†Electronic Supplementary Information (ESI)

Design of Anaerobic Membrane Bioreactors for the Valorization of Dilute Organic Carbon Waste Streams

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AeF	Aerobic polishing filter
AF	Anaerobic filter
AFMBR	Anaerobic fluidized membrane bioreactor
AnMBR	Anaerobic membrane bioreactor
BOD	Biochemical oxygen demand
CAS	Conventional activated sludge
CH_4	Methane
CHP	Combined heat and power
CIP	Cleaning in-place
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COP	Cleaning out-of-place
CSTR	Continuously stirred tank reactor
DM	Degassing membrane
FS	Flat sheet
GAC	Granular activated carbon
GHG	Greenhouse gas
GWP	Global warming potential
HF	Hollow fiber
HH	Human health
HRT	Hydraulic retention time
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHS	Latin hypercube sampling
MGD	Million gallons·day^{-1}
MT	Multi-tube
N	Nitrogen
NaOCl	Sodium hypochlorite
NH_3	Ammonia
NH_4^+	Ammonim
NPV	Net present value
OLR	Organic loading rate
P	Phosphorus
PES	Polyethersulfone
PET	Polyethylene terephthalate
PO_4^{3-}	Phosphate
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidenefluoride
QSD	Quantitative sustainable design
RD&D	Research, development, and deployment
SGD	Specific gas demand
SRT	Solids residence time
t_{bw}	Backwashing duration
TEA	Techo-economic analysis
TMP	Transmembrane pressure
WRRF	Water resource recovery facility
WTTP	Wastewater treatment plant

1. Configurations Evaluated

Table ESI-1. List of all 150 AnMBR configurations examined in this manuscript.

CSTR none Submerged HF PET DM	AF none Cross-flow FS PET no DM
CSTR none Submerged HF PET no DM	AF none Cross-flow FS PTFE DM
CSTR none Submerged HF PTFE DM	AF none Cross-flow FS PTFE no DM
CSTR none Submerged HF PTFE no DM	AF none Cross-flow FS sinter steel DM
CSTR none Submerged HF PES DM	AF none Cross-flow FS sinter steel no DM
CSTR none Submerged HF PES no DM	AF none Cross-flow FS PES DM
CSTR none Submerged HF PVDF DM	AF none Cross-flow FS PES no DM
CSTR none Submerged HF PVDF no DM	AF none Cross-flow FS PVDF DM
CSTR none Submerged FS PET DM	AF none Cross-flow FS PVDF no DM
CSTR none Submerged FS PET no DM	AF none Cross-flow MT PET DM
CSTR none Submerged FS PTFE DM	AF none Cross-flow MT PET no DM
CSTR none Submerged FS PTFE no DM	AF none Cross-flow MT PTFE DM
CSTR none Submerged FS sinter steel DM	AF none Cross-flow MT PTFE no DM
CSTR none Submerged FS sinter steel no DM	AF none Cross-flow MT ceramic DM
CSTR none Submerged FS PES DM	AF none Cross-flow MT ceramic no DM
CSTR none Submerged FS PES no DM	AF none Cross-flow MT PES DM
CSTR none Submerged FS PVDF DM	AF none Cross-flow MT PES no DM
CSTR none Submerged FS PVDF no DM	AF none Cross-flow MT PVDF DM
CSTR none Cross-flow FS PET DM	AF none Cross-flow MT PVDF no DM
CSTR none Cross-flow FS PET no DM	AF GAC Submerged HF PET DM
CSTR none Cross-flow FS PTFE DM	AF GAC Submerged HF PET no DM
CSTR none Cross-flow FS PTFE no DM	AF GAC Submerged HF PTFE DM
CSTR none Cross-flow FS sinter steel DM	AF GAC Submerged HF PTFE no DM
CSTR none Cross-flow FS sinter steel no DM	AF GAC Submerged HF PES DM
CSTR none Cross-flow FS PES DM	AF GAC Submerged HF PES no DM
CSTR none Cross-flow FS PES no DM	AF GAC Submerged HF PVDF DM
CSTR none Cross-flow FS PVDF DM	AF GAC Submerged HF PVDF no DM
CSTR none Cross-flow FS PVDF no DM	AF GAC Submerged FS PET DM
CSTR none Cross-flow MT[i] PET DM	AF GAC Submerged FS PET no DM
CSTR none Cross-flow MT PET no DM	AF GAC Submerged FS PTFE DM
CSTR none Cross-flow MT PTFE DM	AF GAC Submerged FS PTFE no DM
CSTR none Cross-flow MT PTFE no DM	AF GAC Submerged FS sinter steel DM
CSTR none Cross-flow MT ceramic DM	AF GAC Submerged FS sinter steel no DM
CSTR none Cross-flow MT ceramic no DM	AF GAC Submerged FS PES DM
CSTR none Cross-flow MT PES DM	AF GAC Submerged FS PES no DM
CSTR none Cross-flow MT PES no DM	AF GAC Submerged FS PVDF DM
CSTR none Cross-flow MT PVDF DM	AF GAC Submerged FS PVDF no DM
CSTR none Cross-flow MT PVDF no DM	AF AeF Submerged HF PET DM
CSTR GAC Submerged HF PET DM	AF AeF Submerged HF PET no DM
CSTR GAC Submerged HF PET no DM	AF AeF Submerged HF PTFE DM
CSTR GAC Submerged HF PTFE DM	AF AeF Submerged HF PTFE no DM
CSTR GAC Submerged HF PTFE no DM	AF AeF Submerged HF PES DM
CSTR GAC Submerged HF PES DM	AF AeF Submerged HF PES no DM
CSTR GAC Submerged HF PES no DM	AF AeF Submerged HF PVDF DM
CSTR GAC Submerged HF PVDF DM	AF AeF Submerged HF PVDF no DM

CSTR GAC Submerged HF PVDF no DM	AF AeF Submerged FS PET DM
CSTR GAC Submerged FS PET DM	AF AeF Submerged FS PET no DM
CSTR GAC Submerged FS PET no DM	AF AeF Submerged FS PTFE DM
CSTR GAC Submerged FS PTFE DM	AF AeF Submerged FS PTFE no DM
CSTR GAC Submerged FS PTFE no DM	AF AeF Submerged FS sinter steel DM
CSTR GAC Submerged FS sinter steel DM	AF AeF Submerged FS sinter steel no DM
CSTR GAC Submerged FS sinter steel no DM	AF AeF Submerged FS PES DM
CSTR GAC Submerged FS PES DM	AF AeF Submerged FS PES no DM
CSTR GAC Submerged FS PES no DM	AF AeF Submerged FS PVDF DM
CSTR GAC Submerged FS PVDF DM	AF AeF Submerged FS PVDF no DM
CSTR GAC Submerged FS PVDF no DM	AF AeF Cross-flow FS PET DM
AF none Submerged HF PET DM	AF AeF Cross-flow FS PET no DM
AF none Submerged HF PET no DM	AF AeF Cross-flow FS PTFE DM
AF none Submerged HF PTFE DM	AF AeF Cross-flow FS PTFE no DM
AF none Submerged HF PTFE no DM	AF AeF Cross-flow FS sinter steel DM
AF none Submerged HF PES DM	AF AeF Cross-flow FS sinter steel no DM
AF none Submerged HF PES no DM	AF AeF Cross-flow FS PES DM
AF none Submerged HF PVDF DM	AF AeF Cross-flow FS PES no DM
AF none Submerged HF PVDF no DM	AF AeF Cross-flow FS PVDF DM
AF none Submerged FS PET DM	AF AeF Cross-flow FS PVDF no DM
AF none Submerged FS PET no DM	AF AeF Cross-flow MT PET DM
AF none Submerged FS PTFE DM	AF AeF Cross-flow MT PET no DM
AF none Submerged FS PTFE no DM	AF AeF Cross-flow MT PTFE DM
AF none Submerged FS sinter steel DM	AF AeF Cross-flow MT PTFE no DM
AF none Submerged FS sinter steel no DM	AF AeF Cross-flow MT ceramic DM
AF none Submerged FS PES DM	AF AeF Cross-flow MT ceramic no DM
AF none Submerged FS PES no DM	AF AeF Cross-flow MT PES DM
AF none Submerged FS PVDF DM	AF AeF Cross-flow MT PES no DM
AF none Submerged FS PVDF no DM	AF AeF Cross-flow MT PVDF DM
AF none Cross-flow FS PET DM	AF AeF Cross-flow MT PVDF no DM

2. Supporting Information for LCA and TEA

Table ESI-2. Key static cost and efficiency assumptions for all designs. All other costs were determined using Capdet.[1]

Parameter	Value	Citation
Unit Cost of GAC	$\$13.78 \cdot kg^{-1}$	2
Unit Cost of Electricity	$\$0.10 \cdot kWh^{-1}$	3
Unit Cost of EF-120 Degassing Membrane (DM)	$\$10,000 \cdot DM^{-1}$	4
Flow Rate through DM	$30\ m^3 \cdot hr^{-1}$	5
Power Consumption by DM	$3\ kW \cdot DM^{-1}$	a
Unit Cost of Sodium Hypochlorite (NaOCl)	$\$0.14 \cdot L^{-1}$	6
NaOCl Usage Rate (12.5% solution)	$2.2\ L \cdot yr^{-1}$ per $m^3 \cdot d^{-1}$	6
Unit Cost of Citric Acid	$\$0.22 \cdot L^{-1}$	6
Citric Acid Usage Rate (100% solution)	$0.6\ L \cdot yr^{-1}$ per $m^3 \cdot d^{-1}$	6
Unit Cost of Bisulfite	$\$0.08 \cdot L^{-1}$	6
Bisulfite Usage Rate (38% solution)	$0.35\ L \cdot yr^{-1}$ per $m^3 \cdot d^{-1}$	6
Unit Cost of Wall Concrete	$\$850 \cdot m^{-3}$	2
Unit Cost of Slab Concrete	$\$460 \cdot m^{-3}$	2
Unit Cost of Earthwork	$\$10.50 \cdot m^{-3}$	2
Unit Cost of Packing Media	$\$195 \cdot m^{-3}$	2
Sludge Disposal Cost	$\$0.14 \cdot kg^{-1}$	6
Membrane Replacement Labor Cost	15% of membrane cost	6
CHP Construction Cost	$1,225·kW generated	2
Fuel Cell CHP Efficiency	40.5%	7
Microturbine CHP Efficiency	27%	8
Internal Combustion CHP Efficiency	36%	7
Combustion Gas CHP Efficiency	31.5%	7

[a] DMs were assumed to operate at energy neutrality such that electricity consumption by DMs was equivalent to electricity production from methane recovered by the DMs.

Determination of Blower Cost

Specific gas demand (SGD) per unit membrane area was assumed and was multiplied by membrane surface area to determine SGD per unit. This was then multiplied by the number of units to determine total SGD. The number of blowers needed for a given design was determined by comparing the required air flow to the capacity of an individual blower (three different sized blowers were used: 7,500, 18,000, and 100,000 scfm). Starting with the smallest blower under the required air flow, number of blowers (*N*) was increased until the SGD was met.

Design capacity for blower system (TCFM) [scfm]	Capacity of individual blower (CFMB) [scfm]	Purchase cost of standard blower [$]	Blower size [scfm]
0–30,000	$\text{CFMB}=\frac{\text{TCFM}}{\text{N}^{a}}$ $\frac{\text{TCFM}}{\text{N}} < 7{,}500\ \text{scfm}$	$58{,}000 \cdot 0.7 \cdot \text{CFMB}^{0.6169}$ (**Equation ESI-1**)	3,000
30,000–72,000	$\text{CFMB}=\frac{\text{TCFM}}{\text{N}}$ $\frac{\text{TCFM}}{\text{N}} < 18{,}000\ \text{scfm}$	$218{,}000 \cdot 0.377 \cdot \text{CFMB}^{0.5928}$ (**Equation ESI-2**)	12,000
>72,000	$\text{CFMB}=\frac{\text{TCFM}}{\text{N}}$ $\frac{\text{TCFM}}{\text{N}} < 100{,}000\ \text{scfm}$	$480{,}000 \cdot 0.964 \cdot \text{CFMB}^{0.4286}$ (**Equation ESI-3**)	50,000

Determination of Pumping Cost

Pumping cost was determined according to the following equation:

$$Pump\ Cost = 2.065 \cdot 10^{5} + 7.721 \cdot 10^{4} \cdot Q_{avg} \quad \text{(Equation ESI-4)}$$

where Q_{avg} is the average influent flow rate (MGD).

Table ESI-3. Materials and processes in the life cycle inventory (LCI).

Material or Process	LCI Data Source
Aluminum	Aluminum ingot, production mix, at plant/US
Bitumen	Bitumen, at refinery/kg/US
Ceramic*	Alumina, at plant/US
CHP	Mini CHP plant, common components for heat+electricity {CH}| construction | Alloc Def, U
Chromium Steel	Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U
Citric Acid	Citric acid {RER}| production | Alloc Def, U
Concrete	Concrete, normal {CH}| production | Alloc Def, U
Copper	Copper {RER}| production, primary | Alloc Def, U
Copper	Copper concentrate {RER}| copper mine operation | Alloc Def, U
Disposal	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Alloc Rec, U
Electricity, coal	Electricity, anthracite coal, at power plant/RNA
Electricity, hydro	Electricity, high voltage {ASCC}| electricity production, hydro, pumped storage | Alloc Def, U
Electricity, natural gas	Electricity, natural gas, at power plant/US
Electricity, nuclear	Electricity, nuclear, at power plant/US
Electricity, oil	Electricity, high voltage {GB}| electricity production, oil | Alloc Def, U
Electricity, solid waste incineration	Electricity, high voltage {CH}| treatment of municipal solid waste, incineration | Alloc Def, U
Electricity, wind	Electricity, high voltage {ASCC}| electricity production, wind, <1MW turbine, onshore | Alloc Def, U
Excavation	Excavation, hydraulic digger {RER}| processing | Alloc Def, U
Extrusion of plastic pipes	Extrusion, plastic pipes {RER}| production | Alloc Def, U
Flat glass	Flat glass, uncoated {RER}| production | Alloc Def, U
GAC*	Carbon black {GLO}| production | Alloc Def, U
HDPE	Polyethylene, high density, granulate {RER}| production | Alloc Def, U
Inorganic chemicals	Chemical, inorganic {GLO}| production | Alloc Def, U
LDPE	Polyethylene, low density, granulate {RER}| production | Alloc Def, U
Limestone	Lime {CH}| production, milled, loose | Alloc Def, U
Limestone	Limestone, crushed, for mill {CH}| production | Alloc Def, U
Limestone	Limestone, unprocessed {CH}| limestone quarry operation | Alloc Def, U
Organic chemicals	Chemical, organic {GLO}| production | Alloc Def, U
PES*	Polysulfone {GLO}| polysulfone production, for membrane filtration production | Alloc Def, U
PET	Polyethylene terephthalate, granulate, amorphous {RER}| production | Alloc Def, U
PTFE*	Tetrafluoroethylene {RER}| production | Alloc Def, U
PVDF*	Polyvinylfluoride, film {US}| production | Alloc Def, U
Reinforcing steel	Reinforcing steel {RER}| production | Alloc Def, U
Rock wool	Rock wool {CH}| production | Alloc Def, U
Rock wool	Rock wool, packed {CH}| production | Alloc Def, U
Sintered steel*	Sinter, iron {GLO}| production | Alloc Def, U

Sodium hypochlorite	Sodium hypochlorite, without water, in 15% solution state {RER}| sodium hypochlorite production, product in 15% solution state | Alloc Def, U
Synthetic rubber	Synthetic rubber {RER}| production | Alloc Def, U
Tap water	Tap water, at user {CH}| tap water production and supply | Alloc Def, U
Transport via freight train	Transport, freight train {US}| diesel | Alloc Def, U
Transport via truck	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, U

An "*" indicates a material or process for which inventory data were not directly available and a surrogate was used. Direct emissions of nitrogen (as ammonium) and phosphorus (as phosphate) were also included in the life cycle inventory.

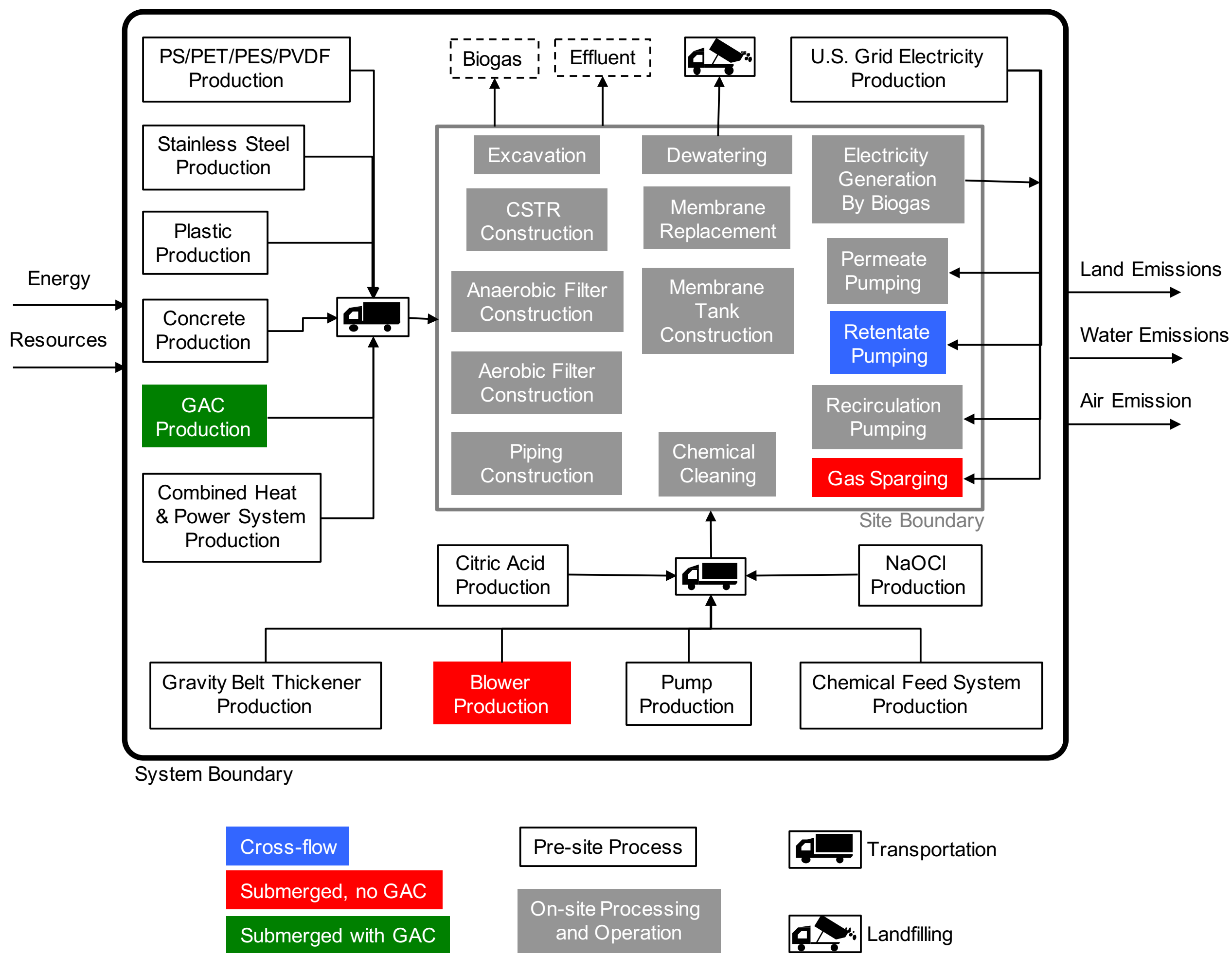

Figure ESI-1. System boundary for LCA/TEA of AnMBRs, including both construction and operation. First- and second-order environmental impacts are considered. Impacts pertaining to specific designs are indicated.

Table ESI-4. Maximum and minimum values for the TEA, net energy consumption, and LCA metrics examined in Figure 3. All values are in equivalents per m^3 of wastewater treated and are medians (from 3,000 simulations) from each design. Once the median value for each design was determined for each metric, the minimum and maximum values across all designs were identified.

	Minimum [value of "0" in Figure 3]	**Maximum** [value of "1" in Figure 3]
Cost [$]	$0.07	$0.17
Net Energy Consumption [kWh]	-0.09	1.57
Ozone Depletion [kg CFC-11]	3.60E-09	7.93E-05
Global Warming [kg CO_2]	5.60E-02	3.97E+00
Smog [kg O_3]	-7.92E-04	6.22E-02
Acidification [kg SO_2]	-1.42E-03	2.88E-02
Eutrophication [kg N]	2.82E-02	2.90E-02
HH Cancer [kg CTUh]	1.55E-09	2.42E-08
HH Non-Cancer [kg CTUh]	1.71E-09	1.24E-07
HH Criteria [kg PM 2.5]	-2.24E-05	9.37E-04
Ecotoxicity [kg CTUe]	1.68E-01	2.40E+00

3. Determination of Energy Consumption

Determination of Pumping Electricity Consumption

The procedure for estimating pumping electricity demand followed the same process as described previously.[9]

The total dynamic head (TDH) is comprised of the static head (H_{ts}), the friction head (H_{sf}, H_{df}), and minor losses (H_m). For AnMBRs, permeate pumping must also be considered by including transmembrane pressure (TMP). TDH can then be calculated by the equation below:

$$TDH = H_{ts} + H_{sf} + H_{df} + H_m (+TMP)$$ (**Equation ESI-5**)

However, because minor losses are insignificant compared to the static and friction heads, H_m can be negated. Terms in the TDH equation are further elaborated below:

Total Static Head, H_{ts} (ft): The total static head of pumping can be calculated by the equation below.

$$H_{ts} = H_{ds} - H_{ss}$$ (**Equation ESI-6**)

Suction Static Head, H_{ss} (ft): Suction static head of pumping is the elevation difference between the water level in the reactor and the centerline of the permeate pump.

Discharge Static Head, H_{ds} (ft): Discharge static head of pumping is the elevation difference between the centerline of the pump and the centerline of the effluent (where water is discharged). The effluent is assumed to be the highest point, thus setting the hydraulic reference.

Suction Friction Head, H_{sf} (ft): Suction friction head can be estimated using the Hazen- Williams equation. Suction friction head refers to the friction loss caused in the pipes on the suction side.

$$H_{sf} = 3.02 L V^{1.85} C^{-1.85} D^{-1.17}$$ (**Equation ESI-7**)

where L is the length of the pipe (ft), V is the velocity of the liquid in the pipe ($ft \cdot s^{-1}$), D is the inner diameter of the pipe (ft) and C is the Hazen-Williams coefficient (110).

Discharge Friction Head, H_{df} (ft): Discharge friction head refers to the friction loss caused in the pipes on the discharge side. The Hazen- Williams equation is also used to calculate this value.

Transmembrane Pressure, *TMP* (ft): This value (defined in Table 2 of the manuscript) is based on the literature, as described in Figure 6 and Table ESI-6.

Brake Horsepower, *BHP***:** BHP is the amount of horsepower required to drive the pump and can be calculated by the equation below:

$$BHP = \frac{Q \cdot TDH}{3960 \cdot \text{Pump Efficiency}}$$ (**Equation ESI-8**)

where Q is the flow rate (gpm), TDH is the total dynamic head (ft), and the pump efficiency is assumed to be 80%.

Energy consumption, E (kW): The amount of energy input into the motor of the pump can be calculated as:

$$E = \frac{0.746 \cdot BHP}{\text{Motor Efficiency}}$$ (**Equation ESI-9**)

where BHP is the break horsepower (hp) and motor efficiency is assumed to be 70%.

Determination of Gas Sparging Electricity Consumption

The procedure for estimating sparging electricity demand followed the same process as described previously.[9] The electricity consumption for gas sparging was determined according to the following equation:

$$P_w = \frac{wRT_1}{29.7ne}\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right]$$ (**Equation ESI-10**)

where P_w is the power requirement (kW), w is the weight flow rate of air – volumetric flow rate of air, Q_a, times specific weight – ($kg \cdot s^{-1}$), R is the engineering gas constant for air (8.314 $kJ \cdot kmol^{-1} \cdot K^{-1}$, T_1 is the absolute inlet pressure (K), p_1 is the absolute inlet pressure (atm), p_2 is the absolute outlet pressure (atm), n is 0.283, and e is the efficiency (0.80)[10].

Determination of Anaerobic Digester Heating Requirements

Digester heating requirements were determined according to the procedure outlined in Tchobanoglous *et al.*, 2013.[11] A side depth of 10 m and a SRT of 20 d was assumed. Waste activated sludge (WAS) was assumed to be thickened to 25,000 $mg \cdot L^{-1}$. Heat transfer coefficients were obtained from Tchobanoglous *et al.*, 2013[11] and can be found in Table ESI-5 below.

Table ESI-5. Heat transfer coefficients (median of range) and temperatures used to calculate digester heating requirements.

300 mm thick concrete wall with insulation	0.7	$W \cdot m^{-2} \cdot °C^{-1}$
300 mm thick concrete floor in contact with dry earth	1.7	$W \cdot m^{-2} \cdot °C^{-1}$
Floating cover with 25 mm insulating board	0.95	$W \cdot m^{-2} \cdot °C^{-1}$
Specific heat of sludge	4,200	$J \cdot kg^{-1} \cdot °C^{-1}$
Temperature of air	17	°C
Temperature of incoming sludge	25	°C
Temperature of ground	10	°C
Temperature of AD	35	°C

Heat loss was calculated according to the following equation:

$$q = UA\Delta T$$ (**Equation ESI-11**)

where q is heat loss ($J \cdot s^{-1}$), U is the heat transfer coefficient ($W \cdot m^{-2} \cdot °C^{-1}$), A is the cross-sectional area over which heat loss is occurring (m^2), and ΔT is the temperature drop across the surface (°C). The required heat is the sum of losses through the walls, floor, and roof of the digester as well as the temperature difference between the digester and the incoming sludge.

4. Design Process Overview

General Assumptions
Greenfield construction.
Effluent standards are met by all designs.
Granular activated carbon (GAC) is not replaced during the project lifetime.
Including GAC with submerged membrane units eliminates the need for gas sparging (fouling is controlled by fluidizing the bed of GAC around the submerged membranes).
Degassing membranes (DMs) do not need to be replaced during the project lifetime.
DM is 100% effective at removing dissolved methane (i.e., all soluble methane is recovered).
The environmental impacts of grid electricity consumption are based on the US 2014 average mix of fuel sources.
A slope of 1.5:1 and a freeboard of 3 ft were assumed for excavation.
All suspended growth biological trains (AnMBR CSTRs and submerged membrane tanks, CAS, and A/B) had the cross-section of Figure ESI-2.

Design of Anaerobic Membrane Bioreactor (AnMBR) Systems
The sizing of completely stirred tank reactors (CSTRs) was dictated by the specified hydraulic retention time (HRT). For anaerobic filters (AFs) and down-flow aerobic sponge filters (AeFs), reactor volumes were dictated by the specified organic loading rates (OLRs). CSTRs were configured as in Figures ESI-2 to ESI-4, and included a cover. The number of AFs was determined by minimizing the number of equally sized units in parallel with a maximum reactor diameter of 12 meters and a maximum working depth of 6 meters. The cross-sectional area of AeFs was determined by hydraulic loading rate (HLR), after which the number of AeFs was determined by minimizing the number of equally sized units in parallel with a maximum reactor diameter of 12 meters.

For cross-flow membrane configurations, membranes cassettes were assumed to be on racks in a building with the pumps. The total membrane area was dictated by the specified flux and the forward flow. Building area was calculated based on the geometry of representative flat sheet (FS) and multi-tube (MT) membrane cassettes (discussed in Section 4.1.2 of the manuscript).

For submerged membrane configurations, the membrane tank was sized based on the total membrane area (dictated by the specified flux and the forward flow) and the geometry of representative flat sheet (FS) and hollow fiber (HF) membrane cassettes (discussed in Section 4.1.2 of the manuscript). The building housing pumps and blowers (if sparging was used) was constructed at the end of the treatment train.

For CSTRs with submerged membrane modules, the least costs and impacts were achieved when membrane tank volume was minimized. As such, these configurations were designed as a membrane tank preceded by a CSTR. If the necessary HRT for the CSTR was greater than the HRT of the membrane tank, an additional biological reactor (without membranes) was designed to precede the membrane tank. The number of trains was calculated by minimizing the number of equally sized trains in parallel with 16 to 48 membrane cassettes in a single row (with two parallel rows per train, as shown in Figure ESI-5 and ESI-6).

Design of High Rate Activated Sludge + Anaerobic Digester (HRAS+AD) System

The HRAS+AD design approach followed the general procedure outlined in Rittmann and McCarty[12] with the calculation of required solids residence time (SRT; 1 day) at a specified mixed liquor suspended solids (MLSS) concentration typical of HRAS systems. Hydraulic retention time (HRT) was calculated based on target removal of soluble BOD and kinetics, and HRT was then used to size the biological reactors. Secondary clarifiers and return activated sludge (RAS) pumping were sized based on a maximum solids loading rate (SLR) of 20 $lbs \cdot ft^{-2} \cdot d^{-1}$ and an underflow solids concentration of 10,000 mg-(TSS)$\cdot L^{-1}$. The number of trains in parallel was calculated following the same procedure as AnMBR membrane tanks: the minimum number of equally sized trains in parallel with reactor length between 23 and 30 meters.

Wasted sludge was sent to an anaerobic digester for biogas production and solids stabilization. The design approach followed the general procedure outlined in Tchobanoglous *et al.*, 2013[11] with the specification of SRT (20 days) and operation under mesophilic conditions (35 ºC). Methane production was calculated based on 35% BOD degradation and an assumed waste conversion of degraded BOD to methane of 70% (corrected for biomass growth in the digester).[11] Heating requirements for the digester were calculated following Tchobanoglous *et al.*, 2013[11] assuming heat transfer coefficients of 0.7, 2.85, and 0.95 $W \cdot m^{-2} \cdot {}^{o}C^{-1}$ for the walls, floor, and floating cover, respectively.[11] Digester heating was achieved first with waste heat from the combined heat and power (CHP) process, with additional heat provided (if required) by burning produced methane solely for heat.

Pump, Blower, and Pipe Sizing

Pumps were sized based on required flows and total dynamic head calculated as the sum of the static head, friction head, and minor losses, and energy consumption was estimated assuming 80% pump efficiency and 70% motor efficiency (56% efficiency overall). Piping for liquids was sized to be the maximum standard pipe diameter that maintained liquid velocity greater than 3 $feet \cdot sec^{-1}$ to avoid solids settling.

Gas header and supply manifold piping (for sparging in AnMBR or aeration in CAS and A/B processes) were designed with a target gas velocity of 70 $feet \cdot sec^{-1}$, and a blower efficiency of 70% and motor effiency of 70% were assumed (49% efficiency overall).

Sludge Thickening

Gravity belt thickeners (GBTs) were designed to operate 24 hours a day, 7 days a week. GBTs were designed such that the maximum hydraulic loading is no more than 150 $gal \cdot m^{-1} \cdot min^{-1}$ with all units in service. The number of GBTs required was based on a maximum GBT width of 3 meters per GBT.

Degassing Membrane

Degassing membranes (DMs) were designed to remove biogas from membrane permeate at a rate of 30 $m^3 \cdot hr^{-1}$ per unit with all units in service.[5] The number of required units was calculated based on the permeate flow rate. The DMs were assumed to be 100% efficient and consumed 3 $kW \cdot DM^{-1}$. If a DM was not utilized in a design, between 30-50% of the biogas remained dissolved in the effluent and was emitted to the atmosphere.

Table ESI-6. Values used to generate Figure 6 and corresponding citations. "Citation" information includes a letter in parentheses (corresponding to the letter in Figure 6) and its corresponding reference (superscript number) in the ESI References section. A "-" denotes values not reported in a given article.

Citation	Configuration	SGD [$m^3 \cdot m^{-2} \cdot h^{-1}$]	CFV [$m \cdot s^{-1}$]	HRT [h]	OLR [g COD·$L^{-1} \cdot d^{-1}$]	TMP [bar]	Flux [LMH]	COD Removal [%]
(a)[14]	Submerged, GAC, Hollow Fiber	-	-	2.2-3.3	1.6-2.2	0.20	6-9	93-96
(b)[15]	Submerged, Flat Sheet	-	-	15-40	-	-	3.5	96.7
(c)[16]	Submerged, Hollow Fiber	-	-	3.5-5.7	1.6-4.5	-	-	85-96
(d)[17]	Cross-flow, Hollow Fiber	0.15	4.70E-05	8.5	-	0.015-0.063	17	94±2.0
(e)[18]	Submerged, Hollow Fiber	0.23	-	6-20	-	0-1	10-20	87±3.4
(f)[19]	Submerged	8-16	-	13-14	1.6-2.0	0.4-0.55	-	90
(g)[20]	-	40-60	-	-	-	-	-	-
(h)[21]	Cross-flow, Flat Sheet	4.8	0.083	-	-	-	-	95
(i)[22]	Cross-flow	-	0.1-0.2	18	-	0.035-0.21	4-12	94-97
(j)[23]	Submerged, GAC	-	-	3-24	-	-	10-20	91-95
(k)[24]	Submerged	-	-	8-12	1.1	0.30	-	97
(l)[25]	Submerged, GAC, Hollow Fiber	-	-	2.2-3.1	6.2	-	7-10	99±1
(m)[26]	Cross-flow, Multi-tube and Hollow Fiber	-	0.4-2	16	-	-	4-41	90-95
(n)[27]	Cross-flow, Flat Sheet	62	0.026	19	0.5-1.1	0.177	7	90
(o)[11]	-	-	-	-	5-15	-	-	-
(p)[28]	Cross-flow	-	1	6	2	-	12.3	90
(q)[29]	Cross-flow	-	1	6	2	-	12.3	92
(r)[30]	Submerged, Hollow Fiber	0.23	-	6-26	1.1	-	9-13.3	-
(s)[31]	Submerged, PAC	3	-	8	2	0.28-0.46	5-8	99
(t)[32]	Cross-flow	-	0.1-0.3	6-12	0.8-10	-	6	95-98

5. Representative Schematics of Designed Treatment Systems

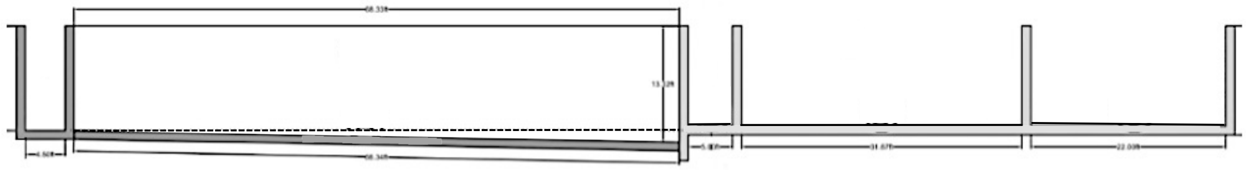

Figure ESI-2. Side view of membrane tank and pumphouse for submerged AnMBRs. Flow proceeds from left to right with the influent distribution channel, membrane tanks in parallel, and the effluent channel with a building for permeate pumps and blowers (if gas sparging is needed).

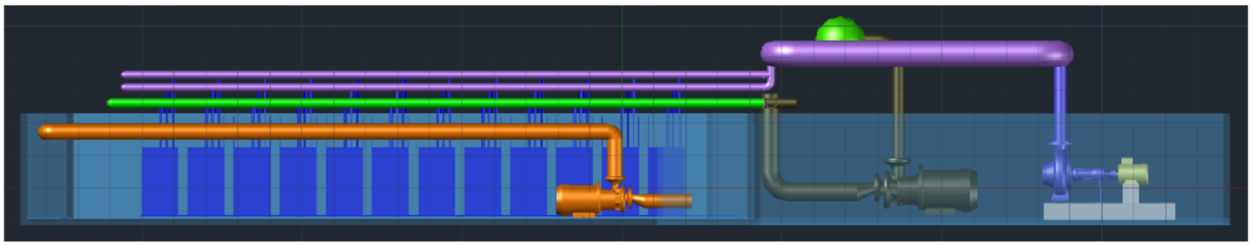

Figure ESI-3. Detailed side view of membrane tank and pumphouse for submerged AnMBRs. All relevant materials are included: reinforced concrete (hatched blue), membrane cassettes (royal blue), permeate piping (green), gas headers (purple), permeate pumps (black), internal recirculation pump and piping (orange), and blowers for sparging (purple and yellow).

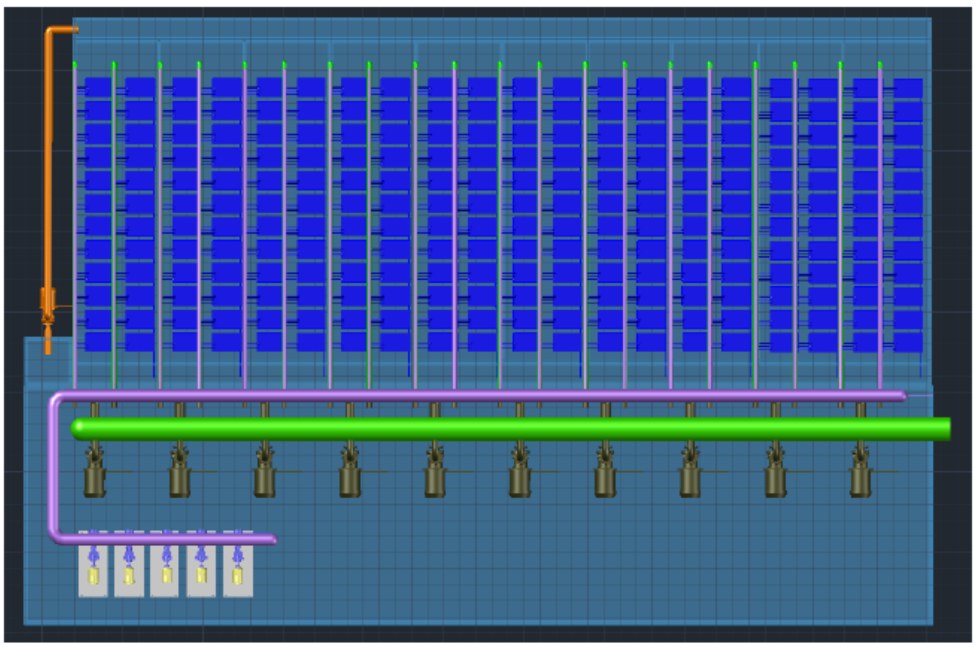

Figure ESI-4. Detailed plan view of membrane tank and pumphouse for submerged AnMBR configuration. All relevant materials are included: reinforced concrete (hatched blue), membrane cassettes (royal blue), permeate piping (green), gas headers (purple), permeate pumps (black), internal recirculation pump and piping (orange), and blowers for sparging (purple and yellow).

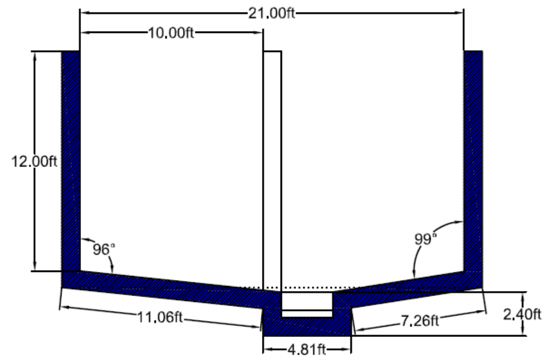

Figure ESI-5. Side view of a single membrane train.

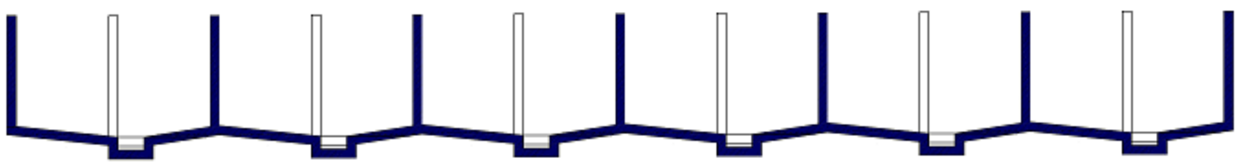

Figure ESI-6. Side view of membrane trains in series.

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