 1,055 | 1,055 | 1,055 | 1,055 |
| Post treatment | Chlorination | Operation | 31,253 | 31,253 | 31,253 | 31,253 |
| | | Sodium hypochlorite, 15% | 1,671 | 1,671 | 1,671 | 1,671 |
| | | Infrastructure | 242 | 242 | 242 | 242 |
| Recycled water delivery | | Operation | 3,151 | 1,798 | 857 | 669 |
| | | Pipe infrastructure | 301 | 148 | 40.2 | 18.8 |
| | | Pipe installation | 5.60 | 2.75 | 0.75 | 0.36 |
| | | Displaced drinking water | -52,299 | -52,299 | -52,299 | -52,299 |
| | | ***Net Impact*** | ***37,230*** | ***35,597*** | ***34,453*** | ***34,225*** |

## Table A-17. Detailed Global Warming Potential Results for 0.1 MGD AeMBR (kg CO2 eq/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 138,259 | 138,259 | 138,259 | 138,259 |
| | | | **0.1 MGD AeMBR [semi rural single family]** | **0.1 MGD AeMBR [single family]** | **0.1 MGD AeMBR [multi family]** | **0.1 MGD AeMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 427 | 223 | 61.0 | 27.9 |
| | | Pipe installation | 44.7 | 21.8 | 5.96 | 4.17 |
| | | Operation | 1,849 | 1,849 | 1,849 | 1,849 |
| Pre Treatment | Preliminary treatment | Operation | 3,767 | 3,767 | 3,767 | 3,767 |
| | | Infrastructure | 0.0039 | 0.0039 | 0.0039 | 0.0039 |
| | Fine screening | Operation | 137 | 137 | 137 | 137 |
| | | Infrastructure | 0.017 | 0.017 | 0.017 | 0.017 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 47,379 | 47,379 | 47,379 | 47,379 |
| | | Infrastructure | 748 | 748 | 748 | 748 |
| | Sludge recycle pumping | Operation | 6,905 | 6,905 | 6,905 | 6,905 |
| | | Infrastructure | 0.45 | 0.45 | 0.45 | 0.45 |
| MBR operation | Scouring | Operation | 9,230 | 9,230 | 9,230 | 9,230 |
| | | Sodium hypochlorite, 15% | 566 | 566 | 566 | 566 |
| | Permeate pumping | Operation | 2,147 | 2,147 | 2,147 | 2,147 |
| | | Infrastructure | 0.43 | 0.43 | 0.43 | 0.43 |
| | Waste sludge pumping | Operation | 54.0 | 54.0 | 54.0 | 54.0 |
| | | Infrastructure | 0.42 | 0.42 | 0.42 | 0.42 |
| MBR | | Infrastructure | 1,857 | 1,857 | 1,857 | 1,857 |
| Post treatment | Chlorination | Operation | 35,878 | 35,878 | 35,878 | 35,878 |
| | | Sodium hypochlorite, 15% | 3,343 | 3,343 | 3,343 | 3,343 |
| | | Infrastructure | 245 | 245 | 245 | 245 |
| Recycled water delivery | | Operation | 5,797 | 3,092 | 1,210 | 833 |
| | | Pipe infrastructure | 603 | 294 | 80.1 | 37.5 |
| | | Pipe installation | 11.2 | 5.48 | 1.50 | 0.69 |
| | | Displaced drinking water | -104,599 | -104,599 | -104,599 | -104,599 |
| | | ***Net Impact*** | ***16,390*** | ***13,144*** | ***10,865*** | ***10,410*** |

# Table A-18. Detailed Global Warming Potential Results for 1 MGD AeMBR (kg CO2 eq/Year)

| | | | 1 MGD AeMBR [semi rural single family] | 1 MGD AeMBR [single family] | 1 MGD AeMBR [multi family] | 1 MGD AeMBR [high density urban] |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
| Wastewater collection | | Pipe infrastructure | 4,572 | 2,235 | 610 | 284 |
| | | Pipe installation | 447 | 218 | 59.6 | 32.0 |
| | | Operation | 18,491 | 18,491 | 18,491 | 18,491 |
| Pre Treatment | Preliminary treatment | Operation | 10,939 | 10,939 | 10,939 | 10,939 |
| | | Infrastructure | 0.039 | 0.039 | 0.039 | 0.039 |
| | Fine screening | Operation | 1,415 | 1,415 | 1,415 | 1,415 |
| | | Infrastructure | 0.17 | 0.17 | 0.17 | 0.17 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 189,378 | 189,378 | 189,378 | 189,378 |
| | | Infrastructure | 1,012 | 1,012 | 1,012 | 1,012 |
| | Sludge recycle pumping | Operation | 68,367 | 68,367 | 68,367 | 68,367 |
| | | Infrastructure | 0.68 | 0.68 | 0.68 | 0.68 |
| MBR operation | Scouring | Operation | 92,296 | 92,296 | 92,296 | 92,296 |
| | | Sodium hypochlorite, 15% | 5,557 | 5,557 | 5,557 | 5,557 |
| | Permeate pumping | Operation | 21,331 | 21,331 | 21,331 | 21,331 |
| | | Infrastructure | 0.45 | 0.45 | 0.45 | 0.45 |
| | Waste sludge pumping | Operation | 537 | 537 | 537 | 537 |
| | | Infrastructure | 0.42 | 0.42 | 0.42 | 0.42 |
| MBR | | Infrastructure | 15,780 | 15,780 | 15,780 | 15,780 |
| Post treatment | Chlorination | Operation | 56,745 | 56,745 | 56,745 | 56,745 |
| | | Sodium hypochlorite, 15% | 34,330 | 34,330 | 34,330 | 34,330 |
| | | Infrastructure | 316 | 316 | 316 | 316 |
| Recycled water delivery | | Operation | 53,441 | 30,920 | 7,562 | 3,798 |
| | | Pipe infrastructure | 6,032 | 2,952 | 776 | 375 |
| | | Pipe installation | 112 | 54.8 | 15.0 | 6.88 |
| | | Displaced drinking water | -1,045,990 | -1,045,990 | -1,045,990 | -1,045,990 |
| | | ***Net Impact*** | ***-464,890*** | ***-493,115*** | ***-520,472*** | ***-524,998*** |

## Table A-19. Detailed Global Warming Potential Results for 5 MGD AeMBR (kg CO2 eq/Year)

| | | | 5 MGD AeMBR [single family] | 5 MGD AeMBR [multi family] | 5 MGD AeMBR [high density urban] |
|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 6,912,954 | 6,912,954 | 6,912,954 |
| Wastewater collection | | Pipe infrastructure | 9,391 | 3,048 | 1,422 |
| | | Pipe installation | 1,092 | 298 | 171 |
| | | Operation | 92,454 | 92,454 | 92,454 |
| Pre Treatment | Preliminary treatment | Operation | 23,040 | 23,040 | 23,040 |
| | | Infrastructure | 0.20 | 0.20 | 0.20 |
| | Fine screening | Operation | 7,083 | 7,083 | 7,083 |
| | | Infrastructure | 0.87 | 0.87 | 0.87 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 950,306 | 950,306 | 950,306 |
| | | Infrastructure | 6,672 | 6,672 | 6,672 |
| | Sludge recycle pumping | Operation | 341,153 | 341,153 | 341,153 |
| | | Infrastructure | 1.68 | 1.68 | 1.68 |
| MBR operation | Scouring | Operation | 408,837 | 408,837 | 408,837 |
| | | Sodium hypochlorite, 15% | 24,725 | 24,725 | 24,725 |
| | Permeate pumping | Operation | 106,653 | 106,653 | 106,653 |
| | | Infrastructure | 0.50 | 0.50 | 0.50 |
| | Waste sludge pumping | Operation | 2,673 | 2,673 | 2,673 |
| | | Infrastructure | 0.43 | 0.43 | 0.43 |
| MBR | | Infrastructure | 70,430 | 70,430 | 70,430 |
| Post treatment | Chlorination | Operation | 78,179 | 78,179 | 78,179 |
| | | Sodium hypochlorite, 15% | 167,159 | 167,159 | 167,159 |
| | | Infrastructure | 627 | 627 | 627 |
| Recycled water delivery | | Operation | 129,905 | 35,795 | 16,973 |
| | | Pipe infrastructure | 14,743 | 4,021 | 1,876 |
| | | Pipe installation | 274 | 74.8 | 34.9 |
| | | Displaced drinking water | -5,229,940 | -5,229,940 | -5,229,940 |
| | | ***Net Impact*** | ***-2,794,540*** | ***-2,906,708*** | ***-2,929,467*** |

# Table A-20. Detailed Global Warming Potential Results for 10 MGD AeMBR (kg CO2 eq/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 13,825,907 | 13,825,907 | 13,825,907 |
| | | | **10 MGD AeMBR [single family]** | **10 MGD AeMBR [multi family]** | **10 MGD AeMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 22,350 | 5,924 | 2,845 |
| | | Pipe installation | 2,184 | 893 | 449 |
| | | Operation | 184,908 | 184,908 | 184,908 |
| Pre Treatment | Preliminary treatment | Operation | 31,791 | 31,791 | 31,791 |
| | | Infrastructure | 0.39 | 0.39 | 0.39 |
| | Fine screening | Operation | 14,166 | 14,166 | 14,166 |
| | | Infrastructure | 1.73 | 1.73 | 1.73 |
| Plug flow activated sludge with MBR | Aeration, AeMBR | Operation | 1,798,060 | 1,798,060 | 1,798,060 |
| | | Infrastructure | 8,457 | 8,457 | 8,457 |
| | Sludge recycle pumping | Operation | 681,623 | 681,623 | 681,623 |
| | | Infrastructure | 2.95 | 2.95 | 2.95 |
| MBR operation | Scouring | Operation | 820,408 | 820,408 | 820,408 |
| | | Sodium hypochlorite, 15% | 49,338 | 49,338 | 49,338 |
| | Permeate pumping | Operation | 212,622 | 212,622 | 212,622 |
| | | Infrastructure | 0.58 | 0.58 | 0.58 |
| | Waste sludge pumping | Operation | 5,339 | 5,339 | 5,339 |
| | | Infrastructure | 0.44 | 0.44 | 0.44 |
| MBR | | Infrastructure | 138,680 | 138,680 | 138,680 |
| Post treatment | Chlorination | Operation | 89,561 | 89,561 | 89,561 |
| | | Sodium hypochlorite, 15% | 334,318 | 334,318 | 334,318 |
| | | Infrastructure | 1,016 | 1,016 | 1,016 |
| Recycled water delivery | | Operation | 259,305 | 71,086 | 33,442 |
| | | Pipe infrastructure | 29,506 | 8,037 | 3,752 |
| | | Pipe installation | 548 | 150 | 69.7 |
| | | Displaced drinking water | -10,459,900 | -10,459,900 | -10,459,900 |
| | | ***Net Impact*** | ***-5,775,714*** | ***-6,003,517*** | ***-6,049,049*** |

## Table A-21. Detailed Global Warming Potential Results for 0.05 MGD AnMBR, 35˚C Reactor Temperature (kg CO2 eq/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 69,130 | 69,130 | 69,130 | 69,130 |
| | | | **0.05 MGD AnMBR [semi rural single family]** | **0.05 MGD AnMBR [single family]** | **0.05 MGD AnMBR [multi family]** | **0.05 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 229 | 116 | 30.5 | 14.4 |
| | | Pipe installation | 22.3 | 10.9 | 2.98 | 1.39 |
| | | Operation | 925 | 925 | 925 | 925 |
| Pre Treatment | Preliminary treatment | Operation | 2,735 | 2,735 | 2,735 | 2,735 |
| | | Infrastructure | 0.0020 | 0.0020 | 0.0020 | 0.0020 |
| | Fine screening | Operation | 68.4 | 68.4 | 68.4 | 68.4 |
| | | Infrastructure | 0.0087 | 0.0087 | 0.0087 | 0.0087 |
| MBR operation | | Heating of influent | 267,455 | 267,455 | 267,455 | 267,455 |
| | | MBR pump | 700 | 700 | 700 | 700 |
| | | Heat loss control | 816 | 816 | 816 | 816 |
| | | Recovery of methane | -16,021 | -16,021 | -16,021 | -16,021 |
| | | Effluent pumping out | 2,377 | 2,377 | 2,377 | 2,377 |
| | | Heat recovery from discharge water | -210,632 | -210,632 | -210,632 | -210,632 |
| | | Biogas recirculation pump | 109 | 109 | 109 | 109 |
| | | Sodium hypochlorite, 15% | 1,001 | 1,001 | 1,001 | 1,001 |
| MBR | | Infrastructure | 3,293 | 3,293 | 3,293 | 3,293 |
| Post treatment | Chlorination | Operation | 31,253 | 31,253 | 31,253 | 31,253 |
| | | Sodium hypochlorite, 15% | 1,671 | 1,671 | 1,671 | 1,671 |
| | | Infrastructure | 242 | 242 | 242 | 242 |
| Recycled water delivery | | Operation | 3,151 | 1,798 | 857 | 669 |
| | | Pipe infrastructure | 301 | 148 | 40.2 | 18.8 |
| | | Pipe installation | 5.60 | 2.75 | 0.75 | 0.36 |
| | | Displaced drinking water | -52,862 | -52,862 | -52,862 | -52,862 |
| | | Methane emissions from permeate | 20,300 | 20,300 | 20,300 | 20,300 |
| | | ***Net Impact*** | ***57,138*** | ***55,505*** | ***54,361*** | ***54,134*** |

## Table A-22. Detailed Global Warming Potential Results for 0.1 MGD AnMBR, 35˚C Reactor Temperature (kg CO2 eq/Year)

| | | | 0.1 MGD AnMBR [semi rural single family] | 0.1 MGD AnMBR [single family] | 0.1 MGD AnMBR [multi family] | 0.1 MGD AnMBR [high density urban] |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 138,259 | 138,259 | 138,259 | 138,259 |
| Wastewater collection | | Pipe infrastructure | 427 | 223 | 61.0 | 27.9 |
| | | Pipe installation | 44.7 | 21.8 | 5.96 | 4.17 |
| | | Operation | 1,849 | 1,849 | 1,849 | 1,849 |
| Pre Treatment | Preliminary treatment | Operation | 3,767 | 3,767 | 3,767 | 3,767 |
| | | Infrastructure | 0.0039 | 0.0039 | 0.0039 | 0.0039 |
| | Fine screening | Operation | 137 | 137 | 137 | 137 |
| | | Infrastructure | 0.017 | 0.017 | 0.017 | 0.017 |
| MBR operation | | Heating of influent | 534,910 | 534,910 | 534,910 | 534,910 |
| | | MBR pump | 1,401 | 1,401 | 1,401 | 1,401 |
| | | Heat loss control | 1,164 | 1,164 | 1,164 | 1,164 |
| | | Recovery of methane | -32,043 | -32,043 | -32,043 | -32,043 |
| | | Effluent pumping out | 4,754 | 4,754 | 4,754 | 4,754 |
| | | Heat recovery from discharge water | -421,263 | -421,263 | -421,263 | -421,263 |
| | | Biogas recirculation pump | 218 | 218 | 218 | 218 |
| | | Sodium hypochlorite, 15% | 2,003 | 2,003 | 2,003 | 2,003 |
| MBR | | Infrastructure | 3,475 | 3,475 | 3,475 | 3,475 |
| Post treatment | Chlorination | Operation | 35,878 | 35,878 | 35,878 | 35,878 |
| | | Sodium hypochlorite, 15% | 3,343 | 3,343 | 3,343 | 3,343 |
| | | Infrastructure | 245 | 245 | 245 | 245 |
| Recycled water delivery | | Operation | 5,797 | 3,092 | 1,210 | 833 |
| | | Pipe infrastructure | 603 | 294 | 80.1 | 37.5 |
| | | Pipe installation | 11.2 | 5.48 | 1.50 | 0.69 |
| | | Displaced drinking water | -105,815 | -105,815 | -105,815 | -105,815 |
| | | Methane emissions from permeate | 40,634 | 40,634 | 40,634 | 40,634 |
| | | ***Net Impact*** | ***81,541*** | ***78,295*** | ***76,016*** | ***75,561*** |

# Table A-23. Detailed Global Warming Potential Results for 1 MGD AnMBR, 35˚C Reactor Temperature (kg CO2 eq/Year)

| | | *Water treated per year (m3)* | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
|---|---|---|---|---|---|---|
| | | | **1 MGD AnMBR [semi rural single family]** | **1 MGD AnMBR [single family]** | **1 MGD AnMBR [multi family]** | **1 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 4,572 | 2,235 | 610 | 284 |
| | | Pipe installation | 447 | 218 | 59.6 | 32.0 |
| | | Operation | 18,491 | 18,491 | 18,491 | 18,491 |
| Pre Treatment | Preliminary treatment | Operation | 10,939 | 10,939 | 10,939 | 10,939 |
| | | Infrastructure | 0.039 | 0.039 | 0.039 | 0.039 |
| | Fine screening | Operation | 1,415 | 1,415 | 1,415 | 1,415 |
| | | Infrastructure | 0.17 | 0.17 | 0.17 | 0.17 |
| MBR operation | | Heating of influent | 5,349,100 | 5,349,100 | 5,349,100 | 5,349,100 |
| | | MBR pump | 14,005 | 14,005 | 14,005 | 14,005 |
| | | Heat loss control | 4,152 | 4,152 | 4,152 | 4,152 |
| | | Recovery of methane | -320,426 | -320,426 | -320,426 | -320,426 |
| | | Effluent pumping out | 47,534 | 47,534 | 47,534 | 47,534 |
| | | Heat recovery from discharge water | -4,212,630 | -4,212,630 | -4,212,630 | -4,212,630 |
| | | Biogas recirculation pump | 2,181 | 2,181 | 2,181 | 2,181 |
| | | Sodium hypochlorite, 15% | 14,826 | 14,826 | 14,826 | 14,826 |
| MBR | | Infrastructure | 42,772 | 42,772 | 42,772 | 42,772 |
| Post treatment | Chlorination | Operation | 56,745 | 56,745 | 56,745 | 56,745 |
| | | Sodium hypochlorite, 15% | 34,330 | 34,330 | 34,330 | 34,330 |
| | | Infrastructure | 316 | 316 | 316 | 316 |
| Recycled water delivery | | Operation | 53,441 | 30,920 | 7,562 | 3,798 |
| | | Pipe infrastructure | 6,032 | 2,952 | 776 | 375 |
| | | Pipe installation | 112 | 54.8 | 15.0 | 6.88 |
| | | Displaced drinking water | -1,061,840 | -1,061,840 | -1,061,840 | -1,061,840 |
| | | Methane emissions from permeate | 407,758 | 407,758 | 407,758 | 407,758 |
| | | ***Net Impact*** | ***474,272*** | ***446,048*** | ***418,691*** | ***414,165*** |

# Table A-24. Detailed Global Warming Potential Results for 5 MGD AnMBR, 35˚C Reactor Temperature (kg CO2 eq/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 6,912,954 | 6,912,954 | 6,912,954 |
| | | | **5 MGD AnMBR [single family]** | **5 MGD AnMBR [multi family]** | **5 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 9,391 | 3,048 | 1,422 |
| | | Pipe installation | 1,092 | 298 | 171 |
| | | Operation | 92,454 | 92,454 | 92,454 |
| Pre Treatment | Preliminary treatment | Operation | 23,040 | 23,040 | 23,040 |
| | | Infrastructure | 0.20 | 0.20 | 0.20 |
| | Fine screening | Operation | 7,083 | 7,083 | 7,083 |
| | | Infrastructure | 0.87 | 0.87 | 0.87 |
| MBR operation | | Heating of influent | 26,745,500 | 26,745,500 | 26,745,500 |
| | | MBR pump | 70,027 | 70,027 | 70,027 |
| | | Heat loss control | 14,144 | 14,144 | 14,144 |
| | | Recovery of methane | -1,602,130 | -1,602,130 | -1,602,130 |
| | | Effluent pumping out | 237,666 | 237,666 | 237,666 |
| | | Heat recovery from discharge water | -21,063,200 | -21,063,200 | -21,063,200 |
| | | Biogas recirculation pump | 10,907 | 10,907 | 10,907 |
| | | Sodium hypochlorite, 15% | 61,775 | 61,775 | 61,775 |
| MBR | | Infrastructure | 178,293 | 178,293 | 178,293 |
| Post treatment | Chlorination | Operation | 78,179 | 78,179 | 78,179 |
| | | Sodium hypochlorite, 15% | 167,159 | 167,159 | 167,159 |
| | | Infrastructure | 627 | 627 | 627 |
| Recycled water delivery | | Operation | 129,905 | 35,795 | 16,973 |
| | | Pipe infrastructure | 14,743 | 4,021 | 1,876 |
| | | Pipe installation | 274 | 74.8 | 34.9 |
| | | Displaced drinking water | -5,314,540 | -5,314,540 | -5,314,540 |
| | | Methane emissions from permeate | 2,008,360 | 2,008,360 | 2,008,360 |
| | | ***Net Impact*** | ***1,870,749*** | ***1,758,581*** | ***1,735,822*** |

# Table A-25. Detailed Global Warming Potential Results for 10 MGD AnMBR, 35˚C Reactor Temperature (kg CO2 eq/Year)

| | | *Water treated per year (m3)* | 13,825,907 | 13,825,907 | 13,825,907 |
|---|---|---|---|---|---|
| | | | **10 MGD AnMBR [single family]** | **10 MGD AnMBR [multi family]** | **10 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 22,350 | 5,924 | 2,845 |
| | | Pipe installation | 2,184 | 893 | 449 |
| | | Operation | 184,908 | 184,908 | 184,908 |
| Pre Treatment | Preliminary treatment | Operation | 31,791 | 31,791 | 31,791 |
| | | Infrastructure | 0.39 | 0.39 | 0.39 |
| | Fine screening | Operation | 14,166 | 14,166 | 14,166 |
| | | Infrastructure | 1.73 | 1.73 | 1.73 |
| MBR operation | | Heating of influent | 53,491,000 | 53,491,000 | 53,491,000 |
| | | MBR pump | 140,053 | 140,053 | 140,053 |
| | | Heat loss control | 24,175 | 24,175 | 24,175 |
| | | Recovery of methane | -3,204,260 | -3,204,260 | -3,204,260 |
| | | Effluent pumping out | 475,333 | 475,333 | 475,333 |
| | | Heat recovery from discharge water | -42,126,300 | -42,126,300 | -42,126,300 |
| | | Biogas recirculation pump | 21,813 | 21,813 | 21,813 |
| | | Sodium hypochlorite, 15% | 111,195 | 111,195 | 111,195 |
| MBR | | Infrastructure | 320,777 | 320,777 | 320,777 |
| Post treatment | Chlorination | Operation | 89,561 | 89,561 | 89,561 |
| | | Sodium hypochlorite, 15% | 334,318 | 334,318 | 334,318 |
| | | Infrastructure | 1,016 | 1,016 | 1,016 |
| Recycled water delivery | | Operation | 259,305 | 71,086 | 33,442 |
| | | Pipe infrastructure | 29,506 | 8,037 | 3,752 |
| | | Pipe installation | 548 | 150 | 69.7 |
| | | Displaced drinking water | -10,625,900 | -10,625,900 | -10,625,900 |
| | | Methane emissions from permeate | 4,080,460 | 4,080,460 | 4,080,460 |
| | | ***Net Impact*** | ***3,678,000*** | ***3,450,198*** | ***3,404,666*** |

## Table A-26. Detailed Global Warming Potential Results for 0.05 MGD AnMBR, 20˚C Reactor Temperature (kg $CO_2$ eq/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 69,130 | 69,130 | 69,130 | 69,130 |
| | | | **0.05 MGD AnMBR [semi rural single family]** | **0.05 MGD AnMBR [single family]** | **0.05 MGD AnMBR [multi family]** | **0.05 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 229 | 116 | 30.5 | 14.4 |
| | | Pipe installation | 22.3 | 10.9 | 2.98 | 1.39 |
| | | Operation | 925 | 925 | 925 | 925 |
| Pre Treatment | Preliminary treatment | Operation | 2,735 | 2,735 | 2,735 | 2,735 |
| | | Infrastructure | 0.0020 | 0.0020 | 0.0020 | 0.0020 |
| | Fine screening | Operation | 68.4 | 68.4 | 68.4 | 68.4 |
| | | Infrastructure | 0.0087 | 0.0087 | 0.0087 | 0.0087 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 700 | 700 | 700 | 700 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -14,241 | -14,241 | -14,241 | -14,241 |
| | | Effluent pumping out | 2,377 | 2,377 | 2,377 | 2,377 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 109 | 109 | 109 | 109 |
| | | Sodium hypochlorite, 15% | 1,001 | 1,001 | 1,001 | 1,001 |
| MBR | | Infrastructure | 3,293 | 3,293 | 3,293 | 3,293 |
| Post treatment | Chlorination | Operation | 31,253 | 31,253 | 31,253 | 31,253 |
| | | Sodium hypochlorite, 15% | 1,671 | 1,671 | 1,671 | 1,671 |
| | | Infrastructure | 242 | 242 | 242 | 242 |
| Recycled water delivery | | Operation | 3,151 | 1,798 | 857 | 669 |
| | | Pipe infrastructure | 301 | 148 | 40.2 | 18.8 |
| | | Pipe installation | 5.60 | 2.75 | 0.75 | 0.36 |
| | | Displaced drinking water | -52,862 | -52,862 | -52,862 | -52,862 |
| | | Methane emissions from permeate | 26,284 | 26,284 | 26,284 | 26,284 |
| | | ***Net Impact*** | ***7,264*** | ***5,631*** | ***4,487*** | ***4,259*** |

## Table A-27. Detailed Global Warming Potential Results for 0.1 MGD AnMBR, 20˚C Reactor Temperature (kg CO2 eq/Year)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 138,259 | 138,259 | 138,259 | 138,259 |
| | | | **0.1 MGD AnMBR [semi rural single family]** | **0.1 MGD AnMBR [single family]** | **0.1 MGD AnMBR [multi family]** | **0.1 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 427 | 223 | 61.0 | 27.9 |
| | | Pipe installation | 44.7 | 21.8 | 5.96 | 4.17 |
| | | Operation | 1,849 | 1,849 | 1,849 | 1,849 |
| Pre Treatment | Preliminary treatment | Operation | 3,767 | 3,767 | 3,767 | 3,767 |
| | | Infrastructure | 0.0039 | 0.0039 | 0.0039 | 0.0039 |
| | Fine screening | Operation | 137 | 137 | 137 | 137 |
| | | Infrastructure | 0.017 | 0.017 | 0.017 | 0.017 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 1,401 | 1,401 | 1,401 | 1,401 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -28,482 | -28,482 | -28,482 | -28,482 |
| | | Effluent pumping out | 4,754 | 4,754 | 4,754 | 4,754 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 218 | 218 | 218 | 218 |
| | | Sodium hypochlorite, 15% | 2,003 | 2,003 | 2,003 | 2,003 |
| MBR | | Infrastructure | 3,475 | 3,475 | 3,475 | 3,475 |
| Post treatment | Chlorination | Operation | 35,878 | 35,878 | 35,878 | 35,878 |
| | | Sodium hypochlorite, 15% | 3,343 | 3,343 | 3,343 | 3,343 |
| | | Infrastructure | 245 | 245 | 245 | 245 |
| Recycled water delivery | | Operation | 5,797 | 3,092 | 1,210 | 833 |
| | | Pipe infrastructure | 603 | 294 | 80.1 | 37.5 |
| | | Pipe installation | 11.2 | 5.48 | 1.50 | 0.69 |
| | | Displaced drinking water | -105,815 | -105,815 | -105,815 | -105,815 |
| | | Methane emissions from permeate | 52,614 | 52,614 | 52,614 | 52,614 |
| | | ***Net Impact*** | ***-17,730*** | ***-20,977*** | ***-23,255*** | ***-23,710*** |

## Table A-28. Detailed Global Warming Potential Results for 1 MGD AnMBR, 20˚C Reactor Temperature (kg CO2 eq/Year)

| | | *Water treated per year (m3)* | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
|---|---|---|---|---|---|---|
| | | | **1 MGD AnMBR [semi rural single family]** | **1 MGD AnMBR [single family]** | **1 MGD AnMBR [multi family]** | **1 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 4,572 | 2,235 | 610 | 284 |
| | | Pipe installation | 447 | 218 | 59.6 | 32.0 |
| | | Operation | 18,491 | 18,491 | 18,491 | 18,491 |
| Pre Treatment | Preliminary treatment | Operation | 10,939 | 10,939 | 10,939 | 10,939 |
| | | Infrastructure | 0.039 | 0.039 | 0.039 | 0.039 |
| | Fine screening | Operation | 1,415 | 1,415 | 1,415 | 1,415 |
| | | Infrastructure | 0.17 | 0.17 | 0.17 | 0.17 |
| MBR operation | | Heating of influent | 0 | 0 | 0 | 0 |
| | | MBR pump | 14,005 | 14,005 | 14,005 | 14,005 |
| | | Heat loss control | 0 | 0 | 0 | 0 |
| | | Recovery of methane | -284,823 | -284,823 | -284,823 | -284,823 |
| | | Effluent pumping out | 47,534 | 47,534 | 47,534 | 47,534 |
| | | Heat recovery from discharge water | 0 | 0 | 0 | 0 |
| | | Biogas recirculation pump | 2,181 | 2,181 | 2,181 | 2,181 |
| | | Sodium hypochlorite, 15% | 14,826 | 14,826 | 14,826 | 14,826 |
| MBR | | Infrastructure | 42,772 | 42,772 | 42,772 | 42,772 |
| Post treatment | Chlorination | Operation | 56,745 | 56,745 | 56,745 | 56,745 |
| | | Sodium hypochlorite, 15% | 34,330 | 34,330 | 34,330 | 34,330 |
| | | Infrastructure | 316 | 316 | 316 | 316 |
| Recycled water delivery | | Operation | 53,441 | 30,920 | 7,562 | 3,798 |
| | | Pipe infrastructure | 6,032 | 2,952 | 776 | 375 |
| | | Pipe installation | 112 | 54.8 | 15.0 | 6.88 |
| | | Displaced drinking water | -1,061,840 | -1,061,840 | -1,061,840 | -1,061,840 |
| | | Methane emissions from permeate | 527,970 | 527,970 | 527,970 | 527,970 |
| | | ***Net Impact*** | ***-510,535*** | ***-538,759*** | ***-566,116*** | ***-570,642*** |

# Table A-29. Detailed Global Warming Potential Results for 5 MGD AnMBR, 20˚C Reactor Temperature (kg CO2 eq/Year)

| | | *Water treated per year (m3)* | 6,912,954 | 6,912,954 | 6,912,954 |
|---|---|---|---|---|---|
| | | | **5 MGD AnMBR [single family]** | **5 MGD AnMBR [multi family]** | **5 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 9,391 | 3,048 | 1,422 |
| | | Pipe installation | 1,092 | 298 | 171 |
| | | Operation | 92,454 | 92,454 | 92,454 |
| Pre Treatment | Preliminary treatment | Operation | 23,040 | 23,040 | 23,040 |
| | | Infrastructure | 0.20 | 0.20 | 0.20 |
| | Fine screening | Operation | 7,083 | 7,083 | 7,083 |
| | | Infrastructure | 0.87 | 0.87 | 0.87 |
| MBR operation | | Heating of influent | 0 | 0 | 0 |
| | | MBR pump | 70,027 | 70,027 | 70,027 |
| | | Heat loss control | 0 | 0 | 0 |
| | | Recovery of methane | -1,424,110 | -1,424,110 | -1,424,110 |
| | | Effluent pumping out | 237,666 | 237,666 | 237,666 |
| | | Heat recovery from discharge water | 0 | 0 | 0 |
| | | Biogas recirculation pump | 10,907 | 10,907 | 10,907 |
| | | Sodium hypochlorite, 15% | 61,775 | 61,775 | 61,775 |
| MBR | | Infrastructure | 178,293 | 178,293 | 178,293 |
| Post treatment | Chlorination | Operation | 78,179 | 78,179 | 78,179 |
| | | Sodium hypochlorite, 15% | 167,159 | 167,159 | 167,159 |
| | | Infrastructure | 627 | 627 | 627 |
| Recycled water delivery | | Operation | 129,905 | 35,795 | 16,973 |
| | | Pipe infrastructure | 14,743 | 4,021 | 1,876 |
| | | Pipe installation | 274 | 74.8 | 34.9 |
| | | Displaced drinking water | -5,314,540 | -5,314,540 | -5,314,540 |
| | | Methane emissions from permeate | 2,600,450 | 2,600,450 | 2,600,450 |
| | | ***Net Impact*** | ***-3,055,585*** | ***-3,167,753*** | ***-3,190,512*** |

## Table A-30. Detailed Global Warming Potential Results for 10 MGD AnMBR, 20˚C Reactor Temperature (kg CO2 eq/Year)

| | | | | | |
|---|---|---|---|---|---|
| | | *Water treated per year (m3)* | 13,825,907 | 13,825,907 | 13,825,907 |
| | | | **10 MGD AnMBR [single family]** | **10 MGD AnMBR [multi family]** | **10 MGD AnMBR [high density urban]** |
| Wastewater collection | | Pipe infrastructure | 22,350 | 5,924 | 2,845 |
| | | Pipe installation | 2,184 | 893 | 449 |
| | | Operation | 184,908 | 184,908 | 184,908 |
| Pre Treatment | Preliminary treatment | Operation | 31,791 | 31,791 | 31,791 |
| | | Infrastructure | 0.39 | 0.39 | 0.39 |
| | Fine screening | Operation | 14,166 | 14,166 | 14,166 |
| | | Infrastructure | 1.73 | 1.73 | 1.73 |
| MBR operation | | Heating of influent | 0 | 0 | 0 |
| | | MBR pump | 140,053 | 140,053 | 140,053 |
| | | Heat loss control | 0 | 0 | 0 |
| | | Recovery of methane | -2,848,230 | -2,848,230 | -2,848,230 |
| | | Effluent pumping out | 475,333 | 475,333 | 475,333 |
| | | Heat recovery from discharge water | 0 | 0 | 0 |
| | | Biogas recirculation pump | 21,813 | 21,813 | 21,813 |
| | | Sodium hypochlorite, 15% | 111,195 | 111,195 | 111,195 |
| MBR | | Infrastructure | 320,777 | 320,777 | 320,777 |
| Post treatment | Chlorination | Operation | 89,561 | 89,561 | 89,561 |
| | | Sodium hypochlorite, 15% | 334,318 | 334,318 | 334,318 |
| | | Infrastructure | 1,016 | 1,016 | 1,016 |
| Recycled water delivery | | Operation | 259,305 | 71,086 | 33,442 |
| | | Pipe infrastructure | 29,506 | 8,037 | 3,752 |
| | | Pipe installation | 548 | 150 | 69.7 |
| | | Displaced drinking water | -10,625,900 | -10,625,900 | -10,625,900 |
| | | Methane emissions from permeate | 5,283,430 | 5,283,430 | 5,283,430 |
| | | ***Net Impact*** | ***-6,151,875*** | ***-6,379,677*** | ***-6,425,209*** |

# Appendix B

# Full Baseline LCIA Results

# Appendix B – Full Baseline LCIA Results

This Appendix presents the summary results for all LCIA indicators evaluated. Table B-1 through Table B-5 provide the LCIA summary results for the AeMBR scenarios. Summary LCIA results for all AnMBR scenarios, with the reactor operating at 35 C are shown in Table B-6 through Table B-10. Summary LCIA results for the AnMBR operating at ambient temperature are illustrated in Table B-11 through Table B-15.

**Table B-1. LCIA Summary Results on Yearly Basis for 0.05 MGD AeMBR**

| | Water treated per year (m3) | 69,130 | 69,130 | 69,130 | 69,130 |
|---|---|---|---|---|---|
| | | **0.05 MGD AeMBR [semi rural single family]** | **0.05 MGD AeMBR [single family]** | **0.05 MGD AeMBR [multi family]** | **0.05 MGD AeMBR [high density urban]** |
| Acidification | kg SO2 eq | 321 | 308 | 298 | 296 |
| Ecotoxicity | CTUe | 295 | 277 | 265 | 262 |
| Energy Demand | MJ | 573,879 | 548,146 | 530,063 | 526,472 |
| Eutrophication | kg N eq | 20.0 | 19.7 | 19.4 | 19.4 |
| Fossil Depletion | kg oil eq | 9,357 | 8,907 | 8,591 | 8,528 |
| Global Warming | kg CO2 eq | 37,230 | 35,597 | 34,453 | 34,225 |
| Human Health Criteria | kg PM 2.5 eq | 17.3 | 16.6 | 16.1 | 16.0 |
| Human Health Cancer | CTUh | 1.2E-06 | 9.3E-07 | 7.1E-07 | 6.6E-07 |
| Human Health NonCancer | CTUh | 0.089 | 0.086 | 0.084 | 0.084 |
| Ozone Depletion | kg CFC-11 eq | 0.0010 | 9.8E-04 | 9.5E-04 | 9.5E-04 |
| Smog | kg O3 eq | 2,469 | 2,365 | 2,293 | 2,279 |
| Water Depletion | m3 | -64,875 | -64,884 | -64,890 | -64,891 |

### Table B-2. LCIA Summary Results on Yearly Basis for 0.1 MGD AeMBR

| | Water treated per year (m3) | 138,259 | 138,259 | 138,259 | 138,259 |
|---|---|---|---|---|---|
| | | **0.1 MGD AeMBR [semi rural single family]** | **0.1 MGD AeMBR [single family]** | **0.1 MGD AeMBR [multi family]** | **0.1 MGD AeMBR [high density urban]** |
| Acidification | kg SO2 eq | 151 | 124 | 105 | 102 |
| Ecotoxicity | CTUe | 478 | 443 | 419 | 414 |
| Energy Demand | MJ | 230,555 | 179,043 | 143,090 | 135,909 |
| Eutrophication | kg N eq | 31.9 | 31.2 | 30.7 | 30.6 |
| Fossil Depletion | kg oil eq | 3,220 | 2,320 | 1,691 | 1,566 |
| Global Warming | kg CO2 eq | 16,390 | 13,144 | 10,865 | 10,410 |
| Human Health Criteria | kg PM 2.5 eq | 8.76 | 7.30 | 6.28 | 6.08 |
| Human Health Cancer | CTUh | 1.2E-06 | 6.1E-07 | 1.6E-07 | 7.2E-08 |
| Human Health NonCancer | CTUh | 0.083 | 0.077 | 0.073 | 0.072 |
| Ozone Depletion | kg CFC-11 eq | 7.7E-04 | 6.9E-04 | 6.4E-04 | 6.3E-04 |
| Smog | kg O3 eq | 1,526 | 1,322 | 1,178 | 1,149 |
| Water Depletion | m3 | -130,095 | -130,112 | -130,125 | -130,127 |

### Table B-3. LCIA Summary Results on Yearly Basis for 1 MGD AeMBR

| | Water treated per year (m3) | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
|---|---|---|---|---|---|
| | | 1 MGD AeMBR [semi rural single family] | 1 MGD AeMBR [single family] | 1 MGD AeMBR [multi family] | 1 MGD AeMBR [high density urban] |
| Acidification | kg SO2 eq | -3,832 | -4,064 | -4,292 | -4,330 |
| Ecotoxicity | CTUe | 3,702 | 3,349 | 3,101 | 3,052 |
| Energy Demand | MJ | -6,756,690 | -7,200,452 | -7,633,332 | -7,705,003 |
| Eutrophication | kg N eq | 232 | 225 | 219 | 218 |
| Fossil Depletion | kg oil eq | -136,244 | -144,052 | -151,578 | -152,833 |
| Global Warming | kg CO2 eq | -464,890 | -493,115 | -520,472 | -524,998 |
| Human Health Criteria | kg PM 2.5 eq | -193 | -206 | -218 | -220 |
| Human Health Cancer | CTUh | -1.2E-06 | -7.4E-06 | -1.2E-05 | -1.3E-05 |
| Human Health NonCancer | CTUh | -0.20 | -0.25 | -0.31 | -0.31 |
| Ozone Depletion | kg CFC-11 eq | -0.0060 | -0.0066 | -0.0072 | -0.0073 |
| Smog | kg O3 eq | -21,733 | -23,537 | -25,251 | -25,538 |
| Water Depletion | m3 | -1,304,680 | -1,304,820 | -1,304,970 | -1,304,990 |

## Table B-4. LCIA Summary Results on Yearly Basis for 5 MGD AeMBR

| | Water treated per year (m3) | 6,912,954 | 6,912,954 | 6,912,954 |
|---|---|---|---|---|
| | | 5 MGD AeMBR [single family] | 5 MGD AeMBR [multi family] | 5 MGD AeMBR [high density urban] |
| Acidification | kg SO2 eq | -23,074 | -24,003 | -24,192 |
| Ecotoxicity | CTUe | 16,128 | 14,896 | 14,659 |
| Energy Demand | MJ | -45,730,658 | -47,514,952 | -47,874,045 |
| Eutrophication | kg N eq | 1,044 | 1,019 | 1,014 |
| Fossil Depletion | kg oil eq | -807,708 | -838,879 | -845,157 |
| Global Warming | kg CO2 eq | -2,794,540 | -2,906,708 | -2,929,467 |
| Human Health Criteria | kg PM 2.5 eq | -1,176 | -1,227 | -1,237 |
| Human Health Cancer | CTUh | -4.7E-05 | -6.6E-05 | -7.1E-05 |
| Human Health NonCancer | CTUh | -1.82 | -2.04 | -2.08 |
| Ozone Depletion | kg CFC-11 eq | -0.041 | -0.043 | -0.044 |
| Smog | kg O3 eq | -136,675 | -143,721 | -145,154 |
| Water Depletion | m3 | -6,526,020 | -6,526,620 | -6,526,740 |

## Table B-5. LCIA Summary Results on Yearly Basis for 10 MGD AeMBR

| | Water treated per year (m3) | 13,825,907 | 13,825,907 | 13,825,907 |
|---|---|---|---|---|
| | | 10 MGD AeMBR [single family] | 10 MGD AeMBR [multi family] | 10 MGD AeMBR [high density urban] |
| Acidification | kg SO2 eq | -47,710 | -49,593 | -49,970 |
| Ecotoxicity | CTUe | 31,719 | 29,340 | 28,811 |
| Energy Demand | MJ | -94,406,078 | -97,998,858 | -98,718,583 |
| Eutrophication | kg N eq | 2,061 | 2,011 | 2,000 |
| Fossil Depletion | kg oil eq | -1,665,090 | -1,727,910 | -1,740,500 |
| Global Warming | kg CO2 eq | -5,775,714 | -6,003,517 | -6,049,049 |
| Human Health Criteria | kg PM 2.5 eq | -2,435 | -2,537 | -2,558 |
| Human Health Cancer | CTUh | -9.3E-05 | -1.4E-04 | -1.5E-04 |
| Human Health NonCancer | CTUh | -3.94 | -4.38 | -4.47 |
| Ozone Depletion | kg CFC-11 eq | -0.085 | -0.090 | -0.091 |
| Smog | kg O3 eq | -284,133 | -298,488 | -301,393 |
| Water Depletion | m3 | -13,053,200 | -13,054,400 | -13,054,600 |

### Table B-6. LCIA Summary Results on Yearly Basis for 0.05 MGD AnMBR (35˚C)

| | Water treated per year (m3) | 69,130 | 69,130 | 69,130 | 69,130 |
|---|---|---|---|---|---|
| | | 0.05 MGD AnMBR [semi rural single family] | 0.05 MGD AnMBR [single family] | 0.05 MGD AnMBR [multi family] | 0.05 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -125 | -139 | -148 | -150 |
| Ecotoxicity | CTUe | 338 | 321 | 308 | 306 |
| Energy Demand | MJ | 563,197 | 537,464 | 519,380 | 515,790 |
| Eutrophication | kg N eq | 25.5 | 25.1 | 24.9 | 24.8 |
| Fossil Depletion | kg oil eq | 15,748 | 15,298 | 14,981 | 14,918 |
| Global Warming | kg CO2 eq | 57,138 | 55,505 | 54,361 | 54,134 |
| Human Health Criteria | kg PM 2.5 eq | -6.00 | -6.73 | -7.24 | -7.35 |
| Human Health Cancer | CTUh | 3.0E-07 | -1.9E-08 | -2.4E-07 | -2.9E-07 |
| Human Health NonCancer | CTUh | 0.034 | 0.031 | 0.029 | 0.029 |
| Ozone Depletion | kg CFC-11 eq | -1.2E-04 | -1.6E-04 | -1.8E-04 | -1.9E-04 |
| Smog | kg O3 eq | 221 | 118 | 45.4 | 31.1 |
| Water Depletion | m3 | -65,909 | -65,918 | -65,924 | -65,925 |

### Table B-7. LCIA Summary Results on Yearly Basis for 0.1 MGD AnMBR (35˚C)

| | Water treated per year (m3) | 138,259 | 138,259 | 138,259 | 138,259 |
|---|---|---|---|---|---|
| | | 0.1 MGD AnMBR [semi rural single family] | 0.1 MGD AnMBR [single family] | 0.1 MGD AnMBR [multi family] | 0.1 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -516 | -543 | -562 | -565 |
| Ecotoxicity | CTUe | 554 | 519 | 494 | 490 |
| Energy Demand | MJ | 627,664 | 576,152 | 540,199 | 533,019 |
| Eutrophication | kg N eq | 40.2 | 39.5 | 39.0 | 38.9 |
| Fossil Depletion | kg oil eq | 22,795 | 21,894 | 21,266 | 21,140 |
| Global Warming | kg CO2 eq | 81,541 | 78,295 | 76,016 | 75,561 |
| Human Health Criteria | kg PM 2.5 eq | -26.2 | -27.7 | -28.7 | -28.9 |
| Human Health Cancer | CTUh | -1.8E-07 | -7.5E-07 | -1.2E-06 | -1.3E-06 |
| Human Health NonCancer | CTUh | 0.013 | 0.0067 | 0.0023 | 0.0014 |
| Ozone Depletion | kg CFC-11 eq | -0.0010 | -0.0011 | -0.0012 | -0.0012 |
| Smog | kg O3 eq | -1,394 | -1,599 | -1,743 | -1,771 |
| Water Depletion | m3 | -132,136 | -132,154 | -132,166 | -132,168 |

### Table B-8. LCIA Summary Results on Yearly Basis for 1 MGD AnMBR (35˚C)

| | Water treated per year (m3) | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
|---|---|---|---|---|---|
| | | 1 MGD AnMBR [semi rural single family] | 1 MGD AnMBR [single family] | 1 MGD AnMBR [multi family] | 1 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -8,246 | -8,303 | -8,706 | -8,743 |
| Ecotoxicity | CTUe | 3,782 | 4,478 | 3,181 | 3,132 |
| Energy Demand | MJ | 1,795,710 | 1,351,948 | 919,068 | 847,397 |
| Eutrophication | kg N eq | 255 | 345 | 243 | 242 |
| Fossil Depletion | kg oil eq | 125,224 | 125,570 | 109,891 | 108,635 |
| Global Warming | kg CO2 eq | 474,272 | 446,048 | 418,691 | 414,165 |
| Human Health Criteria | kg PM 2.5 eq | -428 | -428 | -453 | -455 |
| Human Health Cancer | CTUh | -9.6E-06 | -1.5E-05 | -2.0E-05 | -2.1E-05 |
| Human Health NonCancer | CTUh | -0.54 | -0.49 | -0.64 | -0.65 |
| Ozone Depletion | kg CFC-11 eq | -0.020 | -0.018 | -0.021 | -0.021 |
| Smog | kg O3 eq | -35,489 | -36,212 | -39,008 | -39,294 |
| Water Depletion | m3 | -1,328,340 | -1,328,080 | -1,328,630 | -1,328,660 |

### Table B-9. LCIA Summary Results on Yearly Basis for 5 MGD AnMBR (35˚C)

| | Water treated per year (m3) | 6,912,954 | 6,912,954 | 6,912,954 |
|---|---|---|---|---|
| | | 5 MGD AnMBR [single family] | 5 MGD AnMBR [multi family] | 5 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -43,876 | -44,806 | -44,994 |
| Ecotoxicity | CTUe | 20,307 | 19,075 | 18,838 |
| Energy Demand | MJ | -2,883,092 | -4,667,387 | -5,026,480 |
| Eutrophication | kg N eq | 1,534 | 1,509 | 1,504 |
| Fossil Depletion | kg oil eq | 547,035 | 515,863 | 509,585 |
| Global Warming | kg CO2 eq | 1,870,749 | 1,758,581 | 1,735,822 |
| Human Health Criteria | kg PM 2.5 eq | -2,270 | -2,321 | -2,331 |
| Human Health Cancer | CTUh | -8.5E-05 | -1.0E-04 | -1.1E-04 |
| Human Health NonCancer | CTUh | -3.02 | -3.24 | -3.28 |
| Ozone Depletion | kg CFC-11 eq | -0.10 | -0.10 | -0.10 |
| Smog | kg O3 eq | -197,687 | -204,734 | -206,167 |
| Water Depletion | m3 | -6,649,020 | -6,649,620 | -6,649,740 |

**Table B-10. LCIA Summary Results on Yearly Basis for 10 MGD AnMBR (35˚C)**

| | Water treated per year (m3) | 13,825,907 | 13,825,907 | 13,825,907 |
|---|---|---|---|---|
| | | 10 MGD AnMBR [single family] | 10 MGD AnMBR [multi family] | 10 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -88,646 | -90,529 | -90,906 |
| Ecotoxicity | CTUe | 38,682 | 36,303 | 35,774 |
| Energy Demand | MJ | -7,739,946 | -11,332,727 | -12,052,451 |
| Eutrophication | kg N eq | 2,897 | 2,847 | 2,837 |
| Fossil Depletion | kg oil eq | 1,060,140 | 997,326 | 984,731 |
| Global Warming | kg CO2 eq | 3,678,000 | 3,450,198 | 3,404,666 |
| Human Health Criteria | kg PM 2.5 eq | -4,594 | -4,696 | -4,716 |
| Human Health Cancer | CTUh | -1.7E-04 | -2.1E-04 | -2.2E-04 |
| Human Health NonCancer | CTUh | -6.32 | -6.76 | -6.85 |
| Ozone Depletion | kg CFC-11 eq | -0.20 | -0.21 | -0.21 |
| Smog | kg O3 eq | -401,570 | -415,925 | -418,830 |
| Water Depletion | m3 | -13,295,000 | -13,296,200 | -13,296,400 |

**Table B-11. LCIA Summary Results on Yearly Basis for 0.05 MGD AnMBR (20˚C)**

| | Water treated per year (m3) | 69,130 | 69,130 | 69,130 | 69,130 |
|---|---|---|---|---|---|
| | | 0.05 MGD AnMBR [semi rural single family] | 0.05 MGD AnMBR [single family] | 0.05 MGD AnMBR [multi family] | 0.05 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -180 | -193 | -203 | -205 |
| Ecotoxicity | CTUe | 328 | 310 | 298 | 295 |
| Energy Demand | MJ | -360,134 | -385,867 | -403,951 | -407,542 |
| Eutrophication | kg N eq | 21.2 | 20.8 | 20.6 | 20.5 |
| Fossil Depletion | kg oil eq | -6,186 | -6,635 | -6,952 | -7,015 |
| Global Warming | kg CO2 eq | 7,264 | 5,631 | 4,487 | 4,259 |
| Human Health Criteria | kg PM 2.5 eq | -8.64 | -9.37 | -9.89 | -9.99 |
| Human Health Cancer | CTUh | 4.2E-08 | -2.8E-07 | -5.0E-07 | -5.4E-07 |
| Human Health NonCancer | CTUh | -7.5E-04 | -0.0039 | -0.0061 | -0.0066 |
| Ozone Depletion | kg CFC-11 eq | -9.8E-05 | -1.3E-04 | -1.6E-04 | -1.7E-04 |
| Smog | kg O3 eq | -960 | -1,063 | -1,136 | -1,150 |
| Water Depletion | m3 | -65,899 | -65,907 | -65,913 | -65,914 |

**Table B-12. LCIA Summary Results on Yearly Basis for 0.1 MGD AnMBR (20˚C)**

| | Water treated per year (m3) | 138,259 | 138,259 | 138,259 | 138,259 |
|---|---|---|---|---|---|
| | | 0.1 MGD AnMBR [semi rural single family] | 0.1 MGD AnMBR [single family] | 0.1 MGD AnMBR [multi family] | 0.1 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -624 | -651 | -670 | -674 |
| Ecotoxicity | CTUe | 533 | 497 | 473 | 469 |
| Energy Demand | MJ | -1,211,274 | -1,262,786 | -1,298,739 | -1,305,920 |
| Eutrophication | kg N eq | 31.7 | 31.0 | 30.5 | 30.4 |
| Fossil Depletion | kg oil eq | -20,890 | -21,790 | -22,419 | -22,544 |
| Global Warming | kg CO2 eq | -17,730 | -20,977 | -23,255 | -23,710 |
| Human Health Criteria | kg PM 2.5 eq | -31.5 | -32.9 | -33.9 | -34.1 |
| Human Health Cancer | CTUh | -6.9E-07 | -1.3E-06 | -1.7E-06 | -1.8E-06 |
| Human Health NonCancer | CTUh | -0.057 | -0.063 | -0.068 | -0.069 |
| Ozone Depletion | kg CFC-11 eq | -0.0010 | -0.0011 | -0.0011 | -0.0011 |
| Smog | kg O3 eq | -3,746 | -3,950 | -4,094 | -4,123 |
| Water Depletion | m3 | -132,115 | -132,132 | -132,144 | -132,147 |

**Table B-13. LCIA Summary Results on Yearly Basis for 1 MGD AnMBR (20˚C)**

| | Water treated per year (m3) | 1,382,591 | 1,382,591 | 1,382,591 | 1,382,591 |
|---|---|---|---|---|---|
| | | 1 MGD AnMBR [semi rural single family] | 1 MGD AnMBR [single family] | 1 MGD AnMBR [multi family] | 1 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -9,323 | -9,380 | -9,783 | -9,820 |
| Ecotoxicity | CTUe | 3,570 | 4,266 | 2,970 | 2,920 |
| Energy Demand | MJ | -16,469,959 | -16,913,720 | -17,346,601 | -17,418,271 |
| Eutrophication | kg N eq | 170 | 261 | 158 | 157 |
| Fossil Depletion | kg oil eq | -308,703 | -308,356 | -324,036 | -325,291 |
| Global Warming | kg CO2 eq | -510,535 | -538,759 | -566,116 | -570,642 |
| Human Health Criteria | kg PM 2.5 eq | -480 | -480 | -505 | -507 |
| Human Health Cancer | CTUh | -1.5E-05 | -2.0E-05 | -2.6E-05 | -2.6E-05 |
| Human Health NonCancer | CTUh | -1.23 | -1.19 | -1.34 | -1.35 |
| Ozone Depletion | kg CFC-11 eq | -0.020 | -0.018 | -0.021 | -0.021 |
| Smog | kg O3 eq | -58,834 | -59,557 | -62,352 | -62,639 |
| Water Depletion | m3 | -1,328,120 | -1,327,870 | -1,328,420 | -1,328,440 |

### Table B-14. LCIA Summary Results on Yearly Basis for 5 MGD AnMBR (20˚C)

| | Water treated per year (m3) | 6,912,954 | 6,912,954 | 6,912,954 |
|---|---|---|---|---|
| | | 5 MGD AnMBR [single family] | 5 MGD AnMBR [multi family] | 5 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -49,252 | -50,182 | -50,370 |
| Ecotoxicity | CTUe | 19,250 | 18,018 | 17,781 |
| Energy Demand | MJ | -94,102,172 | -95,886,467 | -96,245,560 |
| Eutrophication | kg N eq | 1,110 | 1,085 | 1,080 |
| Fossil Depletion | kg oil eq | -1,620,020 | -1,651,190 | -1,657,470 |
| Global Warming | kg CO2 eq | -3,055,585 | -3,167,753 | -3,190,512 |
| Human Health Criteria | kg PM 2.5 eq | -2,531 | -2,581 | -2,591 |
| Human Health Cancer | CTUh | -1.1E-04 | -1.3E-04 | -1.3E-04 |
| Human Health NonCancer | CTUh | -6.50 | -6.72 | -6.76 |
| Ozone Depletion | kg CFC-11 eq | -0.098 | -0.10 | -0.10 |
| Smog | kg O3 eq | -314,266 | -321,312 | -322,745 |
| Water Depletion | m3 | -6,647,940 | -6,648,540 | -6,648,660 |

### Table B-15. LCIA Summary Results on Yearly Basis for 10 MGD AnMBR (20˚C)

| | Water treated per year (m3) | 13,825,907 | 13,825,907 | 13,825,907 |
|---|---|---|---|---|
| | | 10 MGD AnMBR [single family] | 10 MGD AnMBR [multi family] | 10 MGD AnMBR [high density urban] |
| Acidification | kg SO2 eq | -99,391 | -101,275 | -101,651 |
| Ecotoxicity | CTUe | 36,569 | 34,190 | 33,661 |
| Energy Demand | MJ | -190,110,189 | -193,702,970 | -194,422,694 |
| Eutrophication | kg N eq | 2,050 | 2,000 | 1,990 |
| Fossil Depletion | kg oil eq | -3,272,360 | -3,335,180 | -3,347,770 |
| Global Warming | kg CO2 eq | -6,151,875 | -6,379,677 | -6,425,209 |
| Human Health Criteria | kg PM 2.5 eq | -5,114 | -5,216 | -5,237 |
| Human Health Cancer | CTUh | -2.2E-04 | -2.6E-04 | -2.7E-04 |
| Human Health NonCancer | CTUh | -13.3 | -13.7 | -13.8 |
| Ozone Depletion | kg CFC-11 eq | -0.20 | -0.21 | -0.21 |
| Smog | kg O3 eq | -634,623 | -648,978 | -651,883 |
| Water Depletion | m3 | -13,292,800 | -13,294,000 | -13,294,300 |

# Appendix C

## Detailed Life Cycle Cost Analysis Results

# Appendix C – Detailed Life Cycle Cost Analysis Results

Detailed cost results for baseline scenarios are presented in Table C-1 through Table C-7. Detailed cost results are provided for the sensitivity analysis performed in Section 5 in Table C-8 and Table C-9.

### Table C-1. Detailed Cost Results for AeMBR WWT Facilities ($/Year)

| | *Water treated per year (m3)* | 69,130 | 138,259 | 1,382,591 | 6,912,954 | 13,825,907 |
|---|---|---|---|---|---|---|
| | | **0.05 MGD AeMBR** | **0.1 MGD AeMBR** | **1 MGD AeMBR** | **5 MGD AeMBR** | **10 MGD AeMBR** |
| Amortized Capital Cost | | 206,783 | 248,937 | 774,819 | 2,633,319 | 4,434,612 |
| Operation and Maintenance (O&M) Cost | Operation - Labor | 203,470 | 227,700 | 431,590 | 911,300 | 1,438,800 |
| | Maintenance - Labor | 51,693 | 57,884 | 109,500 | 213,890 | 317,320 |
| | Materials | 37,991 | 35,674 | 45,330 | 129,290 | 193,300 |
| | Chemicals | 666 | 1,326 | 13,228 | 65,102 | 130,165 |
| Energy Cost | | 11,832 | 15,420 | 64,507 | 279,541 | 533,823 |
| ***Net Total Cost*** | | ***512,435*** | ***586,941*** | ***1,438,973*** | ***4,232,442*** | ***7,048,020*** |

### Table C-2. Detailed Cost Results for the AnMBR WWT Facilities Operating at 35˚C ($/Year)

| | *Water treated per year (m3)* | 69,130 | 138,259 | 1,382,591 | 6,912,954 | 13,825,907 |
|---|---|---|---|---|---|---|
| | | **0.05 MGD AnMBR** | **0.1 MGD AnMBR** | **1 MGD AnMBR** | **5 MGD AnMBR** | **10 MGD AnMBR** |
| Amortized Capital Cost | | 251,265 | 305,614 | 1,021,423 | 3,797,222 | 7,165,747 |
| Operation and Maintenance (O&M) Cost | Operation - Labor | 259,180 | 318,633 | 1,271,990 | 4,261,850 | 7,569,450 |
| | Maintenance - Labor | 64,530 | 87,619 | 512,148 | 1,975,949 | 3,600,776 |
| | Materials | 31,928 | 35,099 | 71,578 | 257,024 | 453,831 |
| | Chemicals | 907 | 1,814 | 16,373 | 77,671 | 151,151 |
| Energy Cost | Energy Demand | 19,408 | 25,901 | 209,010 | 1,008,711 | 2,004,555 |
| | Electricity Generated | -2,553 | -5,106 | -51,063 | -255,314 | -510,627 |
| ***Net Total Cost*** | | ***624,664*** | ***769,574*** | ***3,051,460*** | ***11,123,114*** | ***20,434,883*** |

### Table C-3. Detailed Cost Results for the AnMBR WWT Facilities Operating at 20˚C ($/Year)

| | *Water treated per year (m3)* | 69,130 | 138,259 | 1,382,591 | 6,912,954 | 13,825,907 |
|---|---|---|---|---|---|---|
| | | **0.05 MGD AnMBR** | **0.1 MGD AnMBR** | **1 MGD AnMBR** | **5 MGD AnMBR** | **10 MGD AnMBR** |
| Amortized Capital Cost | | 250,491 | 304,510 | 1,016,655 | 3,779,655 | 7,134,650 |
| Operation and Maintenance (O&M) Cost | Operation - Labor | 259,180 | 318,633 | 1,271,990 | 4,261,850 | 7,569,450 |
| | Maintenance - Labor | 64,530 | 87,619 | 512,148 | 1,975,949 | 3,600,776 |
| | Materials | 31,928 | 35,099 | 71,578 | 257,024 | 453,831 |
| | Chemicals | 907 | 1,814 | 16,373 | 77,671 | 151,151 |
| Energy Cost | Energy Demand | 5,448 | 6,731 | 19,119 | 60,858 | 109,845 |
| | Electricity Generated | -2,292 | -4,585 | -45,848 | -229,238 | -458,476 |
| ***Net Total Cost*** | | ***610,191*** | ***749,822*** | ***2,862,016*** | ***10,183,769*** | ***18,561,228*** |

## Table C-4. Detailed Cost Results for Construction and Operation of the Recycled Water Delivery System ($/Year)

| | Amortized Capital Cost | O&M Cost | Energy Cost | Total Cost |
|---|---|---|---|---|
| **0.05 MGD [semi rural single family]** | 69,428 | 2,377 | 463 | ***72,268*** |
| **0.05 MGD [single family]** | 33,943 | 1,162 | 264 | ***35,369*** |
| **0.05 MGD [multi family]** | 9,257 | 317 | 126 | ***9,700*** |
| **0.05 MGD [high density urban]** | 4,320 | 148 | 98 | ***4,566*** |
| **0.1 MGD [semi rural single family]** | 138,856 | 4,753 | 853 | ***144,462*** |
| **0.1 MGD [single family]** | 67,885 | 2,324 | 455 | ***70,664*** |
| **0.1 MGD [multi family]** | 18,514 | 634 | 178 | ***19,326*** |
| **0.1 MGD [high density urban]** | 8,640 | 296 | 123 | ***9,058*** |
| **1 MGD [semi rural single family]** | 1,388,565 | 47,531 | 7,860 | ***1,443,956*** |
| **1 MGD [single family]** | 678,854 | 23,237 | 3,880 | ***705,972*** |
| **1 MGD [multi family]** | 185,142 | 6,337 | 1,112 | ***192,592*** |
| **1 MGD [high density urban]** | 86,400 | 2,957 | 559 | ***89,916*** |
| **5 MGD [single family]** | 3,394,270 | 116,186 | 19,106 | ***3,529,562*** |
| **5 MGD [multi family]** | 925,710 | 31,687 | 5,265 | ***962,662*** |
| **5 MGD [high density urban]** | 431,998 | 14,787 | 2,496 | ***449,282*** |
| **10 MGD [single family]** | 6,788,540 | 232,373 | 38,138 | ***7,059,050*** |
| **10 MGD [multi family]** | 1,851,420 | 63,374 | 10,455 | ***1,925,249*** |
| **10 MGD [high density urban]** | 863,996 | 29,575 | 4,919 | ***898,489*** |

## Table C-5. Detailed Combined AeMBR, Recycled Water delivery, and Avoided DWT Cost Results ($/Year)

| | *Water treated per year (m3)* | Amortized Capital Cost | O&M Cost | Energy Cost | Avoided DWT Cost | Total Cost |
|---|---|---|---|---|---|---|
| **0.05 MGD [semi rural single family]** | 69,130 | 276,211 | 296,196 | 12,295 | -4,423 | ***584,703*** |
| **0.05 MGD [single family]** | 69,130 | 240,726 | 294,982 | 12,096 | -4,423 | ***547,804*** |
| **0.05 MGD [multi family]** | 69,130 | 216,040 | 294,137 | 11,958 | -4,423 | ***522,135*** |
| **0.05 MGD [high density urban]** | 69,130 | 211,103 | 293,968 | 11,930 | -4,423 | ***517,001*** |
| **0.1 MGD [semi rural single family]** | 138,259 | 387,794 | 327,337 | 16,272 | -8,846 | ***731,403*** |
| **0.1 MGD [single family]** | 138,259 | 316,823 | 324,908 | 15,874 | -8,846 | ***657,605*** |
| **0.1 MGD [multi family]** | 138,259 | 267,452 | 323,218 | 15,597 | -8,846 | ***606,267*** |
| **0.1 MGD [high density urban]** | 138,259 | 257,577 | 322,880 | 15,542 | -8,846 | ***595,999*** |
| **1 MGD [semi rural single family]** | 1,382,591 | 2,163,384 | 647,178 | 72,367 | -88,461 | ***2,882,929*** |
| **1 MGD [single family]** | 1,382,591 | 1,453,673 | 622,885 | 68,388 | -88,461 | ***2,144,945*** |
| **1 MGD [multi family]** | 1,382,591 | 959,961 | 605,985 | 65,619 | -88,461 | ***1,631,565*** |
| **1 MGD [high density urban]** | 1,382,591 | 861,218 | 602,605 | 65,066 | -88,461 | ***1,528,889*** |
| **5 MGD [single family]** | 6,912,954 | 6,027,589 | 1,435,768 | 298,647 | -442,303 | ***7,762,004*** |
| **5 MGD [multi family]** | 6,912,954 | 3,559,029 | 1,351,269 | 284,806 | -442,303 | ***5,195,104*** |
| **5 MGD [high density urban]** | 6,912,954 | 3,065,317 | 1,334,369 | 282,038 | -442,303 | ***4,681,724*** |
| **10 MGD [single family]** | 13,825,907 | 11,223,152 | 2,311,958 | 571,960 | -884,606 | ***14,107,071*** |
| **10 MGD [multi family]** | 13,825,907 | 6,286,032 | 2,142,960 | 544,278 | -884,606 | ***8,973,270*** |
| **10 MGD [high density urban]** | 13,825,907 | 5,298,608 | 2,109,160 | 538,741 | -884,606 | ***7,946,510*** |

## Table C-6. Detailed Combined AnMBR (35 °C), Recycled Water Delivery, and Avoided DWT Cost Results ($/Year)

| | *Water treated per year (m3)* | Amortized Capital Cost | O&M Cost | Energy Cost | Avoided DWT Cost | Total Cost |
|---|---|---|---|---|---|---|
| **0.05 MGD [semi rural single family]** | 69,130 | 320,693 | 358,921 | 17,318 | -4,471 | ***692,462*** |
| **0.05 MGD [single family]** | 69,130 | 285,207 | 357,707 | 17,119 | -4,471 | ***655,563*** |
| **0.05 MGD [multi family]** | 69,130 | 260,522 | 356,862 | 16,981 | -4,471 | ***629,894*** |
| **0.05 MGD [high density urban]** | 69,130 | 255,584 | 356,693 | 16,953 | -4,471 | ***624,760*** |
| **0.1 MGD [semi rural single family]** | 138,259 | 444,470 | 447,919 | 21,647 | -8,949 | ***905,088*** |
| **0.1 MGD [single family]** | 138,259 | 373,499 | 445,489 | 21,250 | -8,949 | ***831,289*** |
| **0.1 MGD [multi family]** | 138,259 | 324,128 | 443,799 | 20,973 | -8,949 | ***779,951*** |
| **0.1 MGD [high density urban]** | 138,259 | 314,254 | 443,461 | 20,917 | -8,949 | ***769,684*** |
| **1 MGD [semi rural single family]** | 1,382,591 | 2,409,988 | 1,919,619 | 165,808 | -89,801 | ***4,405,615*** |
| **1 MGD [single family]** | 1,382,591 | 1,700,277 | 1,895,326 | 161,828 | -89,801 | ***3,667,631*** |
| **1 MGD [multi family]** | 1,382,591 | 1,206,565 | 1,878,426 | 159,060 | -89,801 | ***3,154,250*** |
| **1 MGD [high density urban]** | 1,382,591 | 1,107,823 | 1,875,046 | 158,506 | -89,801 | ***3,051,575*** |
| **5 MGD [single family]** | 6,912,954 | 7,191,492 | 6,688,681 | 772,503 | -449,457 | ***14,203,219*** |
| **5 MGD [multi family]** | 6,912,954 | 4,722,932 | 6,604,182 | 758,662 | -449,457 | ***11,636,319*** |
| **5 MGD [high density urban]** | 6,912,954 | 4,229,220 | 6,587,282 | 755,894 | -449,457 | ***11,122,939*** |
| **10 MGD [single family]** | 13,825,907 | 13,954,287 | 12,007,581 | 1,532,065 | -898,643 | ***26,595,290*** |
| **10 MGD [multi family]** | 13,825,907 | 9,017,167 | 11,838,583 | 1,504,383 | -898,643 | ***21,461,490*** |
| **10 MGD [high density urban]** | 13,825,907 | 8,029,743 | 11,804,783 | 1,498,846 | -898,643 | ***20,434,729*** |

## Table C-7. Detailed Combined AnMBR (20 °C), Recycled Water Delivery, and Avoided DWT Cost Results ($/Year)

| | *Water treated per year (m3)* | Amortized Capital Cost | O&M Cost | Energy Cost | Avoided DWT Cost | Total Cost |
|---|---|---|---|---|---|---|
| **0.05 MGD [semi rural single family]** | 69,130 | 319,919 | 358,921 | 3,619 | -4,471 | ***677,989*** |
| **0.05 MGD [single family]** | 69,130 | 284,434 | 357,707 | 3,420 | -4,471 | ***641,090*** |
| **0.05 MGD [multi family]** | 69,130 | 259,748 | 356,862 | 3,281 | -4,471 | ***615,421*** |
| **0.05 MGD [high density urban]** | 69,130 | 254,811 | 356,693 | 3,254 | -4,471 | ***610,287*** |
| **0.1 MGD [semi rural single family]** | 138,259 | 443,367 | 447,919 | 2,999 | -8,949 | ***885,335*** |
| **0.1 MGD [single family]** | 138,259 | 372,395 | 445,489 | 2,601 | -8,949 | ***811,537*** |
| **0.1 MGD [multi family]** | 138,259 | 323,024 | 443,799 | 2,324 | -8,949 | ***760,199*** |
| **0.1 MGD [high density urban]** | 138,259 | 313,150 | 443,461 | 2,268 | -8,949 | ***749,931*** |
| **1 MGD [semi rural single family]** | 1,382,591 | 2,405,220 | 1,919,619 | -18,868 | -89,801 | ***4,216,171*** |
| **1 MGD [single family]** | 1,382,591 | 1,695,509 | 1,895,326 | -22,848 | -89,801 | ***3,478,187*** |
| **1 MGD [multi family]** | 1,382,591 | 1,201,797 | 1,878,426 | -25,616 | -89,801 | ***2,964,806*** |
| **1 MGD [high density urban]** | 1,382,591 | 1,103,055 | 1,875,046 | -26,170 | -89,801 | ***2,862,130*** |
| **5 MGD [single family]** | 6,912,954 | 7,173,925 | 6,688,681 | -149,274 | -449,457 | ***13,263,874*** |
| **5 MGD [multi family]** | 6,912,954 | 4,705,365 | 6,604,182 | -163,115 | -449,457 | ***10,696,974*** |
| **5 MGD [high density urban]** | 6,912,954 | 4,211,653 | 6,587,282 | -165,883 | -449,457 | ***10,183,594*** |
| **10 MGD [single family]** | 13,825,907 | 13,923,190 | 12,007,581 | -310,493 | -898,643 | ***24,721,636*** |
| **10 MGD [multi family]** | 13,825,907 | 8,986,070 | 11,838,583 | -338,176 | -898,643 | ***19,587,835*** |
| **10 MGD [high density urban]** | 13,825,907 | 7,998,646 | 11,804,783 | -343,712 | -898,643 | ***18,561,074*** |

## Table C-8. Detailed Cost Results for Sensitivity Analysis of 1 MGD AnMBR WWT Facilities ($/Year)

| | Amortized Capital Cost | O&M Cost | Energy Cost | Total Cost |
|---|---|---|---|---|
| CN winter no insulation; biogas flare; permeate methane recovery | 1,009,618 | 1,872,089 | 270,460 | ***3,152,167*** |
| CN winter no insulation; biogas flare; no methane biogas recovery | 1,009,314 | 1,872,089 | 269,663 | ***3,151,066*** |
| CN winter no insulation; elect; no permeate methane recovery | 1,017,979 | 1,872,089 | 224,274 | ***3,114,341*** |
| CN winter no insulation; elect; permeate methane recovery | 1,019,782 | 1,872,089 | 217,474 | ***3,109,345*** |
| CN winter no insulation; CHP; no permeate methane recovery | 1,019,910 | 1,872,089 | 207,209 | ***3,099,207*** |
| CN winter no insulation; CHP; permeate methane recovery | 1,022,047 | 1,872,089 | 197,250 | ***3,091,386*** |
| CN winter w/ insulation; biogas flare; permeate methane recovery | 1,013,555 | 1,872,089 | 194,980 | ***3,080,624*** |
| CN winter w/ insulation; biogas flare; no permeate methane recovery | 1,013,252 | 1,872,089 | 194,183 | ***3,079,524*** |
| CN winter w/ insulation; elect; no permeate methane recovery | 1,021,916 | 1,872,089 | 148,794 | ***3,042,799*** |
| CN winter w/ insulation; elect; permeate methane recovery | 1,023,719 | 1,872,089 | 141,994 | ***3,037,802*** |
| CN winter w/ insulation; CHP; no permeate methane recovery | 1,023,847 | 1,872,089 | 131,729 | ***3,027,665*** |
| CN winter w/ insulation; CHP; permeate methane recovery | 1,025,985 | 1,872,089 | 121,770 | ***3,019,843*** |
| MIA; biogas flare; permeate methane recovery | 1,009,634 | 1,872,089 | 19,977 | ***2,901,700*** |
| MIA; biogas flare; no permeate methane recovery | 1,009,314 | 1,872,089 | 19,119 | ***2,900,522*** |
| MIA; elect; no permeate methane recovery | 1,018,479 | 1,872,089 | -28,675 | ***2,861,892*** |
| MIA; elect; permeate methane recovery | 1,020,131 | 1,872,089 | -34,605 | ***3,152,167*** |
| MIA; CHP; no permeate methane recovery | 1,020,521 | 1,872,089 | -46,644 | ***3,151,066*** |
| MIA; CHP; permeate methane recovery | 1,022,471 | 1,872,089 | -55,396 | ***3,114,341*** |

## Table C-9. Detailed Combined 1 MGD AnMBR, Recycled Water Delivery, and Avoided DWT Cost Results for Sensitivity Analysis ($/Year)

| | Amortized Capital Cost | O&M Cost | Energy Cost | Avoided DWT Cost | Total Cost |
|---|---|---|---|---|---|
| CN winter no insulation; biogas flare; permeate methane recovery | 1,194,760 | 1,878,426 | 271,572 | -89,801 | ***3,254,958*** |
| CN winter no insulation; biogas flare; no methane biogas recovery | 1,194,456 | 1,878,426 | 270,775 | -89,801 | ***3,253,857*** |
| CN winter no insulation; elect; no permeate methane recovery | 1,203,121 | 1,878,426 | 225,386 | -89,801 | ***3,217,132*** |
| CN winter no insulation; elect; permeate methane recovery | 1,204,924 | 1,878,426 | 218,586 | -89,801 | ***3,212,135*** |
| CN winter no insulation; CHP; no permeate methane recovery | 1,205,052 | 1,878,426 | 208,321 | -89,801 | ***3,201,998*** |
| CN winter no insulation; CHP; permeate methane recovery | 1,207,189 | 1,878,426 | 198,362 | -89,801 | ***3,194,177*** |
| CN winter w/ insulation; biogas flare; permeate methane recovery | 1,198,697 | 1,878,426 | 196,093 | -89,801 | ***3,183,415*** |
| CN winter w/ insulation; biogas flare; no permeate methane recovery | 1,198,394 | 1,878,426 | 195,296 | -89,801 | ***3,182,314*** |
| CN winter w/ insulation; elect; no permeate methane recovery | 1,207,058 | 1,878,426 | 149,906 | -89,801 | ***3,145,589*** |
| CN winter w/ insulation; elect; permeate methane recovery | 1,208,861 | 1,878,426 | 143,107 | -89,801 | ***3,140,593*** |
| CN winter w/ insulation; CHP; no permeate methane recovery | 1,208,989 | 1,878,426 | 132,841 | -89,801 | ***3,130,455*** |
| CN winter w/ insulation; CHP; permeate methane recovery | 1,211,127 | 1,878,426 | 122,882 | -89,801 | ***3,122,634*** |
| MIA; biogas flare; permeate methane recovery | 1,194,776 | 1,878,426 | 21,089 | -89,801 | ***3,004,491*** |
| MIA; biogas flare; no permeate methane recovery | 1,194,456 | 1,878,426 | 20,232 | -89,801 | ***3,003,313*** |
| MIA; elect; no permeate methane recovery | 1,203,621 | 1,878,426 | -27,563 | -89,801 | ***2,964,683*** |
| MIA; elect; permeate methane recovery | 1,205,273 | 1,878,426 | -33,492 | -89,801 | ***2,960,406*** |
| MIA; CHP; no permeate methane recovery | 1,205,663 | 1,878,426 | -45,532 | -89,801 | ***2,948,756*** |
| MIA; CHP; permeate methane recovery | 1,207,613 | 1,878,426 | -54,284 | -89,801 | ***2,941,954*** |

# Appendix D

# Ambient and Influent Wastewater Temperatures for Climate Scenarios

## Appendix D – Ambient and Influent Wastewater Temperature for Climate Scenarios

Influent wastewater temperature varies from ambient air temperature. Based on information from Metcalf and Eddy (2014), influent wastewater temperature is often higher than ambient air temperature. One reason for this is the addition of warmer water from household activities. In addition, the specific heat of water is greater than air, so the wastewater temperature is generally higher than air for most months except the warmest summer months. Figure D- 1 below shows influent wastewater temperature versus ambient air temperature for example locations across the U.S. (with influent temperatures derived from Metcalf and Eddy (2014), Figure 2-13).

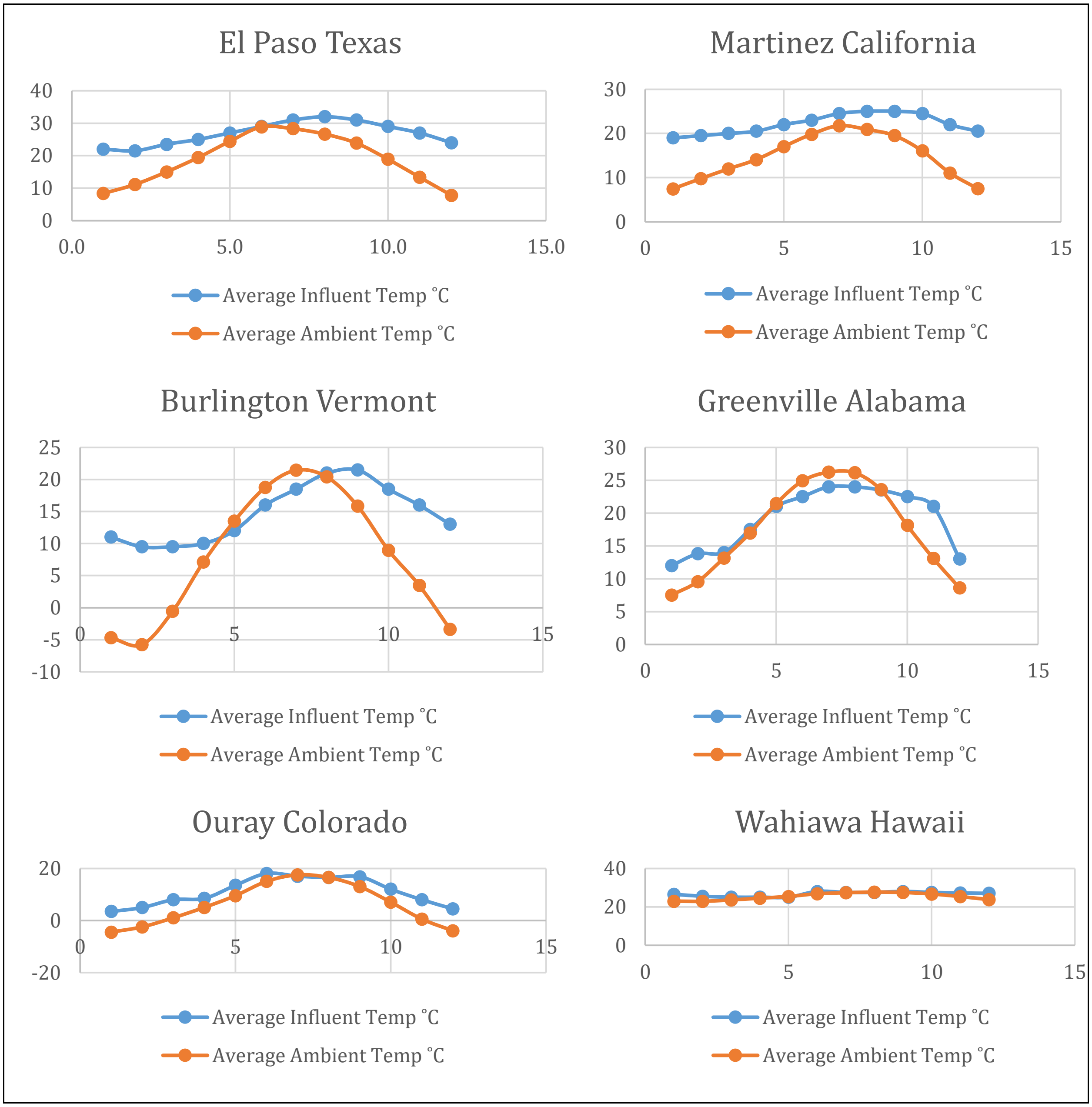


**Figure D- 1. Ambient v. Influent Temperature throughout the Year for Sample Cities in the U.S. (Adapted from Metcalf and Eddy 2014, Figure 2-13**

The annual ambient air temperature profile for Cincinnati most closely matches that of Burlington Vermont (ambient air temperature on average is 6.8 degrees C below average influent temperature). The annual ambient air temperature profile for Miami most closely matches that of Wahiawa Hawaii (ambient air temperature on average is 1.3 degrees C below average influent temperature). We can use these differentials to determine the relative influent wastewater temperatures in the climate scenarios investigated in Section 5.0. Using this approach, we see the following temperature profiles for our two climate scenarios (Figure D-2).

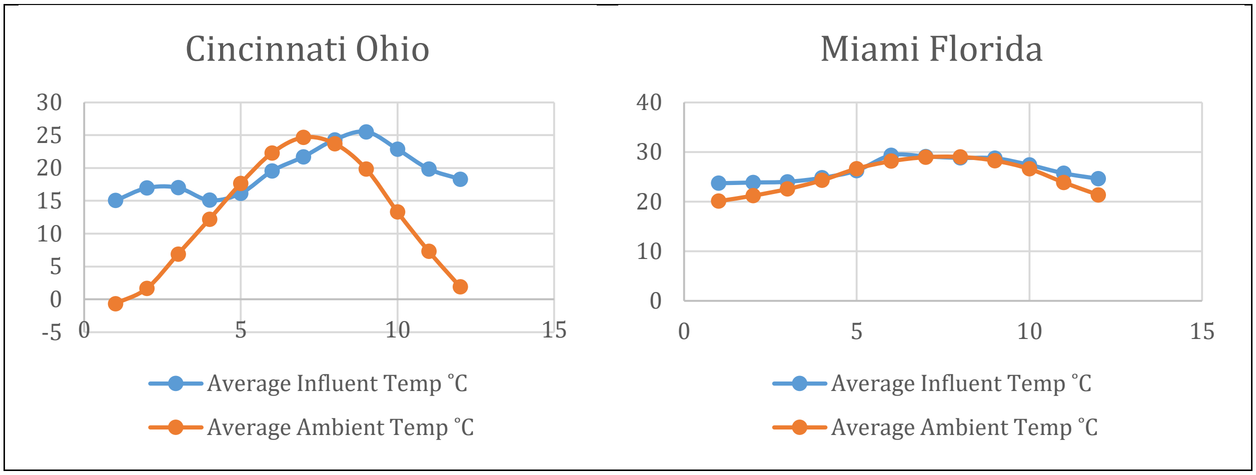


**Figure D-2. Cincinnati, OH and Miami, FL Ambient V. Influent Temperature throughout the Year**

These profiles can be used to generate the ambient and influent temperature parameters within the OpenLCA scenario analyses (Table D-1). It is assumed that May through September represents "summer" and October through April is "winter." Miami, FL scenarios are not run for different seasons as the influent and ambient temperatures remain relative constant throughout the year.

**Table D-1. Scenario Temperature Profiles for Miami, FL and Cincinnati, OH**

| | Cincinnati, OH | Miami, FL |
|---|---|---|
| Annual Average Ambient Temp ˚C | 12.6 | 25.0 |
| Annual Average Influent Temp ˚C | 19.4 | 26.4 |
| May-Sept Ambient Temp ˚C | 21.6 | |
| May-Sept Influent Temp ˚C | 21.4 | |
| Oct-April Ambient Temp ˚C | 6.1 | |
| Oct-April Influent Temp ˚C | 17.9 | |

# Appendix E

# Biogas Flaring and Recovery with CHP

# Appendix E – Biogas Flaring and Recovery with CHP

Emissions inventory information for biogas flaring was compiled from three resources with the maximum reported emission value for each compound being taken as the emission factor for this project. Table E-1 shows the data extracted from each study with the last column displaying the emission factor selected for inclusion in this study. All emission factors in the table are included as kg of compound emitted per cubic meter of biogas flared. Emission factors from Levis and Barlaz 2013 are presented in the original study per cubic meter of biogas $CH_4$ content.

**Table E-1. Biogas Flaring Emission Factors (All values are kg/m$^3$ Biogas Flared)**

| Compound | Levis & Barlaz[a] | Alberta Environment[b] | Environment Canada[c] | This Study (Max Value) |
|---|---|---|---|---|
| Nitrous Oxide | 1.13E-05 | 3.50E-05 | 4.53E-04 | 4.53E-04 |
| PM-Total | 5.95E-05 | | 8.49E-04 | 8.49E-04 |
| PM10 | 1.02E-05 | | 8.49E-04 | 8.49E-04 |
| PM-2.5 | 4.66E-06 | | 8.49E-04 | 8.49E-04 |
| Nitrogen Oxides | 1.22E-02 | | | 1.22E-02 |
| NMVOCs | 2.03E-05 | | | 2.03E-05 |
| Sulfur Oxides | 4.34E-04 | | 9.21E-05 | 4.34E-04 |
| Carbon Monoxide | 6.18E-03 | | 5.56E-05 | 6.18E-03 |
| Ammonia | 1.82E-05 | | | 1.82E-05 |
| Hydrogen Sulfide | 3.92E-06 | | | 3.92E-06 |
| PAH | | | 8.71E-06 | 8.71E-06 |

[a] Levis, J.W., and Barlaz, M.A. 2013. Anaerobic Digestion Process Model Documentation. North Carolina State University. http://www4.ncsu.edu/~jwlevis/AD.pdf Accessed 5 April, 2016.
[b] Alberta Environment. 2007. Quantification Protocol for the Anaerobic Decomposition of Agricultural Materials Project: Excel Biogas Calculator. http://environment.gov.ab.ca/info/library/7917.pdf Accessed 5 April, 2016.
[c] Environment Canada. 2005. Biogas Flare. https://www.ec.gc.ca/inrp-npri/14618D02-387B-469D-B1CD-42BC61E51652/biogas_flare_e_04_02_2009.xls Accessed 5 April, 2016.

For methane recovery with CHP, the model assumes the energy not converted to electric power is captured with a heat exchanger and used to heat the incoming influent. The power available for heat is based on results from Equation 1 in the main report with adaptations for available heat for power shown in Equation E-1.

$$HP_{CH4} = ((PR_{CH4} * LHV_{CH4}) - EP_{CH4}) * MT\_eff \qquad \text{(Eqn. E-1)}$$

Where:
$HP_{CH4}$ = Heat power from recovered headspace methane in kW
$PR_{CH4}$ = Methane production rate (grams CH4/second)
$LHV_{CH4}$ = Lower heating value methane (modeled as 50 kJ/g)
$EP_{CH4}$ = Electric power from recovered headspace methane in kW
MT_eff = Microturbine efficiency (modeled as 34%)

This calculation assumes the CHP system is a microturbine. Microturbines are the most common type of CHP system for the size systems modeled in this study (U.S. EPA CHPP 2011). The average heat recovery efficiency for a microturbine is 30% to 37% (Metcalf and Eddy 2014), with the average of 34% used in this study.

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