Selecting an Advanced Anaerobic Digestion Configuration and Biogas Management Strategy for the City of Tampa

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The City of Tampa (city) owns and operates the Howard F. Curren Advanced Wastewater Treatment Plant (plant). The plant is currently permitted for 96 mil gal per day (mgd) average annual daily flow (AADF) and operates with an AADF of approximately 60 mgd. Liquid treatment includes primary clarification, followed by a high-rate activated sludge process. Solids processing consists of secondary sludge gravity thickening, conventional mesophilic anaerobic digestion, belt filter press dewatering, and a rotary drum drying facility.

The rotary drum drying facility has not been operated since 2010 due to higher operational costs associated with production of a Class AA pelletized biosolids, as compared to either a Class B dewatered cake land application or dewatered cake landfill disposal. Biogas can fuel boilers for digester heating, with the excess gas flared, or can be routed to a combined heat and power (CHP) system for electrical power generation and digester heating through engine heat recovery.

Since much of the facility's infrastructure is reaching the end of its service life, the city has programmed comprehensive renewal/replacement upgrades. To that end, the city has commissioned a phased master plan to assess plant condition and performance, identify and evaluate enhanced treatment options, develop conceptual designs of recommended upgrades, and prioritize implementation.

A pre-existing process schematic is provided in Figure 1.

When the city commissioned a 20-year master plan for the plant to address renewal and replacement of aged facilities, the following treatment process evaluations were also included:

1. Liquid stream alternatives to reduce operational costs, such as methanol use, and improve treatment efficiency.
2. Conversion to advanced digestion processes to maximize solids destruction and biogas production for beneficial reuse.
3. Feasibility of energy and heat recovery from excess digester gas, combined heat and power, and renewable compressed biogas for fueling of the city's compressed natural gas (CNG) fleet vehicles.

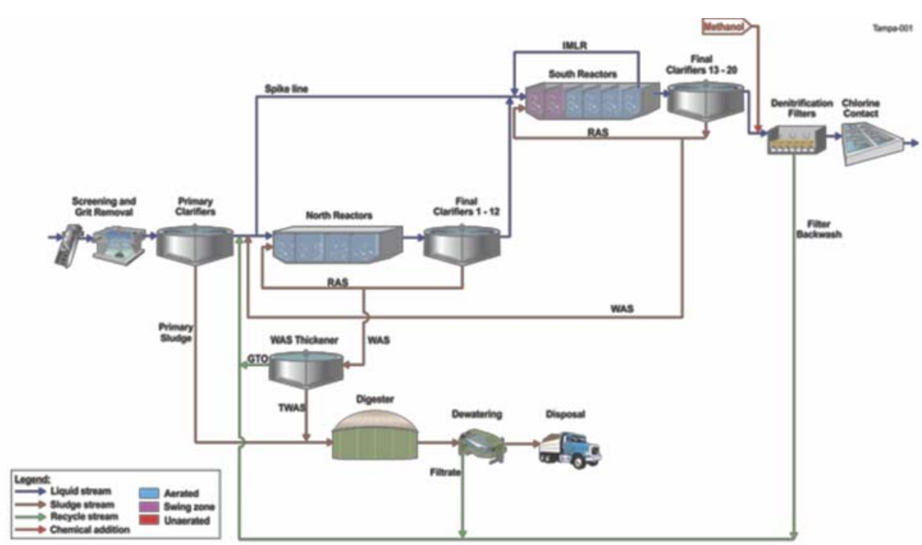

Figure 1. Pre-Existing Process Schematic

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Methodology

The preliminary evaluation of digestion and biogas recovery options consisted of identifying potential options, quantifying solids production projections, preliminary sizing of unit processes, developing mass balance calculations, preliminary facility layouts, and calculating comparative life cycle costs for each option.

Solids treatment options that were evaluated included:

- Upgraded conventional mesophilic anaerobic digestion (MAD)
- Conversion to temperature-phased anaerobic digestion (TPAD)
- Conversion to acid-gas mesophilic digestion (AGMD)
- Addition of thermal hydrolysis pretreatment (THP) to upgraded MAD (THP+MAD)

Biogas energy recovery options included:

- Direct digester heating by hot water boilers and heat exchangers, with flaring of excess gas.
- Replacement of the aged combined CHP system, including heat recovery, to produce electrical energy and capture thermal energy.
- Use as renewable natural gas (RNG) to replace the CNG currently purchased for the city's solids waste and bus vehicle fleets.

Digestion and biogas recovery options were evaluated for two liquids process scenarios:

1. Optimize the existing high-rate activated sludge process (low solids retention time [SRT], greater sludge production, higher volatile content, and higher gas yield).
2. Convert to a parallel Modified Ludzack-Ettinger (MLE) process (higher SRT, lower sludge production, lower volatile content, and lower gas yield).

Results: Advanced Digestion Alternatives

Quantify Solids Production

A GPS-X® process model was developed to predict treatment performance and solids production for both liquid stream alternatives.

Table 1 summarizes the projected long-term organic loading to the digesters for the selected liquid stream alternative (Alternative 1: Optimize existing high-rate activated sludge process).

Table 2 presents GPS-X process modeling results of predicted digestion performance based on the sludge production rates and long-term biological nutrient removal (BNR) process changes. Under these baseline conditions, annual average volatile solids destruction is expected to approximate 58 percent.

Alternative 1: Baseline Maintain/Upgrade Mesophilic Anaerobic Digestion Process

In the baseline condition, existing digesters would continue to operate in a conventional mesophilic mode, with operating temperatures of 95 to 100˚F.

Smaller digesters 1 through 4 were constructed in the 1950s, digester 5 was constructed in the 1970s, and larger digesters 6 and 7 were constructed in the 1980s. Structural analysis of the oldest digesters indicates that concrete tanks can be reused in planned upgrades. A mechanical equipment condition assessment concluded that most digester covers, and all pumping, mixing, heating, and gas handling equipment, should be replaced.

Alternative 2: Conversion to Temperature-Phased Anaerobic Digestion

This alternative evaluates converting the conventional mesophilic anaerobic digestion process into a TPAD configuration, which consists of thermophilic digestion (131 to 140°F), followed in series by mesophilic digestion (95 to 100°F). In temperature-phased mode, thickened waste activated sludge (TWAS), plus primary sludge (PS), would be fed to the thermophilic digesters, and partially digested sludge from the

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Table 1. Projected Plant Anaerobic Digester Long-Term Organic Loads

Parameter	Current Annual Average	Future Annual Average	Future Maximum Month
Plant Influent (mgd)	60.0	80.0	112.9
Primary Clarifiers			
Primary Total Suspended Solids (TSS) Removal	60%	60%	60%
TWAS+PS (Digester Feed)			
Total Solids (TS) (ppd)	106,000	147,000	185,000
Volatile Content (%)	85%	85%	86%
Volatile Solids (ppd)	90,700	126,000	158,000
Flow (mgd)	0.324	0.446	0.560

Table 2. Projected Plant Anaerobic Digester Performance

Parameter	Current Annual Average	Future Annual Average	Future Maximum Month
Plant Influent (mgd)	60.0	80.0	112.9
Primary Digesters in Service	7	7	6
Hydraulic Retention Time (HRT)	28.5	20.7	12.1
Minimum Volume (15-day HRT)	4.860	6.479	9.144
Volatile Solids Reduction (%)	58%	58%	55%
Biogas Flow Total (cfm)	615	832	993
Total CH_4 Gas Flow (cfm)	367	500	605
Dewatered Cake Load (ppd) TS	46,500	65,100	86,000

Table 3. Anaerobic Digester Volatile Solids Reduction Parameters

Parameter	Mesophilic	TPAD
Operating Temperature (°F/°C)	95.0 / 35.0	131.0 / 55.0
Waste Activated Sludge (WAS) Volatile Solids Reduction (VSR_{MAX})	58%	60% (+3%)
Methane Production (cfm)	367	378 (+3%)

Table 4. Minimum Hydraulic Retention Time for Temperature-Phased Anaerobic Digestion (Days)

Parameter	Current Annual Average	Future Annual Average	Future Maximum Month
Thermophilic Minimum HRT	10.0	7.5	5.0
Thermophilic Minimum HRT	20.0	15.0	10.0
Total Minimum HRT	30.0	22.5	15.0

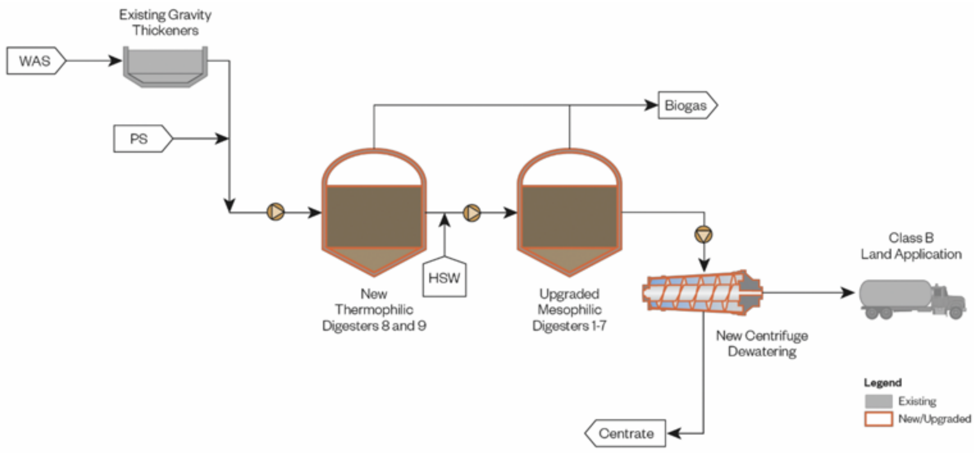

Figure 2. Solids Process Schematic: Temperature-Phased Anaerobic Digestion

Figure 3. Site Plan: Proposed Temperature-Phased Anaerobic Digestion Facilities

Table 5. Anaerobic Digester Volatile Solids Reduction Parameters

Parameter	Mesophilic	Acid-Gas-Phased
WAS VSR_{MAX}	58%	60% (+3%)
Methane Production (cfm)	367	378 (+3%)

Table 6. Minimum Hydraulic Retention Time for Acid-Gas-Phased Anaerobic Digestion (Days)

Parameter	Annual Average Loading	Maximum Month Loading	Maximum Week Loading
Acid-Phase Maximum HRT	2.0	2.0	2.0
Total (Acid+Gas) Minimum HRT	20.0	15.0	10.0

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thermophilic digesters would be transferred to the mesophilic digesters. A raw fats, oils, and grease (FOG) stream would be routed directly to the second-phase mesophilic digesters. When implemented in other facilities, temperature-phased operation has increased the degradable fraction of volatile solids and has also increased digestion reaction rates. Table 3 summarizes the differences in volatile solids reduction between mesophilic and thermophilic anaerobic digesters.

These parameters indicate that thermophilic conditions promote faster and more-complete degradation than mesophilic conditions, resulting in an increase in both volatile solids reduction and digester gas production. The minimum digester HRT required for temperature-phased operation is presented in Table 4.

Based on these HRT criteria, a minimum of two operating thermophilic digesters and six existing operating mesophilic digesters would be required to meet future organic loading conditions (80-mgd sludge production). In addition to the eight operating digesters, a standby digester would be required for "N+1" reliability; therefore, conversion to a TPAD configuration would require a total of nine digesters, including the seven existing digesters and construction of two new thermophilic digesters (minimum total volume of 6.1 mil gal). Key design criteria for the new thermophilic digesters include:

- Cast-in-place concrete construction (to meet structural and temperature insulation criteria)
- Fixed digester covers (for odor control)
- Gas mixing systems (similar to existing digesters)

A new thermophilic digestion process equipment building would also be constructed to house thermophilic-to-mesophilic transfer pumps, heated sludge recirculation pumps, heat exchanger units, and a sludge heat recovery system. The proposed TPAD facilities are shown in Figures 2 and 3.

For maximum-month loading conditions, with one of the two thermophilic digesters out of service, thermophilic residence time meets the minimum recommended HRT of five days. Similarly, with one of the largest mesophilic digesters out of service, mesophilic residence time meets the minimum recommended HRT of 10 days.

A sludge heat recovery system (sludge-to-sludge heat exchangers) would be provided in the thermophilic digester control building to transfer (recover) excess heat from the ther-

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mophilic sludge to "preheat" TWAS+PS feed to the thermophilic digesters and cool thermophilic sludge before it enters the second-stage mesophilic digesters. For the temperature-phased anaerobic digestion alternative, the necessary improvements, in addition to those included for the baseline digestion facilities, include:

- Two new temperature-phased digesters 8 and 9, including gas-holding covers, gas safety equipment, mixing systems, electrical, and instrumentation and control (I&C).
- One new digester building D, including thermophilic sludge transfer pumps, heat exchanger equipment, heating pumps, waste gas burners, gas safety equipment, piping (sludge, gas, water and fuel), electrical, and I&C.

Alternative 3: Conversion to Acid-Gas-Phased Anaerobic Digestion

This section evaluates converting the conventional mesophilic anaerobic digestion process into an acid-gas-phased anaerobic digestion (AGMD) configuration, which consists of acid-phase digestion, where shorter detention times favor the proliferation of acidogenic organisms that produce volatile fatty acids, while suppressing methanogenic growth (pH remains in the weakly acidic range of 5 to 6). This is followed in series by gas-phase digestion, where longer detention times allow the methanogenic organisms to grow.

In the acid-gas-phased mode of operation, TWAS+PS would be fed to the acid-phase digester, where partially digested sludge from the acid-phase digester would be transferred to the gas-phase digesters; a raw FOG stream would be routed directly to the gas-phase mesophilic digesters. When implemented in other facilities, acid-gas-phased operation has increased the degradable fraction of volatile solids and has also increased digestion reaction rates. Table 5 summarizes the differences between mesophilic and acid-gas-phased anaerobic digesters.

The two-phase acid-gas digestion process was developed to provide ideal growth conditions for acid- and gas-producing organisms. Separation of acid and gas phases was found to improve volatile solids reduction, while reducing retention time requirements. The minimum digester HRT required for acid-gas-phased operation is presented in Table 6.

Based on these HRT criteria, a minimum of one operating acid-phase digester and five existing operating mesophilic digesters would be required to meet future organic loading conditions (80-mgd sludge production). A standby digester would be required for "N+1" reliability. Digesters 1 and 2 would be configured to operate as either an acid or a gas reactor. The size of the smaller existing digesters is ideal for use as acid reactors to meet the short two-day HRT; therefore, conversion to an AGMD configuration would not require additional digesters, but rehabilitation of the seven existing digesters. The proposed AGMD facilities are shown in Figures 4 and 5.

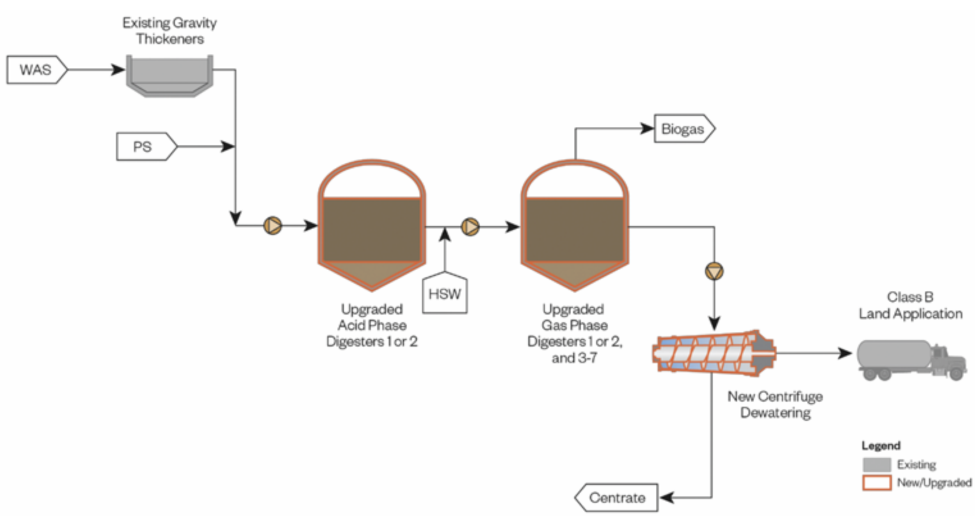

Figure 4. Solids Process Schematic: Acid-Gas Mesophilic Digestion

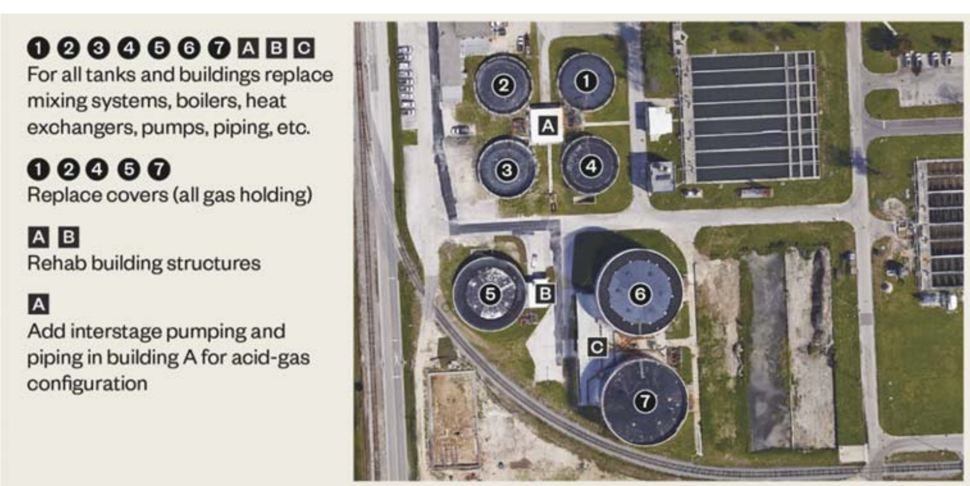

Figure 5. Site Plan: Proposed Acid-Gas Mesophilic Digestion Facilities

Alternative 4: Addition of Thermal Hydrolysis Pretreatment to Baseline Digestion

This section evaluates the addition of THP to the conventional mesophilic anaerobic digestion process configuration. The THP could be added prior to anaerobic digestion at the plant. The process would significantly increase volatile solids reduction across the digesters, reduce postdigested sludge mass, and improve postdigested sludge dewaterability, resulting in much lower hauling costs. Because THP reduces WAS viscosity, it's expected that the anaerobic digesters could be operated with a feed concentration of 8 to 10 percent TS. Increasing the digester feed sludge concentration could potentially allow anaerobic digestion to be consolidated to three mesophilic digesters.

Thermal hydrolysis pretreatment facilities proposed under this scenario would be preceded by a new sludge screenings process to remove small trash and debris, and a new predewatering process to concentrate the feed sludge. The predewatering facility would consist of centrifuges, cake pumps, and polymer storage and feed facilities.

Thermal hydrolysis processes generally expose partially dewatered biological wastewater

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Table 7. Thermal Hydrolysis System Design Criteria

Parameter	Current Annual Average	Future Annual Average	Future Maximum Month
Solids Loading (dry tons/day)	50	70	88
Feed Sludge Solids Concentration	16%	16%	16%
Feed Volume (gpd)	75,600	104,555	131,520
Number of Reactors	3	3	3
Hydrolyzed Sludge Solids Concentration (after postdilution)	8.8%	8.8%	8.8%

Table 8. Anaerobic Digester Volatile Solids Reduction Parameters

Parameter	Mesophilic	THP + Mesophilic
WAS VSR_{MAX}	58%	63% (+3%)
Methane Production (cfm)	367	400 (+9%)

Table 9. Predicted Performance for Advanced Digestion Alternatives

Parameter	Baseline	TPAD	AGMD	THP
Total Number of Digesters Required	7	9	7	3
Volatile Solids Loading (%VS)	85%	85%	85%	85%
Volatile Solids Destruction (VSR)	58%	60%	60%	63%
Digester Gas Production (scfm)	500	515	515	545
Dewatered Cake (%TS)	22%	22%	22%	30%
Dewatered Cake (wet tons/day)	160	155	155	108

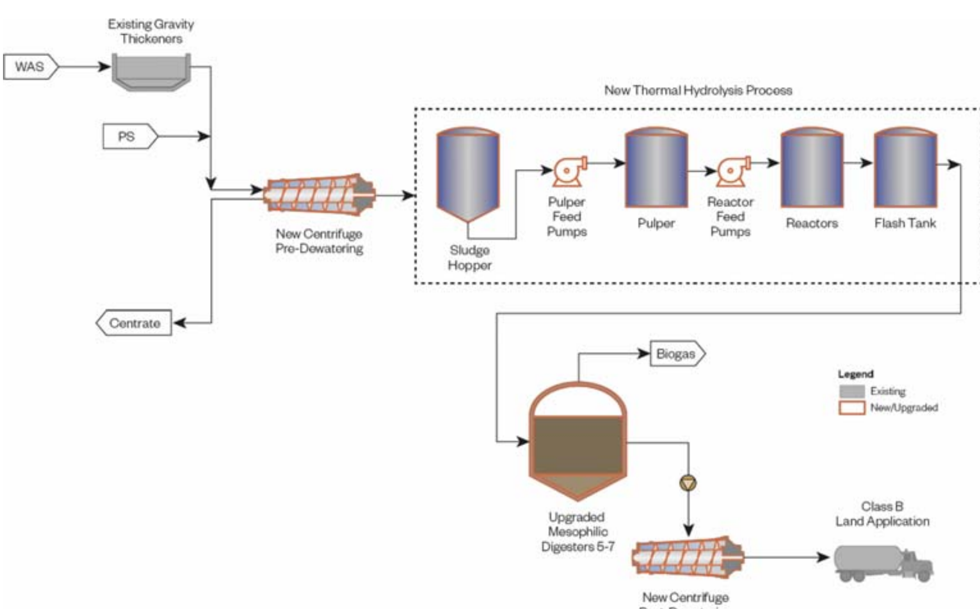

Figure 6. Solids Process Schematic: Thermal Hydrolysis Pretreatment

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treatment residuals to a combination of high temperature and high pressure for a fixed time period, such that the cellular wall structure in the residuals is fractured and soluble organic material contained within the cells is made bioavailable as a substrate in downstream digestion unit treatment processes.

There are several THP system providers. The CAMBI® thermal hydrolysis process has the largest installation base and was assumed for this evaluation. The CAMBI system proposed was based on the design criteria summarized in Table 7.

When implemented in other facilities, the addition of thermal hydrolysis pretreatment has increased the degradable fraction of volatile solids and has also increased digestion reaction rates. Table 8 summarizes the differences between mesophilic and THP anaerobic digestion facilities.

Based on the HRT criteria, a minimum of two existing operating mesophilic digesters would be required to meet future organic loading conditions (80-mgd sludge production). In addition to the operating digesters, a standby digester would be required for "N+1" reliability; therefore, conversion to an THP configuration would not require additional digesters, but instead, rehabilitation of three existing digesters (5, 6, and 7) and construction of new thermal hydrolysis pretreatment and predewatering facilities. Proposed THP facilities are shown in Figures 6 and 7. Table 9 compares predicted performance for each of the four digestion alternatives.

Table 10 compares net present value of capital and annual operation and maintenance (O&M) costs for each of the four digestion alternatives.

Table 11 presents a matrix developed jointly by the city and its engineer, with weighting of decision factors and scoring for each alternative. The scoring system is based on a scale of 1 to 10, with 10 being the most-preferred option. The life cycle operational costs include all energy usage.

Alternatives 2 (TPAD) and 4 (THP) were the lowest ranked and were removed from further consideration. Alternatives 3 (acid-gas) and 1 (baseline upgrades) had the highest and very similar scores of 7.4 and 7.5, respectively. As a result, either option is a good fit for the city. The acid-gas alternative was chosen and the design will allow for an alternate operational mode in conventional mesophilic mode.

Results: Biogas Recovery Alternatives

Biogas Production

Desktop modeling estimated the biogas

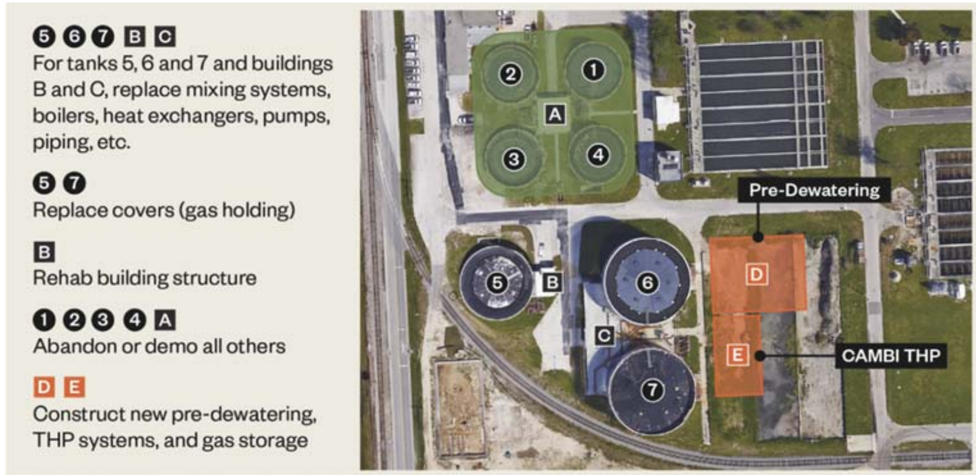

Figure 7. Site Plan: Proposed Thermal Hydrolysis Pretreatment Facilities

Table 10. Net Present Costs for Advanced Digestion Alternatives

Parameter	Baseline	TPAD	AGMD	THP
Capital Cost	$30.6M	$57.1M	$30.8M	$85.6M
Annualized O&M Costs				
Screening, Predewatering	N/A	N/A	N/A	$19.7M
Anaerobic Digestion	N/A	N/A	N/A	$8.6M
Postdewatering	$11.2M	$14.5M	$10.8M	$8.4M
Hauling, Disposal	$34.1M	$33.1M	$33.1M	$22.1M
O&M Labor	$37.9M	$36.6M	$36.6M	$19.4M
Biogas Recovery Savings	$21.0M	$21.0M	$21.0M	$29.5M
Total Net Present Costs	**($27.6M)**	**($28.6M)**	**($28.5M)**	**($30.4)**

Table 11. Digestion Alternatives Decision Matrix

	25%	25%	20%	20%	10%	100%
Digestion Process Alternative	**Operations Costs**	**Capital Cost**	**Ease of Operation**	**Required Maintenance**	**Future Flexibility**	**Total Score**
1. Baseline	9.5	10.0	10	10	6	7.5
2. TPAD	9.5	5.4	8	8	8	6.1
3. AGMD	10.0	10.0	9	9	6	7.4
4. THP	8.2	3.6	5	4	10	4.8

production by first calculating theoretical secondary and primary sludge production prior to digestion, which was then calibrated to fit the existing sludge supervisory control and data acquisition (SCADA) data from 2015 monthly averages. Biogas production was then estimated by using the modeled sludge production, historical sludge characteristics from 2015 (monthly averages), and industry standard gas production rates to generate a low and high estimated range of digester gas biogas production, which is expected to increase ~1 percent per year.

Figure 8 shows the expected annual digester gas production for the liquid and biosolids alternatives. Alternative 1 represents optimizing the existing liquid stream, and alternatives 2a and 2b represent different parallel liquid feed options. The liquid stream treatment alternatives were found to have the largest impact on biogas production; the biosolids treatment alternatives did not have a large impact on the biogas production. From Figure 2 it's clear that optimizing the existing liquid stream produces the most biogas, which can be utilized in the most beneficial way possible. This biogas production relationship was similar for the other biosolids alternatives evaluated (TPAD+acid-gas, and T+P+Mesophilic).

The following biogas utilization alternatives were identified and evaluated:

- *Alternative 0 – Flare all Biogas.* Alternative 0 assumes that all biogas is flared and natural gas is purchased to provide digester heating. The purpose of evaluating this alternative is to establish a "zero resource recovery" baseline to compare the revenue generation of the other biogas utilization alternatives.
- *Alternative 1 – Biogas to Boilers.* This alternative makes beneficial utilization of the biogas by fueling the existing boilers to provide digester heating. All unused biogas would be flared. This alternative eliminates the capital costs and O&M costs associated with biogas-fueled engines.
- *Alternative 2 – CHP.* This alternative explores technologies and strategies that utilize digester gas to produce electric energy to offset purchased and thermal energy that can be recovered for digester heating. The electric energy is used to offset the purchased utility power at the current retail rate. Thermal energy is recovered from the exhaust and engine cooling system to provide the digester/building heating demands. It was assumed that the benefits gained from offsetting the purchased electric energy under the retail rate would be from the energy usage component of the total utility bill, only to account for the loss of demand offset from CHP system downtime. It was determined the annual average electric energy offset benefit would be approximately $0.07/kilowatt hour (kWh) for the CHP alternative.
  - *Alternative 2a – Refurbish Existing Engines.* Refurbish the existing five 500-kW Waukesha CHP engines for reuse in lieu of purchasing new engines.
  - *Alternative 2b – New CHP System Engines and Building.* Remove the existing Waukesha engines and heat recovery equipment and install new engines furnished with engine jacket heat recovery in a new building.
  - *Alternative 2c – New CHP System Engines in Existing Building.* Remove the existing Waukesha engines and heat recovery equipment and install new engines furnished with engine jacket heat recovery in the existing building.
- *Alternative 3 – Biogas to RNG for Vehicle*

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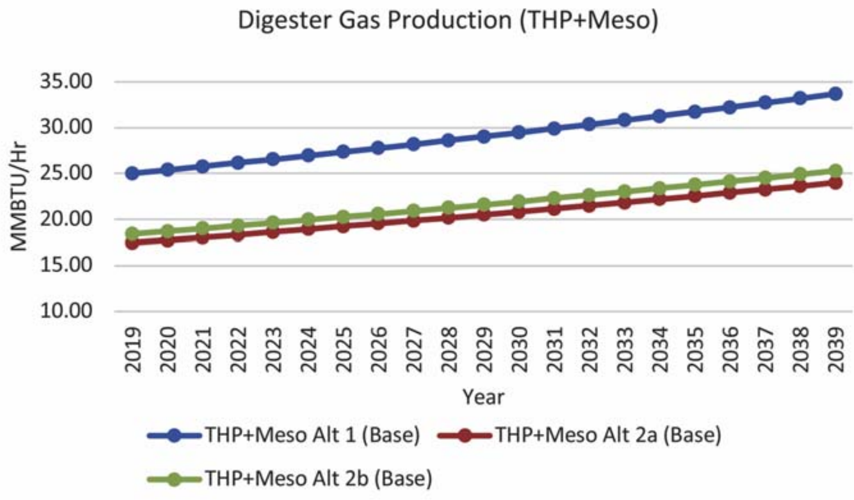

Figure 8. Mesophilic Biosolids Treatment Digester Gas Production

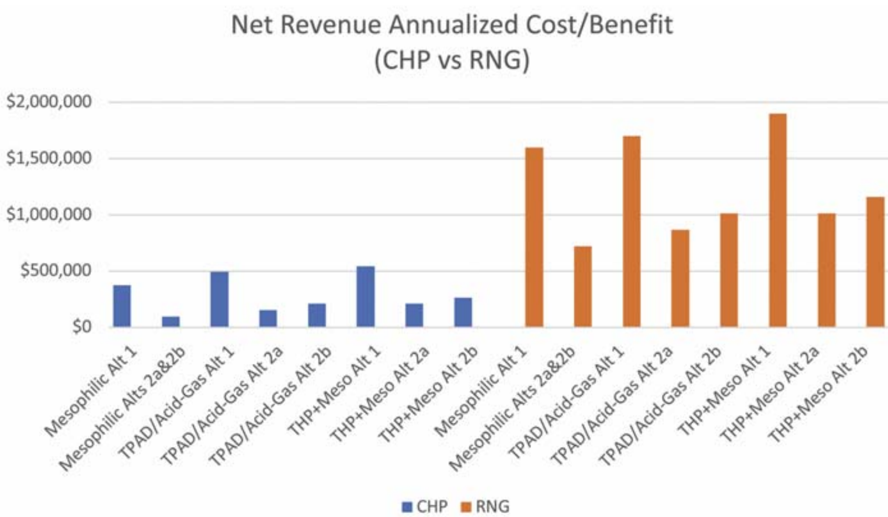

Figure 9. Net Revenue Annualized Cost/Benefit

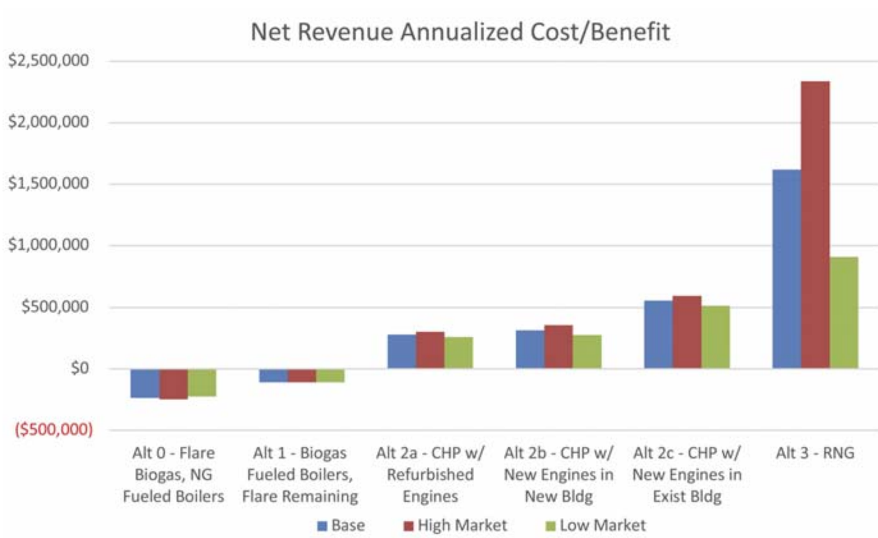

Figure 10. Annualized Net Revenue Cost/Benefit

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Fueling. Recover and condition/compress biogas to be used in the city's CNG-capable vehicles. For this alternative, digester gas is treated (or "upgraded") to natural-gas-pipeline quality (RNG) and will be used as a transportation fuel to gain the benefit from the renewable identification number (RIN) commodity market. For the purposes of this alternative, it's assumed that all biogas will be treated to natural-gas-pipeline quality standards and injected into the natural gas pipeline. The CNG will be "wheeled" through the TECO Energy (Tampa) natural gas pipeline network out to a wide network of customers, including the city's CNG fueling stations. Between the city's existing 60 refuse trucks and 60 CNG busses from the Hillsborough Area Regional Transit Authority (HART), it's anticipated that approximately 1.1 mil gasoline gal equivalents (GGE) of RNG per year will be consumed, which is the majority of RNG produced.

The biogas utilization feasibility evaluations were performed using Hazen's energy balance and analysis tool (EBAT), which models the complex relationship of energy production, demands, and costs to provide accurate long-term cost/benefit assessments for multiple biogas utilization alternatives. The EBAT model was used to generate a 20-year life cycle cost/benefit analysis (LCA) for each of the biosolids and liquid stream alternatives and the impact on the biogas production and utilization alternatives. The 20-year LCA incorporates capital cost debt service, energy savings, and O&M costs to calculate the true 20-year life cycle cost/benefit for each alternative.

The EBAT model also calculates 20-year life cycle costs for current market conditions, as well as high and low market conditions, so that the full range of economic outcomes for the biogas utilization alternatives can be understood. The EBAT model calculates all costs/revenues for the year incurred (nominal dollars) over the 20-year life cycle. To simplify the costs and be consistent with previous studies, the revenue and cost data are shown as "annualized," which represent the net present value of the 20-year lifecycle costs expressed in present-day dollars over a 20-year amortization period.

Using the biogas production information, the EBAT model was used to calculate the annualized net revenue cost/benefit for CHP (with new engines) and RNG. Figure 9 summarizes the annualized net revenue cost/benefit for all evaluated treatment alternatives for both the

CHP (with new engines) and RNG biogas utilization alternatives. In addition to producing more biogas, as shown previously, Figure 9 clearly shows that optimizing the existing liquid stream treatment has the potential to produce the most revenue for the plant.

The city selected the existing liquid stream treatment alternative and the acid-gas biosolids treatment alternative. The combination of these alternatives is expected to produce ~3 percent more biogas.

Figure 10 shows the annualized net operating cost for all alternatives. The study results show that alternatives 2 (CHP) and 3 (vehicle fueling/RNG) are the only two alternatives with a positive annualized net operating cost and could produce revenue for the plant.

As shown in Figure 10, the RNG alternative could produce greater revenue than the CHP alternative under the market conditions at the time of this report. It's important to note that the RNG alternative can have a higher revenue potential and may have a higher level of volatility due to the uncertainly on the long-term health of the RIN market.

Table 12. Biogas Recovery Options

Combined Heat and Power	Renewable Natural Gas
Offsets Purchased Electrical Power	Offsets CNG Purchased for City Fleet
Up to $0.5M/Year of Net Annualized	Up to $1.5M/Year of Net Annualized Savings
Familiar Technology	Additional Gas Pretreatment
Stable and Predictable Market	Long-Term Market Uncertainty

Conclusions

For digestion, conversion to AGMD results in the lowest life cycle cost, primarily because the existing smaller digesters 1 and 2 can be repurposed as acid-phase reactors to avoid the need for new tanks, while increasing biogas for energy recovery. The TPAD and THP+MAD options also improve biogas production, but would require significant additional capital infrastructure, resulting in reduce economic attractiveness.

For biogas recovery, cost benefits from energy production make CHP and RNG options more financially attractive than the base option of a digester heating and flaring excess biogas. Table 12 summarizes preliminary findings/conclusions for the biogas recovery options.

It's recommended that the RNG alternative be investigated further with TECO Energy and that the following next steps be taken:

- Initiate a detailed utility pipeline assessment with TECO. This will determine if there is a nearby injection point for the plant or if a pipeline extension would be required.
- If the first step is viable, an interconnection capacity study can be initiated to determine if there is capacity in the pipeline for the additional natural gas.