Improving Wards Island WRRF Energy Recovery Through Coupled Thermal Hydrolysis and Cogeneration Systems

THE CITY COLLEGE OF NEW YORK
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Abstract

New York City, the United States' largest municipality, operates fourteen wastewater resource recovery facilities (WRRFs) that treat over 1.3 billion gallons of wastewater daily. This design report implements thermal hydrolysis pretreatment (THP) to Wards Island WRRF as a technique to increase anaerobic digester gas (ADG) production and improve solids handling, all in an effort in meeting New York City's net-zero carbon emission goals. The design conducted shows that implementation of THP is capable of generating enough energy to operate the THP system, offset purchased energy demands, and reduce solids handling costs compared to the existing system. A comparison between the initial costs of implementing a thermal hydrolysis facility and savings in utilities and sludge hauling reveals a 13.5-year return on investment.

Summary of Project Team Effort

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Design Problem

New York City set goals to achieve net-zero carbon emissions by 2050; the focus areas that the City plans to target to achieve this goal includes reducing demands, incorporating renewable natural gas into the pipeline, and decarbonizing sources of heat (National Grid, 2020). Water resource recovery facilities, or WRRFs, are at the forefront of advancements that are expected to be a major contributor to meeting net-zero carbon emission goals. This design report proposes to implement a thermal hydrolysis process (THP) to improve the anaerobic digester process at Wards Island WRRF, as it approaches its end-of-life. Improvements include:

1. Increased anaerobic digester gas (ADG) production
2. Improved energy allocation of high-quality energy
3. Increased digester capacity
4. Improved biosolids handling

Introduction

Wastewater Treatment Process in New York City

New York City operates 14 WRRFs that collectively treat over 1.3 billion gallons of wastewater daily. Influent wastewater enters the WRRF from the sewer system, which is initially screened to remove large debris. The wastewater then enters primary settling tanks, which allows lighter solids to float and heavier solids, or sludge, to sink. The liquid wastewater and lighter solids are aerated and disinfected before being released into local waterways. The heavier solids are thickened and subjected to anaerobic digestion, which is expanded upon in subsequent sections.

Sludge Thickening

Sludge thickening is a process that reduces the hydraulic loading of sludge while retaining the solids loading by removing excess water and concentrating the suspended solids. Reducing the volume of sludge benefits the facility by improving plant capacity, reducing costs for chemical sludge conditioning, and reducing heating requirements (Metcalf & Eddy | AECOM, 2014, pp. 1486). Considering that sludge is often sent to anaerobic digesters for solids stabilization, the benefits of sludge thickening can greatly improve the anaerobic digestion process. By increasing the digester capacity, other feedstocks can be introduced to improve anaerobic digester gas (ADG) production which is a high contender as a sustainable source of renewable energy. Energy requirements for digester heating are also reduced due to the lower sludge flow resulting from thickening. Effective sludge thickening is shown to improve ADG production, reduce heating demands, and reduce chemical dosage which translate to financial savings for the facility.

Common technologies implemented for sludge thickening include gravity thickening, gravity belt thickening, rotary drum thickening, and belt filter press thickening. Gravity thickening, gravity belt thickening, and rotary drum thickening uses gravity to separate suspended solids from the sludge, while belt filter presses apply forces greater than the gravitational force to thicken sludge. For this study, implementing belt filter presses is considered as an alternative to the existing gravity thickening process with the purposes of improving digester capacity.

Belt filter presses combine drainage and mechanical processes to remove water. The sludge is first conditioned with a polymer that aids in coalescing particulates together which improves the separation of water from the sludge. The conditioned sludge is then distributed on a conveyor belt that is made of a porous, fabric-like material that allows the drainage of free-water from the sludge. This phase of thickening is the same mechanism that gravity belt thickeners use to conduct thickening, resulting in sludge with a solid content of 5% to 7% (Metcalf and Eddy, 2014). Belt filter presses implement a second step after the gravity draining phase, where a second belt of porous, fabric-like material is layered on top of the sludge, “sandwiching” the sludge. The belt is then tensioned by a series of rollers to apply force to squeeze any additional water that is enmeshed in the sludge. This last phase can produce sludge with a solid content up to 23% by weight (Metcalf & Eddy, 2014).

Mesophilic Anaerobic Digestion

Anaerobic digestion involves a series of processes in which specialized bacteria and archaea break down biodegradable material in the absence of oxygen. The process of anaerobic digestion takes place through four successive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis; the anaerobic digestion process is dependent on the interactions between the diverse microorganisms that are able to carry out the four aforementioned stages. In single-stage batch reactors, all wastes are loaded simultaneously, and all four processes are allowed to occur in the same reactor sequentially (Meegoda et al.,2018).

Anaerobic digestion was initially intended to be a process that stabilized biosolids prior to disposal to avoid issues such as active pathogen emission, putrefaction, and odor (Metcalf and Eddy, 2014). The process has evolved to enhance its ability to produce methane and stabilize biosolids which has made the process more favorable as it can serve as a source of renewable energy while processing waste sludge into reusable biosolids, depending on its final quality.

The quality of the biosolids is categorized as either “Class A” or “Class B”, which are defined based on its contaminant concentration, pathogen content, and vector attraction potential (EPA, 2021). Class A is the highest quality and therefore has the most stringent requirements compared to Class B. Biosolids classified as Class A are allowed to be reused in a wider range of methods, such as Agriculture while Class B requirements are less stringent; therefore its reuse methods are more limited. Mesophilic anaerobic digestion of sewage sludge alone often produces Class B biosolids and therefore would need further sludge treatment to improve the quality of the biosolids. For this design, pre-digestion thermal hydrolysis of primary and waste activated sludge is assessed to help achieve Class A biosolids by the application of heat to virtually sterilize the sludge prior to digestion.

Thermal Hydrolysis

The conventional thermal hydrolysis process (THP) has been widely used in wastewater treatment plants to enhance digestion performance. THP consists of heating the sludge to high temperatures at high pressures. There are more than 82 full-scale, THP-operating wastewater treatment plants in operation. For the purpose of this project, the THP system is modeled after Cambi’s THP system.

In the Cambi THP system, raw sludge is collected and dewatered to a solids content of 16-18% and is fed into a one of six batch reactors in a semi-continuous process to allow batch treatment of sludge while ensuring continuous flow before and after THP. Table 1 depicts the synchronous phases that each reactor operates such that continuous flow is maintained.

Table 1.Schedule of phase process in Cambi THP Process.

Time Interval (H:MM)		0:00 - 0:15	0:15 - 0:30	0:30 - 0:45	0:45 - 1:00	1:00 - 0:15	1:15 - 1:30
Reactor	1	Fill	Preheat	Heat		Steam Explosion	Empty
	2	Empty	Fill	Preheat	Heat		Steam Explosion
	3	Steam Explosion	Empty	Fill	Preheat	Heat	
	4	Heat	Steam Explosion	Empty	Fill	Preheat	Heat
	5	Heat		Steam Explosion	Empty	Fill	Preheat
	6	Preheat	Heat		Steam Explosion	Empty	Fill

Sludge Preheat

Once a reactor is filled, the sludge is preheated to approximately 100°C with a mix of recycled steam recovered from downstream processes and fresh steam generated from high pressure boilers (CAMBI, n.d.).

High Heat Thermal Hydrolysis

After the preheat phase, the vessel is sealed so that high pressures can be maintained to raise the sludge temperature to 160°C using high pressure steam at 6 bars. The pressure and temperature are held within the reactor for approximately 30 minutes. During this period, cellular material, such as extracellular polymeric substances (EPS), are broken down, releasing water soluble material into the sludge, and sterilizing the sludge (Barber, 2020). Additionally, proteins are partially degraded, giving rise to the production of ammonia (NH4+) and, thus, reaching high concentrations of this compound in the pretreated sludge and the digestate. Higher temperatures and pressures also allow for substantial cell destruction of organic matter in the sewage sludge which make the sludge more easily biodegradable, ultimately increasing ADG production.

Steam Explosion and Cooling

After the 30-minute holding time, the pressure in the reactor is released allowing the pressure to drop drastically. The immediate pressure drop causes the superheated water that is bound in the sludge to rapidly boil and convert to steam, and the rapid expansion in volume essentially disintegrates larger sludge flocs. This reaction further improves the degradability by increasing the surface area of particulate matter, providing easy access to food for the anaerobic organisms in the digesters. The steam that is generated from this process is recovered and is used in the preheating phase which reduces the energy demand of the treatment process. As the steam is released and recovered, the temperature of the sludge is near 100°C, which is still too hot for the anaerobic digesters. Heat exchangers can be employed to recover more waste heat for preheating, or other processes to reduce the temperature of the feed sludge.

Project Scope

The purpose of this design project is to implement thermal hydrolysis at the Wards Island wastewater resource recovery facility in New York City. Implementing thermal hydrolysis with the intentions to improve biodegradation of solids, increase anaerobic digester capacity, and increase anaerobic digester gas production. On the other hand, thermal hydrolysis requires an energy demand to sustain an increased temperature and pressure of the sludge. Due to this, the design project also seeks a net-zero energy demand to net-positive process energy production.

Design Solution

Alternative #1 - No Build

The Wards Island Wastewater Resource Recovery Plant is located on Randall’s and Wards Island situated at the northern end of the East River between the Manhattan and Queens boroughs of New York City. The plant services over one million people in the areas of the western Bronx and Eastern Manhattan and has an average dry weather flow capacity of 275MGD (Water Technology, 2011). The plant uses approximately 36,000 gallons of Distillate Fuel #2 per month to power its Anaerobic Digesters and fulfill facility heating needs. To alleviate energy costs, the plant currently employs boilers to utilize the energy of biogas produced as a byproduct of Anaerobic Digestion. It uses about 260 million cubic feet of anaerobic digester gas beneficially in boilers and wastes 280 million cubic feet of Anaerobic gas annually. A schematic diagram of the wastewater treatment process at Wards Island WRRF is shown in Figure 1.

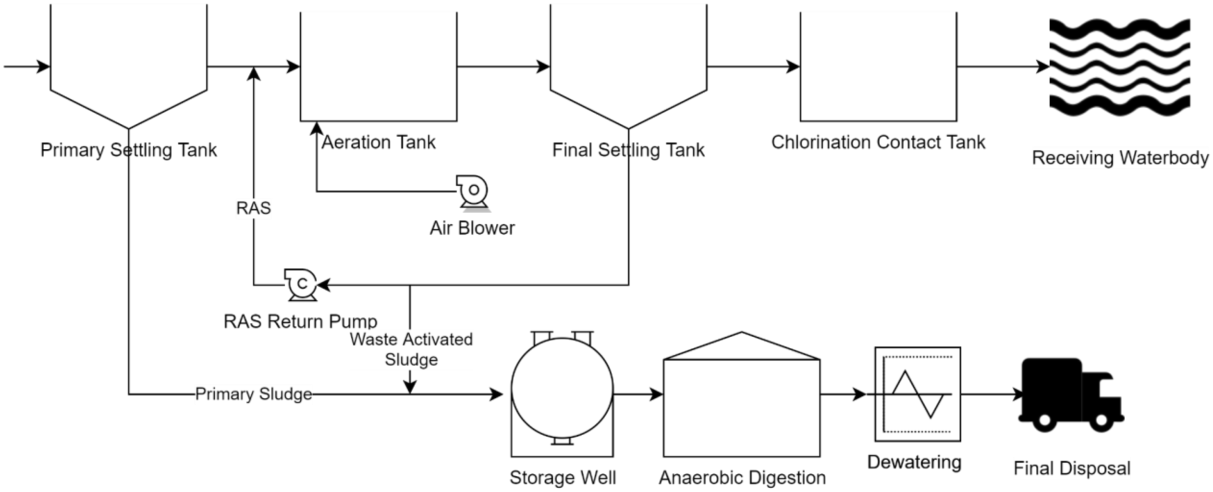

Figure 1. A schematic diagram of the wastewater treatment process at Wards Island WRRF

Sludge Thickening

Wards Island WRRF implements gravity thickening to increase the solids content of the sludge prior to anaerobic digestion. Both primary sludge and WAS are mixed together and settled in one of twelve circular tanks, each with a diameter of approximately 70 feet and a depth of 10 feet. The base of these tanks is conical which allows the sludge to accumulate towards the center of the tank where the thickened sludge is pumped out. Although mechanical arms are not used to sweep the sludge blanket towards the center, they are used to skim the surface to remove floatable material. The collected sludge is sent to a storage basin prior to pumping into the anaerobic digesters.

Table 2 shows the 2020 thickened sludge characteristics from the Wards Island WRRF gravity thickeners and Figure 2 shows the solids content of the gravity thickened sludge. The average percent solid of sludge at Wards Island WRRF was 2.94% with a standard deviation of 0.55%.

Table 2. Statistics of gravity thickened sludge characteristic.

Parameter	*Flow*		*Solids Loading*		*Percent TS*	*Percent VS*
Units	*1000 ft^3/day*	*m^3/day*	*1000 lb/day*	*1000 kg/day*	*%*	*%*
Average	113.0	3991	204.1	92.56	2.9	2.4
Standard Dev.	23.36	825.0	46.26	20.98	0.5	0.5
95th Percentile	150.0	5298	275.5	125.0	3.8	3.2
5th Percentile	76.76	2711	133.1	60.36	2.2	1.7

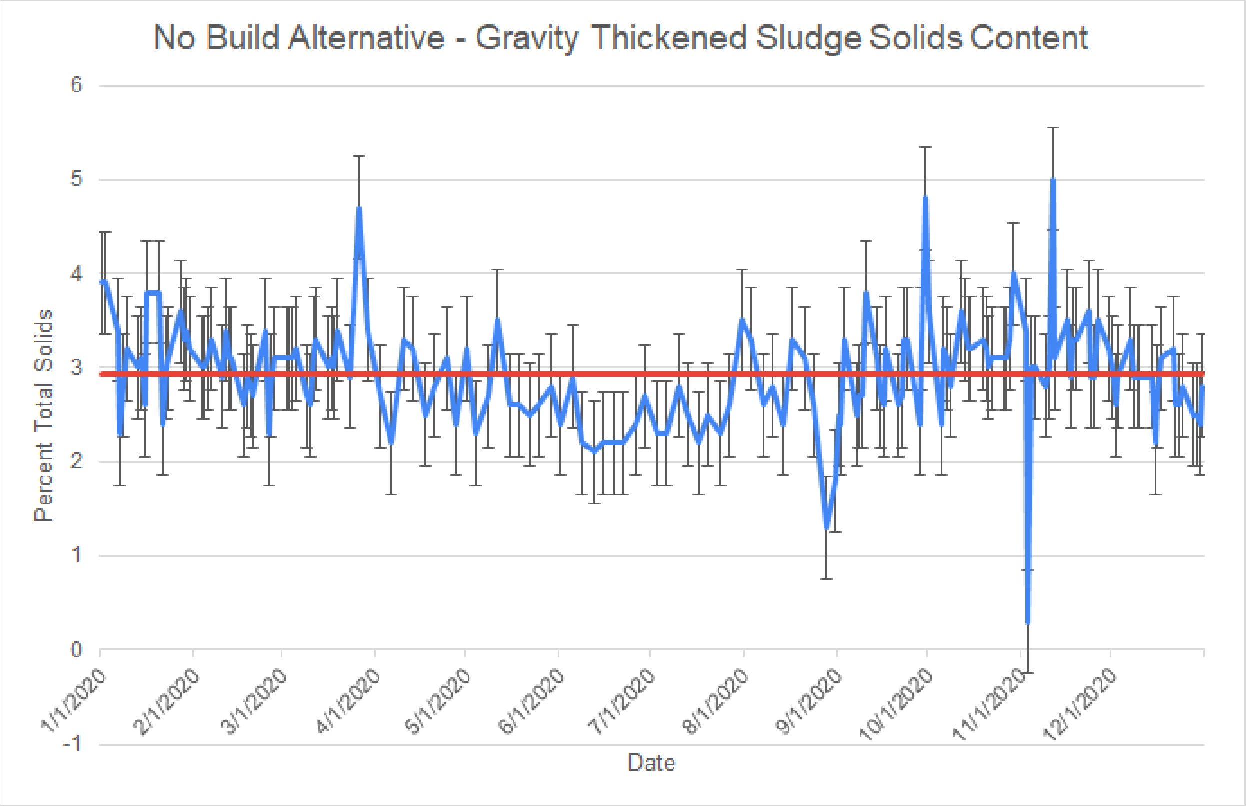

Figure 2. Total solids content of the gravity thickened sludge.

Anaerobic Digestion

Wards Island WRRF currently employs mesophilic anaerobic digestion to treat and reduce the volume of plant sludge streams. The monthly averaged Solids Retention Time (SRT), calculated from the facility's collected data, of the Mesophilic digesters at Wards Island for the year of 2020 are shown in Figure 3 below. The SRT varied between 14 and 20 days with an overall average of 16.41 days. The variations in the SRT for Wards Island are determined by the rate of sludge production. The EPA requires a minimum of 15 days mean cell residence time in an Anaerobic digester as a process to significantly reduce the pathogen content of sludge (Pathogens and Vector Attraction Reduction,2018). It is evident from analysis of the plant's previous SRTs that Wards Island WRRF is approaching its anaerobic digestion capacity. The plant should have enough digester capacity to maintain a minimum of a 15-day SRT year-round which it fails to currently meet. This warrants upgrades in the near future to increase capacity.

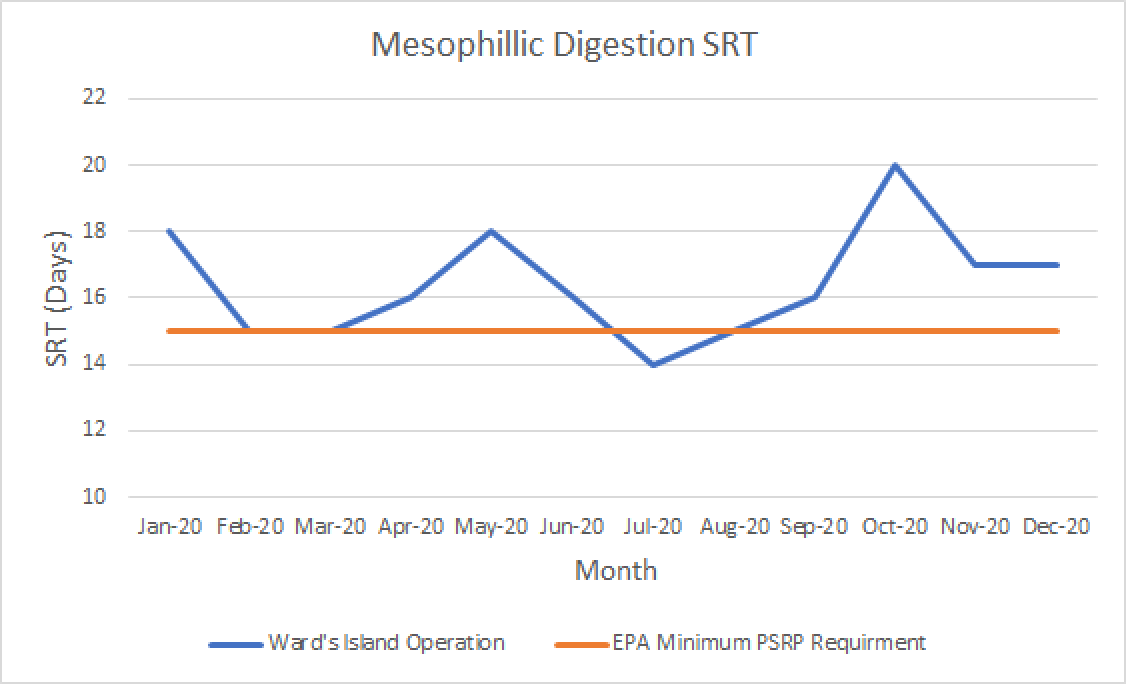

Figure 3. SRT of mesophilic anaerobic digester.

Fuel Demand and Generation

Wards Island WRRF uses Number 2 (No.2) fuel and ADG to provide the heat for its digesters. The plant does not currently have a biogas storage facility and therefore, any excess ADG is flared. Figure 4 below shows a smoothed-out version of the plants No.2 fuel (Distillate fuel #2) usage, the amount of energy received from ADG (combusted gas), and the amount of energy wasted in the flared ADG (flared ADG). The Fuel #2 usage was smoothed out with a 6-month rolling average since the information obtained was only from the fuel storage tank refills rather than from the fuel usage levels. Heating demands for NYC are lower in the summer than in the winter, biogas is mostly or entirely flared during that season and No.2 fuel usage is reduced.

The potential energy in the flared ADG is consistently greater than the energy generated from No.2 Fuel. If the plant was to store ADG rather than flare it, they could eliminate their need for fuel purchasing.

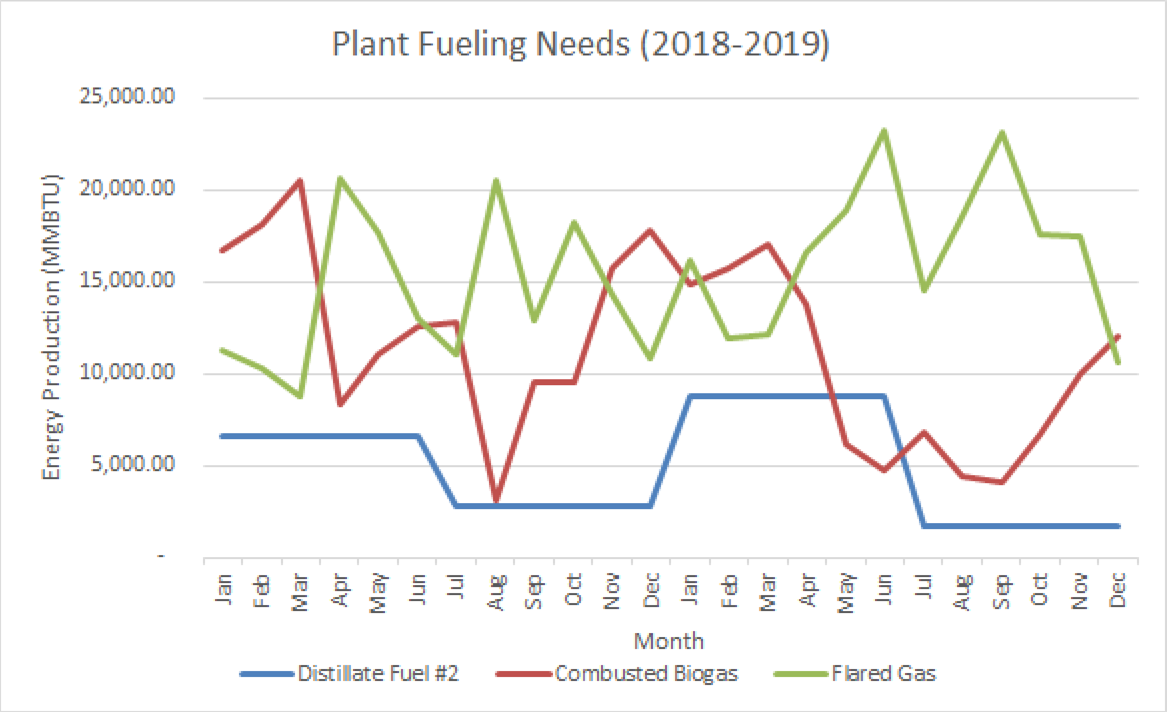

Figure 4. Plant fueling demands and flared ADG.

Alternative #2 - Retrofitting Thermal Hydrolysis

Analysis of the Wards Island WRRF shows that it is nearing its maximum capacity for anaerobic digestion. Being located on an island in NYC, the addition of more digesters impose a significant footprint on the facility lot, therefore process optimization and improvements is preferred prior to major infrastructure changes. A solution to the plant's capacity issues that requires minimal area expansion is the Cambi Thermal Hydrolysis Process (THP). Implementation of THP would only require Wards Island to install high pressure boilers and the Cambi THP system with enough capacity to handle at least one and a half hours of sludge stream volume as well as additional thickeners. This is a significantly smaller unit than an additional anaerobic digester which would have to store 15 days' worth of its sludge stream volume, making THP an attractive option for Wards Island. A schematic diagram of the proposed implementation of thermal hydrolysis is shown in Figure 5, which only accounts for the sludge treatment of the wastewater treatment process.

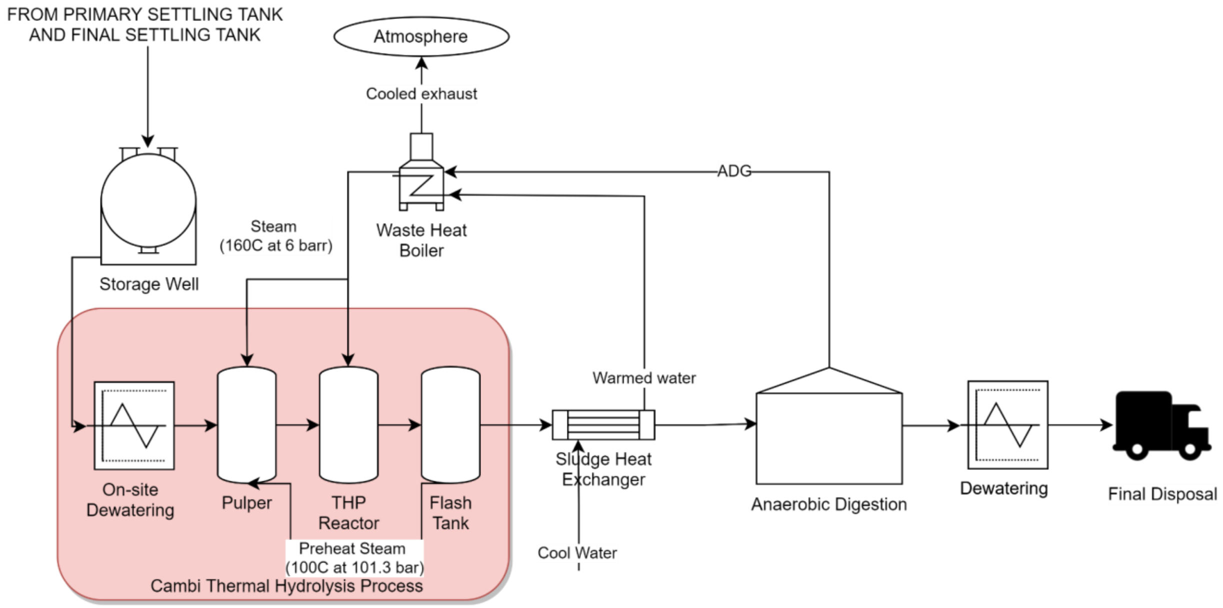

Figure 5. A schematic diagram of the proposed thermal hydrolysis implementation.

Sludge Thickening (Belt Filter Press)

Belt filter press design is based on the 95th percentile of the solid loading observed in the 2020 year. As mentioned earlier, this design utilizes the gravity thickeners to do pre-thickening prior to belt filter press thickening. The rationale for this design choice, opposed to thickening exclusively with belt filter presses, is to reduce the sludge loading on to the belt filter presses which would otherwise increase polymer demand and increase the number of units needed to procure and maintain. This decision ultimately reduces energy demand and costs as gravity thickening uses gravity as a “free resource” to provide some level of treatment. From historical data, gravity thickening has been shown to be effective, as it produces sludge with a solid content of 3% from very dilute sludges typically observed to be less than 1% in solids content (Metcalf and Eddy, 2014).

A mass balance approach is used in determining the sludge characteristics of thickening gravity thickened sludge using belt filter presses; the assumptions used are as followed:

1. All sludges have a density of 1000 kg/m^3, or 62.4 lb/ft^3.
2. Belt filter presses produce sludge with a total solids content of 16% by weight.
3. Solids capture efficiency is 95% (η).

Equation 1. Mass balance equation.

$\dot{m} = C_{eff} \times Q_{eff} \times \eta$ to the below serves as the basis of the mass balance calculations. The influent mass flow ($\dot{m}_{in}$) is known to be 276,000 lb/day from historical data acquired and setting a target effluent sludge TS content (C_{eff}) of 16%, the flow (Q_{eff}) of the sludge is determined to be 24,900 ft^3/day. This flow and solids loading rate is the feed characteristics of the THP process.

Equation 1. Mass balance equation.

$$\dot{m} = C_{eff} \times Q_{eff} \times \eta$$

For anaerobic digestion design, the feed is based on average flow conditions observed in 2020. This allows for conservative ADG production estimates when considering the energy balance of the design. The average influent mass flow is known to be 204,000 lb/day from historical data acquired and setting the same target effluent sludge TS content of 16%, the flow of the sludge is determined to be 18,400 ft^3/day.

Thermal Hydrolysis Pretreatment

The THP configuration for this design is a mixed-sludge pre-digestion thermal hydrolysis process. Mixed sludge refers to the combination of primary sludge and WAS that is fed in the THP reactors. Other configurations exist where only the WAS stream is thermally hydrolyzed, and the primary sludge is used as the diluent to the thermally hydrolyzed sludge before feeding to the digesters. This configuration reduces the energy demand of THP by reducing the amount of sludge to be treated but may risk losing Class A biosolids by introducing pathogenic organisms from having the primary sludge bypass THP to the digesters. Alternatively, the THP reactors can be placed after anaerobic digestion ensuring that any pathogenic organisms are sterilized prior to dewatering. Although this can produce Class A biosolids and improve sludge dewaterability, the benefits of thermal hydrolysis on anaerobic digestion is lost because it is placed after. Implementing THP before and after anaerobic digestion is also a consideration to achieve all the benefits of THP, however the energy demand to operate the process on two sludge streams is costly.

These different configurations are implemented to achieve certain end-product goals, whether it is to improve biosolids degradability, increase ADG production, or improve dewaterability. The rationale for implementing a mixed-sludge pre-digestion thermal hydrolysis process is to increase ADG production in a net positive energy system while sterilizing pathogenic organisms from the sludge.

Pre-Heating Phase

The belt filter press is designed to thicken the sludge to 16%. Cambi does not recommend thickening the sludge greater than 16% as it decreases efficiency. Sludge with a TS above 16% would require extensive amounts of pumping and heating costs (Ringoot, Kleiven, & Panter, 2012). After the sludge is thickened, it is sent to a pulper, which raises the temperature from room temperature, which is assumed to be 20°C, to 100°C. The increase in temperature is facilitated with direct steam injection that is sourced from recycled steam and steam generated from boilers.

The energy demand for this phase is derived by Equation 2. Energy equation to heat sludge.

$$E = \dot{m} \times C \times \Delta T$$

$E = Q \times \rho \times (\%TS \times C_{solid} + [1 + \%TS] \times C_{water}) \times \Delta T$ below. The mass flow rate of the sludge ($\dot{m}$) can be determined from the flow (Q), which is informed to be 18,400 ft^3/day, based on the belt filter press design prior to this section and assuming the density of the sludge (ρ) to be 62.4 lb/ft^3. Since the design total solids content ($\%TS$) is set to 16% TS, 16% of the overall specific heat capacity is contributed by the assumed sludge solid specific heat capacity (C_{solid}) of 0.65 Btu/lbC (1.5 kJ/kgC) (Metcalf and Eddy, 2014) and the remaining 84% is water which is assumed to have a specific heat capacity (C_{water}) of 1.8 Btu/lbC (4.18 kJ/kgC). As mentioned above the change in temperature (ΔT) for the preheat phase is 80°C, which determines that the overall energy demand of this phase is 201 MMBtu/day. Since the Cambi THP process includes a steam recycle process, this energy demand is offset by the energy input from the recycled steam, which ultimately reduces the demand on fresh steam. A detailed calculation is shown in Appendix A; a physical copy of the spreadsheet is available upon request.

Equation 2. Energy equation to heat sludge.

$$E = \dot{m} \times C \times \Delta T$$

$$E = Q \times \rho \times (\%TS \times C_{solid} + [1 + \%TS] \times C_{water}) \times \Delta T$$

Thermal Hydrolysis Phase

After preheating, the sludge is heated even further from 100°C to 160°C at a pressure of 6 bars. After reaching 160°C, the sludge is held at this temperature for 30 minutes. Determining the energy demand in this phase is similar as in the preheating stage with the exception that the temperature change is 60°C opposed to 80°C, and that the introduced steam in the preheating stage contributes some water into the sludge which is mixed. The change in mass flow rates and total solids is accounted for with mass balance. The energy demand for this phase is determined to be 177 MMBtu/day.

Steam Explosion and Cooling Phase

After being thermally hydrolyzed, the pressure held within the reactor is released, bringing the system to atmospheric pressure rapidly. The sudden change in pressure results in a steam explosion that rapidly disintegrates water-bound organic material in the sludge, which improves the anaerobic digestibility. The steam produced by the pressure drop is sent to another reactor in the preheat stage to preheat the incoming sludge, and the outgoing sludge is cooled and fed to the anaerobic digesters.

The quantity of steam that is generated during the steam explosion can be described with Equation 3. Steam generation from steam explosion.

which indicates the fraction of water in the sludge that is converted into steam (W) based on the enthalpy of the condensate before the steam explosion ($h_{0,l}$), enthalpy of the condensate after the steam explosion (h_l), and the enthalpy of evaporation of the condensate after the steam explosion (h_e). In the THP process, 160°C sludge is immediately cooled to 100°C when the pressure is released, which translates to 11.4% by weight of sludge water being

Equation 3. Steam generation from steam explosion.

$$W = \frac{h_{0,l} - h_l}{h_e}$$

converted to steam. This results in approximately 177,000 lb/day of steam generated from the steam explosion; assuming this steam is saturated at 100°C, the energy content of this steam is estimated to be 140 MMBtu/day. This energy content is used to offset the demand of fresh steam into the preheating stage; and because steam is directly injected into the sludge, minimal losses can be expected (Metcalf and Eddy, 2014).

Table 3 summarizes the energy and steam demand of the phases of thermal hydrolysis.

Table 3. Energy and Steam Demand of THP cycles.

Phase	Energy Demand (MMBtu/day)	Steam Demand (lb/day)
Preheating	**+201**	**245,000***
THP	**+177**	**150,000**
Recycle Steam	**-140**	**-177,000**
Total Demand	**+238**	**218,000**
Total Boiler Demand**	**+318**	

*Value is the sum of two steam masses at different temperatures to meet the energy demand.
**Boiler demand accounts for 75% boiler efficiency.

Anaerobic Digestion

The anaerobic digestion requirements for sludge after it has undergone thermal hydrolysis pretreatment phase are less stringent than they would be without pretreatment. The heat treatment provided by thermal hydrolysis also meets the EPA’s requirements for Processes to Significantly Remove Pathogens (PSRP) which states that sludge must either go through the anaerobic digestion process at a 15-day SRT or be heated to at least 120° for at least 20 minutes.

The design of the digesters is based on the average solids loading condition, as variation in sludge loading are buffered by storage tanks and splitter boxes, unlike in the THP design which uses the 95th percentile solids loading condition.

Sludge Loading Capacities

The design of the anaerobic digestion phase is based on maintaining Wards Island WRRF digesters’ design SRT of 18 days, as stated in the Wards Island Operation and Maintenance Manual. With this design choice and determining the sludge flow to be 43,400 ft^3/day, the required volume needed with an 80% digester capacity is 975,000 ft^3, which would occupy 3.87 digesters.

Evenly distributing this flow while staying below the 80% digester capacity, 4 digesters are utilized with each digester at 77.4% capacity. The addition of THP pre-digestion, increases the digestion capacity by approximately 50% by volume, ultimately accepting a maximum feedstock flow of 89,600 ft^3/day. This design increases capacity, allowing 4 digesters to be used for other feedstocks, such as food waste or other WRRFs' sludges.

Specific organic loading rate ($SOLR$) is a value used to quantify the amount of organics that is loaded into the digester normalized to a unit volume. This value is often used to size the digester which is determined from Equation 4. Specific organic loading rate equation. $SOLR = \frac{\dot{m} \times \%VS}{V}$. In the THP design, the SOLR is determined to be 0.17 lb/ft^3/day (2.77 kg VS/m^3/day), knowing the average total solids loading ($\dot{m}$) is 204,000 lb/day, the design volume (V) is 975,000 ft^3, and the historical average volatile solids content ($\%VS$) being 82.7%. This result is reasonable when compared to a typical design criterion of 0.16 lb/ft^3/day for single-stage mesophilic anaerobic digesters (EPA, 2016).

Equation 4. Specific organic loading rate equation.

$$SOLR = \frac{\dot{m} \times \%VS}{V}$$

The digester sizing and SOLR suggests that this system is organic loading constrained as increasing the sludge flow would not impact the process greatly since the facility has the capacity to handle greater flow. Since the SOLR is at an approximate value to typical design criteria, increasing the concentration of organics could have a greater impact on anaerobic digester operation than increasing flow.

Anaerobic Digester Gas Production

The ADG production (Q_{ADG}) and associated energy production (E_{ADG}) from anaerobic digestion is based on the solids loading that is fed into the digester ($\dot{m}$), a conversion factor (f_{VSR}) of 15 ft^3/lb VS reduced, and the energy content of ADG, as shown in Equation 5. ADG production equation.

$Q_{ADG} = \dot{m} \times \%VS \times VSR \times f_{VSR}$. The total solids loading into the digester is approximately 204,000 lb/day, and with an average volatile solids content ($\%VS$) of 82.7% as seen in historical data, the volatile solids loading is approximately 168,000 lb/day.

Equation 5. ADG production equation.

$$Q_{ADG} = \dot{m} \times \%VS \times VSR \times f_{VSR}$$

The amount of that volatile solids that is destroyed is described by the percent volatile solid reduction (VSR), which is 52.8% on average at Wards Island WRRF with the No-Build alternative. Case studies and literature that have implemented Cambi's THP process suggests that the VSR increase resulting from THP can range from 30% to 50%. The low end of the range at 30% was selected to be conservative, which estimates that the VSR with THP is approximately 68.7%, resulting in 115,000 lb/day of volatile solids to be converted to ADG. Applying the 15 ft^3 ADG/lb VS destroyed conversion factor, approximately 1,730,000 ft^3/day of ADG is expected to be produced, which equates to 1,039 MMBtu/day, or 31,200 MMBtu/month if the energy content of ADG (f_{ADG}) is 600 Btu/ft^3, as shown in Equation 6. ADG energy production.

$E_{ADG} = Q_{ADG} \times f_{ADG}$.

Equation 6. ADG energy production.

$$E_{ADG} = Q_{ADG} \times f_{ADG}$$

Energy Balance Analysis

The designs discussed are compared based on the historical or expected energy demand/production respective to Alternative 1 and 2 around the sludge handling process, starting from thickening to solids disposal. Transition from the No-Build alternative to the THP system poses some losses and gains in the energy balance. In the No-Build alternative, energy is consumed in the form of electricity, No. 2 heating oil, and ADG recovered from the anaerobic digesters.

The energy demands for Alternative 1 are sourced from historical data provided by the WRRF; purchased energy consists of electricity and No. 2 heating oil to meet electrical and heating demands at the facility. Energy production at the WRRF consists of only ADG reuse that is generated from the facility's anaerobic digester, which is used exclusively for digester heating. When retrofitting the THP system into the WRRF, energy sources are reallocated based on the energy demands and generation of the design which consists of:

1. THP system
2. Cogeneration
    a. Electricity Generation
    b. Waste Heat Recovery
3. ADG Production

The combination of these energy demands and generators contributes to the gains and losses in the energy balance.

THP Demand

Implementing THP applies a demand that is introduced into the No-Build alternative. As discussed in *Thermal Hydrolysis Pretreatment*, the energy demand of this system is solely based on the energy input needed to generate the steam for the process. The entire THP process, accounting for the sludge preheating and high heat phase, requires an energy demand of 318 MMBtu/day. This system is designed to operate exclusively off of the ADG that is produced from the anaerobic digesters, which is expected to produce energy at an average rate of 31,200 MMBtu/day.

Digester Heating

In the No-Build alternative, Wards Island WRRF consumes ADG generated from the digesters for digester heating. In the THP alternative, heating is not necessary as the sludge is already heated prior to being fed into the digester. The energy savings from eliminating the need to heat the digesters directly varies from month to month due to the temperature variability that comes with the changing seasons in NYC. During the 2017 to 2018 year, the average ADG production was 18.9 million ft^3/month, which equates to approximately 11,300 MMBtu/month.

In the THP process, the sludge is heated beyond what the digester can accept, which is approximately 40°C, so heat exchangers are often employed to remove excess heat from the sludge. Since the ADG demand in the No-Build alternative is eliminated in the transition to the THP alternative, all the ADG produced is allocated for replacing energy demands or generating energy in the form of electricity and heat to offset on-site demand.

Replacing No. 2 Heating Oil

No. 2 heating oil is used for heating purposes, similar to the ADG reuse for digester heating that occurs in the No-Build alternative, with the exception that this purchased fuel is used mainly for space heating, water heating, and HVAC related operation. With the energy savings from eliminating digester heating, the reallocation of that ADG can be used to replace the No. 2 heating oil functions. Like with digester heating, heating demands vary throughout the year with temperature fluctuations caused by seasonal changes. The average No. 2 heating oil demand is approximately 36,000 gallon/month, which equates to 4,970 MMBtu/month. Immediately comparing the ADG energy recovered from eliminating digester heating (11,300 MMBtu/month) and ADG energy demand for replacing No. 2 heating oil (4,970 MMBtu/month), it can be seen that the recovered energy exceeds the demand. This excess energy can contribute to other demands such as the THP process or electricity generation.

Combined Heat and Power (CHP) & Cogeneration

With the expected excess ADG, implementation of cogeneration systems is considered due to its overall efficiency and ability to produce two forms of energy that are useful to WRRFs: electricity and heat. The excess ADG is the sum of average energy demands and sources discussed in previous sections, totaling to approximately 16,700 MMBtu/month. With an assumed electrical efficiency of 30% and heat recovery efficiency of 50%, 1.46 million kWh and 8,330 MMBtu of heat can be generated each month. The electricity generated could offset 18.2% of Wards Island WRRF’s month electricity demand. The waste heat can be used for different uses whether it's for space heating, steam generation, or even for cooling, however, this design reuses the waste heat for sludge drying in order to offset costs for hauling solids for final disposal.

Sludge Drying

Sludge disposal is costly depending on the method of disposal, the quantity of solids produced, and the distance traveled to the solid disposal site. Sludge drying is an effective way to reduce the cost of sludge disposal by evaporating off a significant amount of water weight by applying heat to the sludge. Knowing the cake mass flow rate of 200,000 wet lb/day, with a dry solid content of 25% solid, it would require 226 MMBtu/day to raise the temperature of the sludge to 100°C and boil off the water weight. This results in 200,000 lb/day, or 100 wet tons/day, of sludge cake produced which needs to be hauled away for final disposal. However, cake dryness as a result of indirect dryers is expected to range from 65% to 95% (Metcalf and Eddy, 2014). This range would produce 153 wet ton/day to 105 wet ton/day. Additionally, the process of heating the sludge to these temperatures virtually inactivates any pathogen bringing the sludge closer to meeting Class A quality.

Figure 5 depicts the producers and consumers of energy in the No-Build alternative (top) and the THP alternative (bottom). The greatest impacts to improve the energy balance is the usage of the waste ADG (top, yellow) in the No-Build alternative and the replacement of the digester heating demand (top, red) by THP. This allows excess ADG to be used for on-site beneficial use such as replacing heating demands from No.2 heating oil and cogeneration.

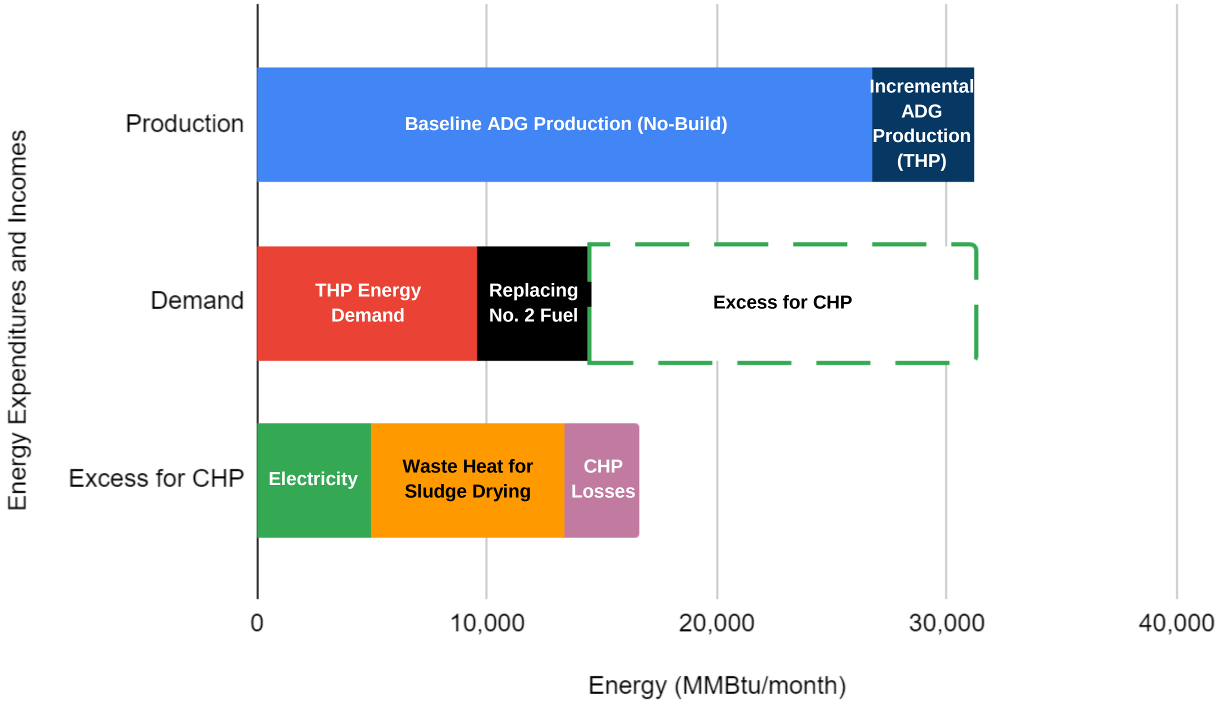

Figure 6. Energy production and allocation to upgrade Wards Island WRRF demands.

Design Summary

The energy balance suggests that Wards Island stands to gain energy production with the implementation of THP. The excess heating demand is compensated by the incremental increase in ADG production, but the plant must be more efficient in its utilization of its produced ADG for this to be true.

Cost Analysis

Current Operational Costs

Since this alternative does not require the addition or construction of any new facilities within the plant, there is no capital cost for this alternative. The operational costs of the anaerobic digesters will consist of employee costs, fuel costs, and digester maintenance costs. Since the number of digesters and the required employee intervention will remain the same in both analyzed alternatives, it is assumed that these two factors will be equal and need not be calculated. The operational costs then rely completely on the cost of the Distillate Fuel No.2. In both 2018 and 2019 the Wards Island WRRF spent about 1.25 million dollars.

The sludge disposal costs of the plant are approximately 130 dollars per wet ton of sludge. With a volume of 282 tons of sludge produced per day or 8,460 tons per month. This equates to a cost of about 1.1 million dollars per month and 13.2 million dollars per year.

The total plant digester and sludge operating cost then becomes 14.5 million dollars per year.

Thermal Hydrolysis

Approximating the cost of thermal hydrolysis can be difficult due to the relative novelty and lack of implementation across the world. In order to estimate the cost of thermal hydrolysis, an informative UK study generated a series of cost curves for thermal hydrolysis and major associated infrastructure (Barber, 2016). The facilities accounted for existing anaerobic digestion and sludge-holding facilities. Equation 7 estimates the cost of implementing a thermal hydrolysis facility (C_{THP}).

Equation 7. Model of capital cost for the Cambi THP system (Barber, 2016).

$$C_{THF} = 6 * 10^6 * Q^{0.5509}$$

Using Equation 7 and the average mass flow rate of TS (Q), the cost of implementing a thermal hydrolysis facility at Wards Island WRRF is approximately 100 million dollars. A detailed calculation is shown in Appendix B.

Cogeneration

Implementing a cogeneration facility at Wards Island WRRF would alleviate the electricity costs of the Wards Island WRRF. The excess ADG produced by thermal hydrolysis can generate about 2000 kW/month with a capital cost rate of about 2240 USD/kW (United States EPA, 2011). Therefore, the cogeneration facility itself would cost about 4.5 million dollars.

Improvements in the sludge drying process of the Wards Island WRRF allow for a smaller volume of sludge to be hauled to waste facilities and lower sludge hauling costs. It is estimated that the sludge produced within Wards Island can be brought down to 70% solids concentration, which would bring the volume of sludge produced down to 140 tons per day, or 50,400 tons per year. Assuming the sludge hauling costs remain constant ($130/wet ton), the sludge hauling costs with the implementation of THP becomes 6.6 million dollars.

Return on Investments

With the elimination of fuel purchasing and the 6.6-million-dollar reduction in sludge hauling costs caused by THP, the overall reduction in operational costs associated with THP becomes 7.7 million dollars a year. With a capital cost of 104.5 million dollars, the plant can anticipate a 13.57-year return of investment.

Conclusions

The design shows that implementing THP at Wards Island WRRF can provide benefits by improving ADG production from 30% to 50% as is found in literature and case study experience, a resource that is used in our design to not only power the THP system, but to produce enough excess gas to offset digester heating demands, No.2 fuel demands, and approximately 18.2% of Wards Island WRRF's electricity demands. Additionally, enough waste heat is produced from cogeneration so that significant sludge drying is possible, further reducing cost and producing Class A biosolids which opens up more pathways for more sustainable practices.

Future Studies

Modifications to the current model could be made to increase the overall energy efficiency of the cambi process. Biogas production increases from the thermal hydrolysis pretreatment gives plants the opportunity to explore methods in co-generation. The pressure relief phase of thermal hydrolysis can be used to generate electricity and power the WRRF. Following pressure relief, sludge heat can be recycled during the cool down phase to minimize the energy needed in the heating phase. This can be accomplished by incorporating a series of heat exchangers into the sludge cool down phase. These methods were incorporated in a Dublin WRRF which allowed the plant to reduce its overall energy utilization after incorporating the Cambi Thermal Hydrolysis process (Pickworth et. al., 2006).

Furthermore, future models would benefit further by building a database on the biogas production of the Wards Island WRRF. Biogas values used in this model were estimated from measured VS reduction values, however the underlying assumption necessary for this estimation can be inaccurate. To fully understand the potential for increased energy production with the implementation of the Cambi process, direct measurement of the plant's biogas production should be employed for at least one year.

With the decrease in SRT that comes with the implementation of THP, Wards Island would have an increase in capacity that might allow for the implementation of co-digestion. Co digestion would provide additional energy benefits to the city when factoring in solid waste management energy expenses.

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Appendix A: Energy Calculations

Sludge Thickening				**Sludge Preheating**			
Temperature		20	C	Temperature		100	C
Sludge Flow				*Sludge Flow (effl.)*			
	95 %tile	24,906	cfd		95 %tile	28,838	cfd
	Average	18,448	cfd		*Average*	22,380	cfd
TS Mass Flow Rate							
	95 %tile	275,520	lb/day				
	Average	204,082	lb/day				
Percent TS				*Percent TS*			
	95 %tile	16.0%	by wt.	*Design Percent TS*		13.8%	
	Average	16.0%		*Average Percent TS*		13.2%	
Average Percent VS		82.7%		*Average Percent VS*		82.7%	
				Steam Input Mass Flow		68,853	lb/day
				Recycle Steam Mass Flow		176,528	lb/day
Energy Balance Variables				*Phase Heat Demand*		2.01E+08	Btu/day
Boiler Efficiency		75%				201	MMBtu/day
Boiler Steam Temp.		160	C	*Recycled Heat*		1.40E+08	Btu/day
						140	MMBtu/day
				Steam Input		8.16E+07	Btu/day
						81.6	MMBtu/day
						997	kW

High Heat/Pressure THP					**Steam Recycle**					**Sludge Blending**			
Temperature		160	C		Temperature		100	C		Temperature		65.6	C
Sludge Flow (effl.)					*Sludge Flow (effl.)*					*Sludge Flow (effl.)*			
	95 %tile	31,234	cfd			95 %tile	28,405	cfd			95 %tile	49,811	cfd
	Average	24,776	cfd			*Average*	21,947				*Average*	43,353	cfd
Water Content		1,700,351	lb/d							*TS Mass Flow Rate*			
											95 %tile	275,654	lb/day
											Average	204,215	lb/day
Percent TS					*Percent TS*					*Percent TS*			
Design Percent TS		12.76%			*Design Percent TS*		14.03%			*Design Percent TS*		8%	
Average Percent TS		11.91%			*Average Percent TS*		13.45%			*Average Percent TS*		6.81%	
Average Percent VS		82.7%			*Average Percent VS*		82.7%						
Steam Mass Flow		149,522	lb/day							Blend Sludge Flow		21,406	cfd

Total Steam Input		218,375	lb/day							Blend Sludge %TS		0.01%	
Steam to TS ratio		0.79	kg steam/kg TS		*Percent Flash*		11.36%	by wt.					
	Metcalf & Eddy (Eqn. 13-18)	0.80	kg steam/kg TS		*Steam Mass Flow*		176,528	lb/day					
Phase Heat Demand		1.77E+08	Btu/day							**Heat Exchanging**			
		177	MMBtu/day							Target Sludge Temp.		40	C
		2,164	kW		*Recycled Heat*		1.40E+08	Btu/day		Energy Transfer		143,218,765	kJ/day
Total Heat Demand		378	MMBtu/day				140	MMBtu/day				136,057,827	Btu/day
Boiler Heat Demand		318	MMBtu/day									136	MMBtu/day
Boiler ADG Demand		529,823	cfd							Heat Exchanger Effic.		75%	
		1.59E+07	cfm							Coolant (Water) Flow		3,500	cfd
												26,177	gal/d
												99	m^3/d

Appendix B: Cost Calculations

Capital THP Cost		**Units**	6000000		**Cogen. Cost**	Abbr.		
Energy Requirement	378	MMBTU/day			Electrical Capacity	E_gen	2000	kW
C = 6*10^6*(Q^0.5509)		GBP			Capital Cost Rate		2240	USD/kW
Cost	$72,683,938	GBP			**Total Capital Cost**		**$4,480,000**	
	$99,567,038	**USD**			**Annual Savings**		**17,569,598**	**kWh/year**
Recovered Heat and ADG	%VSR Increase	30%	35%	40%	45%	50%		
Energy Production	MMbtu/day	1,039	1,079	1,118	1,158	1,198		
	Monetary Value	$2,077.20	$2,157.09	$2,236.98	$2,316.88	$2,396.77		

A more detailed approach to our calculations is attached to our Report Folder for your Attention.