Feasibility Study of Energy Recovery by Incineration - A Case Study of the Triangle Wastewater Treatment Plant

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Executive Summary

Wastewater Treatment Plants (WWTPs) require a significant amount of electricity throughout the water treatment process. WWTPs also need to dispose their sludge waste, a by-product of the wastewater treatment process, which is another significant expense. But, some sludge management options provide more benefits than others. Wastewater sludge is a biomass and thus energy can be recovered from it. Among the various energy recovery methods, incineration looks promising and has many advantages. Previous research has shown that per unit sludge, incineration may be able to recover twice the amount energy compared to anaerobic digestion. The energy then can be used for generating electricity or for other thermal applications. In addition to its energy recovery performance, incineration also has the advantage of greatly reducing the volume of sludge (approximately by 95%), and rendering the remains inert due to high temperatures. On the other hand incineration requires high capital and operational and maintenance (O&M) cost and can produce a substantial air emissions, requiring sophisticated air emission control equipment.

To get a better understanding of sludge incineration as an energy recovery option, and to help local WWTPs explore sludge disposal alternatives, Triangle Wastewater Treatment Plant (TWWTP), a small-sized WWTP located in Durham County, North Carolina was selected. It currently has no energy recovery system. A feasibility study was conducted to evaluate incineration as an energy recovery and sludge disposal option for the TWWTP. Three aspects were looked at to answer the feasibility question: 1) The system's energy (in this case, electricity) generation performance; 2) A cost-benefit analysis; and 3) An environmental impact assessment.

The analysis was structured in a way to compare the TWWTP’s current sludge disposal method i.e. composting. A business-as-usual (BaU) scenario was defined under the assumption that the disposal rate remains the same in the future, while the wastewater flow steadily rises to reach the plant's designed capacity in 2035. Huber Technology's "sludge2energy" energy-recovery system was narrowed down on as the ideal plant design and slightly adjusted to fit TWWTP's context.

An energy balance model was created to simulate the sludge2energy pilot plant operation for an hour. It was noticed however that TWWTP's sludge had a higher thermal value than that used in the sludge2energy system's pilot plant. This meant a larger, 200 kW turbine option could be explored for the proposed plant, up from the 80 kW of the pilot plant, increasing the net electricity generation. Energy generation projections were made for two scenarios: 1) Only sludge is used as fuel, 2) Sludge as primary fuel with natural gas backup. The plant performance was also judged from the point of view of it being a sludge disposal solution. Applicable federal, state and local policies and incentives were explored and a net present value of the project was calculated. Finally the environmental impact of sludge incineration was compared to the current sludge disposal solution.

Corresponding to our research questions, the results were: 1) The modified sludge2energy system can generate a maximum of 1200 MWh annually providing 20% of TWWTP's requirement in 2016. This fraction is likely to decrease as the wastewater flow and hence electricity consumption increases; 2) As an electricity generator, its electricity is too expensive. As a sludge disposal method, it is again more expense than the current solution. The net present value (NPV) is approximately negative $14 million for both the fuel scenarios; 3) The environmental impact of this incineration system is lower than the BaU disposal solution, due to comparatively lower life cycle air emissions and greater waste volume reduction.

But despite being an environmentally friendlier solution, sludge incineration, specifically in the case of the TWWTP is not feasible due to financial considerations. Several factors including high investment and operational costs, low calorific value of sludge, and low electricity rates in North Carolina have all lead to the negative NPV, with the most significant driver being the O&M costs, making the incineration plant a bad investment. Due to limited time, this study cannot be considered a comprehensive decision-making guide. Future studies need to bolster it by incorporating technical, legal and a deeper financial analysis. However, we still recognize the value of energy recovery by sludge incineration. Therefore, we suggest that the TWWTP continue monitoring the various factors that affect the plant feasibility.

1. Introduction

1.1 Potential of energy recovery from sludge

With a steadily increasing world population and the increasing rate of urbanization worldwide, the quantity of raw wastewater treated by municipal wastewater treatment plants (WWTP) is likely to continue rising. Research suggests that more than 330 km^3/year of (mostly) municipal wastewater was produced globally in 2013[1]. Consequently, sewage sludge disposal poses a significant challenge for municipal WWTPs. Additionally, increasingly stringent regulations on sludge reuse and disposal may force the WWTPs to seek ways to reduce their environmental impact and expedite the phase-out of conventional sludge disposal methods that may not be as sustainable and viable. Disposal methods include landfilling, low efficiency incineration and agricultural use as soil fertilizer[2] among others. For all of these reasons, it is crucial for WWTPs to evaluate all options for sludge management.

Another challenge for WWTPs is energy consumption. Electric power plays a critical role in helping wastewater treatment facilities sustain their 24/7 operations in almost all of the major processes, including collecting, treating and discharging. Wastewater treatment is energy intensive and represents 3% to 4% of total U.S. energy consumption[3]. Also, wastewater treatment process often accounts for the largest proportion of energy consumed by local city government facilities[4].

Recently, there has been increasing public interest regarding energy recovery from sewage sludge, as this has the potential for simultaneously addressing the demand for energy supply and the environmental impacts of conventional sludge treatment[5].

Sludge is a valuable source of energy, which can be recovered in the form of heat, electricity or biofuel through various sludge treatment options. Most widely adopted approaches include anaerobic digestion, co-digestion, incineration in combination with energy recovery, and co-incineration[6].

Currently, energy recovery by incineration serves as the best practice for energy recovery from sludge, both inside and outside of the United States[7,8,9], and has been adopted by some WWTPs around the world. To further enhance the public's understanding of energy recovery technologies and to explore the considerations behind its pragmatic application, we targeted the Triangle WWTP (TWWTP) of Durham County, North Carolina for our case study, and tested the feasibility of sludge incineration as an energy recovery method for its context. The following sections will elaborate on this research. By conducting a feasibility study for a real-world WWTP, this research is intended to provide pragmatic input to the decision-making at the TWWTP, and to serve as a possible reference for policy makers, the private sectors and the general public interested in energy recovery from sludge.

1.2 Incineration

Previous studies have shown that compared to anaerobic digestion, incineration can extract twice the amount of energy per unit sludge[10]. With the goal of maximizing energy extraction, while at the same time offering a better sludge disposal option we chose incineration as the energy recovery technology. Additionally, compared with other sludge treatment methods, incineration has the advantage of large mass and volume reduction of sludge (by approximately 95%), while also rendering the residue completely inert. On the other hand, incineration also has the disadvantages of high capital and operation costs, including the payment of skilled operating and maintenance staff. It also requires air emissions control system and ash disposal[11].

Sufficient oxygen and heat are two factors required to ensure complete combustion of the sludge. The minimum heat requirement includes the sum of sensible heat in the ashes, plus the latent heat needed to evaporate the moisture[12]. Therefore, dewatering the sludge is an essential pretreatment to reduce the fuel requirement for incineration.

Multiple technologies can be used for sludge incineration: multiple-hearth; fluidized bed; electric; co-incineration with refuse; single hearth cyclone; rotary kiln, wet air oxidation, etc[13]. The most commonly used ones in current industrial practice are multiple-hearth furnace and fluidized bed furnace [12], but the selection of furnace type depends on the size of incineration plant and economical requirements.

2. Triangle Wastewater Treatment Plant

Three WWTPs serve Durham and surrounding areas, they are 1) North Durham, South Durham and 3) Triangle WWTPs. North Durham and South Durham plants mainly process residential wastewater[14]. The TWWTP receives mainly industrial and commercial wastewater. North and South Durham plants each have facilities for energy recovery by anaerobic digestion to better utilize their sewage[15], while TWWTP has not yet adopted an energy recovery system due to its size, wastewater characteristics etc. Therefore, we targeted TWWTP for our study.

The TWWTP is located in Durham County and serves the southeast portion of Durham County, which includes areas within and outside Durham City limits, and it also serves the Research Triangle Park (RTP) within the Durham County. It is rated for an average daily flow of 12 million gallons per day (MGD). The plant discharges treated water into the Jordan Lake and is thus designed to meet appropriate nutrient load requirements[16].

2.1 History of TWWTP[17]

In the early 1960's, the system consisted of a simple treatment solution using two facultative lagoons, which rely on atmospheric reaeration and algal respiration to treat the waste[18]. In 1973 and 1983 the plant was upgraded to first a 3 MGD Extended Aeration system and then to a 6 MGD one. But by 1997 the plant was at 80% capacity and due to anticipated customer growth in the service area and due to the Clean Water Responsibility and Environmentally Sound Policy Act Durham County decided to further increase capacity and improve treatment methods employed. The plant largely as it being today was completed in 2005 with a 12 MGD capacity and with an Enhanced Biological Nutrient Removal system. Components of TWWTP are shown in Appendix A.

More recently however a few more additions were made to the plant. These include:

Recycled Water Facility[19]

The recycled water facility was completed in 2012; this facility is intended to provide water for use in landscape irrigation, cooling towers and construction activities. Recycled water is cheaper than municipal water and was built, as a redundant water supply is very important for the Research Triangle Park for facilities. A distribution system is expected to be installed to cover all possible customers over the next decade.

Sludge Handling (Bio solids) Facility

The sludge handling facility consists of holding tanks, centrifuges and an automated truck loading station. The end product of this facility is cake sludge with 20% dry solids, which is then pumped into trucks to be transported to a local composting facility. Then the sludge cake is sold to an external company to be converted into Class compost for the landscaping market.

Future projects under consideration are extensions to the recycled water system and a waste to energy facility.

2.2 Current Situation

In 2015 the facility received on average 4.78 MGD[1]. In 2015, HDR Engineering, Inc. of the Carolinas

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1 Calculated from TWWTP 2015 Influent Data

(HDR) has conducted a survey investigating alternative bio waste treatments and energy recovery potential[20]. The survey has projected that the plant will reach peak capacity by 2035.

The process flow diagram of TWWTP in Figure 1 below:

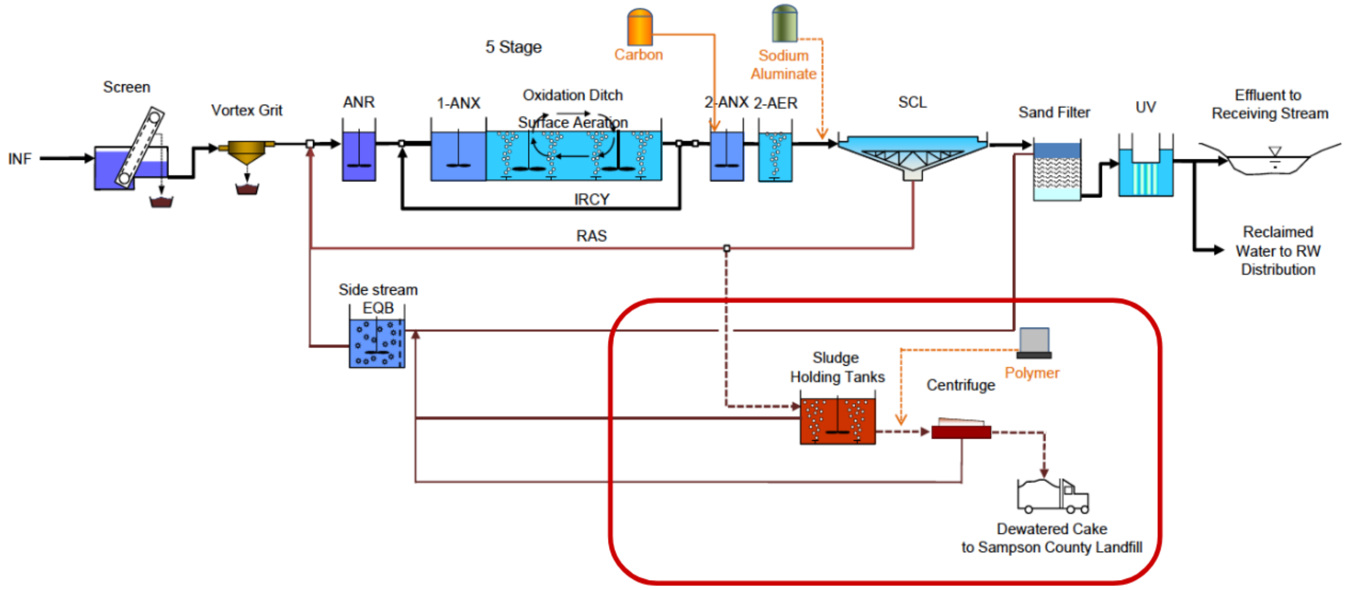


Figure 1: Process flow diagram of TWWTP

As can be seen from highlighted section in the diagram, the treated sludge is first sent to holding tanks. From there a polymer is added to it before feeding it to the centrifuges. These polymer particles act like flocculants, aggregating smaller particles in to a bigger mass. The dewatered sludge from the centrifuge is then shipped to a preferred service provider for composting into Class-A compost for use in commercial landscaping[21].

2.3 Sludge Treatment in TWWTP

2.3.1 Sludge Characteristic

The study used sludge that had been dewatered in a centrifuge with an average solid content of 17.54%. Using a sample of the treated secondary sludge provided by the TWWTP, a Bomb Calorimeter was used to determine the calorific value of the sludge. The calorific value was found to be 13.2061 MJ/kg. Located in the Research Triangle Park (RTP), the TWWTP receives more than 70% of its wastewater from industrial users [20]. This leads to a lower organic load and hence the low calorific value of the sludge. The average, maximum and minimum monthly sludge load in the 2015 calendar year is shown in Table 1.

Table 1: Monthly sludge characteristics of CY 2015

	Total wet mass (kg/month)	**Dewatered mass (kg/month)**
Average	571268.76	237174.64
Max	760792.56	324575.17
Min	440583.47	177507.96

2.3.2 TWWTP Sludge Management

The dewatered and thickened sludge is shipped by McGill Environmental Systems (McGill) to produce Class A compost for agricultural and landscape use[22]. The TWWTP pays McGill a per-trip shipping fee ($150 per haul), along with a per ton processing fee ($26 per ton), and the rent for two trailers at $995 each per month as can be seen in Table 2. The monthly transportation cost of sludge can vary from $18,000 to $30,000, with an average cost of $22,797.

Table 2: Sludge management expenses breakdown for CY 2015

Fee Type	**Price**	**Quantity/month**	**Cost**
Sludge Treatment	$26/ton	~630 tons	$ 273,562/yr
Shipping Fee	$150/haul	25-38 hauls	
Trailer	$995/month	2 (20 tons/haul)	

2.3.3 TWWTP Energy Expense

The TWWTP plant is divided into three major parts, each of which have independent electricity bills. The first part includes the influent pump station and administrative building; the second part includes the sludge building and centrifuges; the third part includes all other electricity consumers onsite. The monthly average energy consumption of the plant as a whole is 497,703 kWh, with 36,444 kWh for the sludge building and centrifuges specifically. The TWWTP pays multiple electricity rates based on the different functions of each part, and the total average monthly electricity bill is $37,502, with $4,991 for sludge handling specifically. But for the purposes of this study an average electricity rate of $0.07/kWh was assumed.

3. Methods

3.1 Incineration Energy Recycle System

3.1.1 Sludge Incineration System Overview

WWTPs vary in size and so do incineration plants. Currently the Triangle Wastewater Treatment Plant generates approximately 4 MGD and its designed capacity is 12 MGD. It is thus considered a small plant. Also considering that the cost should be within reasonable range, we selected the sludge2energy system provided by Huber for our case study. It is designed to handle 9000 tons per annum (tpa) of sludge, which would be sufficient to meet the current sludge incineration demand of TWWTP, but will also be sufficient cover the demand in future. Based on our projection of sludge generation growth by the year 2035, TWWTP would be producing approximately 10000 tpa.

The system mainly uses the technology of sludge combustion and generates electrical power by means of a gas microturbine. The process is described in Figures 2 and 3.

The treated wastewater from the WWTP comes in at 4% dissolved solids (DS). It is then dewatered to 25-30%. In the case of the TWWTP and as mentioned previously, centrifuges perform dewatering. Currently for shipping to the composter, sludge is dewatered to approximately 17%[23]. Ideally, this will have to be increased for the sludge2energy plant to 29%. This sludge is then fed into the dryer which dries it further to 65% DS. The dewatered sludge goes to the incinerator and the heat from the incinerator is fed to the microturbine and back to the dryer. The sludge is reduced to ash and phosphorus can be recovered from this ash.

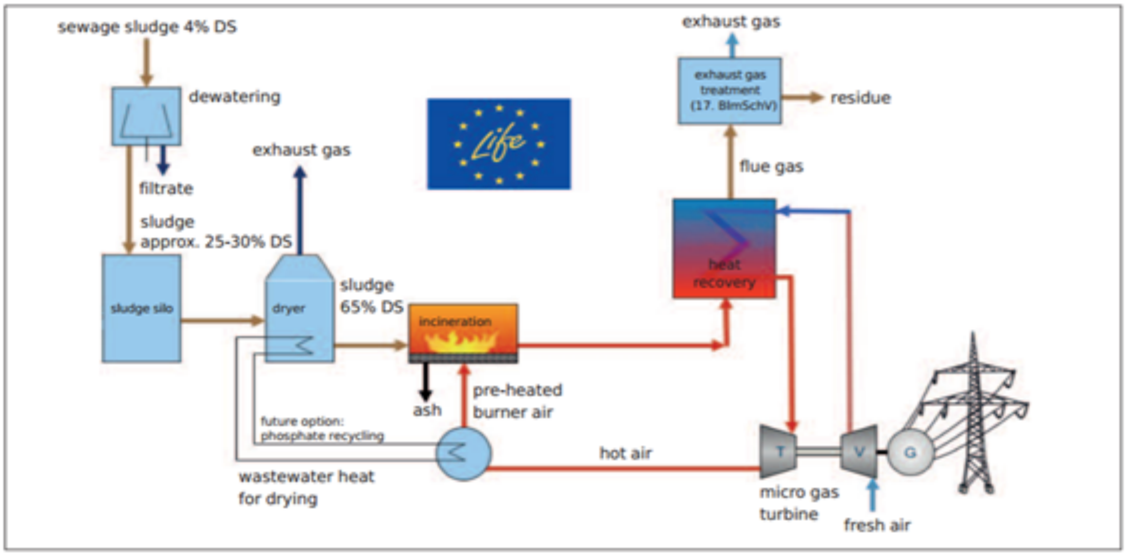
The component of the system will be discussed in greater detail in the next section.

3.1.2 Major System Components

The sludge2energy system is comprised of three key components: 1. A dryer, 2. An incinerator, 3. A microturbine. These components of the specific sludge2energy system are discussed below.

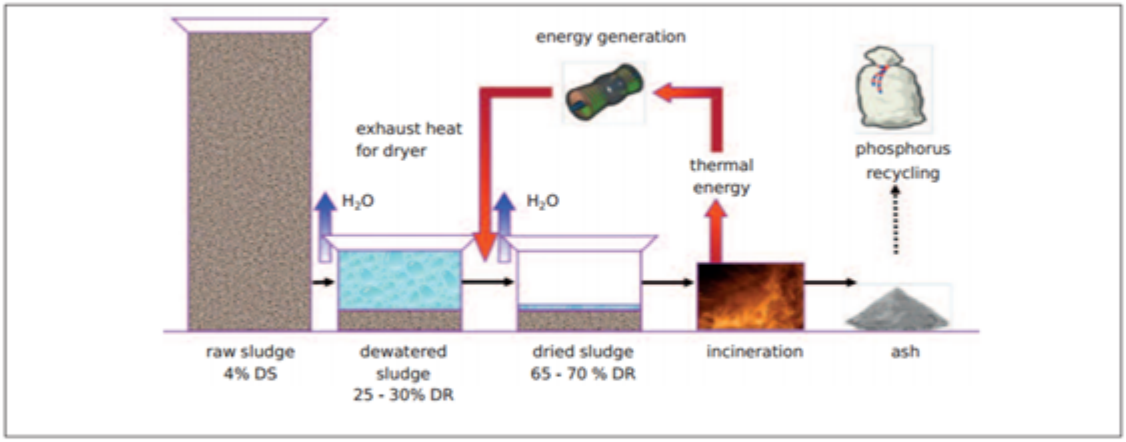
The Dryer - HUBER Belt Dryer BT^{plus}

The sludge2energy plant uses the HUBER Belt Dryer BT^{plus} as the sludge drying solution. It can be used as a standalone dryer or as part of the sludge2energy system. The dryer can dry approximately 15000



Flow diagram of the sludge2energy system

Figure 2: Flow diagram of the sludge2energy system



Treatment stages of the sludge2energy system

Figure 3: Treatment stages of the sludge2energy system

ton/annum of sludge from 17% to 90% DS when used as part of the system, using the thermal heat provided through by the incinerator (D. Weinert, personal communications, February 2017). This feature allows the system to reduce energy consumption and only use fuels such as natural gas when there is a shortfall of thermal energy from sludge. Another feature is its operation at low temperature of 120 °C, which reduces odor and the risk of fire. Odors and other air pollutants are removed before the exhaust air is released into the atmosphere, in compliance with German TA standards (Technical Instructions for Air Pollution Prevention). Also, the features of heat exchangers and helix airflow of the belt system allows for higher energy efficiency drying. A diagram explaining the dryer can be seen in Appendix B

The Incinerator - Grate Stoker Furnace

The incineration component uses grate stoker furnace as part of the system for thermal utilization of sludge. After the sludge is incinerated in the furnace, energy is transferred into the hot air, which is then passed through a heat exchanger and then utilized in the microturbine in a Brayton cycle. The capacity of the furnace is 1 MW thermal and it produces much more heat than is need by the microturbine. This extra heat and the exhaust from the microturbine are fed back to the dryer[24]. The grate stoker type furnace is usually the least expensive type of a furnace[25].

The incineration process produces exhaust gases that contain acidic and noxious gases or other pollutants that might be hazardous to human health and environment. These include pollutants such as SO2, NOx, HCI and fly ash. Through measures including dry-sorptive process and cyclone separator, these pollutants can be effectively removed and filtered. All of these ensure that the emissions coming out of the system adhere to requirements of air pollution prevention standards (the applicable German standards 17th BlmSchV).

Micro gas turbine - TURBEC T100P

The sludge2energy plant is designed using a TURBEC turbine type T100P of an 80 kW capacity. The design has since been bought by Ansaldo Energia, which offers three different versions of the turbine[26]:

1. Biogas fired
2. Externally fired
3. Natural gas fired

The externally fired design is needed for a biomass incineration plant.

3.2 Business as Usual (BaU) Scenario

Our team conducted a site visit in October 2016 to gather information integral to this feasibility study. From the visit, we further enhanced our understanding about the current sludge disposal operations at Triangle Wastewater Treatment Plant. All information was incorporated into our Business as Usual scenario. Under this scenario, the sludge produced receives preliminary treatment by the wastewater treatment plant and then is transported and received by McGill. The disposal rates are shown in Table 2 above.

The company HDR Inc. was engaged by the TWWTP to conduct study the feasibility of sludge disposal options (the recommendation being a solar dryer system). The resulting report had assumptions regarding the projected flow till the year 2035. Using these assumptions and the data about the monthly sludge load, projections were made till the 2035 of the annual sludge load (Figure 4) as well as the annual sludge disposal cost (Figure 5). All the data tables regarding this calculation can be accessed in Appendix C.

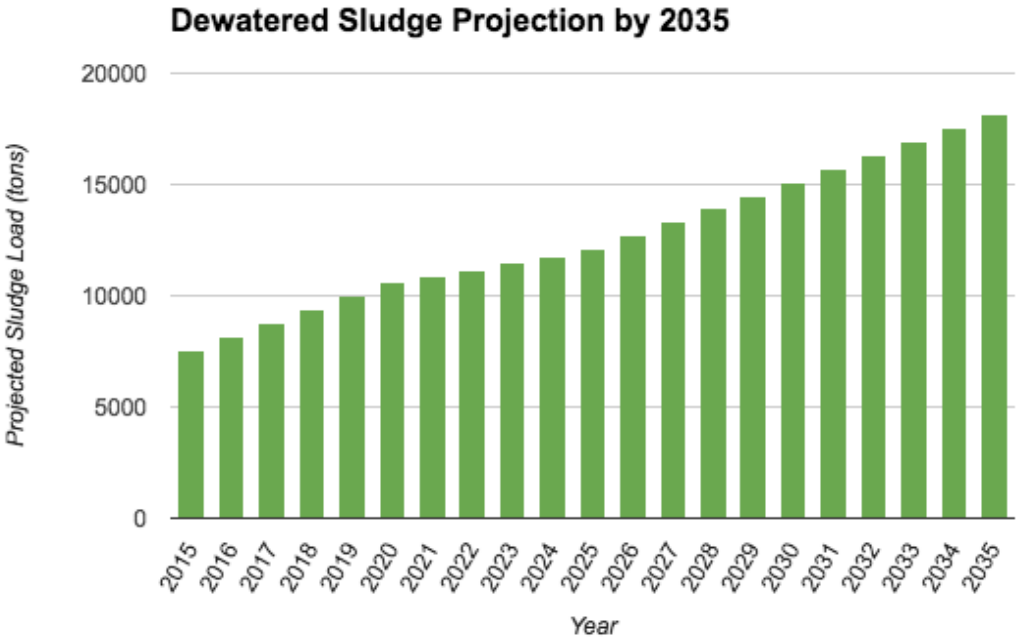


Figure 4**:** Dewatered sludge load projection till 2035.

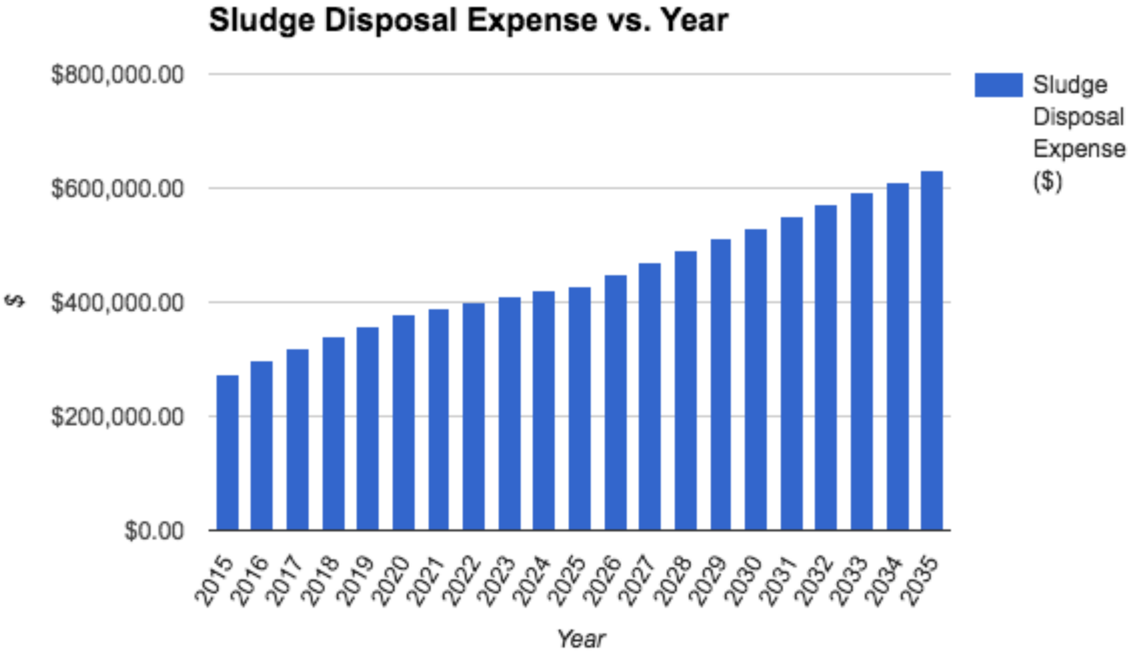


Figure 5**:** Sludge disposal expense projection based on varied monthly sludge percentage in BaU scenario

3.3 Energy Balance Modeling

3.3.1 sludge2energy Pilot Plant

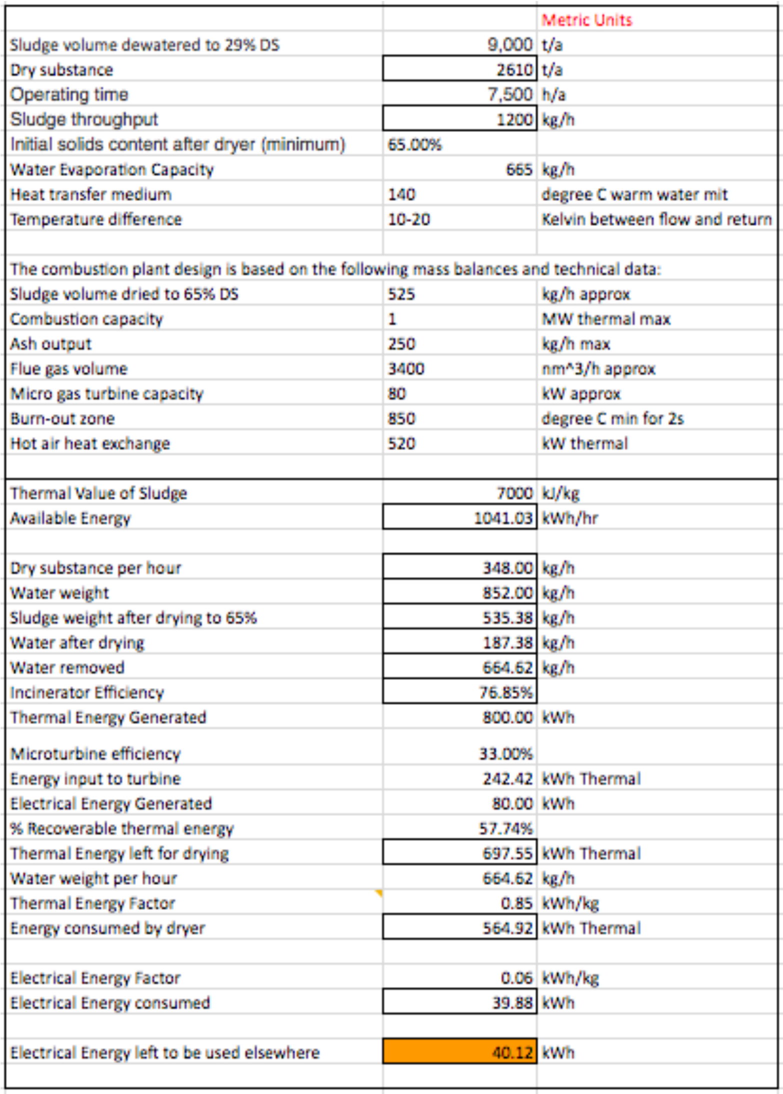
One of the main participants of the sludge2energy pilot study and plant, “Huber Technology” was contacted and information regarding our project was communicated to them. However, Huber was unable to share the technical information regarding the entire system.

Our next approach was to simulate the plant by inferring the process from publicly available information. For this purpose, we used a report on Huber’s website[27] that describes the system. The discussion on energy balance in the report was used to create an excel model.

During the course of the modeling, it became apparent that there was a need to discover a way to calculate the percentage thermal energy that can be recovered from the turbine exhaust. Regression analysis was performed to find an equation for the same. This equation was used in both the pilot plant model as well as the model for the proposed TWWTP incineration plant. The data points where acquired from an EPA report[28]. The data can be seen in Appendix D. The resulting equation is:

% Energy Recoverable from Turbine Exhaust = -0.0736*ln (Nominal Electric Capacity)+0.8999

The model resulting from this exercise can be seen in Figure 6 below and simulates an hour of plant operation. A detailed explanation of the model is present in Appendix E.



		Metric Units
Sludge volume dewatered to 29% DS	9,000	t/a
Dry substance	2610	t/a
Operating time	7,500	h/a
Sludge throughput	1200	kg/h
Initial solids content after dryer (minimum)	65.00%	
Water Evaporation Capacity	665	kg/h
Heat transfer medium	140	degree C warm water mit
Temperature difference	10-20	Kelvin between flow and return
The combustion plant design is based on the following mass balances and technical data:		
Sludge volume dried to 65% DS	525	kg/h approx
Combustion capacity	1	MW thermal max
Ash output	250	kg/h max
Flue gas volume	3400	nm^3/h approx
Micro gas turbine capacity	80	kW approx
Burn-out zone	850	degree C min for 2s
Hot air heat exchange	520	kW thermal
Thermal Value of Sludge	7000	kJ/kg
Available Energy	1041.03	kWh/hr
Dry substance per hour	348.00	kg/h
Water weight	852.00	kg/h
Sludge weight after drying to 65%	535.38	kg/h
Water after drying	187.38	kg/h
Water removed	664.62	kg/h
Incinerator Efficiency	76.85%	
Thermal Energy Generated	800.00	kWh
Microturbine efficiency	33.00%	
Energy input to turbine	242.42	kWh Thermal
Electrical Energy Generated	80.00	kWh
% Recoverable thermal energy	57.74%	
Thermal Energy left for drying	697.55	kWh Thermal
Water weight per hour	664.62	kg/h
Thermal Energy Factor	0.85	kWh/kg
Energy consumed by dryer	564.92	kWh Thermal
Electrical Energy Factor	0.06	kWh/kg
Electrical Energy consumed	39.88	kWh
Electrical Energy left to be used elsewhere	40.12	kWh

Figure 6**:** Energy balance model of the sludge2energy pilot plant.

Some important numbers in the model include:

- Capacity: 9000 metric tons per annum of sludge dewatered to 29%
- Hours of operation: 7500 hours per annum
- Sludge throughput: 1200 kg per hour
- Microturbine capacity: 80 kW
- Thermal value of sludge: 7000 KJ per kg
- Thermal Energy left in microturbine exhaust: ~700 kWh
- Energy consumed by dryer: 564.92 kWh thermal
- Net electrical output: 40 kWh

3.3.2 Proposed TWWTP Incineration Plant

The first step in modeling the proposed incineration plant was to calculate the thermal value of the input sludge. This calculation was done by using the calorific value of the sludge previously found and by accounting for the latent heat of vaporization of the water in the post-dryer sludge (65% DS).

The waste incineration plant for TWWTP was based on the pilot plant model with two important differences: 1) the thermal value of TWWTP sludge, and 2) the size of the turbine. It can be noticed that there is excess thermal energy at the end of the process in the pilot plant model. It was decided that the addition of a higher capacity turbine could be justified, given this excess thermal energy and if the thermal value of the sludge was found to be greater than that from the pilot study.

3.4 Cost Estimates

The estimated value of investment for the incineration plant is based on other similar projects. For practicable concerns, the financial costs here are divided into two components: Capital cost and Operation & Maintenance (O&M) cost. Ten examples of incineration plants with an energy recovery system of wastewater or municipal solid waste were selected from all over the world for the estimate. Primary investments, including buildings of each process equipment, construction, balance of plant and conjunctions were considered and extracted as the capital cost, and were then converted from their original currency in the year when the studies were conducted to US dollars in 2017. The components of annual O&M cost vary from plant to plant, based on different functions and locations. Here for the sake of simplicity, they were considered as a whole, and converted from their original currency to USD in 2017. Finally, the capacity of each incineration plant is also noted, in the unit of thousand tonnes per year (ktpa).

Some other assumptions have to be made to complete the estimation: First, despite the difference in sizes, different projects applied different technologies in terms of dryer, incinerator, and turbine. Also, labor costs, construction costs, etc. vary regionally. The technical and geographic disparities were ignored, and efforts were focused towards estimating costs based on sludge processing capacity. Secondly, some reports mentioned the operating hours of the plant while some did not. If the capacity factor were not mentioned, it was assumed that the plant ran 24/7. Finally, taxes, incentives, and other regulatory expenses/revenues are not included in the estimate.

To estimate the capital cost and O&M cost based on capacity, linear and nonlinear regressions were performed using STATA with robust standard error (scatter plots stating the relationships are shown as Figure 7). Capacity was the explanatory variable, and capital cost and O&M cost were the response variables respectively, for the two sets of calculations.

The regression model of capital cost (M$) and capacity (ktpa):

$$Y(Capital) = 0.610\ (Capacity) + 7.887$$

The regression model of O&M cost (M$/yr) and capacity (ktpa):

$$Y(O\&M) = 0.0283\ (Capacity) + 1.633$$

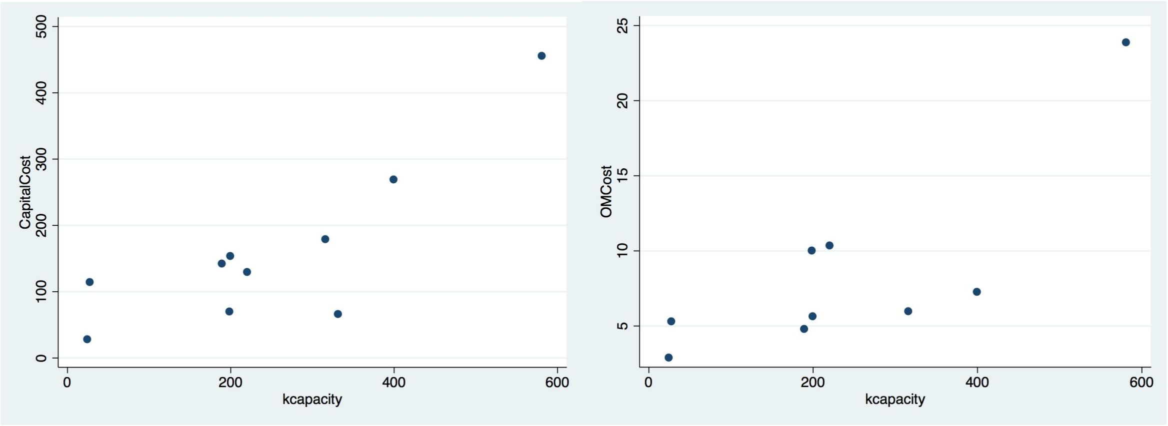


Figure 7**:** Capital cost (M$) vs. Capacity (ktpa); O&M cost (M$/yr) vs. Capacity (ktpa)

Both regression models for capital cost (t=3.59, p=0.007) and for O&M cost (t=2.68, p=0.032) are statistically significant. The statements of statistics of both regressions are shown in Appendix F.

3.5 Policies and Incentives

To find potential external benefits for the project, we studied relevant local policies using the Database of State Incentives for Renewables & Efficiency (DSIRE), a comprehensive regional energy incentive database developed by the NC Clean Energy Technology Center. Policies for “microturbine”, “combined heat and power (CHP)”, “biomass” and “sewage” were considered as applicable and categorized according to their functions.

3.5.1 Regulatory Policies

1. Interconnection Standards & Interconnection Standards for Small Generators: State and federal level policies, which respectively guarantee distributed generators to feed their electricity generated to grid[29, 30].
2. Net Metering: State policy ensuring the application of net metering of Electric Generating Units

(EGUs) to earn credits on their utility bills[31].

3.5.2 Financial Incentives

1. Clean renewable energy bonds (CREBs): A federal loan program, which offers a bond pool for renewable energy projects. The newest allocation into the pool is as high as $1.4 billion in 2015[32].
2. Modified Accelerated Cost-Recovery System (MACRS): A federal depreciation program helping to recover investments through a depreciation bonus. The system could receive 40% of the bonus if put into service during 2018, and 30% during 2019[33]. For the purpose of this report it was assumed that this plant should be operational by 2018. The depreciation schedule for a five-year property can be seen in Table 3 below.

Table 3**:** Depreciation Schedule for a 5-Year Property

Year 1	**Depreciation Rate**
1	20.00%
2	32.00%
3	19.20%
4	11.52%
5	11.52%
6	5.76%

3.5.3 Technical Resource

Energy assessment services/customized energy designs can be requested under technical resources programs, such as Duke Energy Carolinas' PowerShare, Duke Energy Carolinas' Large Business Energy Analysis, and U.S. Environmental Protection Agency's ENERGY STAR for Industry.

3.6 Financial Analysis

To analyze the financial feasibility of our proposed plant, we decided to calculate its net present value (NPV). The NPV was found for two project scenarios 1) If plant is run on sludge alone and 2) If plant runs on sludge and natural gas when there is not enough sludge. This was done because it was noticed from the sludge projections that there was not enough sludge to run the plant for the rated 7500 hours per year for most of the years between 2018 and 2035, the period under consideration. The project was analyzed for operation between the years 2018-2035 to account for the construction time.

The annual cash flow was calculated as:

Cash Flow = Electricity Expense Saved + Sludge Disposal Expense Saved + Depreciation - (Annualized Capital Cost + Fixed O&M Cost + Fuel Cost)

Variable O&M cost (not including fuel) although expected to be non-trivial in real life, for the purposes of this study they are assumed to be zero. Fuel costs are included only in the case where the plant is run on natural gas when there is insufficient sludge. The annual electricity production was not enough to offset the needs of the WWTP and thus there are no profits due to sale of electricity or taxes. The NPV in this case thus simply becomes a comparison with the current solution.

Electricity was assumed to be $0.07/kWh and natural gas $8/mmBtu in line with assumptions made in other feasibility studies for the TWWTP.

The next step was finding the appropriate fixed charge factor in order to annualize the capital cost. The fixed charge rate for investor owned electric utility from the Handbook of Electric Power Calculations[34] was used as a proxy for this project. The breakdown can be seen in Table 4 below.

This fixed charge factor was only used to calculate the levelized cost of electricity in order to compare with the rates currently applicable to TWWTP. It should be noted that when sludge is disposed using this method, the electricity produced is a byproduct. But when calculating the sludge disposal expense saved, the electricity expense saved was not accounted for and the proposed plant was treated like a sludge disposal plant. Similarly for electricity expense saved, the plant was treated as a power plant without any other benefits.

For the purpose of the NPV calculation, the rate of return of 7.7% as mentioned above was used.

Table 4**:** Fixed-charge factor

Charge	**Rate %**
Return	7.7
Depreciation	1.4
Taxes	6.5
Insurance	0.4
Total	**16**

4. Results

4.1 Energy Balance

4.1.1 sludge2energy Pilot Plant

Comparing the Huber report[35] with the pilot energy model created, it can be seen that the simulation has been accurate. The net electrical energy production is 40 kWh for every hour of operation. Figure 6 above shows that the amount of heat available for use in thermal drying (700 kWh) is much more than is needed (565 kWh thermal).

4.1.2 TWWTP Incineration Plant

The thermal value of sludge calculation can be seen in Table 5 below.

Table 5**:** Thermal value of TWWTP sludge.

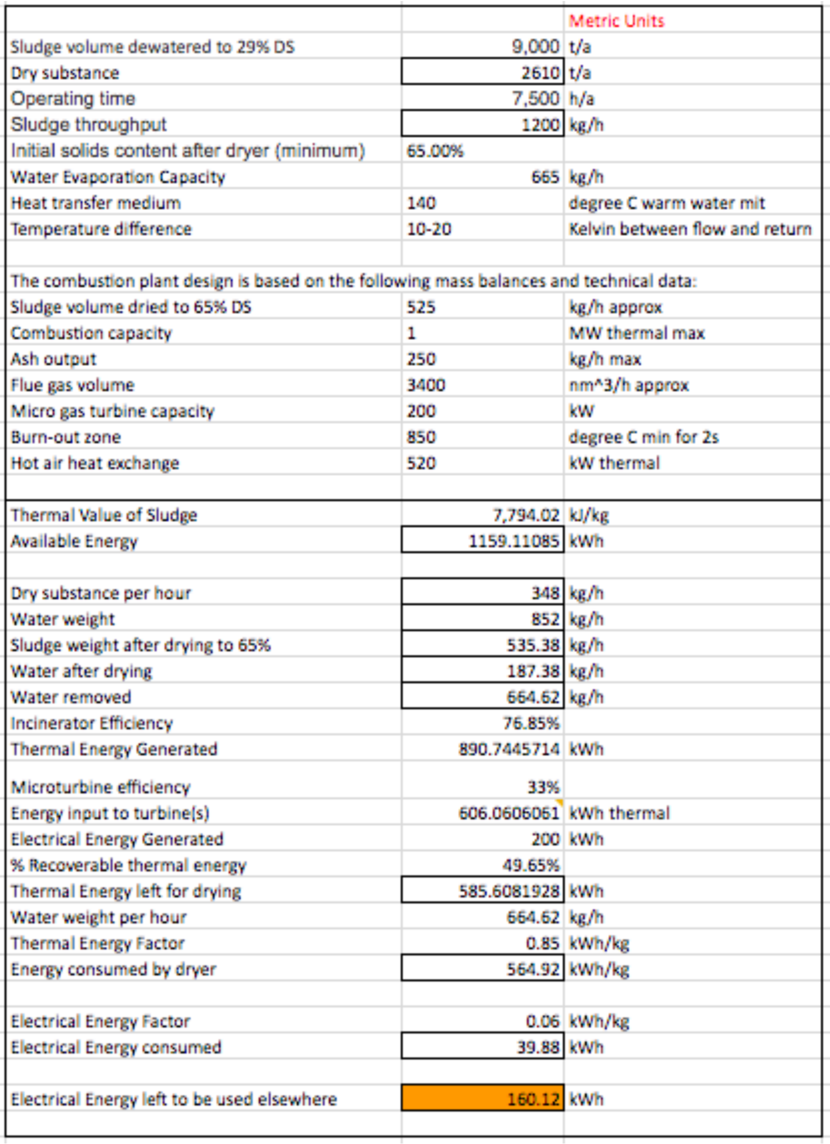
Input	535.00	kg/hr
Dry solids	347.75	kg/hr
Calorific value of sludge	13,206.10	kJ/kg
Heat Generated	4,592,421.28	kJ/hr
Latent heat of vaporization	2.257	MJ/kg
Energy expended in vaporizing water	422,623.25	kJ/hr
Actual useful heat	4,169,798.03	kJ/hr
Thermal Value of Sludge	**7,794.02**	kJ/kg

The thermal value of TWWTP's sludge is significantly higher than that used in Huber's pilot plant. This combined with the fact that there was excess thermal energy available in the process; a bigger turbine option was explored. The resulting energy balance model can be seen in Figure 8 below.

The capacity of the plant was kept the same, i.e. 9000 tonnes/year of 29% DS, as was the sludge throughput and the hours of operation of the plant. The parameters that were changed are: 1) the thermal value of the sludge. 2) The size of the turbine and 3) % recoverable thermal energy from the turbine exhaust. It can be seen that increasing the size of the turbine from 80 kW to 200 kW leaves just enough energy to be use in the dryer. The net electricity production of the plant is 160.12 kWh per hour of operation when the plant is run at full capacity.

4.1.3 Energy Generation Projections

The sludge2energy plant has been designed for mono-combustion, meaning using a single type of fuel. As mentioned previously it was decided that it would also be prudent to also explore energy generation if the TWWTP incineration plant burns natural gas when sludge is unavailable. Projections for annual electrical production were done till the year 2035 using the energy model and the sludge projections, and two



		Metric Units
Sludge volume dewatered to 29% DS	9,000	t/a
Dry substance	2610	t/a
Operating time	7,500	h/a
Sludge throughput	1200	kg/h
Initial solids content after dryer (minimum)	65.00%	
Water Evaporation Capacity	665	kg/h
Heat transfer medium	140	degree C warm water mit
Temperature difference	10-20	Kelvin between flow and return
The combustion plant design is based on the following mass balances and technical data:		
Sludge volume dried to 65% DS	525	kg/h approx
Combustion capacity	1	MW thermal max
Ash output	250	kg/h max
Flue gas volume	3400	nm^3/h approx
Micro gas turbine capacity	200	kW
Burn-out zone	850	degree C min for 2s
Hot air heat exchange	520	kW thermal
Thermal Value of Sludge	7,794.02	kJ/kg
Available Energy	1159.11085	kWh
Dry substance per hour	348	kg/h
Water weight	852	kg/h
Sludge weight after drying to 65%	535.38	kg/h
Water after drying	187.38	kg/h
Water removed	664.62	kg/h
Incinerator Efficiency	76.85%	
Thermal Energy Generated	890.7445714	kWh
Microturbine efficiency	33%	
Energy input to turbine(s)	606.0606061	kWh thermal
Electrical Energy Generated	200	kWh
% Recoverable thermal energy	49.65%	
Thermal Energy left for drying	585.6081928	kWh
Water weight per hour	664.62	kg/h
Thermal Energy Factor	0.85	kWh/kg
Energy consumed by dryer	564.92	kWh/kg
Electrical Energy Factor	0.06	kWh/kg
Electrical Energy consumed	39.88	kWh
Electrical Energy left to be used elsewhere	160.12	kWh

Figure 8**:** Energy balance model of simulated TWWTP incineration plant.

projections were performed: 1) With only sludge as the fuel (Option 1) and 2) With sludge as the primary fuel with natural gas as backup fuel (Option 2). Appendix G gives a detailed breakdown of annual electricity generation of these two options. A comparison of electricity generated is shown in Figure 9 below.

As can be seen from the figure, the option where only sludge is used as fuel reaches the maximum generation of 1200 MWh only in the year 2032 whereas the option that uses natural gas as backup as a constant generation throughout its life.

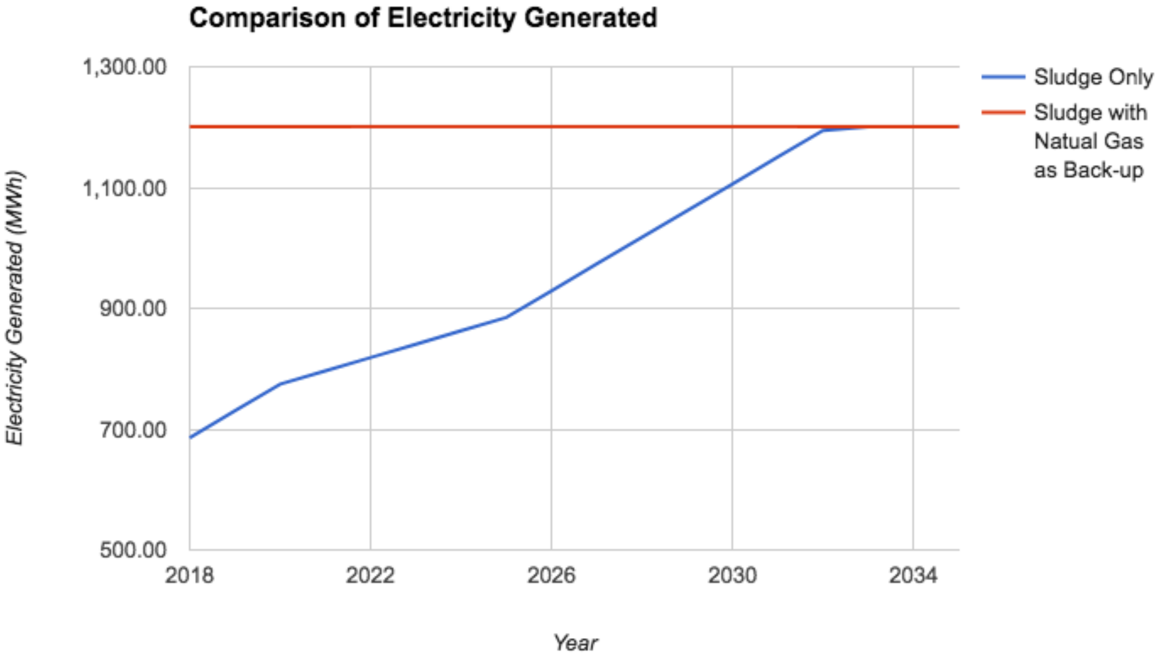


Figure 9**:** Comparison of electricity produced by the two fueling scenarios.

4.2 Financial Feasibility

The regression models estimated a capital cost is 13.377 million dollars, and O&M cost is 1.888 million dollars per year for a 9000 tpa incineration plant. The comparison of cost of electricity for Options 1 and 2 compared to the current electricity price paid by TWWTP is shown in Figure 10 below. It should be kept in mind that this cost does not account for the sludge disposal expense saved. Similarly, the disposal costs per ton for Options 1,2 and the business-as-usual scenario are shown in Figure 11 below. And finally the NPV of both the project options are stated in Table 6.

Even at it's lowest, the cost of electricity produced by the sludge2energy plant is much higher than the

$0.07/kWh currently paid by the TWWTP.

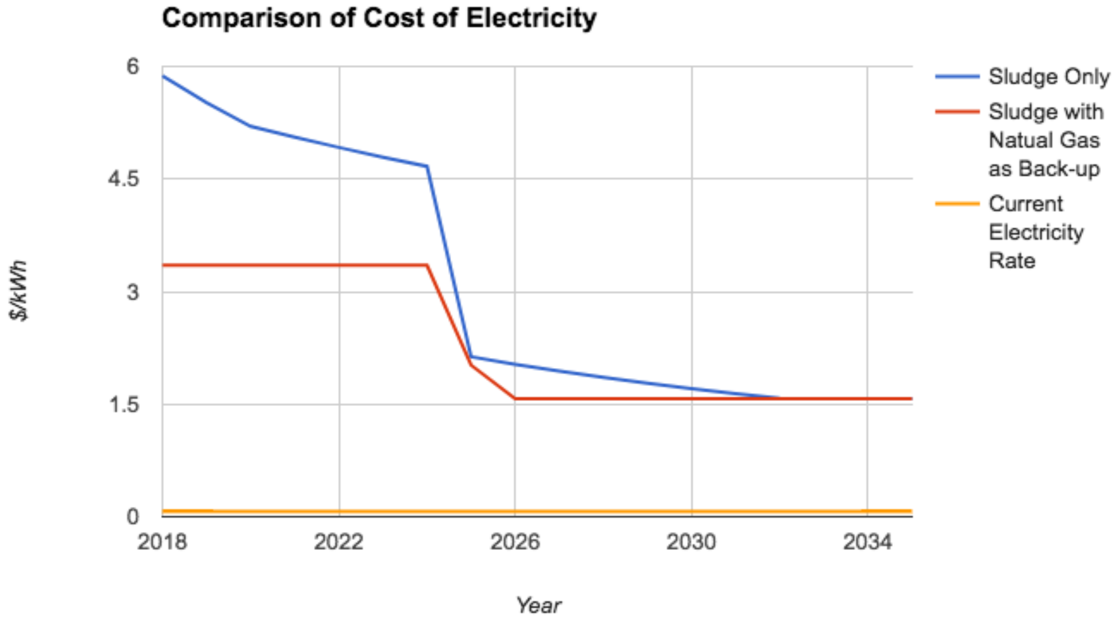


Figure 10**:** Comparison of cost of electricity.

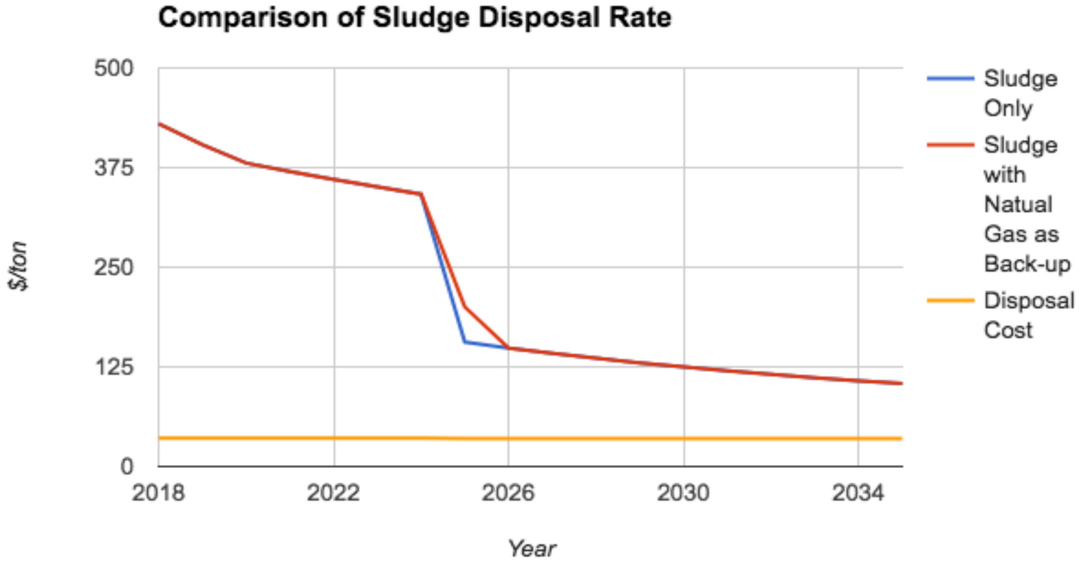


*Figure 11***:** *Comparison of sludge disposal costs.*

Table 6: Project NPVs

Fuel	**NPV ($)**
Sludge	-$14,523,481.55
Sludge + Natural Gas	-$14,333,341.85

Table 2 shows the break-up of the sludge disposal rates. An average composite rate for it is approximately $35/ton disposed. This again, as can be seen in Figure 11 is much lower than the cost of sludge disposal for the sludge2energy system. The dips in both Figure 10 and 11 around the halfway mark are due to the end of the payback period of the sludge2energy plant. Beyond this point, only O&M costs are applicable. Finally the net present value indicates that this investment will lead to a loss of $14 million in present value terms i.e. the project costs outweigh the project benefits.

4.3 Environmental Assessment

4.3.1 Air Emissions

One problem associated with the volumetric reduction is the emission of combustion gases. Thus, air emission control is necessary for any incineration system. The environmental impact or benefit of adopting incineration to sludge treatment is assessed, in this case, by comparing it with composting, which is the current disposal method.

McGill's emissions data was unavailable, but there exist Life Cycle Assessment studies that compare various disposal methods and have demonstrated that incineration is generally more environmentally friendly than composting in terms of air emissions. For instance, in Sweden, the estimated emissions of incineration and agricultural use as sludge handling methods are shown in Table 7[36]; in China, the comparison is shown in Table 8[37]. Moreover, the sludge2energy system selected for the case study prevents unacceptable emissions by ensuring complete combustion. Its flue gas cleaning system is designed to meet the requirement of Germany's Federal Emission Control Act (17. BImSchV), a stringent air emission standard. The breakdown of emission limit values for gases is listed in Appendix H. Based on the study, the air emissions for the sludge2energy system selected are expected to be even lower.

Table 7**:** Emissions of agricultural use and incineration as sludge treatment in Sweden.

Emission	Unit/tonne of MD sludge	Agriculture Use	Incineration
CO2	kg	25	-250
CH4	g	-12	-82
N2O	g	-190	-1.4
NH3	g	1900	--
Hg to air	g	--	0.1
SOx	g	-840	-260
NOx	g	820	1150

* Values are relative to original sludge treatment as land reclamation, positive means greater emission; negative means lower emissions than the baseline.

Table 8**:** Emissions of composting and incineration as sludge treatment in China.

Emission	Unit/tonne of dry sludge	Composting	Incineration
SO2	kg	0.5	-6.9
CO	kg	0.3	-3
NOx	kg	1.2	-0.9
VOC	kg	0	0
PM10	kg	0	0
GWE	kg CO2	2.6 × 100	2.1× 100

*Values are relative to dewatering and landfill. Negative means lower emissions.

4.3.2 Waste Volume Reduction

In terms of land occupancy and hazardous waste reduction, incineration has the advantage of dramatically reducing the volume of sludge by 90-96%, whereas a report shows that McGill can only reduce approximately 50% of both volume and mass of the waste[38]. Even though volume reduction is not the primary goal of composting, transporting large amounts of hazardous waste from the plant to the composting site can still cause environmental damage. In contrast, the incineration plant has the environmental benefits of preventing potential air, water and land pollution by disposing of sludge on site, and transporting very little nontoxic ash.

5. Discussion

The main purpose of this research is to evaluate the prospect of installing a sludge incineration system for energy recovery at TWWTP. It could be a pragmatic decision to have an energy recovery facility at WWTPs to hedge the risk of increasing sludge production, increasing energy expense and stringent sludge disposal norms in future. But every WWTP is different and thus decision-making should be with the help of feasibility studies that are case specific, something our project endeavored to do.

In order to find out if it could be prudent for TWWTP to have an energy recovery by sludge incineration plant, our research addressed the following aspects of the sludge2energy plant:

- Energy Production Analysis
- Financial Analysis
- Environmental Impact Assessment

Energy Production Analysis. The annual energy production of the proposed plant is not sufficient enough offset a significant proportion of TWWTP's electricity requirement. The amount of sludge produced is a limiting factor only when sludge is used as a fuel. As can be seen in Figure 9, maximum electricity production in this case is achieved only in the year 2032 when the sludge load reaches a level where the plant can be run all of it rated 7500 hours. Beyond this point the limiting factors are 1) the maximum hours of operation, 2) the calorific value of the sludge, which directly affects 3) the size of the microturbine. The proposed plant design is ideal for the given constraints. Owing to these constraints the maximum annual electricity generation capacity is 1200 MWh. In 2016, the TWWTP consumed 5972 MWh (K. Manning, personal communications, February 2017) of electricity, thus in 2016, the proposed plant could have provided about 20% of the plant's electricity. But compared to 2016, in the year 2035, when the TWWTP is expected to reach full capacity, the wastewater flow will almost double. The electricity consumption of the plant is thus also expected to increase accordingly, further reducing the share that the proposed plant can supply.

An unknown is if the load schedule of TWWTP will match the production by the proposed plant. For the purpose of our study we assumed that it would be a captive power plant. Perhaps a net-metering agreement can be reached with the utility that would eliminate this problem. A focused technical study on the actual mechanics of the interconnection can inform this question.

The "sludge + natural gas" fuel solution also has a few problems. It is not known if the natural gas infrastructure at the TWWTP can support this plant. In the case of insufficient capacity further investment will be required to install the required infrastructure. Another issue with this configuration could be due to the design of the microturbine. The manufacturer of the turbine lists three different designs[26]: 1) Biogas fired, 2) Externally fired and 3) Natural gas fired. The one used for the sludge will need to be the externally fired version. The advantage of the externally fired version is that thermal energy can come from various source of biomass but if natural gas is used, the externally fired version could be inefficient. It would be preferable to have a microturbine that would function as both as and when required. A specially commissioned microturbine is again likely to cost extra.

Financial Analysis. As is evident from the cash flow formula used to calculate the NPV, the NPV here is just a comparison of the proposed plant to the current disposal method while accounting for the time value of money. The result of the calculation is clear, the proposed plant would end up costing the TWWTP about $14 million more in present value terms compared to the current disposal solution. From the point of view of the per unit cost of electricity, even at it's lowest it is $1.57/kWh, which is much more than the electricity rate paid by TWWTP ($0.07/kWh). This low rate of electricity in North Carolina is one of the contributing factors to the negative NPV. The electricity rates would have to be $1.85/kWh for the sludge only option and $1.39/kWh for the sludge + natural gas option for the NPVs to become zero. The highest average retail rates of electricity in the US are in Hawaii (¢26.17/kWh), Connecticut (¢17.77/kWh) and Alaska (¢17.59/kWh), which are still much lower than that[39].

Considering the capital cost of the plant, the breakdown of the cost of the three main components of the system i.e. 1) Huber Belt Dryer, 2) 200kW Microturbine and 3) A 1 MW Thermal Grate Stoker Furnace, can be seen in Table 9 below. The cost of the belt dryer was made available to us by Dieter Weinert of Huber (Personal Communication, February 20, 2017). Microturbines range between $700 and $1,100 per kW (increasing by $75-$350/kW for heat recovery)[40] and the Grate Stoker furnace between $1,880 and $4,260 per kW thermal[41]. The total cost of these major components of the sludge2energy system comes up to $5.5-8 million. What remains after this is the balance of plant and construction cost. It is possible that the capital cost of $13.38 million used in our study is an overestimate. But due to depreciation, the NPV is not affected greatly by the capital cost, the very high O&M cost of $1.89 million seems to be responsible for that.

The values of the O&M cost that set the NPV to zero are $286,644 and $307,605 for sludge only and sludge + natural gas options respectively, which doesn't seem entirely unreasonable. The plant would not be considered very desirable if the annual O&M cost is 14% of the capital cost.

But in all of this discussion it is unknown if the cost is an object at all for the TWWTP. Do they care about a negative NPV? Is a negative NPV acceptable if it is within a certain threshold? There are various non-economic aspects that probably affect this decision. It is entirely possible that the TWWTP prefers having a sludge disposal solution right next to them than relying on a third party that is 20 miles away, as is the case currently. Relying on a third party also means that TWWTP would be vulnerable to any rate increases in the future, possibly making a dedicated sludge disposal system a better alternative. We concentrate here on the sludge disposal aspect of the sludge2energy system and not the energy recovery potential because it is understood that TWWTP's primary concern is sludge disposal. The energy recovered would simply be a by-product for them.

Table 9**:** Cost Breakdown of Individual Plant Components

	Low Estimate	**High Estimate**
Cost of Huber Belt Dryer BT14	$3,500,000.00	$3,500,000.00
Microturbine Cost per kW	$775.00	$1,450.00
Total Cost of 200kW Microturbine	$155,000.00	$290,000.00
Grate Stoker Furnace Cost per kW	$1,880.00	$4,260.00
Total Cost of 1MW Thermal Grate Stoker Furnace	$1,880,000.00	$4,260,000.00
Total Cost of Major Plant Components	**$5,535,000.00**	**$8,050,000.00**

Environmental Impact Assessment. Surprisingly sludge incineration proved to be more environmentally friendly than composting. Incineration renders the ash inert whereas composted sludge may still have residual chemicals that might harm the soil that it is applied on or might affect public health due to direct contact or through leasing of these chemicals into water bodies. Moreover, it generates less air pollution compared to composting with emission control.

An unknown here are the emission norms for the TWWTP site where this plant will likely be built. It is possible that adjacent property owners might protest the construction of such a plant due to air quality or noise concerns. A future study should look into this aspect.

Although incineration as a sludge treatment and energy recovery method has several advantages over composting from the environmental and cost-certainty perspective, sludge incineration using the sludge2energy system is not recommended for the TWWTP due to the negative NPV of this investment. There are various aspects that could not be quantified and incorporated into the NPV and thus the final verdict rests on the decision makers at Durham County and the TWWTP, given our analysis.

5.1 Recommendations for Future Study

Our study has various limitations and shortcomings that could not be addressed with our project timeline. Following are the recommended next-steps that future studies should look at in order to develop a more complete understand of the sludge2energy system from the point of view of TWWTP:

- Formulate a more robust method to estimate the capital, fixed O&M and variable O&M costs.
- Evaluate a fixed charge factor that is more closely applicable to TWWTP's context.
- Integrate costs currently ignored including the variable O&M cost, cost of running the centrifuge greater hours in order to feed the sludge2energy system etc.
- Incorporate a technical feasibility analysis to look at the:
    - Interconnection requirements
    - Fuel delivery
    - Turbine design
    - Real air emission characteristics (affected by the actual makeup of the sludge)
    - Real-life operational characteristics
- Conduct a legal review to understand the requirements for constructing a sludge incineration plant at TWWTP's property.

- Evaluate the impact of any grants and incentives that could not be incorporated into the current NPV calculation.
- Explore aspects currently not considered that my make this investment more or less attractive.
- Assess TWWTP's preferences regarding the financial aspect of such an investment.

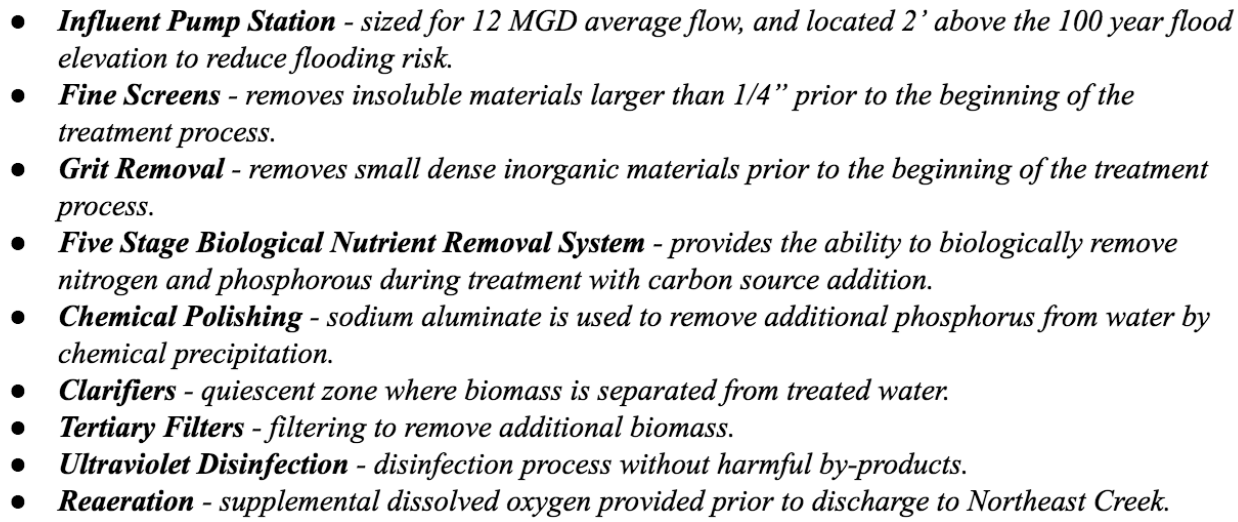
5.2 Conclusion

Results of the study indicate that a sludge2energy plant for wastewater sludge incineration is not financially feasible. As a power plant, the cost of electricity produced is too high. As a sludge disposal method, it is much more expensive than the current solution. Combining everything with the help of a NPV calculation reveals that compared to the current disposal solution, sludge incineration would be a worse choice. However, if environmental considerations and future financial risk weigh heavily, this could be a good solution.

This study identifies a sewage sludge incineration plant design that is suitable for small scale WWTPs. The modeling efforts in support of the study also resulted in a usable energy balance model for the sludge2energy design. Although lacking sophisticated cost estimation methods, our model is largely robust and can be used for future investigations. This study is also likely to be beneficial for the TWWTP, as it provides them a model for future investigations of incineration, as well as the ability to study the business-as-usual scenario, in case the inputs to the study change. However, this study cannot be relied on solely for decision-making purposes. Technical, legal and a few more financial inputs should be incorporated to guide the decision-making process in order to conclusively resolve this discussion.

Appendix

Appendix A: TWWTP Treatment Process



- ***Influent Pump Station*** *- sized for 12 MGD average flow, and located 2' above the 100 year flood elevation to reduce flooding risk.*
- ***Fine Screens*** *- removes insoluble materials larger than 1/4" prior to the beginning of the treatment process.*
- ***Grit Removal*** *- removes small dense inorganic materials prior to the beginning of the treatment process.*
- ***Five Stage Biological Nutrient Removal System*** *- provides the ability to biologically remove nitrogen and phosphorous during treatment with carbon source addition.*
- ***Chemical Polishing*** *- sodium aluminate is used to remove additional phosphorus from water by chemical precipitation.*
- ***Clarifiers*** *- quiescent zone where biomass is separated from treated water.*
- ***Tertiary Filters*** *- filtering to remove additional biomass.*
- ***Ultraviolet Disinfection*** *- disinfection process without harmful by-products.*
- ***Reaeration*** *- supplemental dissolved oxygen provided prior to discharge to Northeast Creek.*

Figure 12**:** Treatment processes of Triangle Wastewater Treatment Plant

Appendix B: Huber Belt Dryer

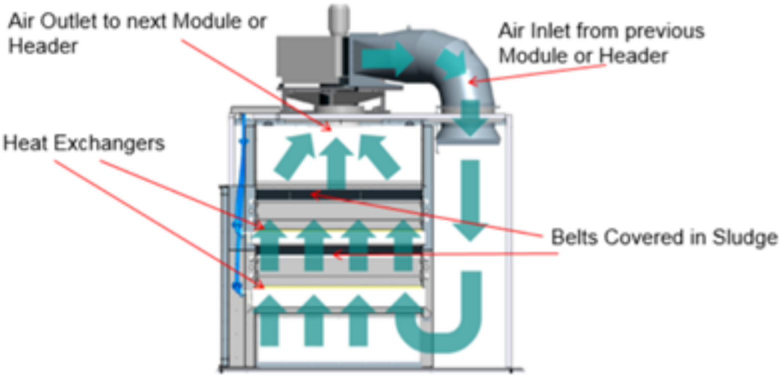


Figure 13**:** Functioning of the Huber Belt Dryer BT plus

Appendix C: Sludge Projections

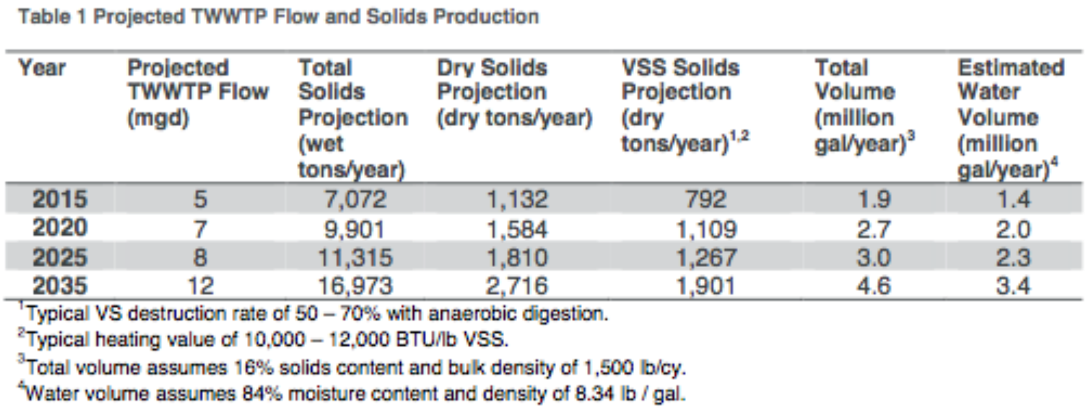


Table 1 Projected TWWTP Flow and Solids Production

Year	Projected TWWTP Flow (mgd)	Total Solids Projection (wet tons/year)	Dry Solids Projection (dry tons/year)	VSS Solids Projection (dry tons/year)[1,2]	Total Volume (million gal/year)[3]	Estimated Water Volume (million gal/year)[4]
2015	5	7,072	1,132	792	1.9	1.4
2020	7	9,901	1,584	1,109	2.7	2.0
2025	8	11,315	1,810	1,267	3.0	2.3
2035	12	16,973	2,716	1,901	4.6	3.4

[1] Typical VS destruction rate of 50 – 70% with anaerobic digestion.
[2] Typical heating value of 10,000 – 12,000 BTU/lb VSS.
[3] Total volume assumes 16% solids content and bulk density of 1,500 lb/cy.
[4] Water volume assumes 84% moisture content and density of 8.34 lb / gal.

Figure 14**:** Sludge Projection assumption from “Durham County Final Organic Byproducts Survey Summary Report”

This can be extended to the following table.

Table 10**:** Projected flow till year 2035

Year	**Projected TWWTP Flow (mgd)**	**% Increase Over Previous Year**	**% Increase Over Base Year**
2015	5	0.00	0
2016	5.4	8.00	8
2017	5.8	7.41	16
2018	6.2	6.90	24
2019	6.6	6.45	32
2020	7	6.06	40
2021	7.2	2.86	44

2022	7.4	2.78	48
2023	7.6	2.70	52
2024	7.8	2.63	56
2025	8	2.56	60
2026	8.4	5.00	68
2027	8.8	4.76	76
2028	9.2	4.55	84
2029	9.6	4.35	92
2030	10	4.17	100
2031	10.4	4.00	108
2032	10.8	3.85	116
2033	11.2	3.70	124
2034	11.6	3.57	132
2035	12	3.45	140

Using this table and the Table 10 below, which shows the monthly sludge load, projections were made till the year 2035. The projections are shown in Table 11.

Table 11**:** 2015 Sludge Summary

Month (2015)	**Net WT (lbs)**	**Tonnage (tons)**
January	1322380.00	661.19
February	1069760.00	534.88
March	1677260.00	838.63
April	1545920.00	772.96

May	1369900.00	684.95
June	1180960.00	590.48
July	1368460.00	684.23
August	1054140.00	527.07
September	971320.00	485.66
October	1105520.00	552.76
November	1016960.00	508.48
December	1430600.00	715.30

Table 12**:** Sludge Projection

Year	**Sludge Treated (tons)**	**Sludge Disposal Expense ($)**
2018	9,370.17	$338,604.46
2019	9,974.70	$359,122.17
2020	10,579.23	$379,039.88
2021	10,881.49	$389,148.73
2022	11,183.75	$399,257.58
2023	11,486.02	$409,666.44
2024	11,788.28	$419,775.29
2025	12,090.54	$429,734.14
2026	12,695.07	$449,951.85
2027	13,299.60	$470,319.56
2028	13,904.13	$490,537.27
2029	14,508.65	$510,754.97

2030	15,113.18	$531,122.68
2031	15,717.71	$551,340.39
2032	16,322.23	$571,258.09
2033	16,926.76	$591,775.80
2034	17,531.29	$612,143.51
2035	18,135.82	$632,511.22

Appendix D: Regression Analysis - Thermal Energy Recoverable from Turbine Exhaust

Table 13: % Recoverable Thermal Energy from Turbine Exhaust[42]

Nominal Electric Capacity (kW)	**Recovered Thermal Energy (kWh)**
30	61
65	119.8
200	258.9
240	376
320	450
1000	1299
Result of Regression	**-0.0736*ln(Nominal Electric Capacity)+0.8999**

Appendix E: Explanation of the Energy Balance Model

The energy balance model of the sludge2energy system as it was designed is seen in the figure below. It was created with the help of a report on Huber's website titled "sludge2energy: A way to energy-autarkic operation of sewage treatment plants"[43].

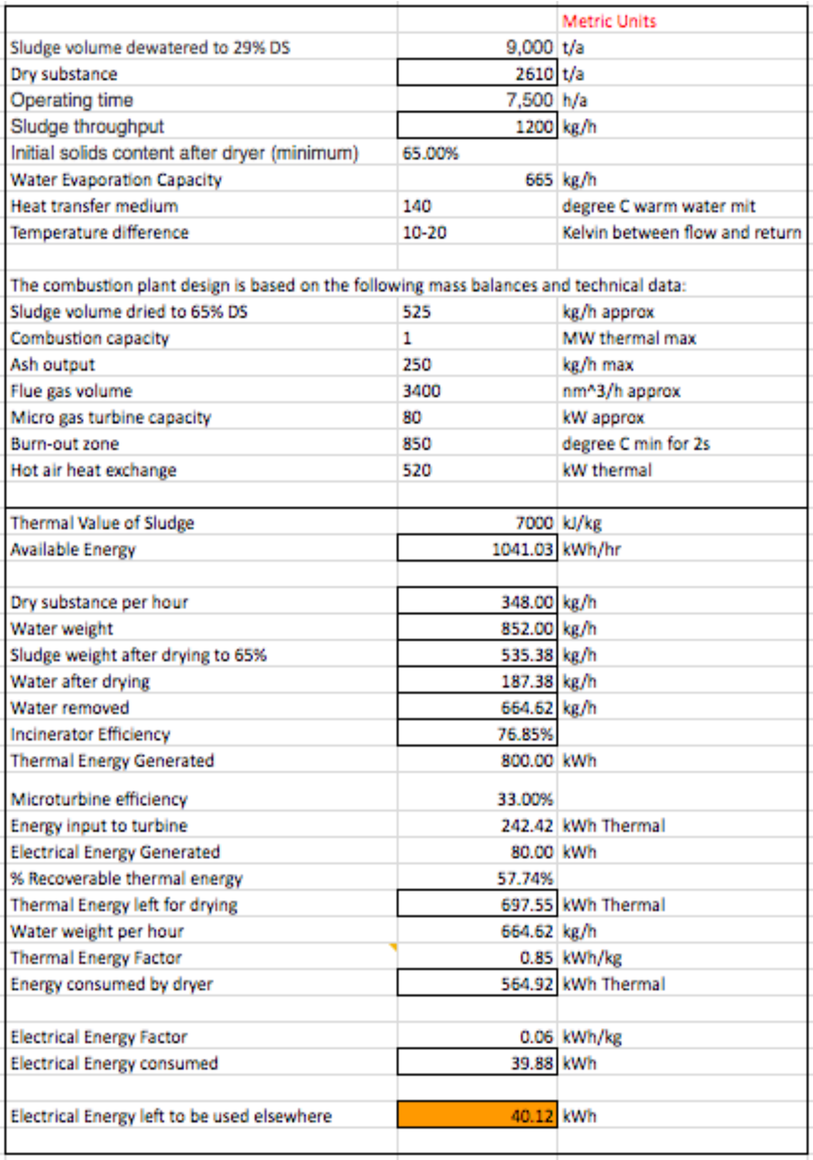
The first section of the model lists important plant parameters such as: plant capacity, operating time, sludge throughput etc. These parameters came directly from the report. The second was derived from the discussion about the energy balance. This discussion is reproduced in Figure 11.

The actually energy calculation happen in the second part. We know that sludge input to the sludge2energy system from the TWWTP has 29% dissolved solids. Therefore if the plant processes 1200 kg of sludge in an hour, the actual solid content is 348 kg. This solid content remains constant even after the dryer. So if the solid content is 348 kg and if the dryer dries to 65%, the weight of the sludge remaining after drying will be 535 kg (including some water). This number for us was 10 kg greater than that provided in the parameters, but we used our own estimate.

The per hour energy input was calculated by multiplying 535 kg by the thermal value of the sludge. But not all of it is extracted by the incinerator, thus only 800 kWh of heat is available (given in the report) to be used from the 1041 kWh that was present in the sludge. The incinerator efficiency can thus be calculated for use in the proposed plant model.

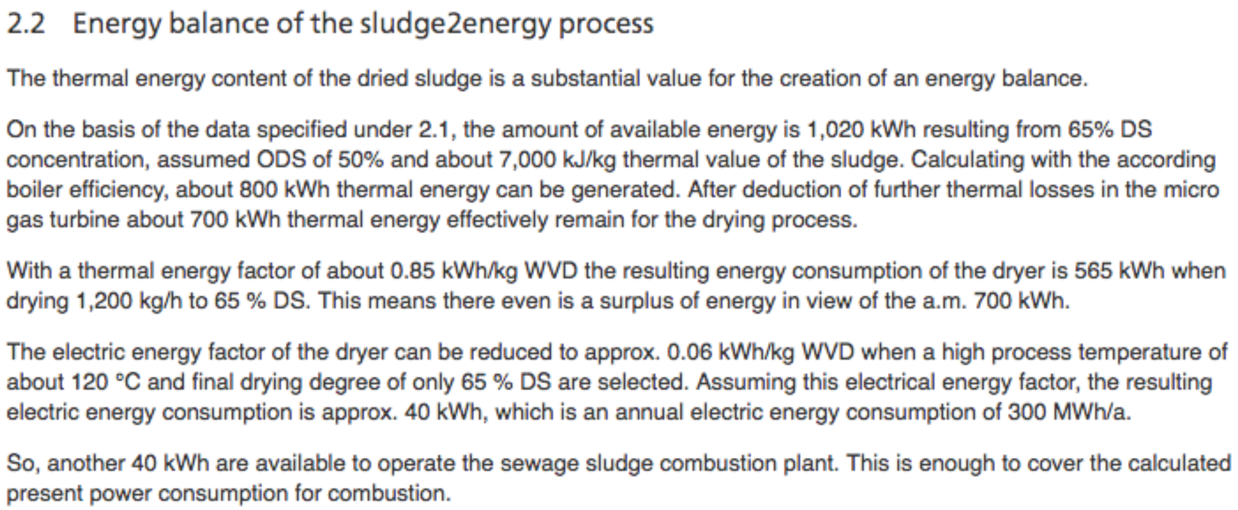
Given the microturbine has an 80 kW capacity and assuming an efficiency of 33%, the actual heat input to the turbine would need to be 242.4 kWh. Using the linear regression equation for finding the energy in the turbine exhaust, 57.74% of the energy can be recovered, combined with this, the energy not sent to the turbine, we get approximately 700 kWh of heat left for use in the dryer. With a thermal energy factor of 0.85 kWh/kg and 664.62 kg of water that needs to be removed per hour, the energy consumption of the dryer is 565 kWh thermal. It is also known that the electrical energy factor is 0.06 kWh/kg. Multiplying this again with the weight of the water evaporated gives us the electrical energy consumed by the dryer per hour, which is 40 kWh. This means that there is a net electrical generation of 40 kWh per hour of operation

The same principle was applied to the proposed plant model. Most of the parameters remained the same, except the thermal value of the sludge, the size of the turbine and the % energy recoverable from the turbine exhaust. Changing these parameters gives us the proposed plant model.



		Metric Units
Sludge volume dewatered to 29% DS	9,000	t/a
Dry substance	2610	t/a
Operating time	7,500	h/a
Sludge throughput	1200	kg/h
Initial solids content after dryer (minimum)	65.00%	
Water Evaporation Capacity	665	kg/h
Heat transfer medium	140	degree C warm water mit
Temperature difference	10-20	Kelvin between flow and return
The combustion plant design is based on the following mass balances and technical data:		
Sludge volume dried to 65% DS	525	kg/h approx
Combustion capacity	1	MW thermal max
Ash output	250	kg/h max
Flue gas volume	3400	nm^3/h approx
Micro gas turbine capacity	80	kW approx
Burn-out zone	850	degree C min for 2s
Hot air heat exchange	520	kW thermal
Thermal Value of Sludge	7000	kJ/kg
Available Energy	1041.03	kWh/hr
Dry substance per hour	348.00	kg/h
Water weight	852.00	kg/h
Sludge weight after drying to 65%	535.38	kg/h
Water after drying	187.38	kg/h
Water removed	664.62	kg/h
Incinerator Efficiency	76.85%	
Thermal Energy Generated	800.00	kWh
Microturbine efficiency	33.00%	
Energy input to turbine	242.42	kWh Thermal
Electrical Energy Generated	80.00	kWh
% Recoverable thermal energy	57.74%	
Thermal Energy left for drying	697.55	kWh Thermal
Water weight per hour	664.62	kg/h
Thermal Energy Factor	0.85	kWh/kg
Energy consumed by dryer	564.92	kWh Thermal
Electrical Energy Factor	0.06	kWh/kg
Electrical Energy consumed	39.88	kWh
Electrical Energy left to be used elsewhere	40.12	kWh

Figure 15**:** Energy balance model of the sludge2energy pilot plant.



2.2 Energy balance of the sludge2energy process

The thermal energy content of the dried sludge is a substantial value for the creation of an energy balance.

On the basis of the data specified under 2.1, the amount of available energy is 1,020 kWh resulting from 65% DS concentration, assumed ODS of 50% and about 7,000 kJ/kg thermal value of the sludge. Calculating with the according boiler efficiency, about 800 kWh thermal energy can be generated. After deduction of further thermal losses in the micro gas turbine about 700 kWh thermal energy effectively remain for the drying process.

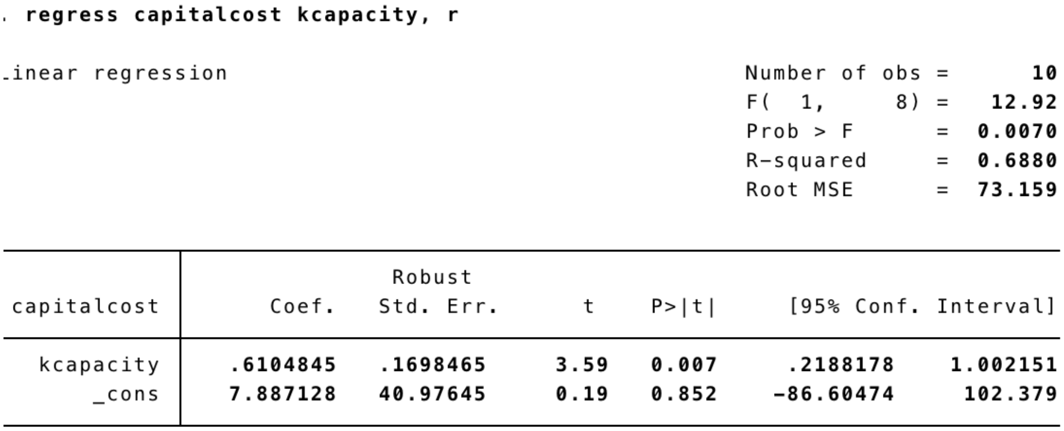
With a thermal energy factor of about 0.85 kWh/kg WVD the resulting energy consumption of the dryer is 565 kWh when drying 1,200 kg/h to 65 % DS. This means there even is a surplus of energy in view of the a.m. 700 kWh.

The electric energy factor of the dryer can be reduced to approx. 0.06 kWh/kg WVD when a high process temperature of about 120 °C and final drying degree of only 65 % DS are selected. Assuming this electrical energy factor, the resulting electric energy consumption is approx. 40 kWh, which is an annual electric energy consumption of 300 MWh/a.

So, another 40 kWh are available to operate the sewage sludge combustion plant. This is enough to cover the calculated present power consumption for combustion.

Figure 16**:** Energy balance discussion of sludge2energy plant in Huber's report.

Appendix F: Regression Analysis – Plant Costs

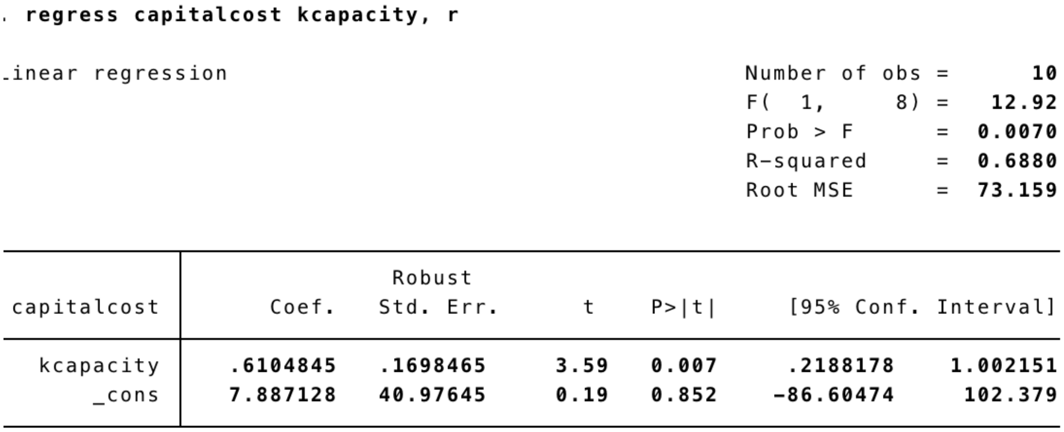


```
. regress capitalcost kcapacity, r

inear regression                                       Number of obs =      10
                                                       F(  1,     8) =   12.92
                                                       Prob > F      =  0.0070
                                                       R-squared     =  0.6880
                                                       Root MSE      =  73.159

------------------------------------------------------------------------------
             |               Robust
 capitalcost |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   kcapacity |   .6104845   .1698465     3.59   0.007     .2188178    1.002151
       _cons |   7.887128   40.97645     0.19   0.852    -86.60474     102.379
------------------------------------------------------------------------------
```

Figure 17**:** Statement of statistics of regressions of cost estimates: Capital Cost (M$) on sludge capacity (ktpa).



```
. regress capitalcost kcapacity, r

inear regression                                       Number of obs =      10
                                                       F(  1,     8) =   12.92
                                                       Prob > F      =  0.0070
                                                       R-squared     =  0.6880
                                                       Root MSE      =  73.159

------------------------------------------------------------------------------
             |               Robust
 capitalcost |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   kcapacity |   .6104845   .1698465     3.59   0.007     .2188178    1.002151
       _cons |   7.887128   40.97645     0.19   0.852    -86.60474     102.379
------------------------------------------------------------------------------
```

Figure 18**:** Statement of statistics of regressions of cost estimates: O&M cost (M$/yr) on sludge capacity (ktpa).

Appendix G: Energy Projections Data

Table 14: Energy Projection with only sludge as the fuel

Year	Sludge Incinerated (tons)	Hours of Plant Operation (hr)	Electricity Generated (kWh)
2018	5,665.91	4,283.36	685,864.33
2019	6,031.45	4,559.70	730,113.64
2020	6,397.00	4,836.05	774,362.95
2021	6,579.77	4,974.22	796,487.61
2022	6,762.54	5,112.39	818,612.26
2023	6,945.31	5,250.57	840,736.92
2024	7,128.08	5,388.74	862,861.57
2025	7,310.85	5,526.91	884,986.23
2026	7,676.39	5,803.26	929,235.54
2027	8,041.94	6,079.60	973,484.85
2028	8,407.48	6,355.95	1,017,734.16
2029	8,773.02	6,632.29	1,061,983.47
2030	9,138.56	6,908.64	1,106,232.79
2031	9,504.11	7,184.99	1,150,482.10
2032	9,869.65	7,461.33	1,194,731.41
2033	10,235.19	7,500.00	1,200,923.08
2034	10,600.73	7,500.00	1,200,923.08
2035	10,966.28	7,500.00	1,200,923.08

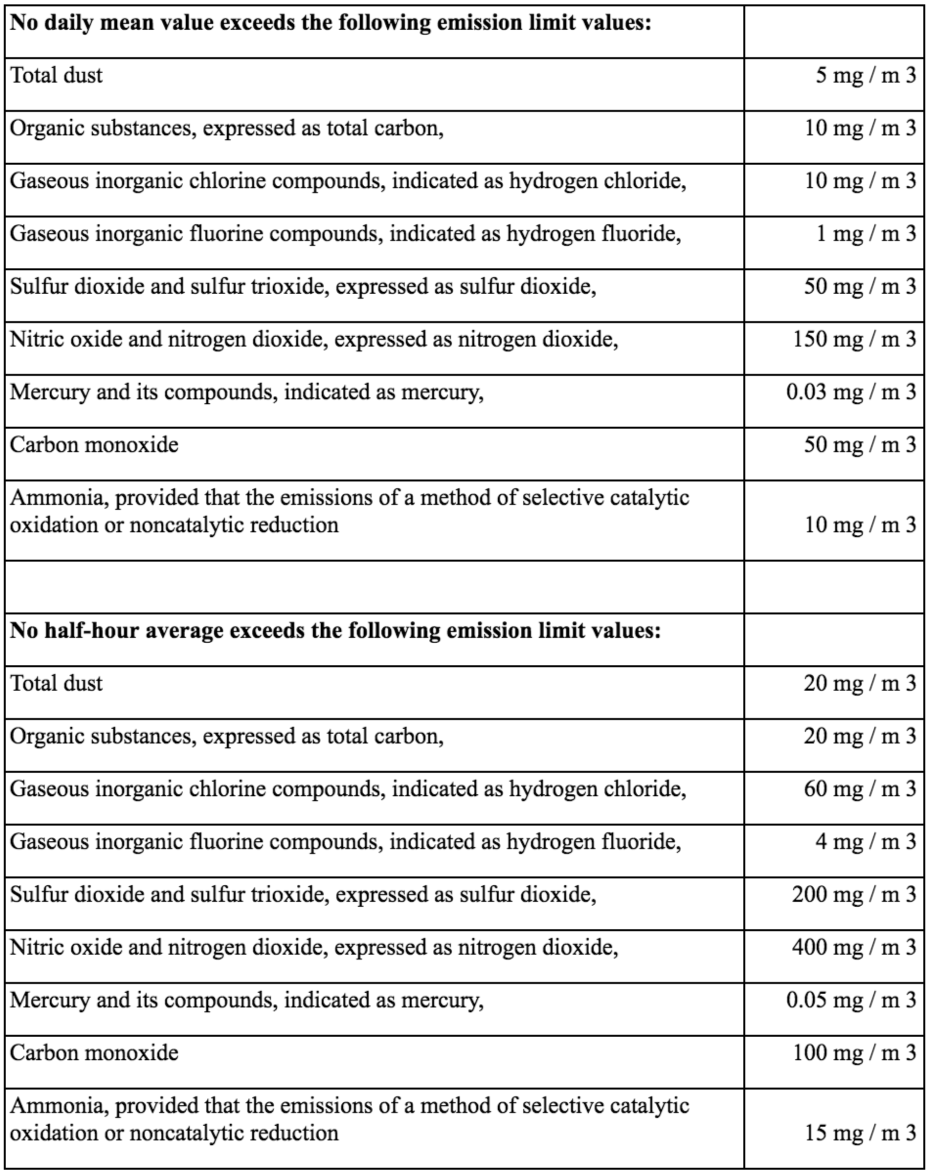
Table 15: Energy projection with sludge as the primary fuel with natural gas as backup

Year	Sludge Incinerated (tons)	Hours of Plant Operation on Sludge (hr)	Hours of Plant Operation on Natural Gas (hr)	Thermal Energy Input using Natural Gas (kWh)	Electricity generated due to Sludge (kWh)	Electricity Generated Due to Natural Gas (kWh)	Total Electricity Generated (kWh)
2015	4,569.28	3,454.32	4,045.68	2,451,927.10	553,116.39	647,806.68	1,200,923.08
2016	4,934.82	3,730.67	3,769.33	2,284,444.90	597,365.70	603,557.37	1,200,923.08
2017	5,300.37	4,007.01	3,492.99	2,116,962.71	641,615.02	559,308.06	1,200,923.08
2018	5,665.91	4,283.36	3,216.64	1,949,480.51	685,864.33	515,058.75	1,200,923.08
2019	6,031.45	4,559.70	2,940.30	1,781,998.32	730,113.64	470,809.44	1,200,923.08
2020	6,397.00	4,836.05	2,663.95	1,614,516.12	774,362.95	426,560.13	1,200,923.08
2021	6,579.77	4,974.22	2,525.78	1,530,775.02	796,487.61	404,435.47	1,200,923.08
2022	6,762.54	5,112.39	2,387.61	1,447,033.92	818,612.26	382,310.82	1,200,923.08
2023	6,945.31	5,250.57	2,249.43	1,363,292.83	840,736.92	360,186.16	1,200,923.08
2024	7,128.08	5,388.74	2,111.26	1,279,551.73	862,861.57	338,061.50	1,200,923.08
2025	7,310.85	5,526.91	1,973.09	1,195,810.63	884,986.23	315,936.85	1,200,923.08
2026	7,676.39	5,803.26	1,696.74	1,028,328.44	929,235.54	271,687.54	1,200,923.08
2027	8,041.94	6,079.60	1,420.40	860,846.24	973,484.85	227,438.23	1,200,923.08
2028	8,407.48	6,355.95	1,144.05	693,364.04	1,017,734.16	183,188.91	1,200,923.08
2029	8,773.02	6,632.29	867.71	525,881.85	1,061,983.47	138,939.60	1,200,923.08
2030	9,138.56	6,908.64	591.36	358,399.65	1,106,232.79	94,690.29	1,200,923.08
2031	9,504.11	7,184.99	315.01	190,917.46	1,150,482.10	50,440.98	1,200,923.08
2032	9,869.65	7,461.33	38.67	23,435.26	1,194,731.41	6,191.67	1,200,923.08
2033	10,235.19	7,500.00	0.00	0.00	1,200,923.08	0.00	1,200,923.08

2034	10,600.73	7,500.00	0.00	0.00	1,200,923.08	0.00	1,200,923.08
2035	10,966.28	7,500.00	0.00	0.00	1,200,923.08	0.00	1,200,923.08

Appendix H: German Waste Incineration Standard

Ordinance on Incineration and Co-Incineration of Waste - 17th BImSchV: Emission limit values for waste incineration plant



No daily mean value exceeds the following emission limit values:	
Total dust	5 mg / m 3
Organic substances, expressed as total carbon,	10 mg / m 3
Gaseous inorganic chlorine compounds, indicated as hydrogen chloride,	10 mg / m 3
Gaseous inorganic fluorine compounds, indicated as hydrogen fluoride,	1 mg / m 3
Sulfur dioxide and sulfur trioxide, expressed as sulfur dioxide,	50 mg / m 3
Nitric oxide and nitrogen dioxide, expressed as nitrogen dioxide,	150 mg / m 3
Mercury and its compounds, indicated as mercury,	0.03 mg / m 3
Carbon monoxide	50 mg / m 3
Ammonia, provided that the emissions of a method of selective catalytic oxidation or noncatalytic reduction	10 mg / m 3
No half-hour average exceeds the following emission limit values:	
Total dust	20 mg / m 3
Organic substances, expressed as total carbon,	20 mg / m 3
Gaseous inorganic chlorine compounds, indicated as hydrogen chloride,	60 mg / m 3
Gaseous inorganic fluorine compounds, indicated as hydrogen fluoride,	4 mg / m 3
Sulfur dioxide and sulfur trioxide, expressed as sulfur dioxide,	200 mg / m 3
Nitric oxide and nitrogen dioxide, expressed as nitrogen dioxide,	400 mg / m 3
Mercury and its compounds, indicated as mercury,	0.05 mg / m 3
Carbon monoxide	100 mg / m 3
Ammonia, provided that the emissions of a method of selective catalytic oxidation or noncatalytic reduction	15 mg / m 3

Figure 19**:** Ordinance on Incineration and Co-Incineration of Waste - 17th BImSchV (Emission limit values for sludge2energy plant)

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