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Energy-generating potential of anaerobically enhanced primary treatment of domestic wastewater using multiple-compartment bioreactors

Andrew Pfluger, Rebecca Erickson, Gary Vanzin, Martha Hahn, Jennie Callahan, Junko Munakata-Marr, Linda Figueroa

[1]Colorado School of Mines, Department of Civil & Environmental Engineering, Golden, CO 80401

[2]Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure (ReNUWIt)

Abstract

Wastewater reclamation facilities have the potential to be net energy producers if anaerobic bioreactors coupled with energy-generating technologies, such as combined heat and power (CHP), are employed. To characterize the energy-generating potential of multiple-compartment anaerobic bioreactors used for enhanced primary treatment of domestic wastewater, organic removal and observed CH_4 generation from two pilot-scale anaerobic baffled bioreactors operating for more than 2400 days over a range of wastewater temperatures (11 to 24 °C) were characterized. Aggregated data from both bioreactor systems were subjected to uncertainty analysis and modeling to increase confidence in results and to determine the energy-generating potential from five different CHP technologies. Results suggest that multiple-compartment anaerobic reactors converted 76% of the chemical oxygen demand (COD) removed to methane-rich biogas (energy content of 2.0 kWh kg^{-1} COD removed). Observed CH_4 production was most accurately modeled using total COD measurements, not biodegradable COD estimates. The use of the aerobic BOD assay underestimated the amount of anaerobically biodegradable COD. Modeled scenarios suggest that energy generated from several CHP technologies with heat recovery (i.e., effective electrical energy) can provide power equivalent to the amount used by many conventional activated sludge systems. A modeled future scenario where dissolved methane (dCH_4) is recovered for energy generation also suggests that dCH_4 capture provides additional energy generation and is needed to reduce greenhouse gas

emissions. Based on COD, mass balances indicate that using multiple-compartment anaerobic reactors for anaerobically enhanced primary treatment increases the portion of COD in the influent wastewater going to electrical energy from ~8.5% to 21%. Results from this study suggest that replacing conventional primary treatment with anaerobic bioreactors can enhance energy-generating potential at wastewater reclamation facilities.

Water Impact Statement

Anaerobic primary treatment of domestic wastewater using baffled bioreactors converted 76% of the COD removed to methane-rich biogas. Uncertainty modeling suggests that anaerobic primary treatment coupled with combined heat and power technologies can produce electrical energy equivalent to the amount used by conventional activated sludge and can be a path forward for energy-positive wastewater treatment.

1. Introduction

Medium-strength domestic wastewater (tCOD = 430 mg L^{-1} and NH_4^+-N = 40 mg L^{-1}) has a maximum potential chemical energy of 1.80 kWh m^{-3}. Most of the chemical energy potential is found in the organics, i.e., the chemical oxygen demand (COD) (1.49 kWh m^{-3}). If harnessed, the maximum energy potential of wastewater is three to six times the energy required for wastewater treatment using conventional technologies (e.g., conventional activated sludge).[1,2] In practice, however, the transport and treatment of domestic wastewater is very energy-intensive, accounting for approximately 3% of the U.S. electrical energy supply,[3] a proportion similar to that in other countries.[4] Conventional activated sludge (CAS), the most commonly employed wastewater treatment approach, is energy intensive requiring 0.3 to 0.6 kWh per m^3 wastewater treated.[5] Electricity use can account for as much as 40% of a WWTF's operating budget, with approximately 25% of electricity use coming from aeration alone.[6,7]

Potential energy-generating alternatives to the energy-intensive aerobic wastewater treatment paradigm center on anaerobic bioreactors. Anaerobic bioreactor technologies generate methane-rich biogas from the degradation of organics such as fats, carbohydrates, and proteins commonly found in domestic wastewater via hydrolysis, acidogenesis, acetogenesis, and methanogenesis. While anaerobic digestion of wastewater sludge (i.e., primary sludge and waste activated sludge) is a common method for sludge treatment,[8] mainstream anaerobic treatment of domestic wastewater is the focus of several current research efforts. Bioreactor systems such as the anaerobic membrane bioreactor (AnMBR) have demonstrated the ability to achieve discharge standards for wastewater organics and suspended solids set by the U.S. EPA (30 mg L^{-1} for 5-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS)); however, AnMBRs currently use more energy than can be recovered from the methane (CH_4) they generate.[9] Anaerobic sludge blanket processes, such as the upflow anaerobic sludge blanket (UASB) or the anaerobic baffled reactor (ABR), if located within the hydraulic gradient of the facility, can require no energy input but currently fail to meet wastewater discharge standards,[10,11] suggesting that such technologies may be best employed as biologically enhanced primary wastewater treatment. To date, few studies have characterized the methane-generating potential of ABRs treating dilute domestic wastewater under low temperatures.[12] Gopala-Krishna et al. (2008) reported that a bench-scale ABR (10-liter reactor volume) treating synthetic wastewater at temperatures ranging from 20 to 32 °C generated 0.18 to 0.23 L CH_4 g^{-1} COD removed (41 to 55% conversion of COD to CH_4) under various HRTs (6-20 hours).[13] Shoener et al. (2014) used results from Gopala-Krishna et al. (2008), as well as results from three other bench-scale ABRs treating swine wastewater (further details in Section 3.1), to model potential energy recovery from ABRs. Shoener et al. (2014) found that the ABR had greater energy recovery efficiency relative to several other anaerobic technologies, including UASBs, AnMBRs, microbial fuel cells, anaerobic fluidized bed reactors, and anaerobic sequencing batch reactors.[14] While these results are promising, further modeling with data from

pilot-scale bioreactors treating raw domestic wastewater under low wastewater temperatures over long timescales (i.e., taking seasonal variations in wastewater temperature into account) is required to more fully understand the energy-generating potential of ABRs employed for biologically enhanced primary treatment of domestic wastewater.

The objective of this study was therefore to examine the generation of CH_4 and the energy-generating potential of two pilot-scale multiple-compartment anaerobic sludge blanket bioreactors operated over long timescales (cumulatively > 2400 days) under cooler temperatures (11-24 °C) and variable organic loading. Observed CH_4 generation was compared to the theoretical maximum generation of CH_4 from COD removal in the reactor systems. To increase confidence in the measured values for future full-scale anaerobic primary wastewater treatment applications, uncertainty modeling of COD removal, methane generation, and potential energy generation using several combined heat and power (CHP) technologies was employed using Oracle Crystal Ball and Monte Carlo simulation.

2. Materials & Methods

2.1. Anaerobic reactor configurations

Schematics for the two multiple-compartment anaerobic bioreactors examined in this study are shown in Figure S1. ABR 1 (Figure S1.a) was a four-compartment ABR that consisted of four equal-sized rectangular compartments (0.46 m wide/long and 1.22 m tall). The hydraulic volume of ABR 1 was held constant at 869 liters; however, the hydraulic retention time (HRT) was modified from 12 hours to 24 hours after 1357 days of operation to evaluate the impact on substrate removal and CH_4 generation. ABR 1 was characterized for 1740 total days during this study. The second bioreactor, henceforth called ABR 2 (Figure S1.b), was operated as a three-compartment ABR with equal-sized cylindrical compartments (0.15 m radius and 3.66 m tall) for 390 days prior to the addition of a fourth cylindrical compartment (0.15 m radius and 1.22 m tall)

that contained media for biofilm growth (i.e., an anaerobic fixed film reactor (AFFR)). The ABR-AFFR (i.e., ABR 2) was characterized for a total of 720 days during this study. The total hydraulic volume of the first three compartments of ABR 2 was 720 liters, which increased to 810 liters when the AFFR was added. Correspondingly, the HRT for the ABR portion of ABR 2 was 24 hours, which increased to 27 hours when the AFFR was added.

Both reactors had the same hydraulic flow pattern based on a baffled design.[15,16] In each reactor, raw, unheated influent wastewater was treated as it flowed sequentially through a series of four spatially separated reactor compartments. Each reactor compartment contained a downcomer pipe that routed influent wastewater from the feed tank or the previous compartment to the bottom of the compartment beneath the sludge blanket. Wastewater then flowed upward through the sludge blanket into a clarified zone. Wastewater exited each reactor compartment through an effluent pipe located at the top of each compartment, but below the water surface. For ABR 2, each compartment contained a gas-liquid-solid separator that was located above the sludge bed, but below the water surface. The separators were installed after 118 days of operation in ABR 2 as biogas-induced lifting of the sludge bed was observed. Gas-liquid-solid separators were not required in ABR 1. For the AFFR in ABR 2, media for biofilm growth was held in the upper portion of the reactor compartment by the gas-liquid-solid separator. Further reactor description is provided in supplemental information Section S1.a. Influent and effluent wastewater characteristics for each ABR, as each was operated in a different location, are summarized in Table S1. Influent wastewater characteristics for Plum Creek Wastewater Reclamation Authority, the location of ABR 1, are further described in Hahn and Figueroa (2015).[17] Influent wastewater characteristics for Mines Park, the location of ABR 2, are further described in Vuono et al. (2013) and Pfluger et al. (2018).[18,19] Fluid flow through each ABR was powered by a peristaltic pump; however, a pump would not be required for anaerobic primary treatment using ABRs if the bioreactors were placed within the hydraulic

gradient of the facility. Therefore, energy use by ABRs for modeling was assumed negligible and was not included in the analysis.

2.2. Data collection and analyses

Measurements collected from both ABRs included temperature, pH, TSS, volatile suspended solids (VSS), total COD (tCOD), dissolved COD (dCOD), particulate COD (pCOD), BOD_5, alkalinity, biogas production, biogas composition (CH_4 and CO_2), and dissolved CH_4 (dCH_4). Continuously monitored parameters included temperature and pH for both reactor systems. Grab samples were collected weekly from the influent and effluent of each reactor compartment for TSS, VSS, tCOD, dCOD, pCOD, BOD_5, and alkalinity. Grab samples were collected periodically (at least twice monthly) for biogas production, biogas composition, and dCH_4. In total, biogas production and dCH_4 were simultaneously taken on 82 occasions and were used for analysis. COD measurements used for calculation of theoretical CH_4 production were taken on 450 occasions. Table S2 provides further detail concerning the operational conditions under which each sample was taken, to include wastewater temperature, which varied from approximately 10 to 24 °C.

Analyses for TSS, VSS, tCOD, dCOD, pCOD, BOD_5, and alkalinity were conducted according to Standard Methods.[20] Specific methods used are listed in Section S1.b. For ABR 1, pH values were collected with Broadly James pH ProcessProbes and temperature was monitored and logged with submersible HOBO Temp Pro V2 temperature logger. For ABR 2, pH was measured with Cole-Parmer pH electrodes (100 Ohm Pt RTD, EW-27003-23). Temperature was measured with LabJack EI-1034 probes. Biogas flowrate in ABR 1 was measured using Cole Parmer 0 to 500 SSCM gas flow meters. Biogas flowrate in ABR 2 was measured using an Agilent Digital Flow Meter (Optiflow 520). For ABR 1, methods for biogas composition and dCH_4 sampling during the first 900 days of operation are described in Hahn & Figueroa (2015).[17]

Biogas composition was measured using a Shimadzu GC-17A or a Shimadzu GC-8A with TCD detectors and a HayeSep Q 80/100 column with UHP helium carrier gas at 30 mL min^{-1}. For measurements taken after day 900 of ABR 1's operation and for all ABR 2 measurements, biogas composition was determined on a Hewlett Packard 6890 with Agilent 5973 Mass Selective Detector GC-MS with an Agilent 113-3133 GS-Carbonplot capillary column at max temperature of 360˚C, flowrate of 1.2 mL min^{-1}, and helium carrier gas. Section S1.c provides additional information regarding GC measurements. For ABR 2, dCH_4 was analyzed using equilibrium partitioning from the dissolved phase to the gas phase according to the method described in Pfluger et al. (2011) with minor modification (described in Section S1.d).[21] Results were consistent between dCH_4 sampling procedures (Table S3). Methane production from ABR 2 is further described in Pfluger et al. (2018).[19] Sludge retention time (SRT) was estimated using the approach described in Hahn & Figueroa (2015), which accounts for the total mass of volatile solids in the reactor (determined from sludge VSS (g L^{-1}) and sludge volume (L)), the mass removal rate of effluent VSS (g d^{-1}), periodic scum removal from the top of each reactor compartment (g d^{-1}), and sludge removed from episodic events such as biological sampling (g d^{-1}).[18] Methods for determining COD mass balances for the ABR systems based on influent COD, effluent COD, and biogas produced are found in Erickson (2018).[22] All "±" values presented in this study represent one standard deviation. All 10^{th} and 90^{th} percentile values from uncertainty analyses are shown with brackets, i.e., "[10^{th} percentile value, 90^{th} percentile value]". Confidence intervals (95%) are only graphically depicted in Figure 1.

2.3. Energy-related calculations

The biodegradable fraction of COD (bCOD) is degraded in anaerobic systems to create CO_2 and CH_4. A theoretical maximum volume of CH_4 for any given quantity of bCOD removed can be calculated using the relationship 0.35 m^3 CH_4 per kg of $BOD_{ultimate}$ (i.e., bCOD) removed at STP, which is derived using the ideal gas law and stoichiometry. This relationship is modified at

temperatures and pressures other than STP. Theoretical CH_4 production for reactors in this study occurred at a lower atmospheric pressure (0.83 atm) and under variable air temperatures (ABR 1 ranged from 9.9 to 25.8°C; ABR 2 ranged from 8.9 to 28.9°C). Using the ideal gas law, the calculated range of theoretical CH_4 production in this study therefore varied from 0.43 to 0.47 m^3 CH_4 per kg $BOD_{ultimate}$ removed.

BOD_5 measurements were used to estimate bCOD in this study. To estimate bCOD removal, measurements of tCOD and BOD_5 were first used to determine the tCOD-to-BOD_5 ratio for each reactor system. The bCOD for each tCOD measurement was then calculated using experimentally derived tCOD-to-BOD_5 and BOD_5-to-bCOD relationships (values provided in Table 1). Using this approach, theoretical CH_4 production was calculated from the estimated biodegradable fraction of all tCOD measurements (Equation 1A). For comparison, theoretical CH_4 production was also calculated directly from tCOD measurements (Equation 1B).

Equation 1A: $tCH_{4\_bCOD} = Q\left[\frac{tCOD_r}{(R_{CB})(R_{Bb})}\right]V_{CH_4}$

Equation 1B: $tCH_{4\_tCOD} = (Q)(tCOD_r)(V_{CH_4})$

Where: tCH_{4_bCOD} = total theoretical CH_4 production (m^3 CH_4 d^{-1}) from bCOD

tCH_{4_tCOD} = total theoretical CH_4 production (m^3 CH_4 d^{-1}) from total COD

Q = wastewater flowrate (m^3 d^{-1})

$tCOD_r$ = total COD removed by ABR system (kg tCOD m^{-3} wastewater)

R_{CB} = ratio of tCOD to BOD_5

R_{Bb} = ratio of BOD_5 to bCOD

V_{CH4} = theoretical volume of CH_4 produced per kg tCOD removed (m^3 kg^{-1}) adjusted for temperature & pressure

Note: values used in uncertainty analyses for R_{CB} and R_{Bb} are found in Table 1.

McCarty et al. (2011) state that approximately 20% of biodegradable energy potential may be lost in the wastewater treatment process.[5] Specifically, around 8% of energy potential is lost in the conversion of wastewater organics (e.g., carbohydrates, fats, and proteins) to methane. A further 7% of energy potential is lost during anaerobic cell synthesis, while another 5% may be lost in the inefficiency of wastewater treatment itself. Such losses should be accounted for when determining the theoretical CH_4 production of an anaerobic system. In this study, decreases in energy-generating potential due to such losses are accounted for in uncertainty analyses by including an energy potential loss adjustment factor in some modeled scenarios. Specifically, the modeled CH_4 production was multiplied by a factor of 0.8 to simulate 20% loss in energy potential.

The energy content of CH_4 was calculated using the factor 0.222 kWh mol^{-1} CH_4.[14,23] Electrical energy conversion efficiency is dependent on the CHP technology used and ranges from as low as 5% recovery for some steam engines to as high as 63% recovery for some fuel cells.[24] Recovery of additional electrical energy from the conversion of heat, i.e., the effective electrical efficiency, can increase energy recovery efficiency to as high as 80% for reciprocating engines and fuel cells.[24] The range of electrical energy conversion efficiency for each CHP technology used in the uncertainty analysis is provided in Table S4.a.

2.4. Uncertainty analyses

To address uncertainty in pilot-scale ABR data, measurements from both ABR reactors were subjected to uncertainty analysis in Oracle Crystal Ball (release 11.1.2.4.850) using Monte Carlo analysis (50,000 simulations). To increase confidence in measurements for organic removal and CH_4 generation, performance data from both reactor systems were normalized to m^3 wastewater treated (e.g., g COD removed per m^3 wastewater treated), aggregated, and

analyzed over 60 forecast periods in Oracle's Crystal Ball Predictor. The probable low-end, baseline, and high-end values were then incorporated into the uncertainty analysis. Uncertainty parameters for organic removal, theoretical CH_4 generation, and observed CH_4 generation are listed in Table 1. Uncertainty parameters for energy recovery from CHP and energy use in other wastewater treatment processes for comparison (e.g., CAS) are listed in Table S4.b. As both organic removal and CH_4 generation were impacted by temperature, uncertainty parameters were subset into a cold weather condition (15 ± 3 °C) and a warm weather condition (21 ± 3 °C) prior to Monte Carlo simulations. Last, as dCH_4 recovery for energy generation is not currently feasible above bench-scale,[25] a current scenario (i.e., 0% recovery) and future scenario (0 to 100% recovery, uniform distribution) were constructed. For all data, a triangular probability distribution was assumed when low-end, baseline, and high-end values were available. When only two data points were available, i.e., a low-end and high-end value, a uniform probability distribution was assumed.

3. Results & Discussion

3.1. Comparison of observed organic removal and methane generation to other sludge blanket bioreactor studies

Table 2 summarizes a comparison of ABR operating conditions (HRT, temperature, water volume, length of study), tCOD removal (%), and CH_4 generation (L) per g tCOD removed. Table 3 provides a comparison between observed and theoretical CH_4 generation, as well as projected energy generation (kWh m^{-3} wastewater treated), and energy recovery efficiency (kWh kg^{-1} tCOD removed). COD removal varied from 43% to 72% in ABRs 1 and 2 depending on the operating condition; however, observed total (gaseous and dissolved) CH_4 production (L) per g tCOD removed was less variable, with mean values ranging from 0.31 to 0.40 L CH_4 g^{-1} tCOD removed.

These results are near the theoretical limit of ~0.45 L CH_4 g^{-1} tCOD removed (adjusted from STP for temperature and pressure), or 67 to 87% conversion of tCOD to CH_4. These results are higher than reported values for UASB and UASB variants treating ≥ 1 m^3 of raw domestic wastewater under temperatures ≤ 20 °C, which have been reported to range from 0.03 to 0.25 L CH_4 g^{-1} tCOD removed, representing ~9 to 71% conversion (at STP).[26-32] Results from this study are also higher than the bench-scale ABR studies examined in Shoener et al. (2014),[14] which reported a range of 0.04 to 0.23 L CH_4 g^{-1} tCOD removed at temperatures of 30 to 35°C (Table 2).[13,33-35] The increase in observed CH_4 production per g tCOD removed is likely attributable to the long SRT observed in the pilot-scale ABRs. Estimated SRT was 45 ± 13 days for ABR 1 and 61 ± 42 days for ABR 2, which was approximately 60 to 90 times the HRT. Purposeful solids wasting was not required in either ABR, which decoupled SRT from HRT and allowed for increased removal of particulate organic matter and settled solids via degradation in the sludge bed over time. Analysis of the sludge in ABR 1 reactor compartments indicated that ≈ 1% (unpublished) of COD removed by the ABR was retained in the sludge blanket, suggesting degradation by hydrolysis and eventual conversion to methane over time. This long-term degradation likely supported the generation of additional CH_4 relative to the bench-scale ABRs Shoener et al. (2014)[14] examined in their review (listed in Table 2), which contained substantially lower sludge bed volumes and may not have experienced this phenomenon.

The theoretical energy potential in typical domestic wastewater has been estimated using bomb calorimeters to range from 4.1 kWh kg^{-1} COD to 4.9 kWh kg^{-1} COD[2,36] . However, Heidrich et al. (2011) apparently included the energy value of ammonia in the measured energy value normalized to COD, thereby overestimating the energy content from COD.[2] Energy content of COD alone has been recorded as 3.86 kWh kg^{-1} COD based on the higher heat value, and 3.47

kWh kg^{-1} COD based on the lower (or net) heat value.[1,23] Given uncertainty in domestic wastewater energy content estimates, this study conservatively estimated energy content based on the lower (or net) heat value (i.e., 3.47 kWh kg^{-1} COD). The mean potential energy production, measured in kWh per kg COD removed, between reactors and under varying operational conditions was 2.0 ± 1.2, which equates to 76 ± 20% energy recovery efficiency (compared to theoretical energy potential from COD removal adjusted from STP, ~0.45 L CH_4 g^{-1} tCOD removed) (Table 3). Despite some variation between reactors, no statistically significant difference was observed. The observed energy recovery efficiency from COD degradation in this study (76 ± 20%) and the mean potential energy production (2.0 ± 1.2 kWh kg^{-1} COD removed) exceed the values determined by Shoener et al. (2014) (1.1 to 2.0 kWh kg^{-1} COD removed with 29 to 53% energy recovery efficiency) likely due to differences in ABR operating conditions.[14] Shoener et al. (2014) examined bench-scale reactors (10 – 20 liters) operated under wastewater temperatures (30 – 35°C) higher than those commonly observed at wastewater treatment facilities, using wastewaters that are not representative of raw domestic wastewater (i.e., high-strength swine wastewater or low-strength synthetic wastewater) (Table 2).[13,14,33-35]

3.2. Comparison of theoretical and observed methane generation

Four scenarios based on organic removal were modeled for comparison to observed CH_4 generation: (1) tCOD removal; (2) tCOD removal with 20% loss of biodegradable energy potential; (3) bCOD estimated from BOD_5 measurements; (4) bCOD estimated from BOD_5 measurements with 20% loss of biodegradable energy potential. Both examined ABRs treated differing volumes of wastewater, therefore, CH_4 production was normalized to m^3 of wastewater treated for comparison. This study used BOD_5 to estimate bCOD rather than biochemical methane potential (BMP tests). Zhang et al. (2013 and 2018) used BMP tests (15 °C incubation)

to predict maximum potential CH_4 generation for an upflow anaerobic sludge blanket (UASB) with digester bioreactor system receiving influent domestic wastewater.[37,38] BMP and observed CH_4 production results from Zhang et al. (2013 and 2018) suggest that the BMP test underestimates of bCOD more than BOD_5 (discussed further in Section S.1e).[37,38] Modeled theoretical CH_4 and energy production for each scenario is shown in Table 3. Specifically, Table 3.a provides results for scenarios involving modeled CH_4 production from tCOD (scenarios 1 and 2) and Table 3.b provides results for scenarios involving CH_4 production from estimated bCOD (scenarios 3 and 4). Additionally, values for both observed total and gaseous CH_4 production (L CH_4 d^{-1} and L CH_4 m^{-3} WW treated) are displayed separately in Table 3.c. dCH_4 is accounted for in total CH_4 production but is not separately listed in Table 3 (instead found in Table S3).

Figure 1 depicts results for scenarios that most closely modeled observed CH_4 production: tCOD removal with 20% loss of biodegradable energy potential (scenario 2) and bCOD estimated from BOD_5 measurements (scenario 3). Scenario 1 significantly overestimated observed CH_4 production, while Scenario 4 significantly underestimated observed CH_4 production. Scenario 1 (tCOD removal without loss of energy potential) was expected to estimate methane generation beyond observed CH_4 because it represents an absolute maximum CH_4 production. As shown in Figure 1.A, the model based on estimated bCOD (scenario 3) underestimated CH_4 production relative to observed CH_4 measurements. In aerobic conditions bCOD can be accurately estimated from either tCOD and/or BOD_5 based on well-studied relationships; however, for anaerobic sludge blanket bioreactors, a higher fraction of the wastewater organic matter is anaerobically degraded through hydrolysis of particulate COD and settled solids in the sludge blanket and endogenous decay of cells. To predict CH_4 production in an ABR, or similar sludge blanket system, 80% of tCOD removed is supported by our analysis in scenario 2. Figure 1.A depicts the difference between mean values of observed CH_4

production and modeled CH_4 production from estimated bCOD using 95% confidence intervals (for observed production) and modeled 10^{th} and 90^{th} percentile values from the uncertainty analysis (for modeled production) for each 2°C change in wastewater temperature (14 to 26°C). A comparison of mean values of observed CH_4 and modeled CH_4 production for each 2°C temperature interval suggests that observed CH_4 production exceeded modeled CH_4 production from estimated bCOD by at least 21.4 L CH_4 m^{-3} of wastewater treated for temperatures > 16°C. Difference in means (observed minus theoretical CH_4 production) for each temperature interval (L CH_4 m^{-3} of wastewater treated) is depicted along the x-axis in Figure 1.A. The range of differences was 21 – 54 L CH_4 m^{-3} at wastewater temperatures over 16 °C, which equates to a 25 to 42% increase of observed CH_4 relative to theoretical modeled production from estimated bCOD removal. These results suggest that bCOD estimates based on BOD_5 should not be used to estimate CH_4 production.

As seen in Figure 1.B, CH_4 production modeled by tCOD with 20% loss of biodegradable energy potential (scenario 2) is a more accurate predictor of observed CH_4 production for temperatures between 16 and 24 °C. The difference in means (observed minus theoretical) are very similar for 16 – 18 °C (difference = 4.2 L CH_4 m^{-3} wastewater), 18 – 20 °C (difference = 2.9), and 20 – 22 °C (difference = -3.8). For the 22 – 24 °C temperature range, observed was greater than theoretical by a larger amount (25.6 L CH_4 m^{-3} wastewater). For the coldest (14 – 16 °C) and warmest (24 – 26 °C) temperature ranges, modeled CH_4 generation was larger. As shown in Table S.2, the number of observed CH_4 measurements was lower in the for the coldest and warmest temperature ranges examined, suggesting the model could be refined with additional measurements. Total COD measurements overestimate biochemical oxygen demand for aerobic systems due to the oxidation of all organic matter rather than aerobically biodegradable organics. The oxidation of all the organic matter by the tCOD test mimics anaerobic

biodegradation at long SRT, which includes anaerobic hydrolysis and endogenous decay in the sludge blanket. The inclusion of an energy potential loss factor (20%) improves the model by accounting for the presence of recalcitrant carbon and carbon sequestered in biomass. These factors make scenario 2 a better predictor of organic material removal by anaerobic sludge bed processes, and therefore CH_4 generation, relative to BOD_5 or bCOD estimations (i.e., scenarios 3 and 4).

CH_4 generation from anaerobic degradation of physically retained organic solids (i.e., hydrolysis and endogenous decay) in the sludge blanket has also been observed to increase the observed ratio of CH_4 produced per mass of tCOD removed in baffled anaerobic bioreactors.[17,19,39] An examination of ABR 1 before and after an increase in HRT also shows this phenomenon. When the wastewater flowrate to ABR 1 was reduced from 1738 L d^{-1} to 869 L d^{-1} after 1357 days of operation, the influent organic loading was reduced by approximately half; however, ABR 1 produced almost the same volume of CH_4, only decreasing from 164 $\pm$ 39 L CH_4 d^{-1} to 151 $\pm$ 28 L CH_4 d^{-1}. This result suggests that degradation of retained organic solids was a significant contributor to CH_4 production; despite the decrease in organic loading from the influent wastewater by approximately one-half, observed CH_4 production only decreased by ~8%.

A model of CH_4 production for anaerobic sludge blanket processes, therefore, must include a factor accounting for anaerobic activity such as hydrolysis and endogenous decay within the sludge blanket. A model based on tCOD removal, however, is a better predictor as the tCOD measurement oxidized material beyond readily biodegradable organics. Refinement to this model over time is required, especially for lower wastewater temperatures where microbial activity is suppressed and degradation in the sludge blanket may be reduced.

Figure 1. (A) Observed total CH_4 production (gaseous and dissolved) and modeled CH_4 production from estimated biodegradable COD removal versus wastewater temperature (2°C temperature intervals). **(B)** Observed total CH_4 production and modeled CH_4 production from total COD removal accounting for 20% losses versus wastewater temperature (2°C temperature intervals). For both scenarios, observed CH_4 production is colored blue; the upper and lower edges of each box represent the upper and lower 95% confidence intervals for each 2 °C temperature interval. The modeled CH_4 production from biodegradable COD removal is colored red; the upper and lower edges of each box represent the 90^{th} and 10^{th} percentile from uncertainty analysis (Monte Carlo; 50,000 simulations) respectively for each 2 °C temperature interval. For both, the dotted line represents the mean value for each 2 °C temperature interval. The region between the upper and lower edges of each box are filled in to visually depict the range between the upper and lower 95% confidence interval (for observed CH_4 production) and the 90^{th} and 10^{th} percentile from uncertainty analysis (for modeled CH_4 production). The difference in means (observed minus theoretical) for each 2 °C temperature interval is depicted on the x-axis.

3.3. Modeled energy generation from combined heat and power technologies

Figure 2 depicts results of uncertainty modeling (50,000 Monte Carlo simulations) for energy potential from observed CH_4 production (kWh m^{-3} wastewater treated) in ABRs over a range of wastewater temperatures. Results are subset into four categories: energy potential from gaseous CH_4 production under warm and cold wastewater temperatures, and energy potential from total CH_4 production (i.e., gaseous and dCH_4) under warm and cold wastewater temperatures. Energy recovery from total CH_4 production represents a future scenario as full-scale dCH_4 recovery schemes are not currently viable. Future dCH_4 recovery, therefore, was modeled using a uniform distribution ranging from 0 to 100% recovery (Table 1). All modeled values (total of 200,000) are displayed in Figure 2, which shows the variation in potential energy production at any given wastewater temperature. Modeled potential energy from gaseous CH_4 increased from a minimum value of 0.32 kWh m^{-3} (32 occurrences, temperature range = 11.1 to 16.7°C) to a maximum value of 0.78 kWh m^{-3} (65 occurrences, temperature range = 19.6 to 24.4°C). Similarly, the modeled total potential energy increases from a minimum value of 0.44 kWh m^{-3} (3 occurrences, temperature range = 12.1 to 14.6°C) to a maximum value of 1.15 kWh m^{-3} (14 occurrences, temperature range = 20.0 to 23.9°C). These results suggest that seasonal variations in wastewater temperature will impact potential energy production; however, the extent of the variation in modeled potential energy under varying temperatures will likely decrease as future studies provide more data for modeling.

Modeled energy potential from ABR-generated CH_4 represents maximum available energy. CHP technologies, however, are not 100% efficient and losses are observed in the electricity generation process. The U.S. EPA's Combined Heat and Power Partnership Catalog of CHP Technologies (U.S. EPA, 2017), which describes the state-of-the-art concerning commonly used CHP technologies, provides a range of recovery efficiencies, including electrical energy

efficiency and effective electrical efficiency (which accounts for additional electrical energy recovered from produced heat).[24] This study uses uncertainty analysis to examine the electrical energy efficiency and effective electrical energy efficiencies for five CHP technologies: reciprocating engine, steam turbine, gas turbine, microturbine, and fuel cells. The range of electrical energy efficiency and effective electrical energy efficiencies used for uncertainty analysis for each CHP technology are listed in Table S4.a. Figure 3 depicts electrical energy generation potential from each CHP technology from the uncertainty analysis for warm and cold wastewater temperatures (21 $\pm$ 3°C and 15 $\pm$ 3°C, respectively). Both the modeled current scenario (no dCH_4 recovery) and future scenarios where dCH_4 is recovered for energy generation are shown. Figure 3 also compares CHP electrical energy generation potential to the typical range of CAS energy use (i.e., 0.3 – 0.6 kWh m^{-3} wastewater treated). As shown, the fuel cell has the highest current electrical energy recovery from modeled ABR gaseous CH_4 production. Under both warm and cold temperatures, electrical energy generated from the fuel cell approaches the lower range of CAS energy use. Considering effective electrical efficiency, however, reciprocating and steam engines have the highest potential electrical energy generation and can generate enough electrical energy to power many CAS scenarios. Considering a future scenario where dCH_4 is recovered, the reciprocating engine and the steam engine may produce enough effective electrical energy to power even the most energy intensive CAS scenario.

The choice of which CHP technology to implement usually depends on factors beyond electrical or heat energy generating capability. Costs, wastewater flowrate, biogas treatment requirements, physical space, and maintenance requirements are additional considerations for WWRFs.[24,40] Microturbines, for example, provide relatively low electrical energy recovery, but may be more applicable for WWRFs treating lower wastewater flowrates.[41] Reciprocating engines are the most widely installed CHP technology in the U.S. today and are located at

51.9% of CHP sites. The gas turbine, however, generates more electrical capacity (53,320 MW or 64%), despite being at only 15.8% of CHP locations.[24] Fuel cells, which have the highest electrical efficiency (up to 63%), are still an emerging technology and are currently employed at only 2.9% of CHP locations and account for approximately 0.1% of CHP capacity in the U.S.[24]

3.4. Implications for integration of anaerobic primary treatment using ABRs into WWRFs

The current wastewater treatment paradigm centers on aerobic degradation of organics using technologies such as CAS.[1] In the near term, multiple-compartment anaerobic reactor systems for mainstream treatment of domestic wastewater can replace conventional primary treatment technologies, such as primary clarification. Conventional primary treatment typically removes 25 – 35% of BOD and 50 – 65% of TSS,[42] which is less than ABRs, which remove 50 – 70% of organics (Table 2) and 70 – 80% of TSS.[17,19,39] The additional removal of organics and suspended solids from anaerobic primary treatment using ABRs will reduce organic and suspended solids loading for downstream activated sludge treatment, which will reduce required energy use for aeration. While aeration for CAS and associated energy requirements can vary between WWRFs, energy consumption in a typical CAS process with medium strength wastewater (i.e., 430 mg COD L^{-1}) can be estimated as 1.0 kWh electrical input per kg COD removed.[43] Using this approximation and typical values for organic removal in conventional primary treatment (25 – 35%) and observed organic removal in ABRs examined in this study (Table 1), results from uncertainty analysis suggest a decrease in CAS energy use of approximately 30% when ABRs are used as primary treatment. More specifically, modeled energy use in CAS (i.e., from uncertainty analysis; Table S4) after conventional primary treatment was 0.47 $\pm$ 0.11 kWh m^{-3} wastewater treated, while energy use in CAS after anaerobic primary using ABRs was 0.29 $\pm$ 0.07 kWh m^{-3} under warm wastewater temperatures and 0.33 $\pm$ 0.08 kWh m^{-3} under cold wastewater temperatures. This result suggests that anaerobic

Figure 2. Uncertainty modeling results (Monte Carlo analysis, 50,000 simulations (200,000 data points)) for energy potential from observed CH_4 production (kWh m^{-3} wastewater treated) and wastewater temperature. Results for total energy recovered from gas and dissolved CH_4 as well as from just gas CH_4 production are depicted for comparison.

Figure 3. Electrical energy generation potential from various CHP technologies using methane generated from the anaerobic treatment of domestic wastewater using multiple-compartment reactor systems. Values were generated from uncertainty analysis (50,000 Monte Carlo simulations) in Crystal Ball based on observed CH_4. The current scenario represents energy generation potential from observed gaseous methane production. The future scenario accounts for capture of dissolved methane and subsequent conversion to electrical energy. Error bars represent the 10^{th} and 90^{th} percentile from the uncertainty analysis. The cold weather condition was defined as 15 ± 3 °C and the warm weather condition as 21 ± 3 °C. For comparison, the range of CAS electrical energy use is also shown.

primary treatment using ABRs would not only generate CH_4 for electrical energy production but would substantially decrease electrical energy requirements for CAS.

Given no apparent requirement to waste ABR sludge, the requirement to digest and stabilize sludge normally removed by conventional primary treatment would be eliminated. The reduced organic loading to CAS would also likely result in a reduced volume of waste activated sludge produced. Follow-on sludge digestion and stabilization requirements in a WWRF employing anaerobic primary treatment could, therefore, be substantially reduced. Reduction in sludge processing requirements would likely further result in a reduced facility physical footprint and additional reduction in energy use from sludge processing equipment, such as sludge dewatering and thickening. While many processes may be reduced in size due to the use of ABRs, the ABRs themselves may require more physical space than commonly used primary sedimentation basins, which typically have lower hydraulic retention times (i.e., 1.5 to 2.5 hours) and corresponding lower volumes.[1] While additional analysis outside the scope of this study is required to quantify footprint modifications, Figure 4 provides a comparative COD mass balance between a typical WWRF with conventional primary treatment and CAS and a WWRF with anaerobic primary treatment using ABRs with CAS. As shown in Figure 4.a, approximately 35% of COD from the influent wastewater goes to CHP post anaerobic digestion, of which approximately 8.5% is recovered as electrical energy and 16% is converted to heat. An additional 25% of influent COD goes to follow-on solids management processes after anaerobic digestion. In comparison, approximately 62% of the influent COD goes to CHP when anaerobic primary treatment and anaerobic digestion of waste activated sludge are employed, of which approximately 15% is converted to electrical energy via CHP and 28.5% is converted to heat. Further, only 20% of the influent COD goes to anaerobic sludge digestion, suggesting that the digester capacity could be reduced by approximately one-third, and only 8% of COD goes to follow-on solids management processes after anaerobic digestion (Figure 4.b).

Figure 4. COD mass balances for: (a) conventional activated sludge with primary treatment (i.e., gravitational settling), anaerobic digestion, and CHP; (b) conventional activated sludge with anaerobic primary (i.e., ABR), anaerobic digestion of waste activated sludge, and CHP; (c) anaerobic primary with an ABR coupled to an anaerobic secondary treatment process with CHP. COD mass balance for configuration (a) was adapted from Tchobanoglous et al. (2003), WEF (2007), and Wan et al (2016). COD mass balance for configurations (b) and (c) were adopted from observed COD removal in anaerobic primary, Tchobanoglous et al. (2003) and the performance of AnMBRs for anaerobic secondary (Smith et al. 2012). Configuration (b) does not require two separate CHP processes; however, two are displayed for visual simplicity. Dissolved CH_4 was assumed to move from the ABR to secondary treatment processes (e.g., conventional activated sludge or anaerobic secondary). For configuration (c), dissolved CH_4 was assumed removed via stripping and is included in the COD fraction transferred to CHP.

3.5. Path forward for anaerobic primary treatment using ABRs

While anaerobic primary treatment using ABRs is a promising energy-generating technology, further research is required prior to widespread implementation of full-scale systems. First, pilot- or full-scale anaerobic demonstrations coupled with aerobic secondary treatment, i.e., conventional activated sludge, need to be constructed and anaerobically recalcitrant COD removal characterized to determine if discharge standards are achieved. More promising than ABRs coupled with CAS is a treatment configuration coupling ABRs with a subsequent low-complexity anaerobic secondary treatment technology, such as an AFFR; however, further research is needed before full-scale low-complexity demonstrations anaerobic technologies are viable. Figure 4.c provides a generic COD mass balance for an ABR coupled to anaerobic secondary treatment process. Here, approximately 90% of COD from the influent wastewater goes to CHP with 21% conversion to electrical energy and 42% conversion to heat. This

paradigm more than doubles the COD converted to CH_4 and the anticipated electrical energy production.

Second, any paradigm centered on anaerobic treatment of wastewater for carbon removal and CH_4 generation will require further treatment for the constituents of anaerobic effluents, which include ammonia, phosphorus, hydrogen sulfide, and dCH_4.[44] Aerobic secondary, e.g. CAS, with anoxic denitrification is a common method for removing nitrogen; however, this approach can be energy-intensive.[8] Anoxic denitrification could, however, have the tangential benefit of using dCH_4 as an electron acceptor for denitrification, thereby reducing CH_4 volatilization to the atmosphere and reducing greenhouse gas emissions. Aerobic methanotrophic activity in an aerobic secondary process would also likely remove the majority of dCH_4 prior to volatilization.[9,45,46] A possible low-energy solution that simultaneously removes carbon and nitrogen is partial nitritation coupled with anammox; however, full-scale mainstream demonstrations to date are limited.[47,48] Several recent studies discuss approaches to biological and mechanical removal of dCH_4 from anaerobic effluents.[17,25,49] Such approaches include biogenic capture with the downflow hanging sponge, membrane degasification, and dCH_4 recovery for energy generation using microbial fuel cells;[25,50-52] however, no approach has been demonstrated to be energetically or economical viable at full-scale and none are ready for mainstream wastewater treatment. Recovery of dCH_4 is imperative as volatilization to the atmosphere represents both a loss of energy and substantial increase in greenhouse gas emissions.

Third, practical barriers to widespread implementation must be addressed. Several studies have identified barriers to the beneficial use of biogas from anaerobic digestion of primary and waste activated sludge, which may be applicable to implementation of ABRs for anaerobic primary treatment with CHP.[40,53] Identified barriers were mainly economic in nature (e.g., capital costs,

operations and maintenance costs, limited availability of grants or loans), but technical (e.g., concerns over biogas cleaning requirements), social (e.g., lack of community interest), and regulatory (e.g., permitting requirements) barriers were also identified.[40,55] While barriers are likely to vary by location, thorough study of each barrier category (i.e., economic, technical, social, and regulatory) will be required prior industry acceptance.[55]

4. Conclusions

Observed CH_4 generation from two pilot-scale ABRs operating for more than 2400 total days indicates that reactors produce between 0.31 and 0.40 L CH_4 per g tCOD removed, which equates to potential energy production from gaseous CH_4 of 2.0 $\pm$ 1.2 kWh per kg COD removed or 76 $\pm$ 20% energy recovery efficiency. Observed CH_4 production was most closely modeled by using tCOD measurements to predict CH_4 generation. Observed CH_4 production was also higher than values reported for pilot-scale or larger UASBs and bench-scale ABRs in other studies, likely due to degradation of particulate COD and settled solids as well as endogenous decay in the sludge blanket over time. Scenario modeling using Monte Carlo simulations suggests that energy generated from ABR gaseous CH_4 via CHP with heat recovery is enough to power coupled CAS systems, but that capture of dCH_4 is required to enhance energy generation. Results of this study suggest that use of ABRs as biologically enhanced primary treatment with solids digestion for CAS systems, or as part of future complete anaerobic systems, is a viable wastewater treatment paradigm. The replacement of conventional primary treatment with multiple-compartment anaerobic bioreactors would enhance onsite energy-generating potential and reduce solids production at wastewater reclamation facilities.

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Table 1. Uncertainty parameters for Monte Carlo Simulation. Theoretical and observed values were aggregated across reactor systems over two wastewater temperature ranges: warm (21 ± 3°C) and cold (15 ± 3°C).

(a) Organic Removal and Theoretical Methane Generation Values

Uncertainty Parameter	Units	Distribution	Temperature	Baseline Value	Low Value	High Value
g tCOD removed d^{-1}	g tCOD d^{-1}	Triangular	Warm Cold	393.5 329.2	107.4 36.2	679.6 622.2
% COD removal	%	Triangular	Warm Cold	57 51	47 42	66 61
g tCOD removed m^{-3} WW	g tCOD m^{-3}	Triangular	Warm Cold	419.8 355.9	97.5 29.7	742.2 682.0
tCOD-to-BOD_5 ratio	g tCOD g^{-1} BOD_5	Triangular	Warm Cold	2.73 2.47	2.19 2.02	3.27 2.92
BOD rate constant (k)	d^{-1}	Triangular	Warm/Cold	0.20	0.16	0.24
BOD_5-to-bCOD ratio	g BOD_5 g^{-1} bCOD	Triangular	Warm/Cold	0.63	0.54	0.70
L CH_4 g^{-1} bCOD removed	L CH_4 g^{-1} bCOD	Triangular	Warm Cold	0.46 0.45	0.45 0.44	0.47 0.46
Organic to CH_4 conversion	Efficiency (%)	Uniform	Warm/Cold	81	81	95
Air Temperature	K	Triangular	Warm Cold	295.4 288.4	292.6 285.2	298.2 291.7
Dissolved CH_4 Recovery Future Scenario	%	Uniform	Warm/Cold	0	0	100

(b) Methane Generation Values from Crystal Ball Predictor

Uncertainty Parameter	Units	Distribution	Temperature	Baseline Value	Low Value	High Value
Gas CH_4 per m^3 WW	L m^{-3} WW	Triangular	Warm	85.6	66.0	105.3
			Cold	72.0	42.6	101.3
Dissolved CH_4 per m^3 WW	L m^{-3} WW	Triangular	Warm	38.5	26.9	50.1
			Cold	31.8	15.7	47.9
Total CH_4 per m^3 WW	L m^{-3} WW	Triangular	Warm	124.5	95.9	153.0
			Cold	103.8	59.4	148.2
Energy from CH_4 Gas	kWh m^{-3} WW	Triangular	Warm	0.64	0.49	0.78
			Cold	0.53	0.32	0.75
Energy Potential (Gas & Dissolved)	kWh m^{-3} WW	Triangular	Warm	0.93	0.71	1.15
			Cold	0.77	0.44	1.09

Table 2. Characteristics and operational parameters for multiple-compartment anaerobic reactors considered in this study. Characteristics are compared to the four reactors considered in Shoener et al. (2014) in the lower portion of the table.[14] Where applicable, mean values ± one standard deviation are shown.

Reactor	Substrate	Configuration	HRT (h)	Temperature (°C)	Reactor Volume (L)	Study Length (d)	tCOD Removal (%)	L CH_4 g^{-1} tCOD[a]
ABR 1[b]	Raw DWW	4-compart.	12	12-23	869	1357	43 ± 13	0.31 ± 0.19
ABR 1	Raw DWW	4-compart.	24	12-23	869	383	72 ± 8	0.34 ± 0.09
ABR 2[c]	Raw DWW	3-compart.	24	11-24	720	390	43 ± 20	0.31 ± 0.29
ABR 2[c]	Raw DWW	4-compart.	27	11-24	810	330	54 ± 15	0.40 ± 0.24

Comparison to studies examined in Shoener et al. (2014)

Study	Substrate	Configuration	HRT	Temperature (°C)	Reactor Volume (L)	Study Length (d)	tCOD Removal (%)	L CH_4 g^{-1} tCOD
1	Swine WW Supernatant	Horizontal Baffled (6 total)	2.5 d	30 ± 1	20	~180	75	0.17
2	Whole Swine Wastewater	2 Chamber	15 d	35	15	~300	69	0.04
3	Whole Swine Wastewater	3 Chamber	15 d	35	15	~300	62	0.04
4	Low Strength Synthetic WW	Hanging baffles (45°)	6-20 h	30[d]	10	592	>90	0.18 - 0.23[e]

Studies: (1) Yang & Moengangongo (1987);[31] (2) & (3) Boopathy & Sievers (1991);[32] (4) Gopala Krishna et al. (2008)[13] & Gopala Krishna et al. (2009)[33]

[a] Liters of CH_4 produced includes both gaseous and dissolved CH_4

[b] COD removal and methane generation for ABR 1 with a 12-hour HRT is further described in Hahn & Figueroa (2015).[18]

[c] COD removal and methane generation for ABR 2 is further described in Pfluger et al. (2018).[20]

[d] Study reported that the reactor was housed in a chamber held at a constant temperature of 30°C, but that the influent wastewater was between 20 and 32°C.

[e] CH_4 production per g COD removed varied with HRT.

Table 3. Theoretical and observed methane production in the anaerobic reactors examined in this study. For parts (a) and (b) results provided are median values from the uncertainty analysis (Monte Carlo Analysis; 50,000 simulations). 10th and 90th percentile values are depicted in brackets. Maximum calculated values are compared to values accounting for 20% loss in chemical energy potential as suggested by McCarty et al. (2011).[5]

(a) Theoretical total methane and energy production calculated from total COD removal.

Reactor	HRT (h)	L CH_4 d^{-1} (no loss)	L CH_4 d^{-1} (20% loss)	L CH_4 m^{-3} WW treated (no loss)	L CH_4 m^{-3} WW treated (20% loss)	kWh m^{-3} WW treated (no loss)	kWh m^{-3} WW treated (20% loss)
ABR 1	12	120 [111, 130]	96 [89, 104]	69 [64, 75]	55 [51, 60]	1.36 [1.26, 1.47]	1.19 [1.14, 1.22]
ABR 1	24	174 [151, 188]	138 [129, 150]	200 [186, 217]	160 [149, 173]	1.94 [1.81, 2.10]	1.66 [1.55, 1.79]
ABR 2	24	107 [97, 119]	86 [78, 95]	150 [135, 166]	119 [108, 132]	1.20 [1.09, 1.34]	0.96 [0.87, 1.07]
ABR 2	27	105 [95, 116]	84 [76, 93]	132 [120, 146]	107 [97, 118]	1.29 [1.41, 1.43]	1.03 [0.94, 1.14]

(b) Theoretical total methane and energy production calculated from estimated biodegradable COD removal.

Reactor	HRT (h)	L CH_4 d^{-1} (no loss)	L CH_4 d^{-1} (20% loss)	L CH_4 m^{-3} WW treated (no loss)	L CH_4 m^{-3} WW treated (20% loss)	kWh m^{-3} WW treated (no loss)	kWh m^{-3} WW treated (20% loss)
ABR 1	12	70 [61, 80]	56 [49, 64]	40 [35, 46]	32 [28, 37]	0.79 [0.69, 0.90]	0.69 [0.65, 0.72]
ABR 1	24	101 [88, 115]	80 [71, 92]	116 [102, 133]	93 [82, 106]	1.13 [1.00, 1.29]	0.91 [0.80, 1.04]
ABR 2	24	62 [52, 74]	50 [42, 59]	87 [72, 103]	69 [58, 82]	0.70 [0.59, 0.84]	0.56 [0.47, 0.67]
ABR 2	27	61 [51, 73]	49 [41, 58]	77 [65, 91]	62 [52, 73]	0.75 [0.63, 0.89]	0.60 [0.51, 0.71]

(c) Observed methane production (total and gas), projected energy generation, and projected energy recovery efficiency, over the course of each study period (mean values $\pm$ one standard deviation). Total CH_4 is defined as the sum of gaseous and dissolved CH_4.

Reactor	HRT	L CH_4 d^{-1} (Total)	L CH_4 m^{-3} WW treated (Total)	kWh m^{-3} WW treated (Total)	L CH_4 d^{-1} (Gas)	L CH_4 m^{-3} WW treated (Gas)	kWh m^{-3} WW treated (Gas)	kWh kg^{-1} tCOD removed	Energy recovery efficiency (%) (tCOD removal)
ABR 1	12 h	164 ± 39	95 ± 23	0.7 ± 0.2	118 ± 28	68 ± 16	0.5 ± 0.1	2.4 ± 1.4	67 ± 22
ABR 1	24 h	151 ± 28	175 ± 32	1.3 ± 0.2	100 ± 18	116 ± 20	0.9 ± 0.2	1.5 ± 0.4	76 ± 20
ABR 2	24 h	76 ± 34	106 ± 47	0.8 ± 0.4	54 ± 24	75 ± 34	0.6 ± 0.3	1.4 ± 1.3	68 ± 18
ABR 2	27 h	83 ± 23	115 ± 33	0.9 ± 0.3	59 ± 18	82 ± 24	0.6 ± 0.2	2.5 ± 1.2	87 ± 20
All reactors	N/A	109 ± 52	115 ± 47	0.9 ± 0.4	76 ± 36	80 ± 31	0.6 ± 0.2	2.0 ± 1.2	76 ± 20

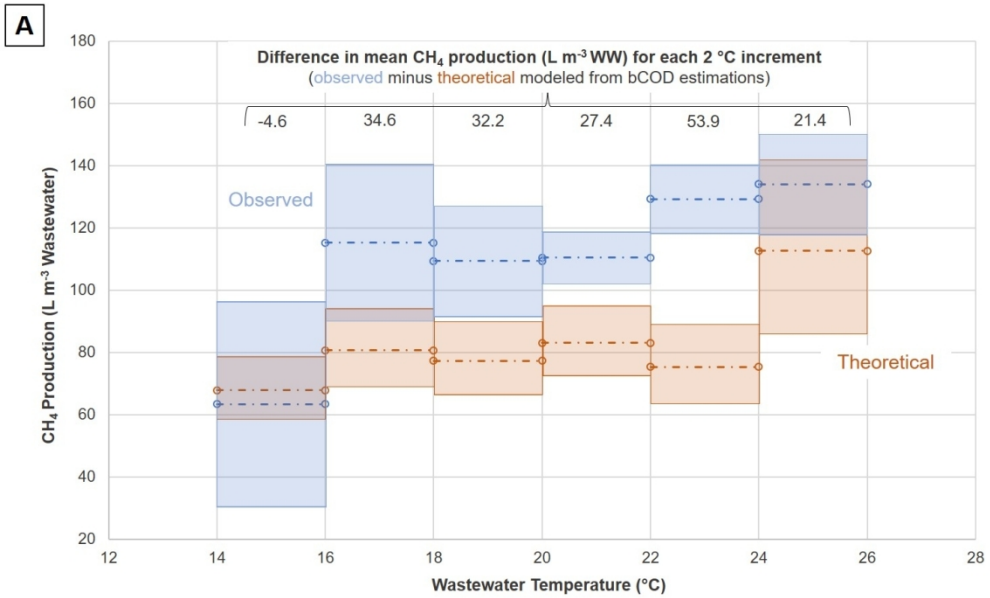

Figure 1. (A) Observed total CH4 production (gaseous and dissolved) and modeled CH4 production from estimated biodegradable COD removal versus wastewater temperature (2°C temperature intervals).

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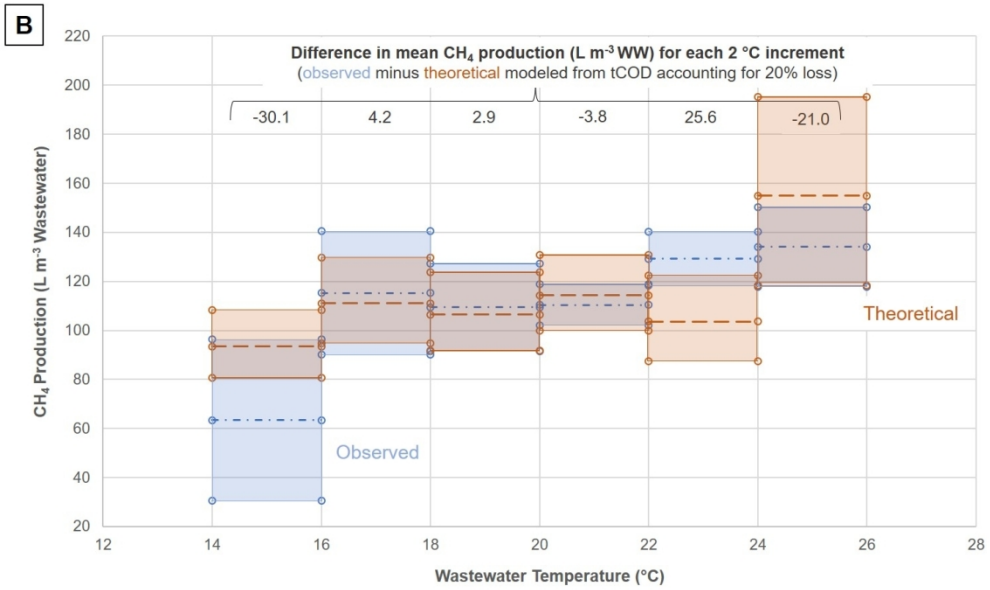

Figure 1. (B) Observed total CH4 production and modeled CH4 production from total COD removal accounting for 20% losses versus wastewater temperature (2°C temperature intervals). For both scenarios, observed CH4 production is colored blue; the upper and lower edges of each box represent the upper and lower 95% confidence intervals for each 2 °C temperature interval. The modeled CH4 production from biodegradable COD removal is colored red; the upper and lower edges of each box represent the 90th and 10th percentile from uncertainty analysis (Monte Carlo; 50,000 simulations) respectively for each 2 °C temperature interval. For both, the dotted line represents the mean value for each 2 °C temperature interval. The region between the upper and lower edges of each box are filled in to visually depict the range between the upper and lower 95% confidence interval (for observed CH4 production) and the 90th and 10th percentile from uncertainty analysis (for modeled CH4 production). The difference in means (observed minus theoretical) for each 2 °C temperature interval is depicted on the x-axis.

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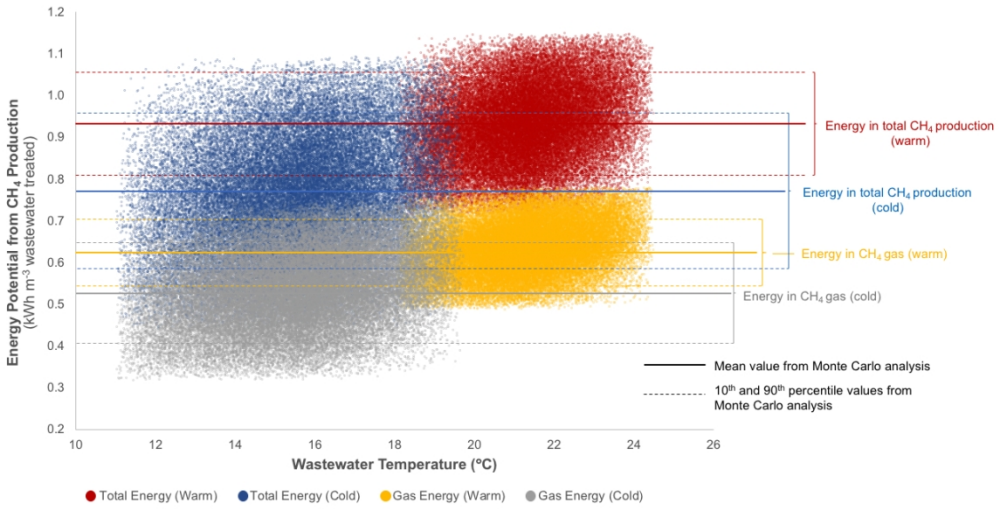

Figure 2. Uncertainty modeling results (Monte Carlo analysis, 50,000 simulations (200,000 data points)) for energy potential from observed CH4 production (kWh m-3 wastewater treated) and wastewater temperature. Results for total energy recovered from gas and dissolved CH4 as well as from just gas CH4 production are depicted for comparison.

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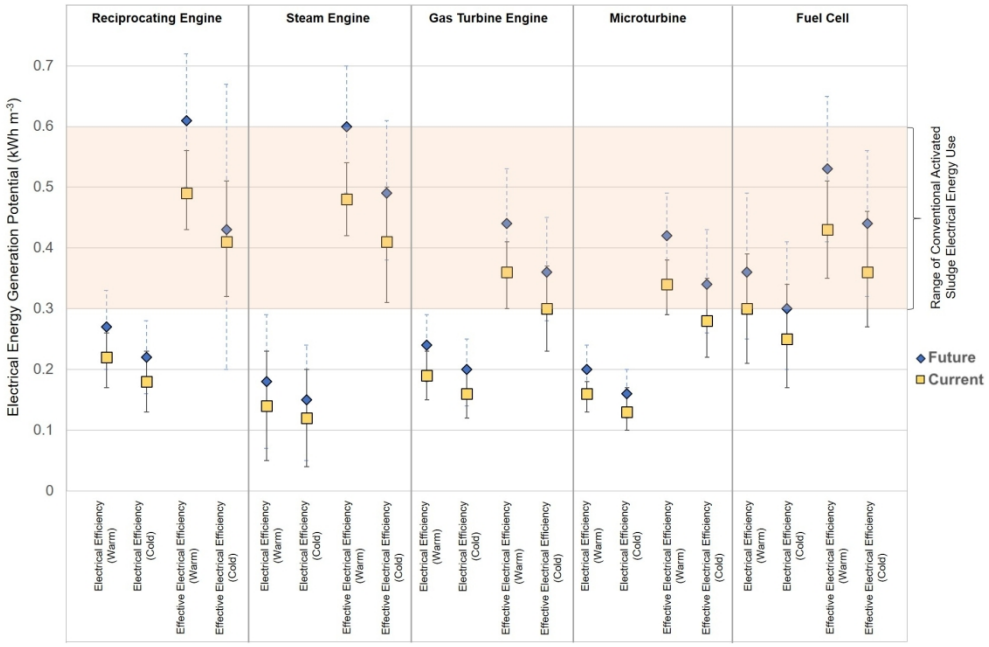

Figure 3. Electrical energy generation potential from various CHP technologies using methane generated from the anaerobic treatment of domestic wastewater using multiple-compartment reactor systems. Values were generated from uncertainty analysis (50,000 Monte Carlo simulations) in Crystal Ball based on observed CH4. The current scenario represents energy generation potential from observed gaseous methane production. The future scenario accounts for capture of dissolved methane and subsequent conversion to electrical energy. Error bars represent the 10th and 90th percentile from the uncertainty analysis. The cold weather condition was defined as 15 ☐ 3 ☐C and the warm weather condition as 21 ☐ 3 ☐C. For comparison, the range of CAS electrical energy use is also shown.

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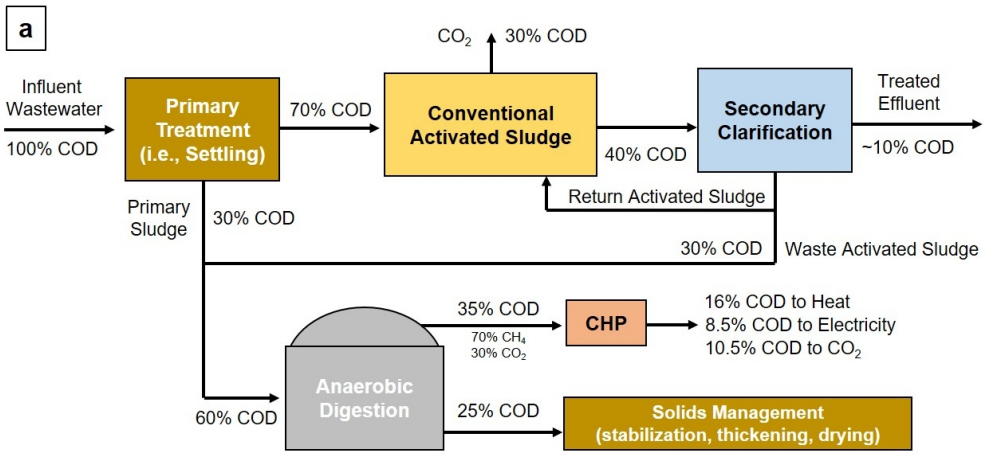

Figure 4. COD mass balances for: (a) conventional activated sludge with primary treatment (i.e., gravitational settling), anaerobic digestion, and CHP

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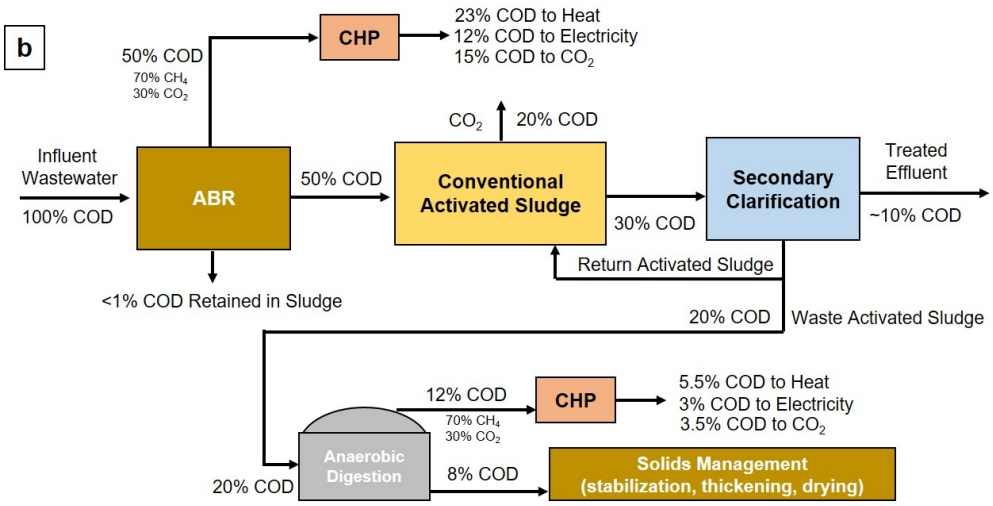

Figure 4. (b) conventional activated sludge with anaerobic primary (i.e., ABR), anaerobic digestion of waste activated sludge, and CHP

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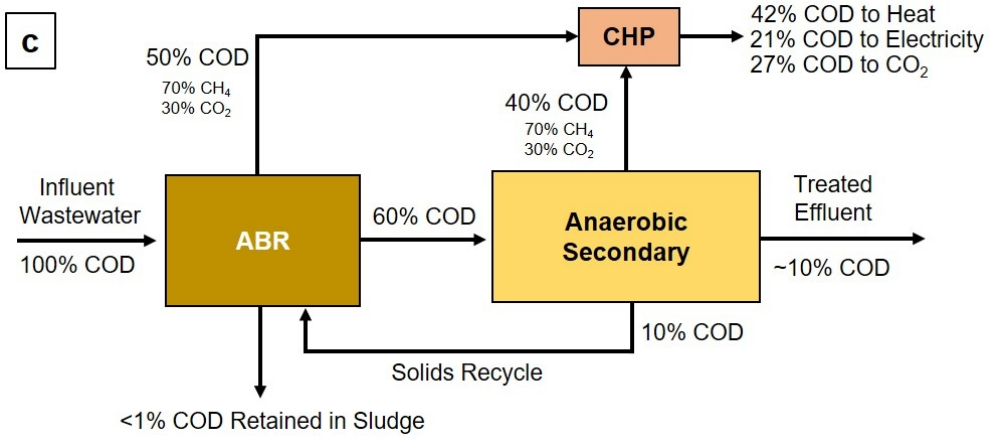
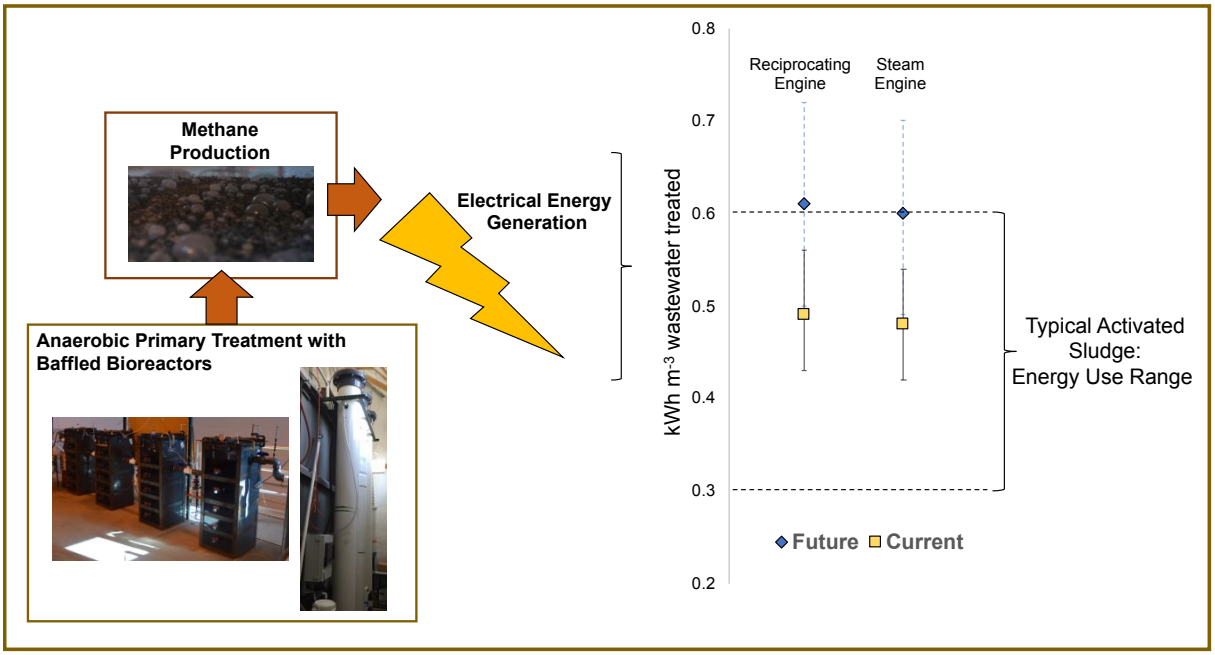


Figure 4. (c) anaerobic primary with an ABR coupled to an anaerobic secondary treatment process with CHP. COD mass balance for configuration (a) was adapted from Tchobanoglous et al. (2003), WEF (2007), and Wan et al (2016). COD mass balance for configurations (b) and (c) were adopted from observed COD removal in anaerobic primary, Tchobanoglous et al. (2003) and the performance of AnMBRs for anaerobic secondary (Smith et al. 2012). Configuration (b) does not require two separate CHP processes; however, two are displayed for visual simplicity. Dissolved CH4 was assumed to move from the ABR to secondary treatment processes (e.g., conventional activated sludge or anaerobic secondary). For configuration (c), dissolved CH4 was assumed removed via stripping and is included in the COD fraction transferred to CHP.

168x76mm (150 x 150 DPI)

Table of Contents Entry



TOC Text: Modeled electrical energy generation from anaerobic primary treatment of domestic wastewater with baffled bioreactors. Energy generation from methane production exceeded energy use by conventional activated sludge in some scenarios.