Under Pressure: Hydrothermal Liquefaction and the Fast Lane to Resource Recovery

Heath Wintz and Matt Atwood

The intersection of wastewater treatment and energy recovery has long been an encouraging path for operators and utility managers. Developments in resource recovery technology are yielding not only efficient methods for removing nutrients and biochemical oxygen demand (BOD), but also transformative processes by which biosolids, agricultural waste, waste activated sludge (WAS), and fats, oil, and grease (FOG) can be converted to biocrude oil.

A capital expenditures (CAPEX) and operating expenses (OPEX) evaluation of recent wastewater treatment facilities (WWTF) expansion projects was conducted by MWH, driven by nutrient removal and biosolids reduction needs for comparison with a proprietary hydrothermal liquefaction (HTL) process developed by Algae Systems LLC. Capital-cost data were gathered from constructed projects, recently bid projects, and projects at a detailed phase of design.

Recent advancements at the Algae Systems pilot facility in Daphne, Ala., have demonstrated the potential to not only compete with thermal hydrolysis and conventional digestion technologies, but yield an energy return on energy invested (EROEI) of five to one.

As this type of carbon-negative wastewater-to-biofuel process has been developed, this potentially disruptive alternative to conventional digestion is poised to allow utility managers to capitalize on what has traditionally been a cost center. This article explores the assessment of capital costs associated with secondary process expansion, biosolids treatment, and disposal, and a CAPEX and OPEX comparison of the HTL process with anaerobic digestion and thermal hydrolysis.

What is Waste?

What's the value of wastewater treatment and biosolids treatment? Among wastewater industry professionals, there is a growing recognition that there is no such thing as waste, but only resources out of place. Utility owners and operators understand that this conservative industry is slow to change due to liability associated with ensuring continued permit compliance and risk of losing public confidence; however, perspectives of "treat and dispose" are giving way to pioneering approaches involving the selective extraction and transformation of wastewater constituents.

Technology development in the wastewater treatment sector is often focused on achieving improvements in nutrient removal, nutrient recovery, and energy efficiency. New methods for nutrient removal and recovery are essential to achieving increasingly stringent discharge standards. Despite the chemical energy embodied in wastewater, conventional treatment processes remain a major energy sink, with the water and wastewater sector currently consuming 3 to 4 percent of the electricity produced in the United States.

In order to help inform the business model of Algae Systems, a growing algae-to-energy company, MWH provided an economic valuation of biological nutrient removal (BNR) processes using CAPEX and OPEX data from recent construction projects.

Innovation in Wastewater Treatment

Algae Systems has undertaken an inventive approach to municipal wastewater treatment, in which wastewater is used to cultivate microalgae using offshore, floating photobioreactors (PBRs). The PBR technology, inspired by National Aeronautics and Space Administration programs for use on the space station, started with research conducted in cooperation with the Stanford Research Institute. The company has harnessed a natural process in an unconventional way to create a carbon-negative wastewater treatment process that is energy-positive, yielding drop-in biofuels and clean water.

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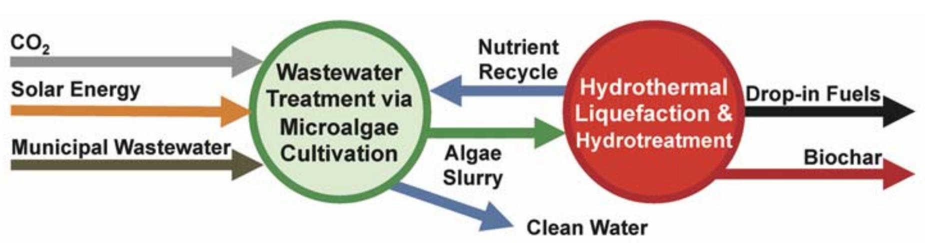
Process

At the facility in Daphne, up to 50,000 gal per day (gpd) of raw influent is microscreened with a 70µm filter, disinfected using peracetic acid at doses of 5-15 mg/L, inoculated with algae, and conveyed to PBRs in Mobile Bay for biological treatment. Simultaneous secondary and tertiary treatment are provided by a continuous batch process within the PBRs. The PBR bags are inoculated with algae and disinfected influent. As a diverse culture of algae and heterotrophs grow, nutrients and carbon dioxide (CO_2) are consumed and aeration is provided by photosynthetically produced oxygen. The slurry from the PBRs is dewatered and fed into the HTL process, which is summarized in Figure 1.



(Source: Algae Systems LLC)

Figure 1. Process Overview: Wastewater to Biofuel

Wastewater Treatment

Nutrient and BOD removal are achieved with no external mechanical mixing or aeration, relying only on minimal wave action of open water. In addition to the heterotrophic culture, the algal polyculture makeup changes in response to dynamic internal and external conditions. Following a peak growth grate period of approximately five days (dependent on environmental factors), the mixotrophic biomass is conveyed back onshore for dewatering via suspended air flotation. Following dewatering, the process has demonstrated removal of 75 percent of total nitrogen, 93 percent of total phosphorus, and 92 percent BOD from influent wastewater, as summarized in Table 1.

Over 50 percent of energy consumed during conventional activated sludge treatment is required for aeration. By utilizing oxygen made available during algal photosynthesis, this process represents a substantial advancement in treatment efficiency.

Process effluent could potentially be further treated, disinfected, and marketed as reclaimed water, or discharged if National Pollutant Discharge Elimination System (NPDES) conditions are met; however, current permit requirements with Daphne Utilities necessitate that the effluent be returned to the collection system and further treated at its wastewater treatment plant (WWTP). Algae derived from the process is dewatered and further processed into bio-oil.

Solids Processing

Dewatered algae are processed using HTL, a high-temperature (>250°C) and high-pressure (700-1400 pounds per sq in. [psi]) process that yields a crude bio-oil. This process is comparable to the natural process that has taken place over millions of years to convert algae, dinosaurs, and other biomass into crude oil with the pressure of sediment and rocks. Comparatively, the few minutes required for the HTL process take place in a geologic "blink of an eye," as opposed to petroleum-based crude.

The bio-oil produced by HTL can be refined to produce a variety of drop-in fuels, while the biochar fraction of the processing can be used as a soil amendment. A sidestream from this process is diverted for nutrient recovery or recycled into the secondary treatment process to support additional algae growth. Similarly, whole biomass could be anaerobically digested for biogas production.

The dewatered biomass was suitable for HTL due to consistent lipid content, low ash content, and consistent elemental composition through varying seasonal environmental conditions. Biomass production rates were predominantly driven by frequency of harvest and temperature. A process schematic, including a photo of the offshore PBRs, is provided in Figure 2.

Algae Systems' cultivation process yields diverse biomass polycultures that evolve seasonally and maintain relatively constant percentages of lipids, carbohydrates, proteins, and ash. The HTL processes the whole algal cells and converts energy from all the energy compartments stored in the cells, including carbohydrates and other compounds, so low or consistent lipid fraction

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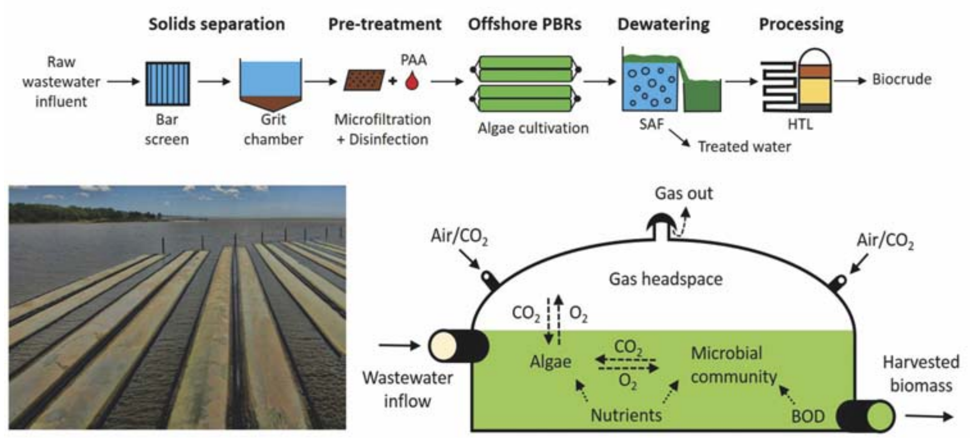
Table 1. Wastewater Treatment Efficiency

Variable	Influent	St. dev	Effluent	St. dev	% Removal
NH_3-N (mg/L)	26.5	5.5	5.4	3.4	80
TN (mg/L)	40.0	8.6	10.1	4.3	75
PO_4-P (mg/L)	2.98	0.62	0.14	0.16	95
TP (mg/L)	4.22	0.58	0.29	0.27	93
COD (mg/L)	542	142	87	55	84
BOD (mg/L)	300	52	24	10	92

(Source: Algae Systems LLC)



(Source: Algae Systems LLC)

Figure 2. Process Schematic

(Source: Algae Systems LLC)

Figure 3. Hydrothermal Liquefaction Process Area - Daphne, Ala.

Table 2. Hydrothermal Liquefaction Energy Analysis for Various Wastewater Treatment Facility Feed Streams (60 WTPD)

Description	Algae HTL	WAS HTL	FOGs HTL
Acceptable % Moisture Range	70-95%	90-99%	70-95%
Wet Tons Per Day Throughput	60	60	60
Typical % Moisture	80%	90%	75%
Typical Energy Produced (kWh/d)	50,000	13,700	257,000
Typical Energy Required (kWh/d)	5,860	6,175	4,124
EROEI (Energy Return on Energy Invested)	8.5	2.2	62

Table 3. MWH-Designed Biological Nutrient Removal Facility Summary

Year	Facility and Location	Biological Process	Solids Process	Capacity (mgd)			2013 AADF (mgd)
				Initial	Expanded	Peak Hr	
2009	Everest WWTF Cape Coral, Fla.	Five-stage Bardenpho	*Offsite	8.5	13.4	37.1	7
2015	Fremont WPCC Fremont, Ohio	A^2/O	Anaerobic	7.6	7.6	24	-

*WAS pumped to Southwest Cape Coral WWTF for stabilization.

Table 4. Ohio Facility Anaerobic Digestion Capital Expenditures (estimated)

Description	Qty	Cost
Rotating Drum Thickener (RDT)	2	$700,000
Settling Tank Equipment Demolition	4	$100,000
20-inch Aeration Piping	300	$45,000
Sludge Pipe Trench	260	$5,200
Blower Building Slab Concrete (cyd)	15	$6,000
RDT Building	1,600	$43,200
RDT Building Slab	60	$24,000
Blower Building Roof	400	$20,000
New Blowers	4	$600,000
New Aeration Equipment	4	$300,000
New Sludge Transfer Pumps	2	$60,000
Anaerobic Digester Equipment Demo	2	$100,000
New Anaerobic Digestion Equipment		$1,500,000
New Belt Press	1	$250,000
Excavation (cyd)	300	$6,000
Heating and Ventilation (3%)		$323
Electrical (5%)		$172,750
Control (3%)		$103,650
Install (50%)		$1,727,500
Equipment		$3,455,000
Total Cost		$5,743,623

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is not necessarily detrimental to fuel conversion via HTL. Lipid content of harvested biomass was 13 ± 2.5 percent, which is of low to moderate value when compared to selected monocultures (e.g., 33), yet energy yields and properties of the produced bio-oil were consistent year-round, despite the changing biomass culture.

Hydrothermal Liquefaction Feedstock Analysis

Various feedstocks were tested at the demonstration facility in Daphne by operating a small-batch, continuous-bench and continuous-full-scale demonstration plant, shown in Figure 3. Results showing the relative energy produced from three feedstocks available at WWTFs are summarized in Table 2.

Results are given at the same 60-wet-tons-per-day (WTPD) scale to highlight differences in energy yield from each feedstock. In addition, acceptable moisture ranges for the different feedstocks and the tested "typical" moisture ranges are included for comparison. The EROEI is shown for each of the feedstock runs; note that EROEI depends heavily on the incoming moisture percentage.

Valuation

In 2014, Algae Systems needed to determine the value of the process it was offering to inform its business model. With such a pioneering new process, an indirect appraisal was necessary to answer fundamental questions, such as:

- What's the value of the BNR process?
- What do utilities pay for biosolids treatment?
- Why is there such variability in disposal costs?

The company asked MWH to help answer these questions by looking at three issues:

1. Comparable secondary treatment technologies for nutrient removal
2. Direct potable reuse technology
3. Biosolids treatment and disposal alternatives

Capital Cost Data Review

A review was done by MWH of capital cost data from recently bid or constructed BNR projects, including the City of Cape Coral Everest WWTF, and the City of Fremont (Ohio) Water Pollution Control Center (WPCC). The Everest WWTF involved the conversion of the facility to a five-stage Bardenpho process, including aeration and clarification facilities. The Fremont WPCC involves the demolition and conversion to an A^2/O process with the same average treatment capacity, but increased wet weather (peak) capacity. The WPCC involved solids stabilization improvements, for which anaerobic digestion was evaluated as part of preliminary engineering study. These facilities are summarized in Table 3.

Solids Stabilization: Capital Expense

Mesophilic anaerobic digestion was evaluated as a comparable solids stabilization technology for the purposes of comparison with the HTL process. The CAPEX and OPEX costs evaluated reflect the specific requirements of the Fremont project. Preliminary engineering cost estimates for aerobic digestion at the Fremont WPCC are based on the facility digesting WAS thickened to 3.2 percent and producing approximately 1.3 dry tons of sludge daily (DTD), and are provided in Table 4.

As many operators understand, lysing of organism cellular walls is a key obstacle to digestion. Pretreatment processes using thermal hydrolysis or electroporation, such as CAMBI™ or OPEN CEL™, can be used to lyse cell walls and enhance digestion. With electrical and chemical input, these processes have increased volatile solids destruction and biogas production, while enhancing sludge dewaterability.

Solids Stabilization: Operating Expense

Operating costs were obtained by request or estimated from process aeration energy calculations, Water Environment Research Foundation publications, and the Water Pollution Control Federation *Manual of Practice 8* (WPCF MOP 8, 1977). Net present worth (NPW) was based upon the following assumptions: average pump efficiency of 68 percent, 365-days-a-year operation, electrical cost of $0.08/kilowatt-hour (kWh), 20-year payback period, and a discount rate of 6 percent. Volatile solids destruction of 45 percent was assumed in a two-day solids retention time for this process, along with a solids cake dewaterability of 19 percent, to yield 6.9 wet tons daily (WTD). The OPEX costs for anaerobic digestion for this facility were estimated based on these conditions and are provided in Table 5.

Hydrothermal Liquefaction Cost Analysis

The experience that Algae Systems had constructing the pilot HTL system at the demonstration facility provided the opportunity to prove the technology and optimize the process. The capacity of this HTL process for this facility was 6 dry tons per day (DTPD), which was far more than required for the biological wastewater treatment process onsite. This excess capacity was constructed to avoid process scale-up issues during future stages of process development.

Hydrothermal Liquefaction Capital Expenses

Algae Systems worked with its partners to refine and consolidate the equipment layout developed at the facility shown in Figure 4 to fit within the constraints of a standard 8-ft by 53-ft shipping container. Drawing from experience of processing dewatered algae biomass, capital and operating costs for this HTL skid were prepared. The modular skid was designed with a process capacity of over 4,000 DTPD of WAS. A conceptual rendering of the HTL skid, without thickening or storage equipment, is depicted in Figure 5.

Capital costs for the containerized HTL process were projected based on actual equipment procurement, engineering, and construction costs from the Daphne demonstration facility. Capital costs provided are for a process feed rate of 23 gal per minute (gpm) for WAS biosolids at 10 percent solids. These costs were escalated to meet capacity requirements of 4,125 DTPD, as shown in Table 6.

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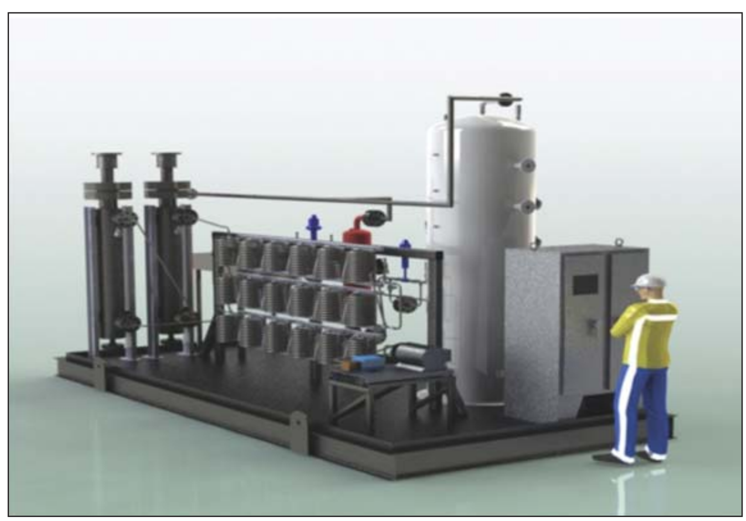
Table 5. Fremont Water Pollution Control Center Anaerobic Operating Expenses (estimated)

Description	Quantity	Unit	Rate ($)	Amount ($)	Total ($/year)
Power Requirements					**$177,000**
Sludge Holding Blowers	653,496	kWh/yr	$0.08	$/kWh	$52,300
Thickening	816,870	kWh/yr	$0.08	$/kWh	$65,400
Sludge Pumping/Mixing	653,496	kWh/yr	$0.08	$/kWh	$52,300
Belt Presses	87,133	kWh/yr	$0.08	$/kWh	$7,000
Chemical Costs					**$22,100**
Polymer	14,600	lbs/yr	$1.50	$/lb	$21,900
Polymer Delivery Fees	2	deliv/yr	$70	$/delivery	$200
Equipment Replacement Cost					**$29,300**
Sludge Holding Blowers	0.05	items/yr	$100,000	$/replacement	$5,000
Sludge Holding Aeration diffusers	0.20	items/yr	$4,875	$/replacement	$1,000
Digester Covers	0.05	items/yr	$100,000	$/replacement	$5,000
Rotating Drum Thickener (RDT)	0.05	items/yr	$125,000	$/replacement	$6,300
Sludge Pumping/Mixing	0.1	items/yr	$5,000	$/replacement	$500
Belt Presses	0.05	items/yr	$150,000	$/replacement	$7,500
Belts	0.25	items/yr	$2,500	$/replacement	$4,000
Staffing Costs					**$478,400**
Operators	1.00	FTE	$80	$/hr/person	$166,400
Technicians	1.00	FTE	$60	$/hr/person	$124,800
Maintenance	1.00	FTE	$50	$/hr/person	$104,000
Administrative	1.00	FTE	$40	$/hr/person	$83,200
TOTAL ANNUAL COSTS					**$961,000**
Net Present Worth of Annual Costs					$8,200,000

(Source: Algae Systems LLC)

Figure 4. Hydrothermal Liquefaction Equipment



(Source: Algae Systems LLC)

Figure 5. Optimized Hydrothermal Liquefaction Skid

Description	Cost
Reactors, Heat Exchangers, and Pressure Vessels	$680,000
Separations, Feedstock and Product Tanks, and Equipment	$670,000
Pumps, Valves, Meters, and Instruments	$290,000
Total Equipment	$1,640,000
Site Engineering, Commissioning (8%)	$340,000
Controls (3%)	$130,000
Electrical (5%)	$210,000
Procurement, Construction, and Delivery (45%)	$1,890,000
Total	$4,200,000

Table 6. Hydrothermal Liquefaction Skid Capital Expenditures (estimated)

Table 7. Hydrothermal Liquefaction Waste Activated Sludge Skid Operating Expenses (estimated)

Description	Quantity/yr	Unit	Rate ($)	Total ($/yr)
Heat	10,751	MMBTU	$2.00	$22,000
Power	1,415,202	kWh	$0.08	$113,000
Supplies				$124,000
Labor/Fringe				$241,000
Total OPEX				$500,000
Net Present Worth of Annual Costs				$5,800,000

Table 8. Hydrothermal Liquefaction Fats, Oil, and Grease Skid Operating Expenses (estimated)

Description	Quantity/yr	Unit	Rate ($)	Total ($/yr)
Heat	7,179	MMBTU	$2.00	$14,000
Power	945,076	kWh	$0.08	$76,000
Supplies				$928,000
Labor/Fringe				$241,000
Total OPEX				$1,259,000
Net Present Worth of Annual Costs				$14,500,000

Table 9. Comparison of Anaerobic Digestion Versus Hydrothermal Liquefaction (Waste Activated Sludge and Fats, Oil, And Grease)

Item	AD	HTL - WAS	HTL - FOG
CAPEX	$4,201,134	$4,202,151	$4,151,457
MGD Wastewater Flow	3.5	20.6	n/a
Capacity in Dry Tonne (WAS or FOG)/Year	700	4,125	31,000
Capacity Compared to AD	1x	6x	44x
kWh/d Fuel Produced	3,361*	28,637	536,940
OPEX	$594,500	$500,000	$1,259,000
Annual Revenue	NA	$401,219	$5,015,232
CAPEX/Dry Tonne Cap.	$6,000	$1,006	$134.19
OPEX/Dry Tonne	$849	$203	$40

*MMBTUs of biogas converted to kWh/d for comparison

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Hydrothermal Liquefaction Operating Expenses: Waste Activated Sludge

Operating costs for the HTL WAS skid were estimated based on performance data from the Daphne demonstration facility; heat, power, and supplies for processing WAS at 10 percent solids; and labor based on operational requirements consistent with operational and safety needs at the demonstration plant. Staffing needs for the process include one lead operator and one shift maintenance technician around the clock. For the purposes of the HTL OPEX estimate, 90 percent operational time, or, 330 days per year, was assumed. The OPEX for the HTL WAS skid are summarized in Table 7.

Hydrothermal Liquefaction Operating Expenses: Fats, Oil, and Grease

Operating costs for the HTL FOG skid were similarly estimated based on performance data from the Daphne facility using raw restaurant trap grease; heat, power, and supplies for processing FOG at 25 percent moisture and labor costs, the same as WAS, were also considered. The OPEX for the HTL FOG skid are summarized in Table 8.

It is apparent that the OPEX for the WAS and FOG skids are substantially different, based on requirements for power and supplies; however, the potential energy yield of the FOG skid is significantly higher than the WAS skid due to the lower incoming moisture and energy value of the raw feedstock material on a mass basis. As noted, the EROEI of the FOG process is over 60:1 due to the energy value of the feed stream and the lower typical moisture content of tested materials.

Comparison

Conventional anaerobic digestion and HTL are vastly different processes. For the purposes of comparing the two, the costs of thickening from the CAPEX and OPEX analyses were removed, as these costs could be applicable for both processes, but were not considered a differentiator. The results were normalized to a CAPEX of approximately $4.2 million in order to illustrate differences in capacity, as well as CAPEX and OPEX costs per dry ton. Annual revenue for the HTL systems are calculated based on $50/barrel value for renewable bio-oil. No revenues were assumed for WAS/FOG tipping fees, the sales of Class A biochar biosolids, or fertilizers from the process. These results are summarized in Table 9.

The energy produced, shown in kWh/day, is based on unoptimized results derived from operations at the demonstration plant. Energy yields can be significantly increased by cofeeding other waste streams, such as FOG. The findings indicate that HTL of WAS can potentially provide nearly six times the solids treatment capacity for the same capital investment over anaerobic digestion. The HTL process allows this to be done with a lower OPEX, positive revenue potential, and positive EROEI. The HTL of FOG provides a significantly higher EROEI and revenue potential.

Net Present Value

The CAPEX and OPEX costs in Table 9 were projected over a 20-year period at 6 percent interest to demonstrate the net present value (NPV) of costs associated with each $4.2 million capital investment. For HTL-WAS and HTL-FOG, additional dashed curves include revenue projections and are illustrated in Figure 10.

It should be noted that while the NPV of costs for a $4.2 million capital investment for anaerobic digestion (AD) and HTL-WAS are nearly identical over a 20-year period, the throughput capacity of HTL is six times greater. When taking into account the revenue stream from bio-oil sales, the OPEX for HTL-WAS is significantly offset.

Findings

Because the process requires minimal energy input and maximizes energy output through algae production and conversion, this technology enables energy-positive wastewater treatment, converting municipal wastewater treatment from a net energy consumer to a net energy producer. While the process is favored by subtropical climates, such as in Florida, the HTL process alone represents an energy-positive modular solution to avoid solids handling process expansions and it can provide significant energy and economic returns, depending on feed stream makeup.

Acknowledgments

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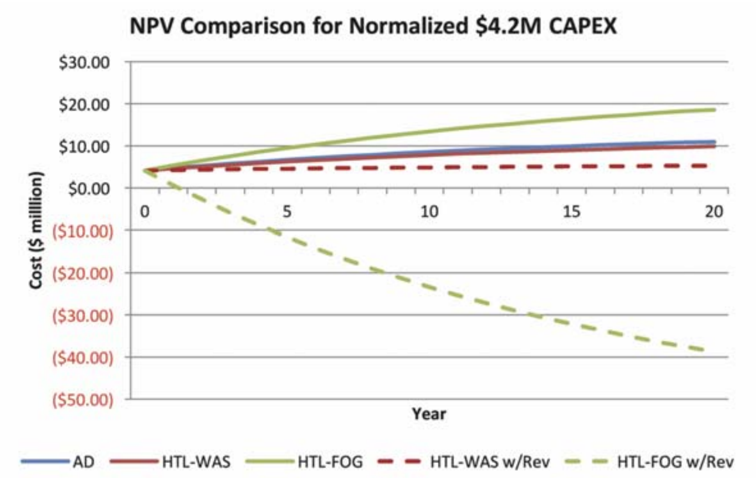

Figure 10. Net Present Value Comparison of Anaerobic Digestion, HTL-WAS, and HTL-FOG With Potential Revenue Offset