ENERGY-WATER NEXUS IN ECO-INDUSTRIAL PARK WITH THERMAL HYDROLYSIS PROCESS FOR BIO-WASTE UTILIZATION

A Thesis

by

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ABSTRACT

Because of the cost and environmental issues, what to do with the waste, mainly sludge, from wastewater treatment is a critical issue to make a cleaner and more sustainable world. Thermal hydrolysis process (THP) before anaerobic digestion of the sludge is getting attention because of its simple implementation and advantages for both economic and environmental aspects. THP needs energy and additional cost, but more benefit can be gained by using sludge as a renewable energy source, fertilizer or feedstock for the monetization strategy because of reduction of operating cost and Green House Gas (GHG) emission. Since GHG is a primary reason of climate change which raises the devastation of sustainability of the world, it is momentous to make an effort to reduce the emission of GHG.

In the eco-industrial park (EIP), for more process water reuse and water disposal under the stricter regulation, the need for wastewater treatment facilities is growing. Also, there is surplus energy from the processes that can be used to operate the THP, so the EIP can serve as a 'sustainable center' where GHG emission is reduced by treating bio-waste in the centralized structure with its surplus heat. By having THP, EIP can improve its sustainability and economy while preparing for the impact of a carbon tax in the near future.

In this study, economic feasibility of THP, impact of carbon tax on the economy of the biological wastewater treatment system with THP, adequate tipping fee range for the outer bio-waste, sensitivity analysis on the characteristic of bio-waste, and impact of THP within EIP having a centralized water exchange network were investigated to assess the possibility of EIP as a sustainable center. Through this study, the spectrum of water-energy nexus can be broadened to deal with the interconnection between energy, water, and waste to improve the sustainability and economic benefit to the EIP and communities around it as well.

DEDICATION

I dedicate my thesis work to my family, to the many friends of the Energy Institute, and to my girlfriend. I would like to express my sincere gratitude to my parents, who are always willing to support, believe and encourage me to go forward.

I also dedicate this thesis to my friends in Energy Institute Master's program who have been going through this 10-month intensive program together with a great collaboration while making it a meaningful experience. I would like to appreciate to students from South Korea who have always been by my side to help me get through this journey.

I would like to dedicate this work and give special thanks to my girlfriend Eunji Hyun for her endurance during the hard time of my absence while giving me a power to overcome the adversity whenever I have a hard time and having been my side for more than 10 years.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

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All work for the thesis was completed independently by the student.

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NOMENCLATURE

THP	Thermal Hydrolysis Process
EIP	Eco-Industrial Park
WAS	Wasted Activated Sludge
HEN	Heat Exchange Network
WEN	Water Exchange Network
WAHEN	Water and Heat Exchange Network
MED	Multi-Effect Distillation
AD	Anaerobic Digestion
BG	Biological Wastewater Treatment

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Background

1.1.1 Increasing stress on the water demand

According to the report of Water Resource Group, global water requirements will increase from 4,500 billion m^3 to 6,900 billion m^3 by 2030 if there is no effort to improve the efficiency of the water use. This demand is 40% above the current readily available water supply. This expected water deficit should be addressed because water is one of the most important but restricted resources in the globe.

The main factor causing the water deficit is the economic growth of developing countries. Even though agriculture accounts for the largest part of the global water withdrawals currently (71%), the water withdrawals from industry also account for a substantial portion (16%). Its portion is expected to increase from 16% to 22% in 2030.

Many countries are trying to find a possible solution to equilibrate the future demand and supply in the industry. The common approach to achieving the equilibrium is to save water by maximizing the efficiency of water by reusing with/without treatment of wastewater. By reusing the wastewater, the stress on the supply can be reduced significantly because of the decreased water intensity of the process. Therefore, many projects are conducted to find the way of reusing the water with the treatment technology or innovative water distribution system that can maximize the efficiency of water. With this effort, water intensity in the industry sector is lessened considerably.

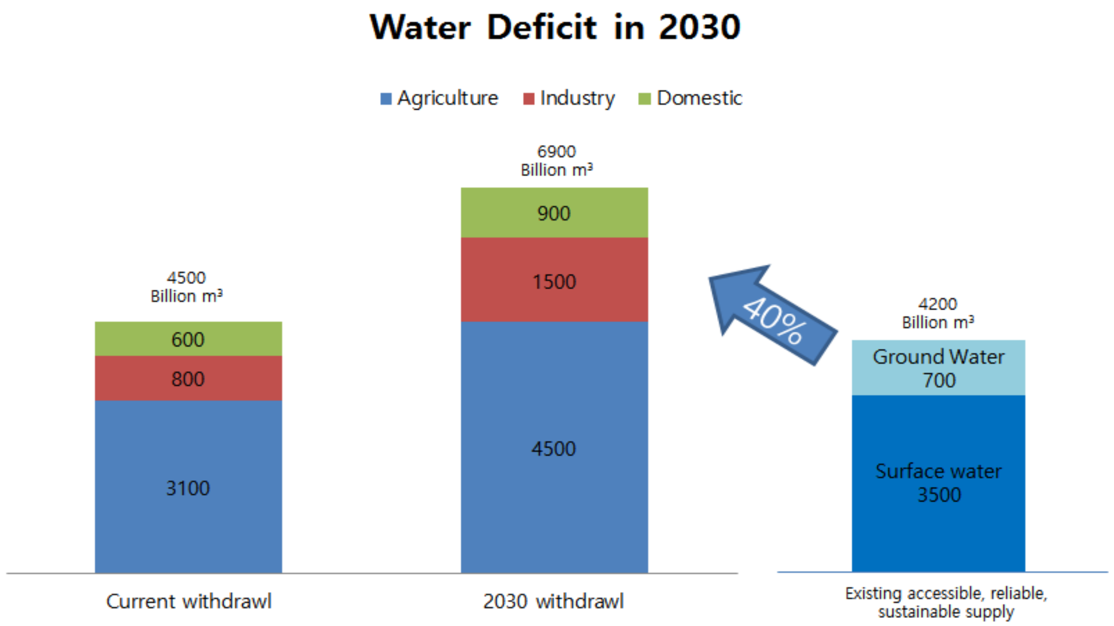

Figure 1. Aggregated global gap between existing accessible, reliable supply and 2030 water withdrawals, assuming no efficiency gains (Source: Water 2030 Global Water Supply and Demand model)

1.1.2 Environmental incentives of water treatment and reuse

In addition to the increasing demand for water, many regulatory and laws to preserve the environment has been made and exercised. For instance, Clean Water Act prohibited the water disposal without fulfilling certain standard, making the water treatment facility necessary in the wastewater source (Copeland 1999). Temperature and pollutant concentration in wastewater are regulated by the Clean Water Act. This act increased wastewater treatment load and incentivized reuse of water after treatment. Due to this increasing demand of water treatment unit, the cost for the treatment of water has been an important issue for the industry.

To address this problem, the cost related to the water including treatment cost and fresh water cost has been minimized by designing each process unit, controlling treatment unit operation (Cote et al. 1995; Descoins et al. 2012; Gernaey et al. 2004), or finding an optimal structure where processes can use other processes' wastewater as a feed with/without treatment (Ponce-Ortega, El-Halwagi, and Jiménez-Gutiérrez 2010; Ponce-Ortega et al. 2011).

1.1.3 Energy-water nexus

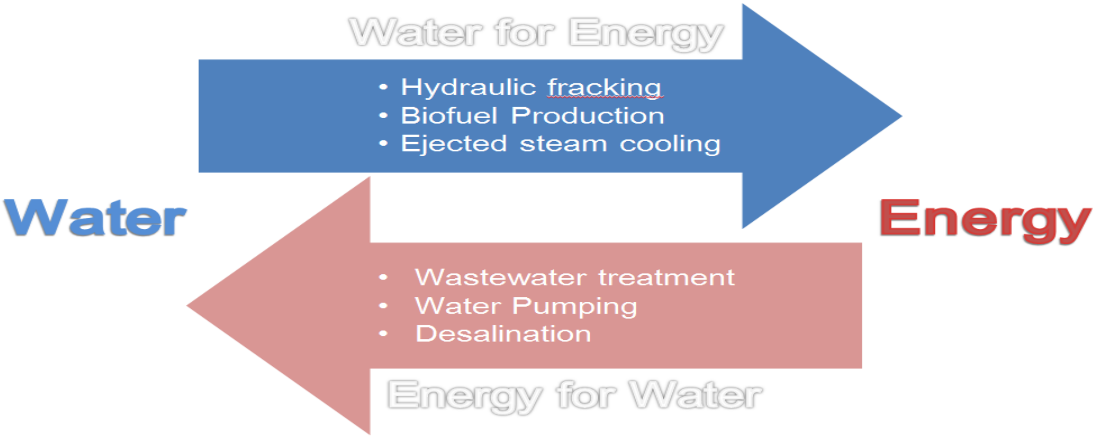

Figure 2. Energy-water nexus diagram

As we can see in the treatment of water and generation of electricity by using steam, energy and water are mutually interchangeable. This competition between energy and water can be understood comprehensively via the idea of energy-water nexus.

The idea of Energy-Water Nexus is visualized in figure *2*. Water has been considered as the most available and high-performance medium of cooling when we design the plant. In particular for thermal power plants, much water for cooling is consumed for cooling down the steam ejected after the generation of electricity. In addition to that, an alternative energy source (e.g. bioenergy) may need more water compared to conventional fossil fuel because of its nature-originated property. These examples demonstrate that the generation of energy requires a significant amount of water.

In another side, we need a significant amount of energy to treat water for using or even disposal. For instance, desalination, which is prevalently used for generating drinking water for the nations where available water sources are insufficient, consumes a lot of heat energy to produce steam for separation of inorganic materials by evaporation. Also, technology such as reverse osmosis of water consumes an enormous amount of electricity for the operation of the high-pressure pump.

As we can see above, the water and the energy are competing in its availability. Along with the trend of ever increasing energy and water demand, this energy-water relationship plays a critical role in sustainability. Therefore, a comprehensive solution which can address these two problems simultaneously by clarifying the competing relationship between water and energy has been the focus of many types of research around the world recently. (Siddiqi and Anadon 2011; Kahrl and Roland-Holst 2008; Hardy, Garrido, and Juana 2012)

1.1.4 Eco-Industrial Park (EIP) and energy-water nexus in EIP

Many efforts have been devised to improve the sustainability of the world. Among the efforts, the concept of the eco-industrial park has been gaining attention because of the significant role of industry in enhancing sustainability. The most famous definition of the eco-industrial park is “A community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only” (Doyle et al. 1996). In the eco-industrial park, participants share facilities, raw material, byproduct or even waste to maximize their profit and minimize the environmental impact. The most fundamental requirement for the formation of EIP is to demonstrate that the sum of benefits achieved by working as the cluster is higher than working as an individual facility.

This fundamental requirement can be achieved by process integration and economy of scale resulting from the formation of the cluster. By forming a cluster, plants can have numerous chances of process integration which can reduce the operating cost (utility cost) remarkably. For example, by using the surplus heat from the one plant, another process can generate electricity for the cluster with a lower price. Without the cluster, the individual process has the limitation of using surplus heat for the useful purpose. Also, water can be reused after proper treatment in the centralized or decentralized facility or adequate mixing with other water streams. If the cluster has many streams, there can be more chance of reducing the cost of wastewater treatment because of the direct mixing options which reduce the treatment cost. Also, if the wastewater from one process can be used directly for another process, it can lessen the consumption of fresh water significantly.

Therefore, Industrial symbiosis by forming cluster can remarkably reduce water and energy consumption. Many types of research have been done to optimize the cluster to maximize the profit by minimizing the utility cost, fresh source cost, treatment cost, etc (Dong, Lin, and Chang 2008; Leewongtanawit and Kim 2008; Manan, Tea, and Alwi 2009; Ponce-Ortega et al. 2011; Boix et al. 2012; Jiménez-Gutiérrez et al. 2014). However, minimizing consumption of one resource can significantly increase the use of another resource as we see in the energy-water nexus concept. Thus, applying the idea of energy-water nexus into the eco-industrial park is necessary to optimize the cluster for the sustainability. By considering the Nexus, the eco-industrial park can be designed comprehensively with elucidating the competing relationship between resources.

1.1.5 Increasing importance of waste-to-energy

Due to the global warming and grave concern on the sustainability, the value of waste is getting more attention. Especially, treating waste from the wastewater treatment facility is crucial because of increasing demand for the water treatment due to the stricter regulation and sustainability issue, which results in more waste to deal with. Therefore, some technologies have been developed to utilize this waste as an energy source. However, the impact of this waste-to-energy technology into the symbiosis of the industrial park has not been analyzed yet. Table 1 shows the types of cooperation between processes that are included in the optimization problem for the eco-industrial park. Exchange of water, energy and regeneration units are already addressed in the optimization problem for the eco-industrial park. However, the transformation of wastes into by-products has not been incorporated in the optimization problem. This cooperation can include resource recovery such as sulfide, nitrogen from the waste and energy recovery from the waste (e.g. biogas from anaerobic digestion).

As the environmental impact and cost of disposing of wastes become more severe problem urgently dealt with, the consideration of waste within the optimization framework becomes more attractive.

Types of cooperation in EIP	**Used in optimization**
Exchange of materials, water and/or energy	o
Share of units (waste treatment, utility)	o
Transformation of wastes into by-products	x

Table 1. Types of cooperation between companies in an EIP (Boix et al. 2015)

1.1.6 Biological water treatment and sludge treatment

1.1.6.1 Water treatment unit

As the cost of the water treatment becomes one of the essential elements in operation of plants, reducing the cost of the treatment unit is a significant issue. For the treatment of organic matters, biological wastewater treatment is generally used. This process has been very successful for a long time but has a serious problem in dealing with sludge that is the waste during the treatment. However, this sludge has significant potential for the energy recovery and reduction of Green House Gas (GHG) emission.

1.1.6.2 Biological treatment of wastewater

There are numerous methods and facilities to treat wastewater depending on the quality of influent and effluent, local characteristic, economic constraints, etc. For example, ozonation can be used for removing the nutrient in the wastewater by chemical species (Masten and Davies 1994). Also, filtration with ultra-filter or reverse osmosis is often used for treating wastewater in various situations because of its reliable operation (Pérez-González et al. 2012). Among these methods, biological treatment of wastewater, including Activated sludge treatment, has been successfully used for more than 100 years to treat the organic matter in the wastewater (Metcalf & Eddy Boston., 1991). Organic matters are acting as food for microorganisms, and microorganisms break the organic matters to conduct metabolism. The most commonly adopted biological processes are (1) activated-sludge process (2) aerated lagoons, (3) trickling filters, (4) rotating biological contactors, and (5) stabilization ponds. Among these processes, activated-sludge processes are the most prevalently used for large scale facility because of its versatile applicability and reliable performance (Metcalf & Eddy Boston., 1991).

1.1.6.3 Activated sludge treatment of wastewater

The objectives of the biological treatment of wastewater are to coagulate and remove the non-settleable colloidal solids and to stabilize the organic matter by degradation. Biodegradable organic matters are decomposed by the bacteria, and the microorganisms grow with the decomposed matter while some of them are dead. Because of the generation of suspended solid from the corpse of the microorganisms and the growth of microorganisms, activated sludge should be disposed to maintain the Food/Microorganism ratio (F/M ratio) through the process (Metcalf & Eddy Boston., 1991). Otherwise, microorganism has insufficient food because of a vast number of microorganisms so that they cannot work in a stable fashion. The average age of the sludge is called mean cell residence time (MCRT) or solid retention time (SRT). This operating parameter is used for designing the aeration basin because it mainly controls the amount of excess sludge that should be disposed of.

1.1.6.4 Stabilization of sludge

Wasted Activated Sludge (WAS) should be treated with several technologies (stabilization, dewatering, conditioning, etc.) before the disposal because US government made a law prohibiting the exhaust of untreated sludge into the land because of the high pathogen in the untreated sludge (Walsh 1995). For the stabilization of the activated sludge, (1) anaerobic digestion, (2) aerobic digestion, (3) lime stabilization, (4) thermal treatment, and (5) compositing are commonly used. These stabilization technologies are used alone or collectively.

1.1.6.5 Dewatering of sludge

Typically, sludge after the anaerobic digestion has a solid content up to 5-7% (Metcalf & Eddy Boston., 1991). The cost of hauling the sludge is correlated with the volume of sludge so that reducing the sludge volume is critical to saving money spent on the disposal cost. Various methods including belt filter press, sludge drying bed, and centrifuge can be used to dewater the sludge according to their process condition and local characteristics. Although those technologies have been successful, massive increase of sludge due to the regulation creates an urgent need to reduce more volume of the sludge. In the conventional mesophilic anaerobic digestion without thermal pretreatment of sludge, various macromolecule structures in the digested sludge prevent water from being removed by confining water in the structure (Neyens and Baeyens 2003). With the thermal pre-treatment, however, these macromolecule structures are destructed so that the solid content in sludge cake can be increased up to 43% while that of untreated is typically 20~30%. (Neyens and Baeyens 2003; Neyens et al. 2004).

1.2. Literature Review

1.2.1 Heat exchange network (HEN)

Due to the growing demand for water and energy, many studies have been conducted. First, energy, especially heat, has long been the subject of many types of research as a fundamental theme in chemical engineering. Heat pinch analysis has been used for a long time to analyze the minimum utility requirement of a given sink and source before determining a specific design or arrangement of process stream (Linnhoff and Flower 1978; Linnhoff and Hindmarsh 1983; Linnhoff 1993). After calculating this minimum utility requirement by either graphically or numerically, optimum arrangements could be identified by minimizing the number of connection under the constrained utility requirement. After this approach, transship model is applied to find out the best arrangement through mathematical programming (Papoulias and Grossmann 1983; Floudas, Ciric, and Grossmann 1986). Heat is treated as a commodity, and each temperature interval is considered as a container. After the arrangement of the structure is specified, the minimum cost of heat exchanger area is calculated.

However, through this sequential procedure, consideration of trade-off between operating cost and capital cost is hard to be incorporated in the model. In an effort to solve this problem, simultaneous mathematical models were developed (Yee, Grossmann, and Kravanja 1990; Yee and Grossmann 1990). These approaches do not rely on the pinch temperature but the match of each hot and cold stream. The criterion of best configuration is not minimizing the utility cost but total annual cost including capital cost and operating cost. (Yee and Grossmann 1990)

In this research, pinch analysis for each plant is used to estimate the cogeneration potential (surplus steam potential) in the processes.

1.2.2 Total site analysis (TSA)

For the large scale plants or industrial cluster, it is hard to implement the optimization based heat exchange due to the high complexity of each process. To find practical optimal solution in industrial cluster, total site analysis can be applied. This methodology was first proposed in (Dhole and Linnhoff 1993). In this analysis, surplus energy can be converted to the form of steam instead of direct heat exchange between streams, which allows practical approach for the utility optimization for the large scale industrial cluster.

In this method, minimum utility consumption in each plant is calculated with the pinch analysis and grand composite curve analysis. From this analysis, cooling and heating load for the process can be identified. Furthermore, in TSA, these cooling and heating loads from the grand composite curve are modified to consider internal heat exchange. In this step, “pocket” part in the grand composite curve is removed. It is basically pinch-analysis base analysis so that it does not have mathematical optimization in this step. After estimating all the process heat and cooling loads for each site, this information is combined to make total site profile, which includes source and sink for the whole cluster. From heat source, steam is generated by using the surplus heat, and this steam can be used for utility requirement for other plants. Therefore, through this method, the entire industrial park can be integrated by the mutual steam utilization system.

1.2.3 Extractable energy analysis for cogeneration targeting

There are several methods to calculate cogeneration potential from the processes. For total site analysis, exergy analysis has been used to minimize the loss of workable energy, which means maximizing the cogeneration potential (Dhole and Linnhoff 1993). Also, T-H shaft work method is proposed in (Raissi 1994). In this model, the enthalpy difference between saturated water and steam in inlet and outlet steam is assumed to be same according to the observation by (Salisbury 1942). However, the exergy analysis is not easy to do because consideration of entropy is vital in this analysis. In addition, T-H shaft model is based on the saturation condition not on the header steam condition, and also it is difficult to model cascade turbine network. In (El-Halwagi, Harell, and Spriggs 2009), El-Halwagi proposed the concept of ‘extractable energy’ to calculate cogeneration potential with mass, heat integration. This method is a graphical method that enables finding a new opportunity for the steam network improvement and cogeneration targeting. This enables easy and fast targeting of the cogeneration potential. The important point is that this method includes mass integration so that it is possible to include the heat generated by bio-waste in cogeneration potential calculation. Moreover, in (Mohan and El-Halwagi 2007), algebraic targeting of the extractable energy is proposed. This analysis enables simple calculation of cogeneration potential, which is important in estimating revenue from biogas in this study.

1.2.4 Water exchange network (WEN)

Similar to the heat integration, many studies have been done to determine the optimal water distribution system that can minimize fresh water usage or total cost of the network. This system has an analogy with the heat integration because similar pinch methodology can be used for freshwater targeting (Wang and Smith 1994). Given contaminant concentration of the source and the allowable contaminant concentration of the sink, target of fresh water can be calculated. Mathematical programming approach for optimal water distribution network has been conducted (Huang et al. 1999; Schaake and Lai 1969; El-Halwagi and Manousiouthakis 1989; El-Halwagi and Manousiouthakis 1990) after the graphical pinch analysis. Typical cost elements are the piping cost to connect the flow, the treatment cost of water (capital and operating), and fresh water cost.

1.2.5 Water and heat exchange network (WAHEN)

Recently, with the help of computing power, instead of considering the water and energy optimization separately, many studies have emerged to consider these two optimization problems simultaneously. They considered both the mass exchange network and the heat exchange network to optimize the system (Dong, Lin, and Chang 2008; Kim et al. 2009; Ahmetović and Kravanja 2014). For this optimization, objective function would be more complex to incorporate the combined cost function of heat exchange network and mass exchange network: heat exchanger construction cost, piping cost, water treatment cost, fresh water cost, utility cost, etc.

1.2.6 Thermal hydrolysis pretreatment of sludge (THP)

Thermal hydrolysis pretreatment is one of the sludge conditioning and stabilization methods. By injecting pressurized steam into the sludge mixture, insoluble gel structure and large molecules in sludge are broken down and solubilized (Kim et al.

2003). This solubilization generates smaller molecules that are easier to be digested by microorganisms and reduces the amount of sludge after treatment. This effect improves the efficiency of anaerobic digestion by raising the biogas production with the increased biodegradability (Noike 1992; Pinnekamp 1989). In addition, due to the loosened structure, the water affinity of sludge solids is reduced, and it is possible to dewater this sludge upto 40% solid contents while untreated sludge can be dewatered only upto 20-30%.

Along with those advantages, Class A sludge can be produced with thermal treatment at sufficient temperature (150~200°C) and time (20~60 min). Class A sludge has little pathogen and vector attraction so that it reduces the hazard of transmitting disease by the vector such as mosquitoes, birds, etc. Thanks to these characteristics, Class A sludge is preferred for the usage and can be used without permission; The Class A sludge can be utilized readily for the agricultural purpose and the restoration of the mining site. (Mehdizadeh et al. 2012). Currently, there is a movement to shift away from Class B toward Class A because of high expense to dispose of sludge due to the stricter regulation and increasing amount of sludge. However, because of high capital cost and operating cost, widespread utilization of thermal treatment has been limited (Metcalf & Eddy Boston., 1991).

1.3 Motivation

Previous researchers have laid a strong foundation for reducing energy and water use in the process. In the previous studies, the focus of the investigation was more toward the network or distribution of resources with a generalized cost function. However, improving the economy of and find a new opportunity from the treatment unit is an essential part to improve water reuse rate and sustainability of EIP. If we can recover a considerable amount of energy or reduce the pollution while generating value from these water treatment facilities, it can make a great contribution to the sustainability of the eco-industrial park.

Typically, organic pollutants in the wastewater are treated by biological treatment unit because of its obvious economic benefits compared to other chemical or mechanical methods (Metcalf & Eddy Boston., 1991). However, one of the problems in the biological method is the disposal of wasted sludge from the treatment. In the past, the sludge can be disposed into the sea after basic treatment. However, since the regulatory prohibited the disposal into the sea, the sludge began to dump into the landfill site or used as an agricultural fertilizer with stabilization. Due to the pathogen and toxic components in the sludge, however, the usage of sludge for the land application is limited or requiring the high operating cost to haul. The cost of sludge disposal accounts for a significant portion (~50%) of the operating expenses of water treatment facility. Therefore, there is a big chance to improve the economy of water treatment facilities if we can find appropriate technology for dealing with sludge.

For stabilization of sludge, anaerobic digestion is one of the most prevalently used technologies because of the chance to recover the energy in the form of biogas with relatively cheap capital and operating cost (compared to incineration), and stability compared to other processes. Recently, improved technology for pretreatment technology before anaerobic digestion has been actively investigated. The objectives of these researches are mainly: 1) enhancing the biogas output, 2) improving final dewaterability of sludge, 3) reducing viscosity. These parameters have considerable effects on the operating cost of wastewater treatment unit. Thermal hydrolysis pre-treatment of sludge before the anaerobic digestion can be effectively used for improving the energy recovery and reducing the hauling cost by improving the dewaterability of the sludge. However, thermal hydrolysis process needs a considerable amount of thermal energy and not feasible in small scale so that there is some limitation for prevalent utilization.

1.4 Problem Statement

Due to the increasing demand of water with environmental regulation, the amount of water that should be reused will increase. Along with this trend, sludge generated from the treatment unit will be serious concern for the industrial cluster that has a large capacity of centralized treatment units, so some strategies to handle this issue are indispensable for sustainable EIP. In this study, thermal hydrolysis process (THP) combined with the anaerobic digestion will be incorporated in the industrial park configuration to investigate the potential of improvement of the sustainability and the cost reduction for wastewater treatment simultaneously.

The main barrier of THP system is high initial capital cost and steam consumption for sludge heating. Currently, most of the municipal water treatment plants are far from other process facilities, and thus, CHP or steam generator should be installed on-site, and biogas produced should be used to generate heat to make steam for the THP.

However, within EIP, the amount of heat needed to make steam for THP can be covered with the surplus heat from other processes due to the centralized steam network. In addition, due to the economy of scale in EIP that usually has large centralized capacity treatment system, the high initial capital cost for THP can be alleviated with the economy of scale. If we can take advantage of the surplus heat from other processes at low cost and economy of scale that is the inherent advantage of EIP, improved biogas production and reduced sludge hauling costs can be achieved while saving a significant amount of cost expense, and it will enhance both the economy and sustainability of the EIP.

As a result, this study can contribute to building an integrated structure including waste-to-energy technology for the enhanced energy recovery and reduction of waste treatment cost. As we can earn a considerable amount of carbon credit from the biogas recovery, the importance of this approach will further enlarge when we consider GHG emission, which is a serious issue these days.

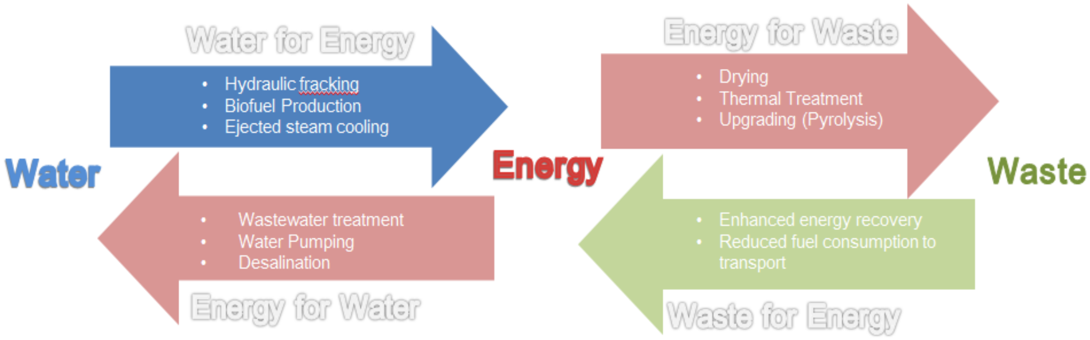

Figure 3. Water-energy-waste nexus

2. METHODOLOGY

2.1 Schematic Diagram of the Problem

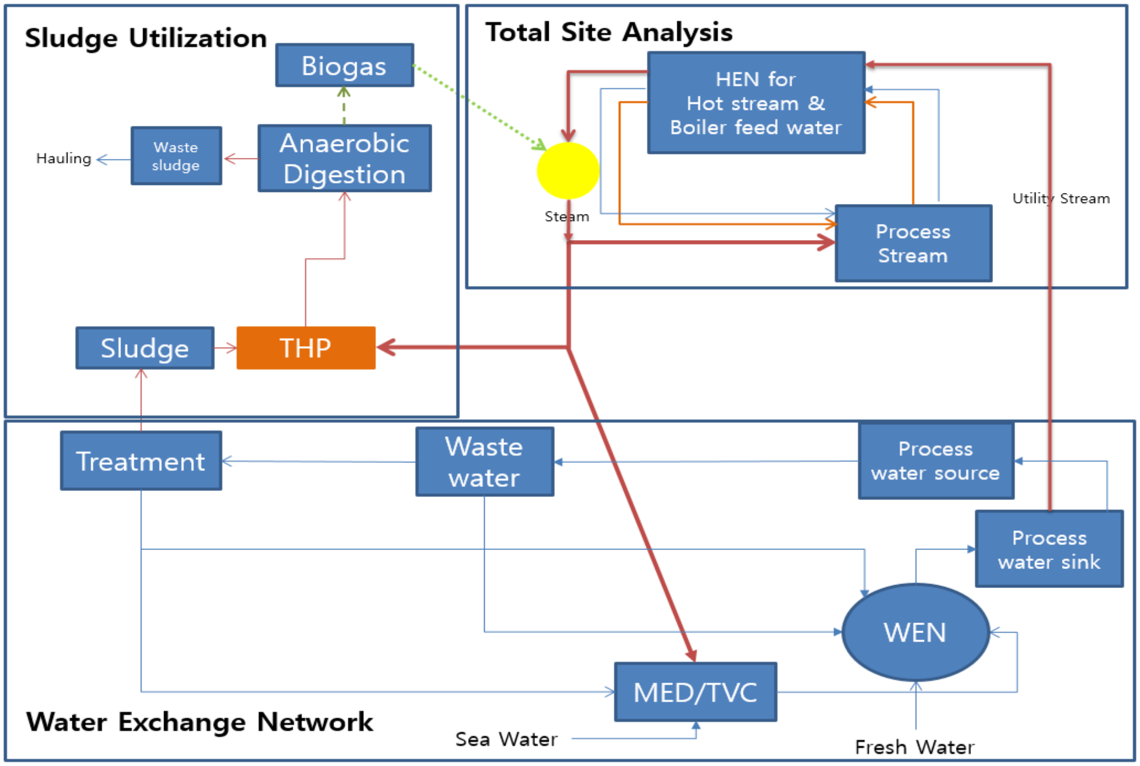

Figure 4. Block diagram of designed structure

Figure 4 represents a holistic view of this study. This research contains mainly three blocks in the structure: 1) Total Site Analysis, 2) Water Exchange Network, and 3) Sludge Treatment. The ultimate goal is to see the impact of waste-to-energy technology, especially thermal hydrolysis of sludge, on the economy and sustainability of eco-industrial park (EIP). The methodology to achieve this consists of 5 steps: 1) modeling, 2) data extraction, 3) total site analysis, 4) water exchange network optimization, and 5) economic analysis.

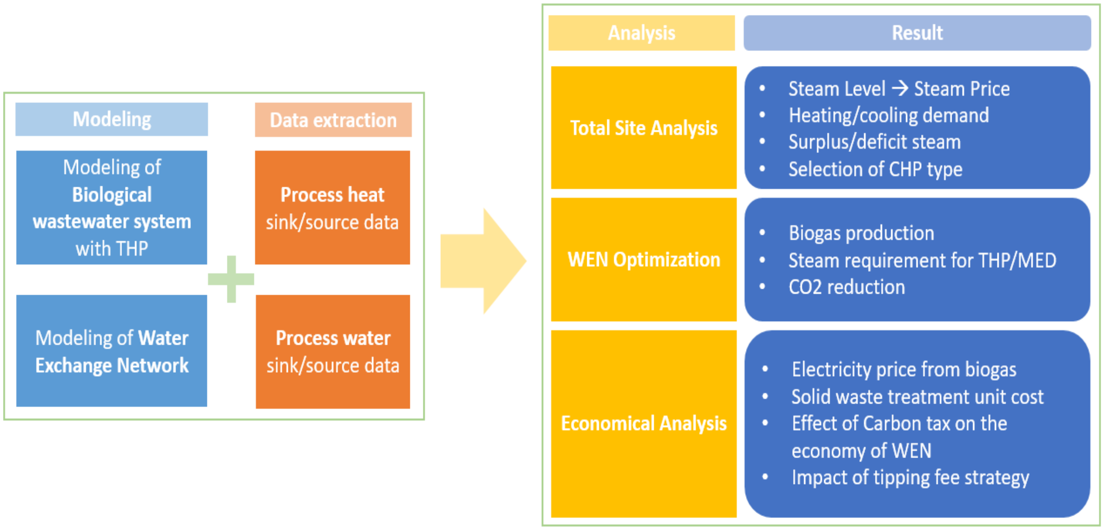

Figure 5. Methodology of analyzing the impact of THP on EIP

2.2 Methodology

2.2.1 Modeling

First, a model for the biological wastewater treatment system and sludge treatment system with THP are required. The input of these models are the flow rate of wastewater and pollutant concentration, and the output will be total annualized cost of the biological treatment unit including sludge treatment and reduced GHG emission from biogas generated from anaerobic digestion of sludge. Before analyzing EIP with optimization of water exchange network (WEN), the impact of the THP on the wastewater treatment facility with a certain capacity and pollutant concentration is investigated first to obtain useful insight from it. This analysis improves the understanding of the biological treatment facility and its potential when it is incorporated into the integrated structure in various scenarios.

After building a model for the treatment system, the optimization framework for the optimal water exchange network is needed in order to assess the wastewater load and characteristic from the processes in the EIP. Once the WEN model is built, this framework will be optimized with process data to determine optimal wastewater characteristic to be treated in the biological treatment system, which is critical to the economy of THP in the EIP.

2.2.2 Data extraction

As stated previously, water/heat source-sink data from the processes in the EIP is required to optimize the water network and analyze the surplus heat in the EIP. Each water source has flowrate, TSS, BOD, and TDS concentration and each water sink has minimum and maximum allowable pollutant content, which serves as constraints. Limitation of pollutant content of the water disposed to the environment is set as EPA standard for the water disposed of, and it will act as upper bound for water disposal.

2.2.3 Total site analysis (TSA)

Total site analysis is conducted to assess the steam level and estimate different CHP option with biogas. The major purpose of TSA is to estimate the cost of the steam used for THP and MED in the water exchange network (WEN), which is crucial for the economy of THP in EIP.

The step of the total site analysis is conducted through the steps below.

- Identifying the characteristics of the streams in each plant
  - Hot, cold stream
  - Feed temperature & Target temperature
  - Heating & cooling loads
- Generating grand composite curve for each site
- Remove 'pocket' region of the grand composite curve by assuming the internal heat exchange within the each site.
- Reorganize the temperature-heat load data with the modified stream data
- Amend the temperature to guarantee heat exchange with steam level
  (Add $0.5\Delta\mathrm{T}_{min}$ for cold stream, subtract $0.5\Delta\mathrm{T}_{min}$for hot stream)
- Select steam level (temperature) and calculate surplus steam from the total site

- Using this information to calculate steam cost

After analyzing the steam level, the price of the steam can be estimated with the electricity generation potential of each steam level. However, the power generation potential of the steam depends on the characteristics and infrastructure of the industrial park. For example, if there is a condensing turbine where even low-pressure (LP) steam can be used for the power generation, low-pressure steam can have value in the industrial park. However, if there is no turbine to use LP steam, surplus LP should be cooled down with the utility so that it has no value or even negative value in the structure unless we can sell the LP to other consumers such as residential area.

If there are condensing turbines in the eco-industrial park, and the steam is generated from surplus heat, this surplus steam will be used for either only electricity generation or cogeneration to produce both. In the power generation only situation, the value of steam can be estimated with the electricity potential that can be produced by using surplus steam into the condensing turbine.

For condensing turbine, the outlet pressure of the condenser is assumed to be 0.125 bara where the saturation temperature is 50.26 ℃.

In this condition,

$$\mathrm{S}_{\mathrm{water}}^{\mathrm{cond}} = 707.062 \left(\frac{J}{kg\ K}\right), H_{water}^{cond} = 210418\ (\frac{J}{kg})$$

$$S_{steam}^{cond} = 8070.19\ \left(\frac{J}{kg\ K}\right), \mathrm{H}_{\mathrm{steam}}^{\mathrm{cond}} = 2591670\ \left(\frac{J}{kg}\right)$$

For each level of steam, the property of the steam can be estimated with equations below.

$$\mathrm{P}_{\mathrm{sat}} = \left(\frac{T_{sat}}{112.72}\right)^{4.3687}$$

$$\mathrm{S}_{\mathrm{sat}} = (-0.5549\log(T_{sat}) + 3.7876)\times T_{sat}^{0.1001\exp(0.0017T_{sat})}$$

$$\mathrm{H}_{\mathrm{sat}} = 0.2029 T_{sat} S_{sat}^{3.647} + 817.35$$

Outlet enthalpy from the condensing turbine for each steam level is calculated by lever-arm rule.

$$\mathrm{x} = \frac{\mathrm{S}^{\mathrm{sat}}_{(HP,MP,LP)} - S^{cond}_{water}}{S^{cond}_{steam} - S^{cond}_{water}}$$

$$\mathrm{H}^{\mathrm{cond}}_{\mathrm{iso}} = H^{cond}_{water} + x(H^{cond}_{steam} - H^{cond}_{water})$$

With iso-entropic efficiency of the turbine, the outlet enthalpy of steam can be estimated.

$$\mathrm{H}^{\mathrm{cond}}_{real} = \mathrm{H}^{\mathrm{sat}}_{\mathrm{(HP,MP,LP)}} - \mathrm{N}_{\mathrm{turbine}}(H^{sat}_{(HP,MP,LP)} - H^{iso}_{cond})$$

From this, the enthalpy difference between inlet and outlet steam can be set as an electricity generation potential of a certain level of steam. By using this potential, the value of steam can be estimated with the price of electricity supplied.

$$\mathrm{W}_{\mathrm{(HP,MP,LP),cond}} = N^{m}\left(H^{sat}_{(HP,MP,LP)} - H^{cond}_{real}\right)$$

$$\mathrm{P}_{\mathrm{(HP,MP,LP)}} = W_{(HP,MP,LP),cond}P_{elec}$$

$\mathrm{N}_{\mathrm{turbine}}$ is the iso-entropic efficiency of the turbine, N^{m} is the mechanical efficiency of the turbine.

In this study, we assume that there is condensing turbine that can use LP steam, and this pricing strategy will be used for the optimization of WEN structure. However, if there is no condensing turbine, then the cost of the steam can change depending on whether there is a heat sink that can use the steam after the cogeneration. If there is no condensing turbine but a heat sink for low-grade heat, then the value of the steam can be represented by using extractable energy concept (El-Halwagi, Harell, and Spriggs 2009) as

$$\mathrm{Price}_{\mathrm{steam}} = CP + Heating = \eta_{eff}\left(H^{higher} - H^{lower}\right)P_{elec} + \frac{H_{lower}}{\eta_{boiler}}P_{fuel}$$

where CP is a cogeneration potential calculated from the difference between extractable energy. Therefore, if there is a plenty of low-pressure steam sink, the impact of THP in the eco-industrial park can be improved due to the increased cogeneration potential and high value from the lower pressure steam. However, if there is no heat sink or steam demand for the lower level steam after the cogeneration, the price of steam can be represented as

$$\mathrm{Price}_{\mathrm{steam}} = CP - Cooling\ Cost = \eta_{eff}\left(H^{higher} - H^{lower}\right) - QP_{cooling}$$

Due to the cooling requirement, we need cooling cost for the lower pressure steam. Therefore, the availability of the condensing turbine that can utilize low-grade energy or heat sink is important in determining the steam cost in the total site analysis. Again, in this study, the availability of condensing turbine is assumed to simplify the analysis.

2.2.4 Optimization of water exchange network (WEN)

With the steam level, steam cost, and water source-sink data, water exchange network (WEN) can be optimized to minimize the total cost of exchange network including wastewater treatment units. In WEN, there are two treatment units: Activated Sludge Treatment (Biological Treatment) for organic material treatment and Multi-Effect Distillation (MED) for inorganic material treatment. For biological treatment system, the model built previously is implemented to calculate the unit cost of the treatment and GHG emission reduction. As the effluent from the biological treatment is not clean enough to be reused for certain processes, MED is needed as an advanced treatment to produce high purity water for those processes.

For this optimization problem, one of the important revenue sources is biogas from the sludge. This biogas has a certain amount of heating value depending on the ratio of methane in it. In our structure, we can use this biogas for two purposes. In one hand, we can use biogas for CHP to generate heat and electricity simultaneously. In another hand, we can use this biogas instead of natural gas for making VHP steam in the steam boiler. In the first option, although we have to install CHP unit, we can use the heating value of biogas more efficiently due to the high efficiency of CHP system. In the second option, we do not have to install CHP because we can use biogas within the steam boiler EIP already have, but the efficiency is lower than the first one.

In the situation with CHP system, the heating value of biogas is divided into two parts: electricity, and steam generation from waste heat. As we assume that there are turbine that can generate electricity with each header level of steam, we can calculate potential revenue of the biogas with the steam cost from the previous analysis.

For example, if there is a gas engine in the industrial park, we can burn biogas to generate electricity and heat from exhaust gas and cooling of the engine. From the literature, the efficiency of each energy generation is set to be 0.44 for electricity, 0.17 for high-grade heat in the exhaust gas, 0.23 for low-grade heat from engine cooling (Fernández-Polanco and Tatsumi 2016). For the case of a gas engine, exhaust gas can be used for MP steam generation, and surplus heat from engine cooling can be used for LP steam generation. Through this assumption, we can calculate the revenue from biogas in the integrated structure as below.

$$\text{Revenue}_{\text{biogas}}^{\text{GE}}(\$/yr) = Q_B m_B \left(\eta_{GE}^{elec} P_{elec} + \frac{\eta_{GE}^{\text{MP}} P_{MP}}{H_{MP}} + \frac{\eta_{GE}^{LP} P_{LP}}{H_{LP}} \right)$$

$Q_B: heating\ value\ of\ biogas\ (kJ/kg)$

$m_B: Mass\ of\ biogas\ produced\ (kg/year)$

$\eta_{GE}^{elec}: efficiency\ of\ CHP\ for\ electricity\ generation\ in\ gas\ engine$

$\eta_{GE}^{MP}: efficiency\ of\ CHP\ for\ heat\ from\ exhaust\ gas\ in\ gas\ engine$

$\eta_{GE}^{LP}: efficiecny\ of\ CHP\ for\ heat\ from\ engine\ cooling\ in\ gas\ engine$

$P_{elec}: electricity\ price\ (\$/kJ)$

$P_{MP}: Price\ of\ medium - pressure\ steam\ (\$/kg)$

$P_{LP}: Price\ of\ low - pressure\ steam\ (\$/kg)$

$H_{MP}: Specific\ enthalpy\ of\ medium - pressure\ steam\ (kJ/kg)$

$H_{LP}: Specific\ enthalpy\ of\ low - pressure\ steam\ (kJ/kg)$

In addition, if more high-grade thermal energy is required with electricity generation, gas turbine can be used. From gas turbine, exhaust gas can reach 600°C, and the efficiency of electricity generation is 28% and high-grade thermal energy is 45% (HP (>350) 16.9%, MP (>200) 16.9%, LP (>100) 11.2%) (Fernández-Polanco and Tatsumi 2016). There is a trade-off between efficiency and the grade of waste heat. In the similar way as gas engine, the revenue from biogas with gas turbine can be represented as

$$\text{Revenue}_{\text{biogas}}^{\text{GT}}(\$/yr) = Q_B m_B \left(\eta_{GT}^{elec} P_{elec} + \frac{\eta_{GT}^{\text{HP}} P_{HP}}{H_{HP}} + \frac{\eta_{GT}^{\text{MP}} P_{MP}}{H_{MP}} + \frac{\eta_{GT}^{LP} P_{LP}}{H_{LP}} \right)$$

Q_B: *heating value of biogas* (kJ/kg)

m_B: *Mass of biogas produced* $(kg/year)$

η_{GT}^{elec}: *efficiency of gas turbine for electricity generation*

η_{GT}^{HP}: *efficiency of energy conversion from exhaust gas to high pressure steam*

η_{GT}^{MP}: *efficiency of energy conversion from exhaust gas to mediume pressure steam*

η_{GT}^{LP}: *efficiecny of energy conversion from exhaust gas to low pressure steam*

P_{elec}: *electricity price* $(\$/kJ)$

P_{MP}: *Price of high − pressure steam* $(\$/kg)$

P_{MP}: *Price of medium − pressure steam* $(\$/kg)$

P_{LP}: *Price of low − pressure steam* $(\$/kg)$

H_{HP}: *Specific enthalpy of high − pressure steam* (kJ/kg)

H_{MP}: *Specific enthalpy of medium − pressure steam* (kJ/kg)

H_{LP}: *Specific enthalpy of low − pressure steam* (kJ/kg)

Finally, in the situation without CHP, the revenue from the biogas can be represented as the price of VHP steam because we use biogas as a fuel in the steam boiler to generate electricity.

$$\text{Revenue}_{\text{biogas}}^{\text{boiler}}(\$/yr) = \frac{H_B m_B \eta_{boiler} P_{VHP}}{H_{VHP}}$$

H_B: *Heating value of biogas*

H_{VHP}: *Enthalpy of VHP steam*

P_{VHP}: *Price of VHP steam*

If the amount of biogas is large enough to make the installation of CHP unit feasible, then the installing CHP will be preferred due to the high efficiency from the biogas. Otherwise, if the process needs high-pressure steam rather than medium or low-pressure steam, then gas turbine or boiler option can be considered.

By using these equations, the main results from this step is the change in the economy of WEN and GHG emission reduction by having THP in EIP. This will show the potential of EIP as a waste treatment center with its own wastewater treatment facility, which requires the considerable capacity of waste treatment facility.

2.2.5 Economic analysis under different scenarios

As the ultimate goal of this study is to analyze the impact of THP in the EIP as measures to improve its economic and environmental sustainability, economic analysis of the optimized structure is conducted. The main results are an improvement with THP in EIP, revenue from biogas, the unit cost for solid waste treatment, and the reduction of GHG emission. As these results can be different under different scenarios or environment of each EIP, analysis under several conditions is investigated. First, the impact of carbon tax on the economy of the eco-industrial park with THP is investigated. Second, bio-waste from outside into EIP is considered to maximize the benefit of THP along with utilization of economy of scale in EIP. Third, since one of the major advantages of THP is to make valuable sludge that can be sold, the sensitivity of treated sludge price on the economy of THP is investigated to assess the feasibility of EIP as a waste treatment facility.

3. MODELING

3.1 Water Exchange Network

The model used in this analysis was based on the previous model built by (Yu et al. 2013). This model is simple enough to be utilized for EIP where network that is too complex is hard to be adopted due to the reliability issue of EIP. Wastewater from the source can be reused for internal sink within the plant first, which is similar to the assumption made in the total site analysis for heat data.

At first, several sets are defined to represent the elements in the framework.

$$P = \{p |\ p = \ site\ (plant)\}$$
$$X = \{x|x = site\ (plant)\}, X = P$$
$$I_p = \{i|i = source\ at\ each\ site\ p\}$$
$$J_p = \{j|j = sink\ at\ each\ site\ p\}$$
$$W = \{w|w = wastewater\ treatment\ unit\}$$
$$T = \{t|t = fresh\ water\ type\}$$
$$\mathrm{Q} = \{\mathrm{q}|\mathrm{q} = \text{pollutant concentration}\}$$

For each water source, flow rate from each water source (Fso) is distributed to either water sink in the same site (Fss) or buffer tank (Fsb). Therefore, flow rate balance can be represented as

$$Fso(p,i) = \sum_{j=1}^{J_p} Fss(p,i,j) + Fsb(p,i)\,, \qquad \mathrm{p} \in \mathrm{P}, \mathrm{i} \in \mathrm{I}$$

Wastewater from sources that are not used for in-plant reuse is mixed and stored in the buffer tank. This might be non-optimal in the sense of the quality of water because clean water from some sources can be contaminated with other polluted water. However, it can be beneficial in the meaning that shock from certain processes can be reduced before being reused in other plants so that reliability can be enhanced.

For buffer tank, wastewater which cannot be used for direct reuse for the in-plant process is stored. This stored wastewater is distributed either to other plants' water sink for the direct reuse (Fbs) or to the first stage of treatment unit (Fbt). FB is the mixed flow rate which is the sum of the flow for each plant's buffer. As we do not use the water in the buffer for the sink inside, p should be excluded in x.

$$\mathrm{FB(p)} = \sum_{i=1}^{I_p} Fsb(p,i)\,, \qquad p \in P$$

$$\mathrm{FB(p)} C_{buffer}^{q}(p) = \sum_{i=1}^{I_p} C_{source}^{q}(p,i) Fsb(p,i)$$

$$\mathrm{FB(p)} = \sum_{j=1}^{J_p} \sum_{x \neq p}^{X} Fbs(p,x,j) + Fbt(p)$$

For treatment unit, wastewaters from buffer tanks in each plant are mixed to enter the first stage of the treatment unit (biological treatment system) and pass through the second stage treatment (MED) sequentially. $\mathrm{Fe}_{\mathrm{mix}}$ is the disposal fraction of mixed flow before treatment. This disposed fraction before treatment with mixing option with treated water can reduce wastewater load because it can be disposed of without treatment. The outlet from the biological treatment system is distributed to water sink (Fts), to further treatment ($\mathrm{FT}_{\mathrm{MED}}$), and to disposal ($\mathrm{FE}_{\mathrm{BG}}$). In biological treatment system, water loss is ignored because it is not significant in general.

$$\mathrm{FT}_{\mathrm{in,BG}} + Fe_{mix} = \sum_{p=1}^{P} Fbt(p)$$

$$C_{mix}^{q}\left(FT_{in,BG} + Fe_{mix}\right) = \sum_{p=1}^{P} Fbt(p) C_{buffer}^{q}(p)$$

$$\mathrm{FT}_{\mathrm{in,BG}} = \sum_{p=1}^{P} \sum_{j=1}^{J_p} Fts(BG,p,j) + FT_{MED} + Fe_{BG}$$

For the MED, there is a significant water loss because of the characteristic of distillation, which produces concentrated wastewater after the process. This water loss is assumed to be 40%, which is generally accepted. Also, if it is possible, some seawater (F_{sea}) can be treated with the wastewater in MED. Treated water can be directed to the water sink (Fts), to the environment (Fe), or for selling to the customer (F_{sell}).

$$(\mathrm{FT}_{\mathrm{MED}} + F_{sea})(1 - R_{loss}) = \sum_{p=1}^{P} \sum_{j=1}^{J_p} Fts(MED, p, j) + Fe_{MED} + F_{sell}$$

$$\begin{aligned}\mathrm{FT}_{\mathrm{MED}} C_{BG}^{q} + F_{sea} C_{sea}^{q} \\ = R_{loss}(FT_{MED} + F_{sea}) C_{MED,dispose}^{q} + (FT_{MED} + F_{sesa})(1 - R_{loss}) C_{MED}^{q}\end{aligned}$$

For each water sink, flow rate from in-plant water reuse (Fss), from other plant's buffer (Fbs), from wastewater treatment unit (Fts), and from fresh water sources (Fw) are mixed.

$$\mathrm{Fsi(p,j)} = \sum_{t=1}^{T} Fw(t,p,j) + \sum_{i=1}^{I_p} Fss(p,i,j) + \sum_{x \neq p}^{X} Fbs(x,p,j) + \sum_{w=1}^{W} Fts(w,p,j)\,, \quad \mathrm{p} \in \mathrm{P}, \mathrm{j} \in \mathrm{J}$$

Pollutant balance for each sink is

$$\begin{aligned}\sum_{t=1}^{T} FW(t,p,j) C_{FW,t}^{q} + \sum_{i=1}^{I_p} C_{source}^{q}(p,i) Fss(p,i,j) + \sum_{x \neq p}^{X} C_{buffer}^{q}(x) Fbs(x,p,j) \\ + \sum_{w=1}^{W} C_{treated}^{q}(w)\, Fts(w,p,j) = C_{sink}^{q}(p,j) Fsi(p,j), \qquad \mathrm{p} \in \mathrm{P}, \\ \mathrm{j} \in \mathrm{J}, \qquad \mathrm{q} \in \mathrm{Q}\end{aligned}$$

The pollutant content in each sink should not exceed certain upper bound in order to be reused for the processes.

$$C_{min}^{q} \leq \mathrm{C}_{\mathrm{sink}}^{\mathrm{q}} \leq C_{max}^{q}, \quad \mathrm{q} \in \mathrm{Q}$$

For the water disposed to the environment, a certain portion of the treated water at each treatment stage (Fe_{BG}, Fe_{MED}) can be disposed after being mixed with wastewater influent (Fe_{mix}), and fresh water (Fwd). Freshwater might be used to meet a regulation for the disposal water. The concentration of pollutant in the water disposed of ($C^{q}_{dispose}$) should be less than the maximum concentration ($C^{q}_{dispose,max}$) set by EPA standard.

$$\mathrm{F}_{\mathrm{disposal}} = Fe_{mix} + \sum_{w}^{W} Fe\,(w) + (FT_{MED} + F_{sea})R_{loss} + \sum_{t}^{T} Fwd(t)$$

$$\begin{aligned}\mathrm{Fe}_{\mathrm{mix}}C^{q}_{mix} + Fe_{BG}C^{q}_{BG} + Fe_{MED}C^{q}_{MED} + FT_{MED}R_{loss}C^{q}_{MED,dispose} + \sum_{t}^{T} FwdC^{q}_{FW,t} \\ = (F_{disposal})C^{q}_{dispose}\end{aligned}$$

$$\mathrm{C}^{\mathrm{q}}_{dispose} \leq C^{q}_{dispose,max}$$

The objective function of WEN is the total annualized cost (TAC). By minimizing the TAC, we can obtain optimal water network. TAC consists of fresh water cost (WC), treatment cost (TC), disposal cost (DC), and revenue by water selling (REV_w). TC has two cost: MED and BG. For MED, unit cost is found in the literature and used. For BG, the cost is determined by the cost function with mass balance in the next part.

$$TAC = WC + TC + DC - REV_w$$

$$WC = AO\left[\sum_{t} C_{pw,t}\left(\sum_{p,j}^{P,J} Fw(t,p,j) + Fwd(t)\right)\right]$$

$$\mathrm{TC} = \mathrm{TC}_{\mathrm{BG}} + TC_{MED}$$

$$\mathrm{TC}_{\mathrm{MED}} = AO \times UC_{MED}(FT_{MED} + F_{sea})(1 - R_{loss})$$

$$\mathrm{TC}_{\mathrm{BG}} = AR \times CAP_{BG} + OP_{BG}$$

$$\mathrm{DC} = \mathrm{AO}\left[\mathrm{EC} \times \mathrm{F}_{\mathrm{disposal}}\right]$$

$$\mathrm{REV}_{\mathrm{w}} = \mathrm{AO} \times \mathrm{P}_{\mathrm{w}}F_{sell}$$

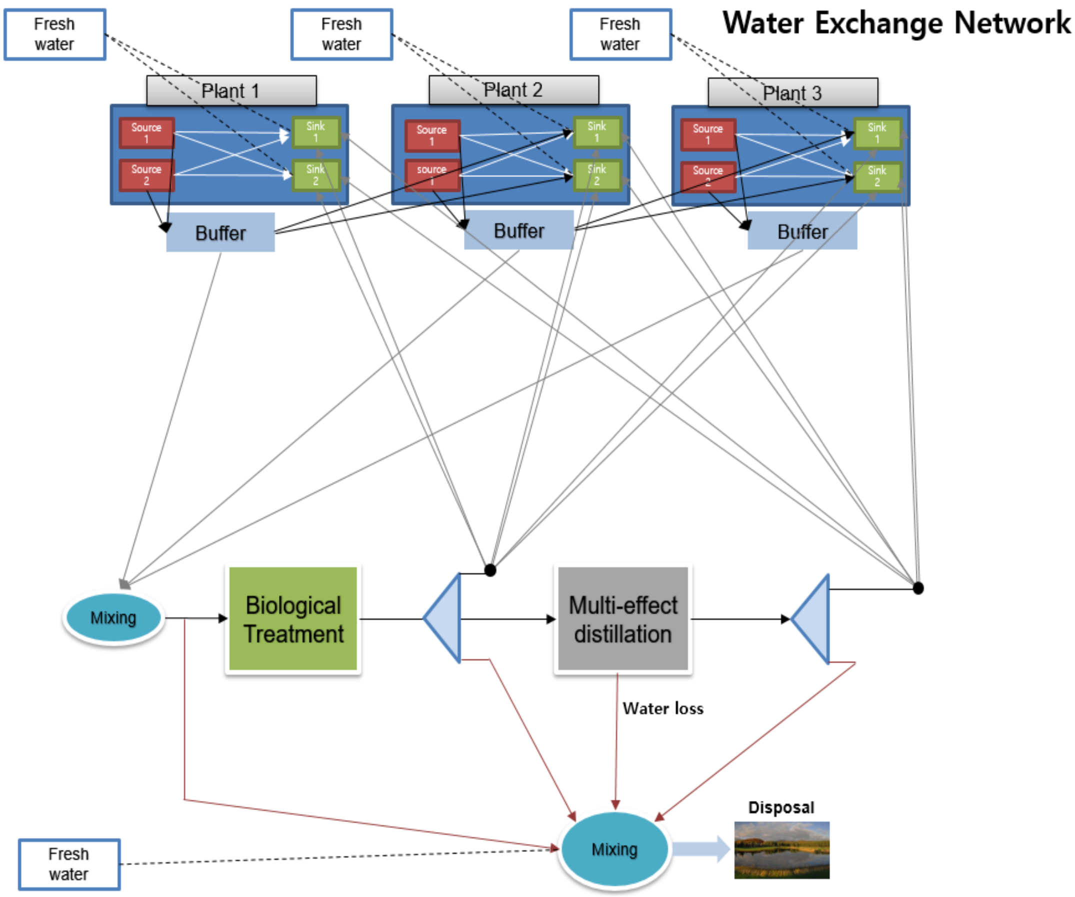

Figure 6. Water exchange network diagram

3.2 Water Treatment Block

In order to calculate the amount of sludge and biogas from the treatment facility, a model for the wastewater treatment facility is needed. Water treatment block consists of typical biological treatment units. In the structure, grit chamber, primary settler, aeration basin, and secondary settler are installed for the removal of pollutants (BOD, TSS) in the wastewater.

In the settler, those pollutants are separated from the treated water as a sludge. There are two types of sludge: primary and secondary(activated sludge). The secondary sludge is biologically active so that it requires stabilization process to be disposed. However, in order to recover energy from the sludge, anaerobic digestion, which is kind of stabilization process, is conducted for both sludges. After being digested in the anaerobic digester, sludge is dewatered for hauling. If both sludges (primary and secondary) are treated with the THP, it might be possible to sell this sludge for the agricultural usage. However, it depends on the characteristic of the industrial park because some pollutants such as heavy metals require additional treatment before being used for those purposes. The potential scenario where the treated sludge can be sold to the farmer will be discussed in the case study.

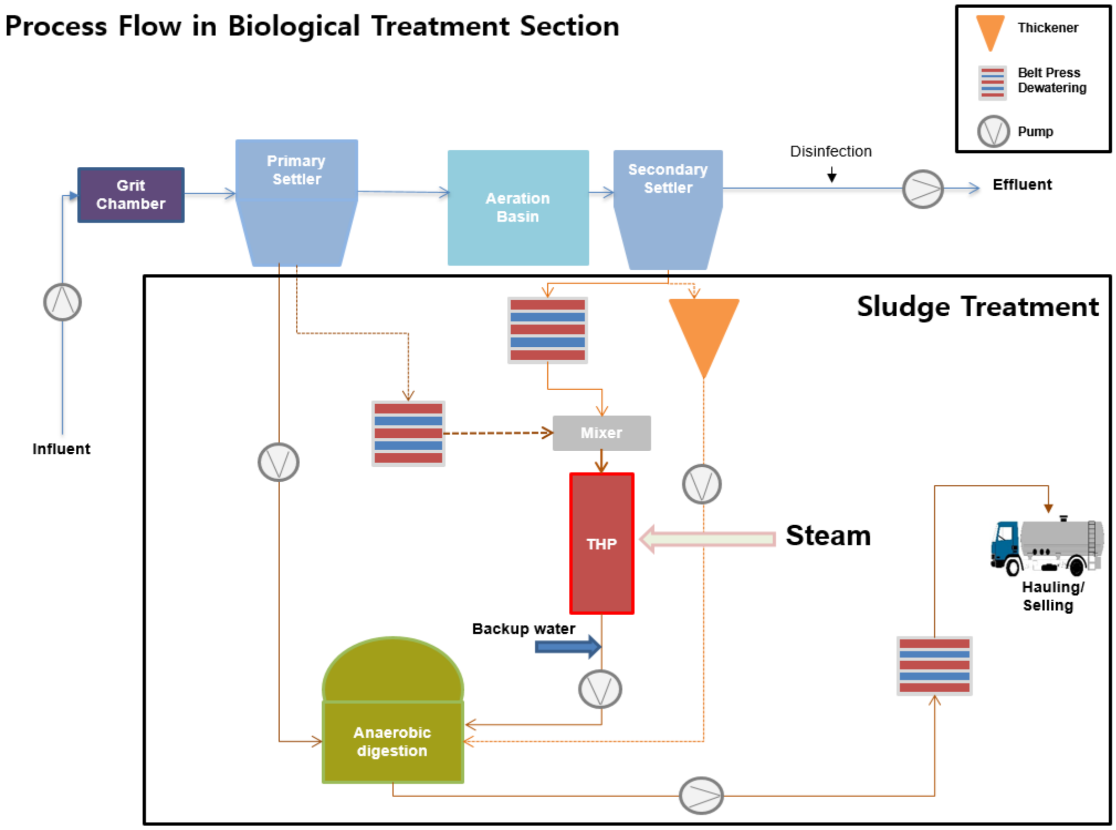

Figure 7. Biological wastewater treatment and sludge treatment system

In this model, to see multiple opportunities according to various process environments, the superstructure-based model was built. As seen in the process diagram below, there are two options for each sludge. For example, primary sludge from the primary settler can be either pumped into the anaerobic digestion directly without dewatering or put into the thermal hydrolysis process (THP) after being dewatered in the belt filter press dewatering unit. Likewise, waste activated sludge from the secondary settler can be either dewatered or thickened by gravity thickener. Ultimately, this model can assess the best option for the industrial park according to their process characteristic or capacity for their treatment of sludge.

3.2.1 Modeling of activated sludge treatment

Aerobic treatment of wastewater is modeled by adjusting Solid Residence Time (SRT) of the system. This value is specified from the literature as a typical value for the removal of organic waste from the wastewater. In addition, sludge production rate from the aerobic treatment is modeled by assuming complete mix aerobic treatment option. The cost will be correlated to the volume of inlet flow and its performance.

3.2.2 Modeling of thermal hydrolysis process

THP can improve biogas yield from the sludge and significantly reduce the hauling cost by improving the dewaterability of the sludge. THP can be used either as a pretreatment before the anaerobic digestion to decompose bio-resist material in the sludge or as post-treatment after anaerobic digestion. If cluster already has enough capacity of an anaerobic digester, using thermal hydrolysis process between the anaerobic digestions was proved to be effective for the sludge treatment and biogas enhancement (Gurieff 2011).

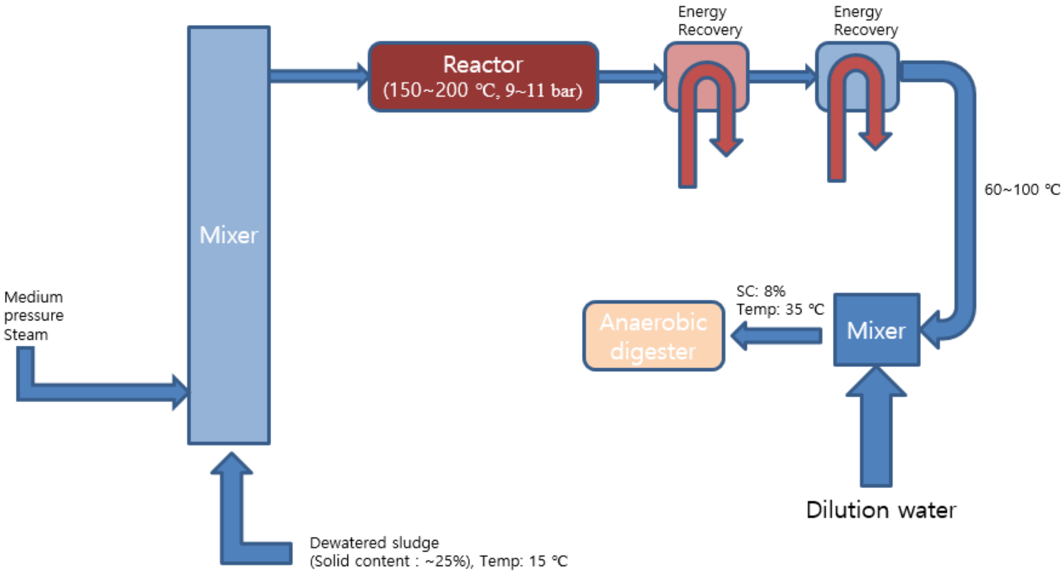

Figure 8. Thermal hydrolysis process of sludge (THP)

This process usually operates under high-temperature (150~200℃) and high pressure (~10 bar), so it consumes a significant amount of steam and needs a high capital cost. Dilution water is used for diluting and controlling the temperature of the sludge from the THP to ensure a robust process operation. From the literature, higher operating temperature induces more enhancement in the biodegradability until 200 ℃. Above that temperature, calcination starts so that the biodegradability decreases. In addition, initial biodegradability significantly affects the level of enhancement according to the literature. Therefore, the model including the impact of operating temperature and initial biodegradability is needed to estimate the applicability of THP into the industrial park. (Bougrier, Delgenès, and Carrère 2008)

3.2.2.1 COD solubilization and biodegradability enhancement

In literature, several results measure the impact of thermal pretreatment on the sludge. After treatment, COD solubilization, biodegradability (biogas production), viscosity and dewaterability are measured.

Importantly, above the 150 ℃, solubilization of COD can be modeled as a linear relationship with the pretreatment temperature regardless of sludge source (Carrère et al. 2008). In addition, enhancement of biodegradability measured by the amount of biogas produced can be modeled in a linear equation as a function of initial biodegradability of the sludge. Combining these two results, biodegradability enhancement can be represented by thermal treatment temperature and initial biodegradability.

$$S_{COD} = 0.0049\ T_{THP} - 0.3122,\ (R^2 = 0.8743)$$

$$\text{Biodegradability enhancement slope } (M_{BE}) = -9.4008\ BE_{initial} + 5.6571$$

$$\begin{aligned}\text{Biodegradability enhancement } (BE) &= M_{BE}S_{COD} + 1 \\ &= -9.4008\ BE_{initial}S_{COD} + 5.6571\ S_{COD} + 1 \\ &= -0.046064BE_{initial}T_{THP} + 0.02772T_{THP} + 2.93493BE_{initial} - 0.766147\end{aligned}$$

Finally, we can calculate enhanced biodegradability by multiplying BE to initial biodegradability.

$$f_{D,after} = f_{D,initial}BE$$

By using these equations, it is possible to check the trend of change in biodegradability according to the initial biodegradability and temperature. Higher biodegradability in the higher operating temperature can be modeled successfully. In addition, for the higher initial biodegradability, thermal hydrolysis process is not effective to improve the biodegradability, which is consistent with the experimental results showing that thermal hydrolysis process to the primary sludge is not as effective as that to the activated sludge.

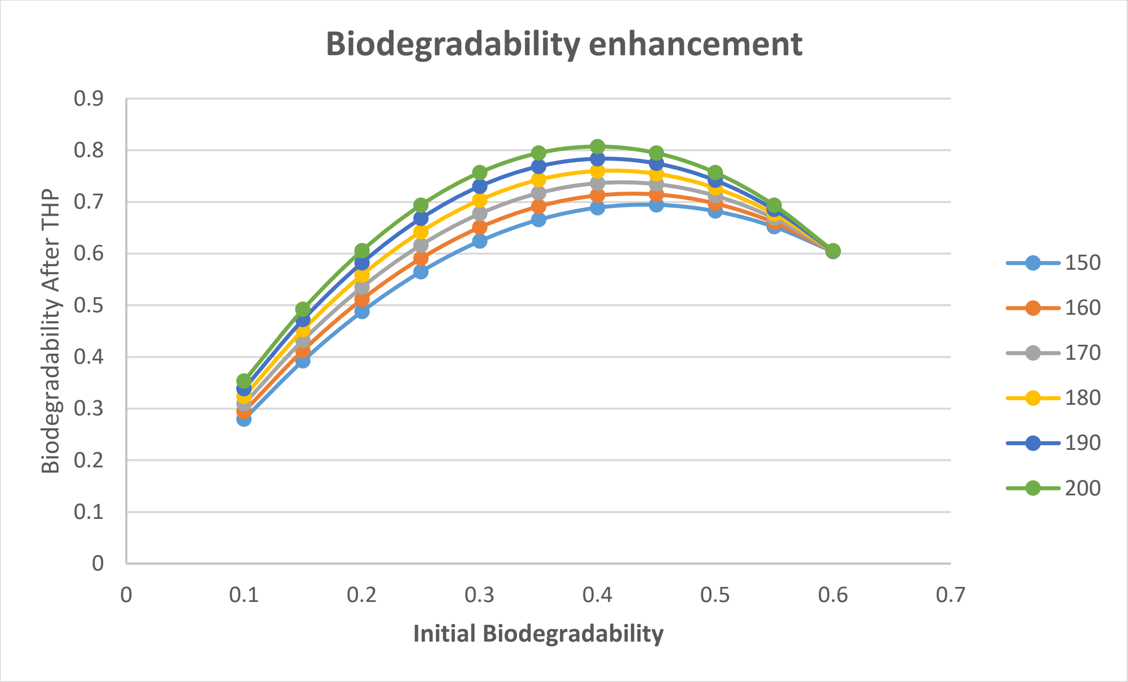

Figure 9. Enhancement of biodegradability according to operating temperature in THP

3.2.2.2 Calculation of biogas generation

Using the equation above for biodegradability enhancement, we can estimate the improvement in biodegradability of sludge by the thermal treatment. However, as we have only the value of enhancement ratio, the theoretical amount of biogas from the untreated sludge is required to calculate the biogas production.

The amount of methane produced can be calculated with the combination of Buswell's formula for methane production potential (Symons and Buswell 1933) and biodegradability information for reflecting sludge characteristic (Labatut, Angenent, and Scott 2011).

$$\text{Methane yield (B)}\left(\frac{L\ \mathrm{CH_4}}{g\ VS}\ @STP\right) = f_D B_0$$

$f_D = biodegradability\ of\ sludge,$

$B_0 = theoretical\ methane\ production$

$$\mathrm{B}_0\left(\frac{L\ CH4}{g\ VS}\ @STP\right)=\frac{22.4\left(\frac{2}{n}+\frac{a}{8}-\frac{b}{4}-\frac{3}{8}c\right)}{12n+a+16b+14c}\text{ for }\mathrm{C_n}H_aO_bN_c$$

3.2.2.3 Theoretical methane production (B_0)

Chemical composition of sludge can be included in the model by specifying the typical composition through experiments. Approximate formula for base case in this analysis is set as $\mathrm{C}_{18}H_{33}O_2$ for carbohydrate, $\mathrm{C}_6H_{10}O_5$ for lipid, and $\mathrm{C}_{11}H_{24}O_5N_4$ for protein. From this formula, fraction of methane in biogas can be calculated by using the equation below (Tchobanoglous, Burton, and Stensel 2003). This methane fraction in the biogas affects the heating value from the biogas.

$$C_nH_aO_bN_c+\left(n-\frac{a}{4}-\frac{b}{2}+\frac{3}{4}c\right)H_2O$$
$$\rightarrow\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-\frac{3}{8}c\right)CH_4+\left(\frac{n}{2}-\frac{a}{8}+\frac{b}{4}+\frac{3}{8}c\right)CO_2+cNH_3$$

$$f_{CO_2}=\frac{4n-a+2b}{8(n)}$$

$$f_{CH_4}=\frac{4n+a-2b}{8n}$$

Most of NH_3 is in the solution as ammonium bicarbonate, so they are not included in gas mole fraction calculation.

3.2.2.4 Typical sludge data and methane potential

	Untreated Primary Sludge		Untreated Activated Sludge	
Item	**Range**	**Typical**	**Range**	**Typical**
Total dry solids (TS),%	1 ~ 6	3	0.4 ~ 1.2	0.8
Volatile solids (% of TS)	60 ~ 85	75	60 ~ 85	70
Grease and fats (% of TS)	5 ~ 8	6	5 ~ 12	8
Protein (% of TS)	20 ~ 30	25	32 ~ 41	36
Cellulose (% of TS)	8 ~ 15	10	-	-

Table 2. Typical composition of untreated sludge

From the common data of chemical composition of sludge (EPA 1979), modeling the theoretical methane production from typical sludge can be achieved.

With the weighted value of each component in sludge, a common model sludge data for the calculation was set. The methane potential of the primary sludge is greater than that of the activated sludge. It is because of the high carbon and hydrogen composition from cellulose content in the primary sludge. However, as the amount of primary sludge is usually much higher than activated sludge, a significant amount of additional steam is needed to treat primary sludge before the anaerobic digestion. Also, due to the less enhancement of biodegradability of primary sludge resulted from the higher initial biodegradability also lessens the efficiency of thermal treating of primary sludge. However, the volumetric reduction of sludge by adopting thermal treatment is significant for primary sludge so that it can have considerable positive effect if we have steam that can be generated from another process at a low price.

From the literature, the range of biogas production from each sludge can be obtained. Similar to our model sludge, the primary sludge has more yield of biogas than the activated sludge. Although actual yield is lower than our CH4 potential, it could be calibrated with the introduction of biodegradability factor. Initial biodegradability is set as 0.5 and 0.35 for the primary sludge, and the activated sludge respectively.

	Chemical composition	**Weighted CH4 potential (B0)**	**Weighted CH4 ratio**
Sludge Type		ml CH4/ g VS	
Primary Sludge	$C_{11.98}H_{24.15}O_{4.27}N_{2.444}$	582.13	0.6629
Activated Sludge	$C_{10.09}H_{21.46}O_{5}N_{3.27}$	438.21	0.6419

Table 3. Theoretical methane (CH_4) production from typical sludge data

	Methane yield		
	ml CH4/ g VS		
Reference	Rittmann & McCarty (2000)	Sato et al. (2001)	Speece (2001)
Primary Sludge	262.5	428.4	253.4
Activated Sludge	192.51	266.1	196.71

Table 4. Literature biogas yield from sludge

3.2.3 Impact of heat integration on the steam requirement

Figure 10 shows the impact of heat integration within the THP process. This result is based on the optimized structure with 300 g/m^3 for TSS and BOD, and 50,000 m^3/day wastewater load.

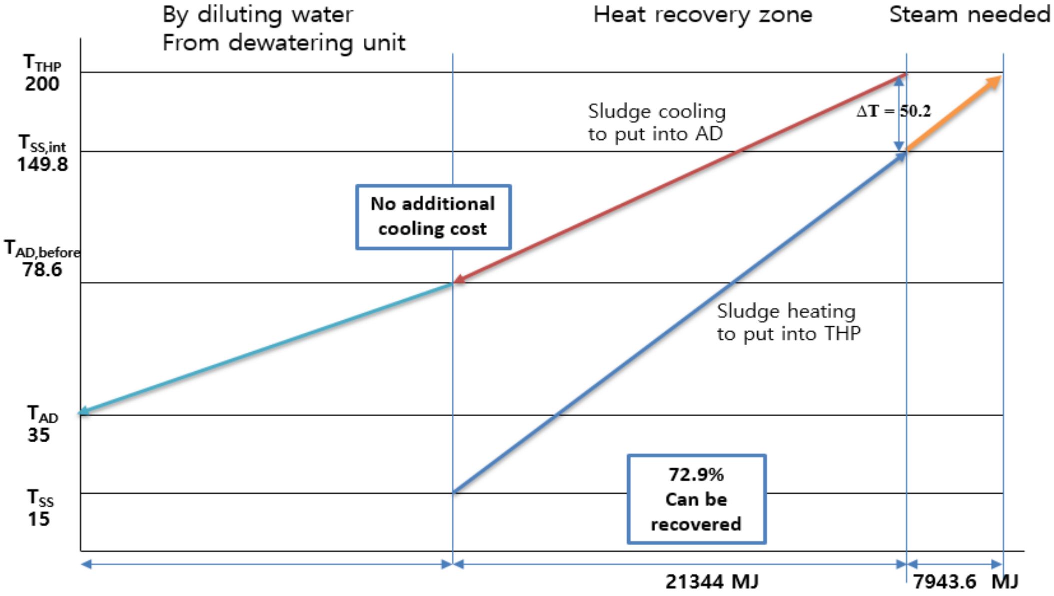

Figure 10. Pinch analysis of THP streams

The solid content in the raw sludge is assumed to be 25%. According to the calculation, a significant amount of energy (72.9%) needed for the sludge heating can be obtained with the economizer (heat exchanger) where the feed sludge is preheated by the outlet sludge stream from the THP process. The minimum temperature difference between the inlet and outlet is calculated as 50.2 °C, which means the heat exchange can be easily implemented. For the heating of the sludge, the slope of the line is less stiff than that of the cooling. It is because of the steam supplied for THP, and it causes more mass and heat content in the outlet stream from THP. The hot outlet stream is mixed with dilution water after being cooled by the raw sludge, so no additional cooling cost is required for the heat exchanger. The temperature of dilution water is set to 15 °C, so this can act as means of dilution and cooling simultaneously.

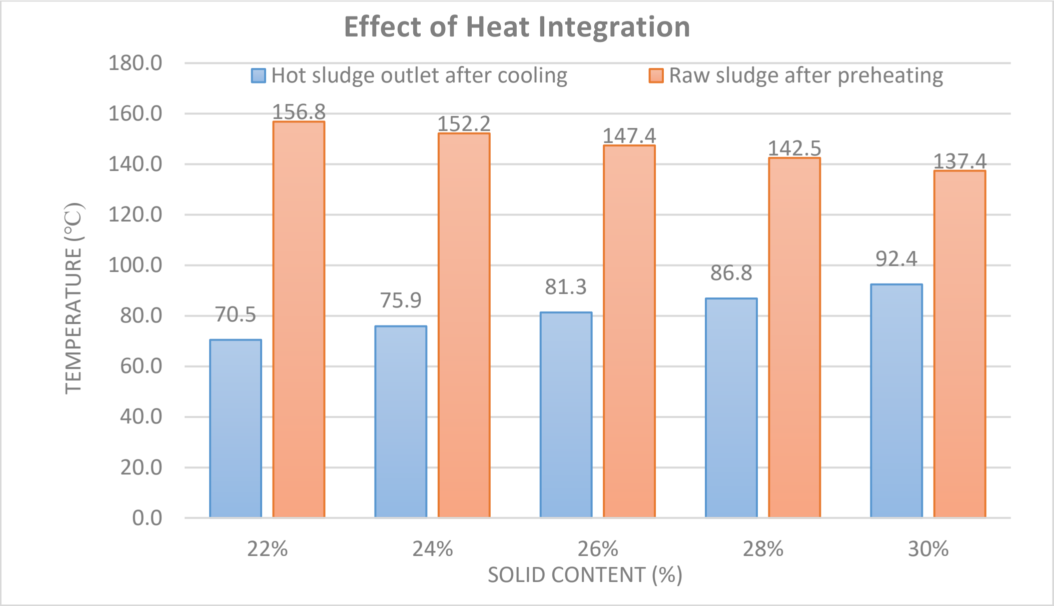

Figure 11. Effect of solid content on the heat integration

One of the interesting point in the heat integration in THP is that the degree of preheating of raw sludge is affected by the solid content in the raw sludge. This is because of the dilution water that should be added to make sludge appropriate for the anaerobic digestion, which generally requires 8% of solid content with 35℃ for mesophilic digestion. As the diluting water controls the temperature as well as the solid content, the heat that can be exchanged is also governed by the change in the solid content of the raw sludge. For example, for the higher solid content sludge, along with the less amount of steam for heating-up the sludge, more diluting water should be added to make the appropriate solid content of the sludge before the anaerobic digestion process. Therefore, the amount of heat available for preheating decreases due to the increased amount of cooling by the dilution water. As the Figure 11 shows, the temperature of the raw sludge after preheating decreases with a higher solid content in the sludge.

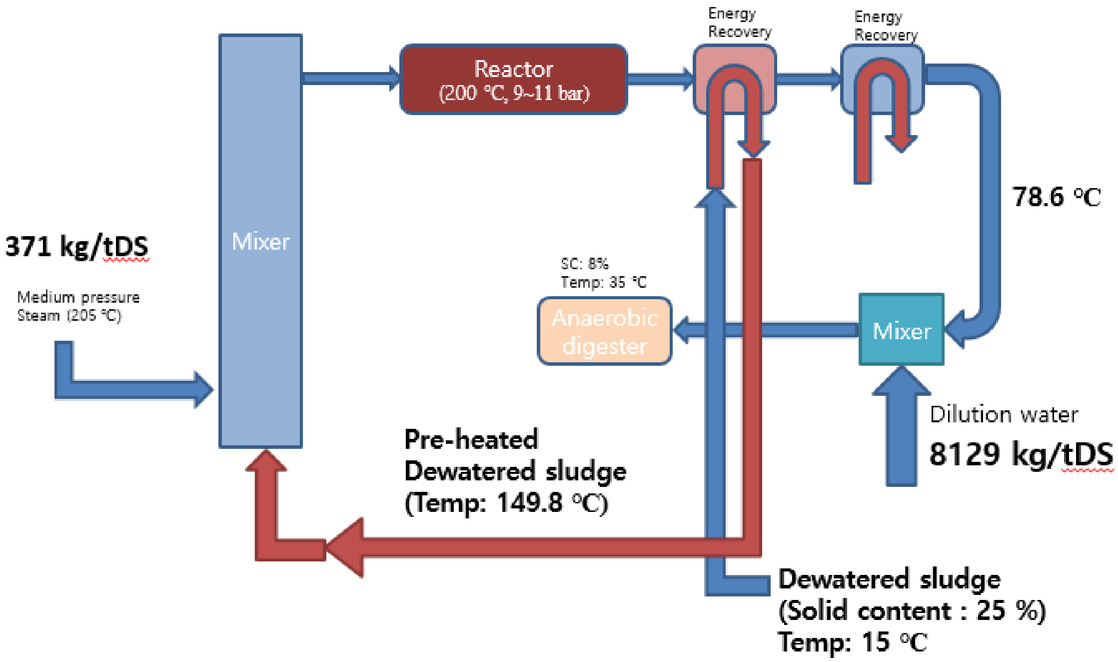

Figure 12. Process flowchart with heat integration

Figure 12 shows the optimized structure of the thermal hydrolysis process. In the optimized structure with the heat integration, it is possible to reduce the steam consumption to 0.371 kg/kg DS which is almost 30% of that without heat integration. However, one of the issue to be considered is that the facility that can endure the high pressure is needed to preheat the raw sludge into that high temperature. In addition, sludge cooking in the heat exchanger due to the high preheating temperature, which might block the flow of sludge, can be another problem. Therefore, although heat integration between outlet and inlet for THP can reduce a significant amount of energy, it would have a limitation in the sense of applicability. Reasonable range of the sludge preheating with outlet stream would be around 80°C, which does not need a high pressure in the heat exchanger and can remove the concern about sludge cooking.

3.2.4 Multi-effect distillation unit for TDS (inorganic matters) treatment

Further treatment is required to remove dissolved solid in the wastewater to reuse the wastewater in the process because of scale formation prevention. For this purpose, Multi-Effect Distillation process is adopted for the industrial park. MED can utilize low-pressure steam or even hot water so that it is very useful for an industrial park to utilize low-grade surplus heat. Therefore, heat from CHP unit can be easily used for generating fresh water from MED. Even though there are detailed models for the MED, simple operational performance and parameters are used for the calculation in this analysis to reduce the complexity of the problem.

$$EOR = \frac{Desalted\ water(ton/day)}{Steam\ used(ton/day)}$$

The performance of MED is represented in the form of economy ratio (EOR). Typically, EOR of MED plant using a low-grade steam (~70°C, 0.35atm) is around 8~12 for the seawater desalination. Thermal energy consumption in MED is found from the literature (Al-Karaghouli and Kazmerski 2013) to calculate the amount of steam for the MED. By using this information with the steam information (enthalpy) from the total site analysis, it is possible to calculate the steam consumption and EOR with a certain level of steam. For the cost of MED treatment, water desalination of seawater (35,000 – 40,000 ppm TDS in feed) treatment cost estimation (Ulrich and Vasudevan 2006) is used. This function uses Cost Index (CEPCI), and fuel price as input variables. This cost can be changed with the different level of steam and pollutant concentration, so detailed model can be used in future work to improve the accuracy. However, the focus of this research is analyzing the potential of biological treatment system within the eco-industrial park under carbon tax era, so this level of the model is sufficient.

$$C_{S,u} = a(CE\ PCI) + b(C_{S,f})$$

$C_{S,u}$: $the\ price\ of\ the\ utility$

$C_{S,f} = price\ of\ fuel\ in\ \$/GJ$

$CEPCI$: $Inflation\ parameter\ in\ US\ (Dec.2016)$

$a = 0.0015 + 6.0\times10^{-5}q^{-0.6}, where\ q(m/s)\ is\ flow\ rate$

$b = 0.13$

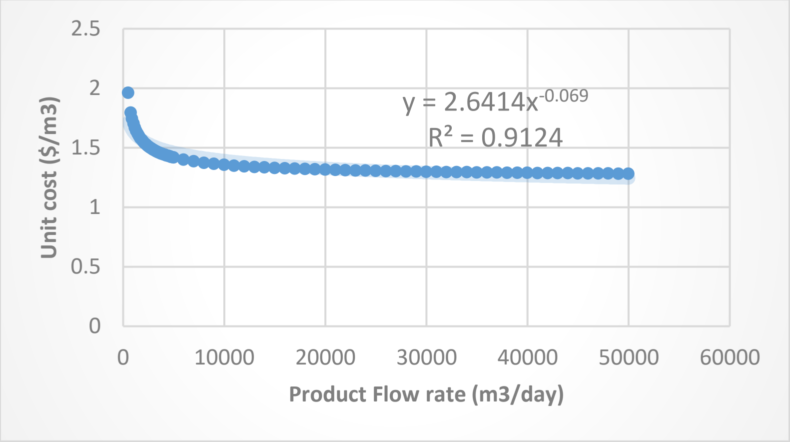

Figure 13. Multi-effect distillation unit cost (CE PCI: 550, $C_{s,f} = 3.167$)

4. RESULTS

4.1. Analysis of Wastewater and Sludge Treatment Block

4.1.1 Base case steam cost

Before analyzing the THP within EIP, THP without being integrated into EIP is analyzed first. For this analysis, the price of steam was calculated by the typical utility cost estimation method from literature (Ulrich and Vasudevan 2006).

$$C_u(\frac{\$}{kg}) = (2.7\times10^{-5}m_s^{-0.9})(CEPCI) + (0.0034p^{0.05})(C_{s,f})$$

By using this equation, the unit cost of 12bar steam is estimated around 0.010 ~ 0.017 (\$/kg). In the first analysis, the unit steam cost is set to be 0.010 (\$/kg), assuming the capacity of the steam generation is large enough to make analysis simpler. This price can be higher in the small scale wastewater treatment system that needs only a small amount of steam for THP.

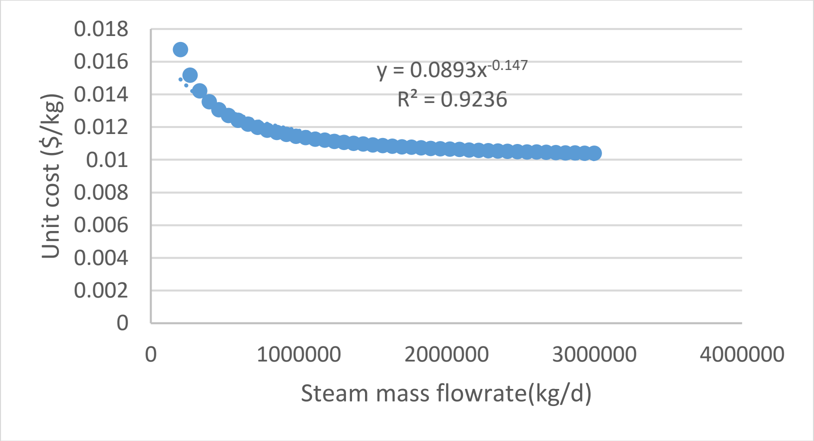

Figure 14. Base case steam cost estimation

4.1.2 Conventional secondary treatment without thermal hydrolysis process (THP)

In order to estimate the impact of THP on the economy of the biological wastewater treatment system, simple steady state model of biological treatment including grit chamber, primary settler, secondary treatment (aeration basin & secondary settler) was built according to the operating and design parameter in the Appendix. A process diagram for the conventional biological wastewater treatment is represented as below. The model for the biological treatment of wastewater and sludge treatment system was formulated through the mass balance and cost estimation by using parameters and cost functions in the Appendix. The cost function is mainly adopted from the (Sharma 2010) and partly modified to linear form to reduce the solving time and feasibility of the problem in the complex integrated structure. The linearization of the cost function can be justified by the module-base installation of the equipment for large-scale wastewater facilities. Design variables are found from the design book (Metcalf & Eddy Boston., 1991) as a typical value of successfully operating units.

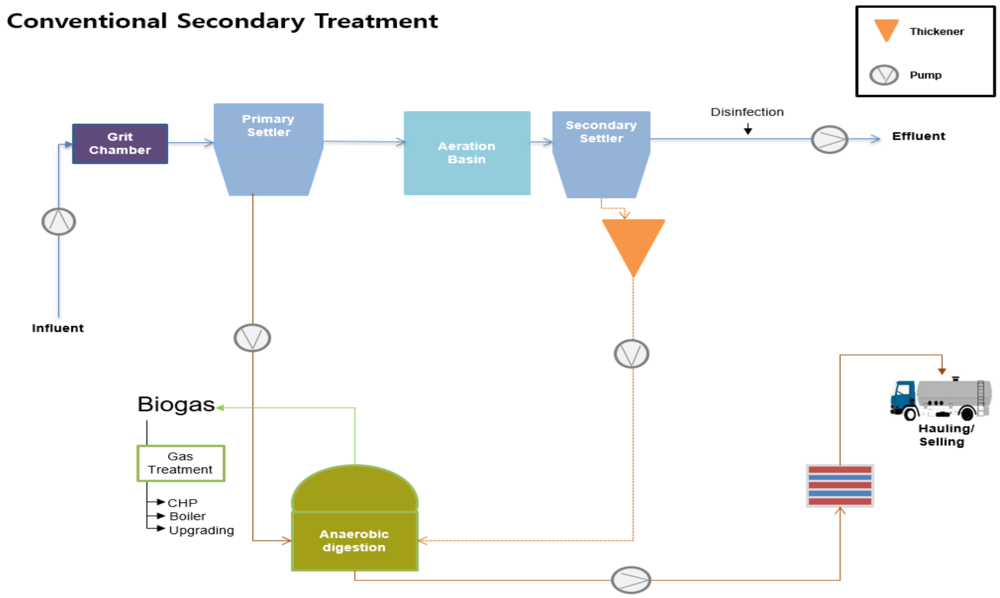

Figure 15. Process flow diagram for conventional biological treatment system

Mass balance in Figure 16 shows a typical value and characteristic of sludge at each step in the sludge treatment section of the conventional system. 50,000 m^3/day capacity with 300g/m^3 pollutant (TSS, BOD) was used for mass balance calculation. When the concentration of TSS and BOD are similar, the mass from primary sludge is greater than that from activated sludge. This demonstrates that it needs more energy to treat primary sludge in THP, which has lower improvement in biogas yield due to the higher initial biodegradability in general. As activated sludge has a significant portion of water in it, thickening step is needed before putting into an anaerobic digester to reduce the capital investment in AD. In AD, biogas is generated from organic material in the sludge, and the final sludge is dewatered before being hauled by truck from landfill tipping contractor.

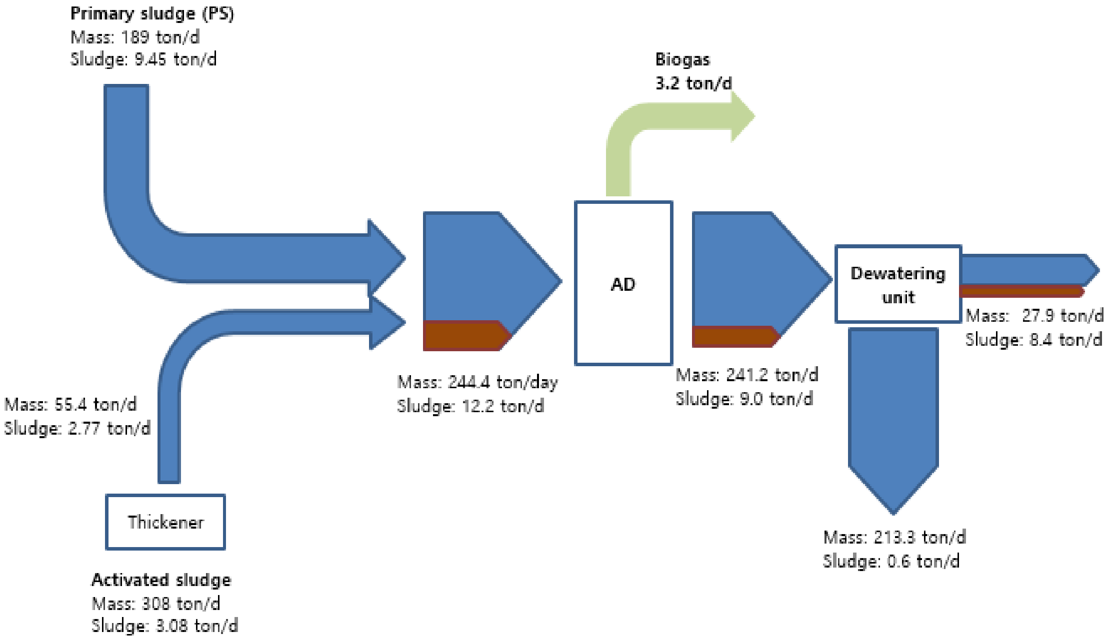

Figure 16. Mass balance in the conventional system

The cost allocation of the conventional system shows that major components of the total annualized cost include hauling cost (19.5%), the capital cost of the anaerobic digester (12.6%), and operating cost of aeration basin (9.8%). The high operating cost for the aeration basin is caused by the high energy consumption for the aeration and mixing system in it. The Large capital cost of the anaerobic digester is due to the large volume of the sludge, which controls the design value (solid retention time) of the anaerobic digester. The important point is that hauling cost accounts for one of the major cost of the biological wastewater treatment system due to the large volume of the sludge and high cost to transport, which confirms the motivation of this study.

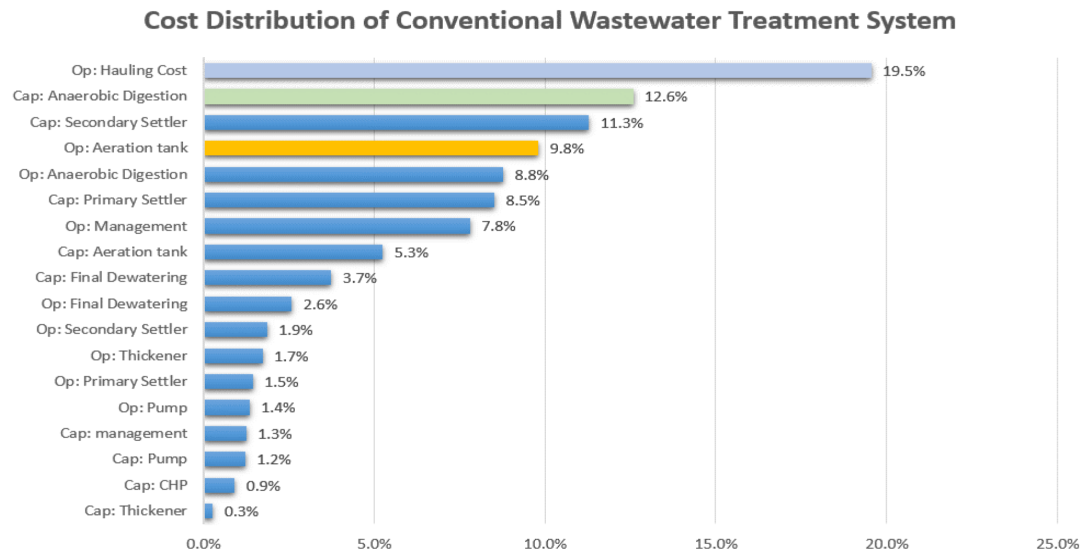

Figure 17. Cost allocation in the conventional system

The unit cost of the biological treatment is decreasing as the wastewater load increases because of the economy of scale. In addition, a high concentration of pollutants in the wastewater significantly affects the unit treatment cost because of the additional cost for the treatment system equipment to handle the large solid load. The portion of the hauling cost in the total annualized cost is increasing as the wastewater load increases because of increasing volume of sludge that should be transported to the landfill site at a certain price in the contract. This shows that there is a great potential of reducing total cost by lowering the hauling cost in the large-scale wastewater treatment facility that has a high solid content.

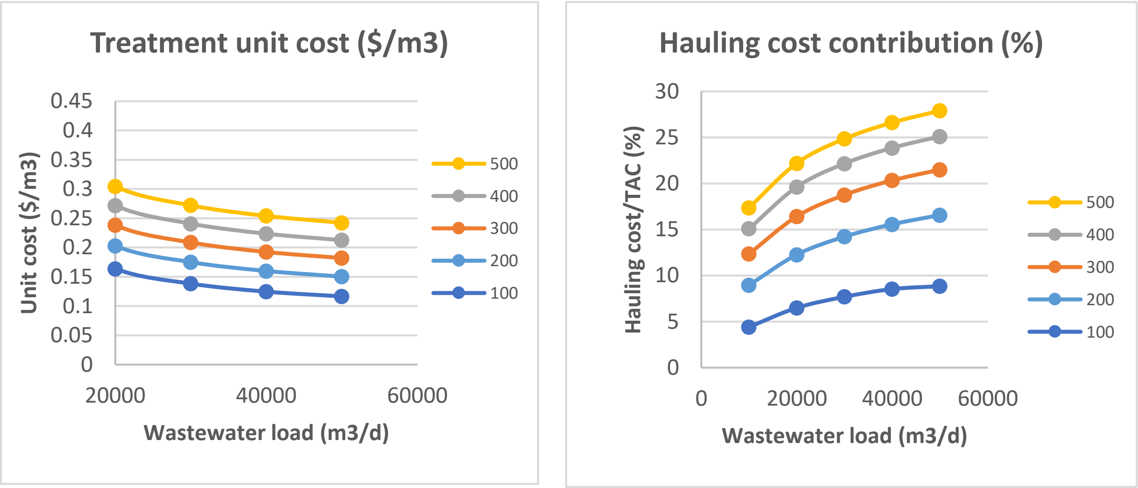

Figure 18. Left: Treatment unit cost according to the capacity and pollutant content, Right: Hauling cost portion in the cost allocation

4.1.3 Secondary treatment system with thermal hydrolysis process

For the wastewater treatment facility with THP, the system is slightly different from the conventional system. The process flow diagram is represented as below. Instead of thickening which can achieve only 5% of solid content of the sludge, dewatering units that can make the solid content more than 20% are needed before the THP unit. The reason of dewatering is that solid content of the sludge is directly linked to the steam requirement for the sludge heating. After the pre-treatment in THP with steam, backup water is supplied to adjust the temperature and solid content of the sludge before AD. In this step, heat from outlet stream can be exchanged with the raw sludge that should be heated, and a considerable amount of heat energy can be saved by this.

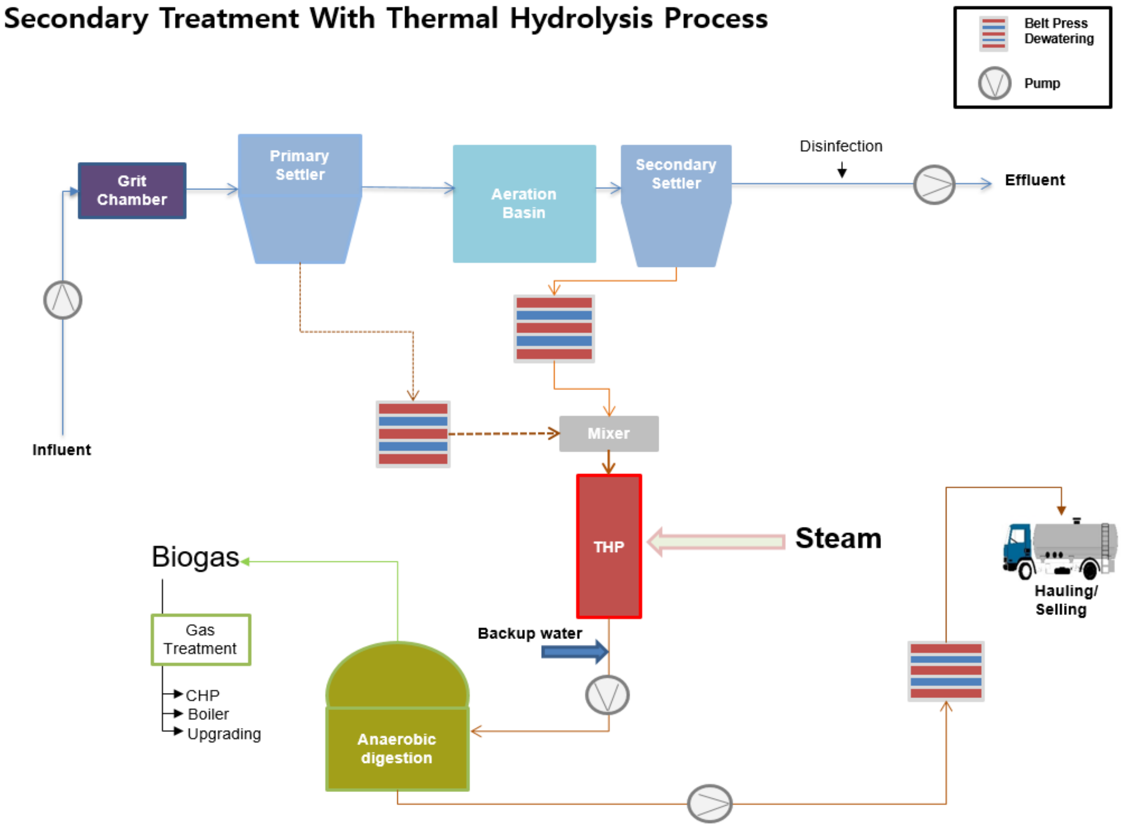

Figure 19. Process flow diagram of the system with THP

The mass balance for the system with THP has some changes compared to the conventional system. First, the mass into the AD decreases almost half due to the dewatering step. With this step, it is possible to reduce steam consumption significantly. The correlation with the solid content of the inlet sludge to THP and steam requirement is shown in Figure 20 to demonstrate the impact of the dewatering performance before THP unit. As the objective in THP is heating up the sludge to decompose it to shorter molecules, the heating requirement for water in the sludge should be minimized. Therefore, the high solid content of sludge should be made before THP unit to reduce heat requirement for sludge heating. As shown in Figure 20, the steam requirement for heating the sludge depending on the operating temperature and solid content of the sludge. The supply steam is assumed to be 205 °C at the saturated condition, which can make the highest operating condition (200 °C) of interest in this analysis.

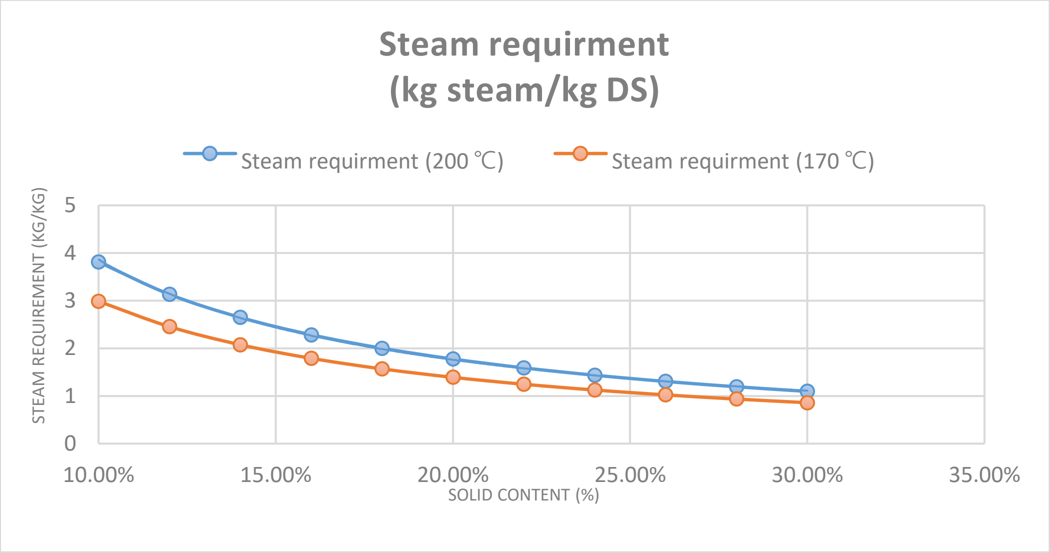

Figure 20. Steam requirement for THP

In addition, with THP, biogas production can be increased by 39.4% with THP due to the improvement in biodegradability of sludge. Finally, the mass of the sludge that should be disposed decreases by almost half, resulting in a significant saving in the hauling cost as well. It is achieved by the improvement in the dewaterability of the sludge during the THP step causing the destruction of the gel structure capturing water inside. The decrease in hauling volume and a shorter distance for hauling due to the non-pathogenic characteristic of the treated sludge can contribute to the reduction of GHG emission during the transportation so that the sustainability of the wastewater treatment facility can be improved.

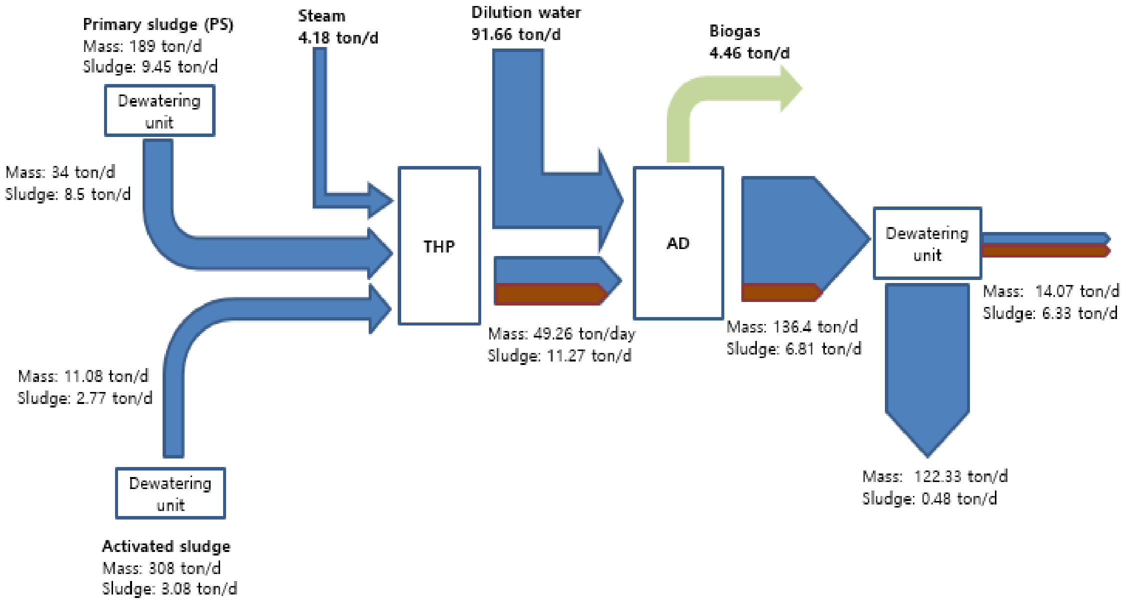

Figure 21. Mass balance of the system with THP

This impact of THP can be demonstrated in the cost allocation graph as well. The portion of hauling cost in the total annualized cost decreases significantly compared to the conventional structure because of the decreased volume of the final sludge. In addition, the capital cost of the anaerobic digester decreases because of the high solid loading rate with THP. This improvement on the solid loading rate in the anaerobic digestion is achieved by thermal decomposition of the compound matrix structure to smaller molecules, which is called hydrolysis, in THP. As the rate-determining step of the anaerobic digestion is the hydrolysis reaction, the reaction rate of the anaerobic digestion can be significantly improved with the thermal pre-treatment before AD. Through this, required retention time of the sludge in AD can be reduced by more than half, and it enables the small volume of the anaerobic digester to stabilize the sludge or recover enough amount of biogas from it.

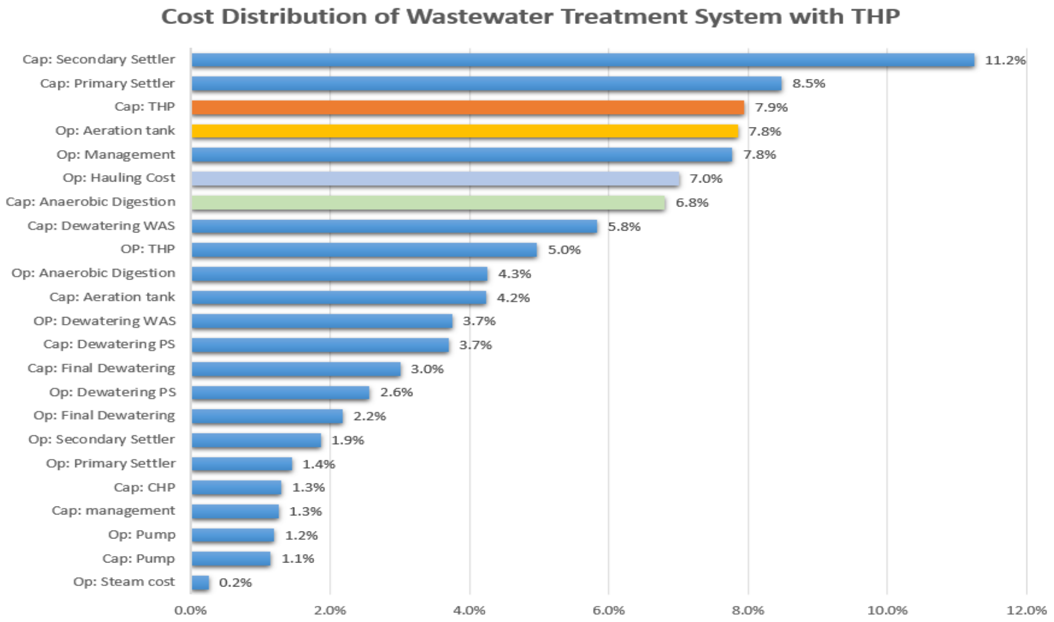

Figure 22. Cost allocation of the system with THP

With this model, the change in the total annualized cost by having THP in the system is analyzed to see the economic advantage of THP in the various capacities of wastewater treatment plant. From the result, it is found that economic benefit from THP compared to the conventional treatment system can be achieved in the wastewater treatment systems having approximately above 300 g/m^3 of pollutant (BOD,TSS) in the 30,000 m^3/day wastewater load. However, for small capacity of the wastewater system, it is almost impossible to gain benefit from THP as shown in the graph for 10,000 m^3/d. In addition, the higher the pollutant concentration and the wastewater load, the more economic benefit is expected with THP. When the capacity of the wastewater plant is 50,000 m^3/day and 500 g/m^3 pollutant, almost 7% of TAC can be saved compared to the conventional system due to the high reduction in the hauling cost and the capital cost for the anaerobic digester. This result shows that THP is sensitive to the economy of scale, and it is adequate to be used with the wastewater treatment facilities having a large enough capacity and high enough pollutant (SS, BOD) content. In this analysis, the opportunity for selling treated sludge was ignored. Therefore, if there are consumers to sell the treated sludge as fertilizer or feedstock, the cost reduction with THP can be improved further.

Figure 23. Total annualized cost reduction with THP

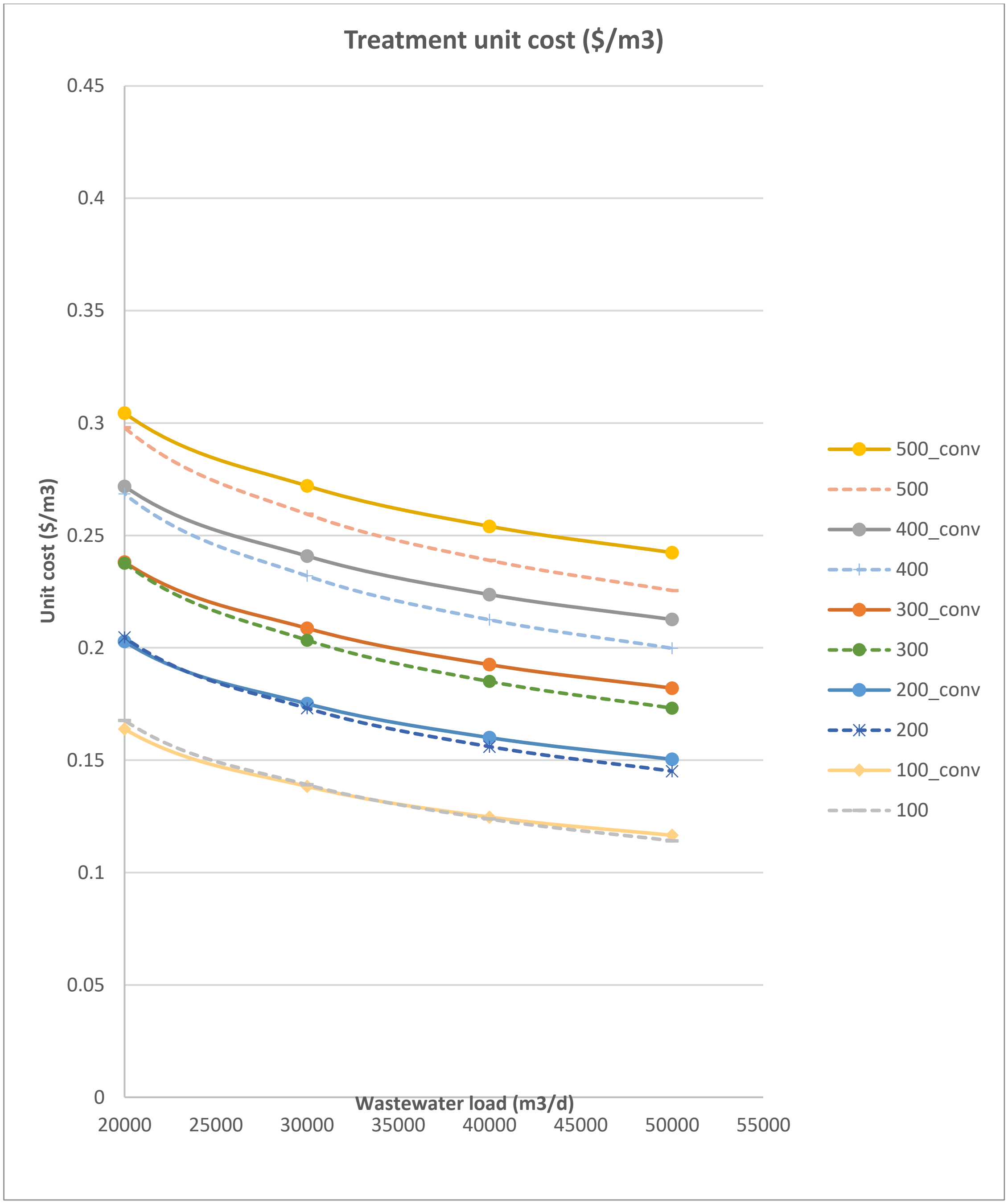

Figure 24. Treatment unit cost of biological treatment with/without THP

4.1.4 Impact of carbon tax on the wastewater treatment unit

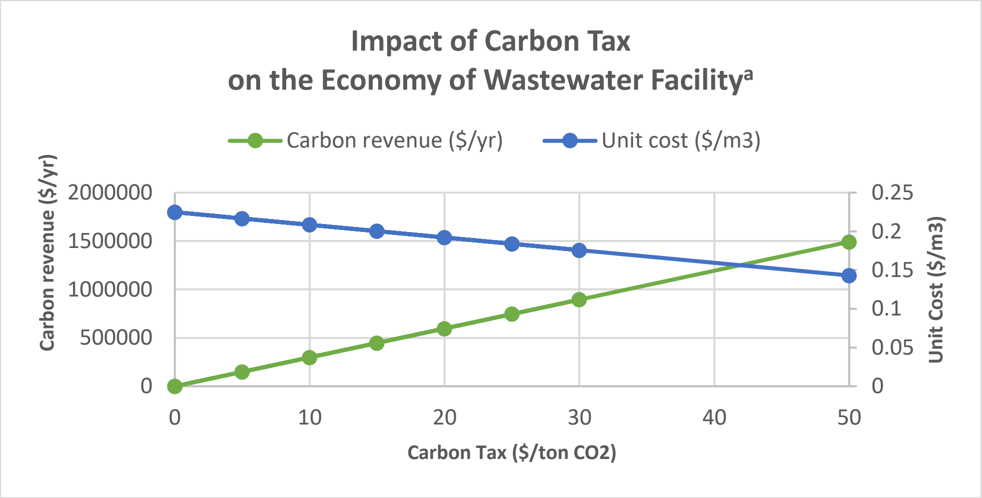

Figure 25. Impact of carbon tax on the economy of wastewater facility

As previously stated, one of the justifications of THP with AD is the reduction of GHG emission from biogas recovery by using the sludge. As the Global Warming Potential (GWP) of methane, which is the major component of biogas, is 25 times higher than that of CO_2, a substantial amount of carbon credit can be obtained with the biogas recovery if the carbon credit is based on the GWP. Therefore, the price of carbon credit or tax has a significant impact on the economy of wastewater treatment plant with biogas recovery, and this can open a new opportunity for sludge treatment facility to be a source of revenue. In this sense, THP can serve as a technology to raise the carbon credit generation within the EIP because we can improve the biogas yield from the sludge with THP. Furthermore, this can promote more wastewater treatment to reuse water due to the economic advantage of it from the carbon credit, enhancing the sustainability of the industrial cluster.

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[a] This graph is from the calculation with the 50,000 m^3/day capacity and 500 g/m^3 TSS and BOD concentration.

As the Figure 25 shows, a carbon tax can be an important revenue source for the wastewater treatment facility and can reduce the unit cost of the treatment up to 36% compared to the base case ($\$0.233/m^3$ to $\$0.147/m^3$) if the carbon tax is \$50/ton CO_2. This specific value can change for the different concentration of a pollutant in the wastewater because the biogas production depends heavily on the sludge production from the wastewater. The wastewater treatment facility generating a large volume of the sludge can have more benefit from the carbon credit, so it will provoke more water reuse in the water-intensive industry because they can take advantage from the large capacity of the wastewater treatment system.

4.2 Feasibility Analysis of Combined Wastewater Treatment Plant as a Sustainable Center with THP

With THP, it is possible to improve the biogas yield in the anaerobic digestion and reduce the final volume of the sludge significantly. Also, this sludge can be used for an application such as fertilizer or feedstock for biodiesel production so that we can generate profit from it. In addition to this, from the economic analysis of THP in various capacities of the wastewater plant, the economy of scale plays a major role in the economic feasibility of THP; The amount of sludge from the internal wastewater treatment is limited, so does the benefit from the THP. This implies, in turn, if the capacity of the wastewater treatment facility is large enough, the benefit from THP can be maximized by enlarging the capacity of the sludge (bio-waste) treatment system. In other words, the economy of scale from the large wastewater load and sludge treatment system can be utilized as a tool to leverage its revenue from waste treatment by enlarging its capacity with outer bio-waste. This shows the possibility of the scenario where combined wastewater treatment facility collects bio-waste from outside with the certain amount of tipping fee and treat it to generate biogas or monetized sludge. This strategy can be valuable because it can enhance the sustainability of the biological wastewater treatment system as well as of the adjacent communities by reducing the carbon emission and environmental impact from the bio-waste.

Therefore, to investigate the feasibility of this strategy, tipping fee required to treat outer bio-waste in the sludge treatment facility of the wastewater treatment plant is calculated as a criterion that determines the feasibility of this business. If tipping fee required is too higher than the general range of landfill tipping fee, no bio-waste sources would want to treat their waste through this option. Therefore, tipping fee required should be competitive to the tipping fee for the landfill dumping.

For the calculation of tipping fee, several assumptions are made. Maximum volume of outer bio-waste was set as 20% of the internal sludge production from wastewater treatment unit in order to see the marginal change from its own capacity and to consider the possibility that the availability of bio-waste is limited. Additionally, although there are numerous different kinds of bio-waste, the characteristic of outer bio-waste was assumed to be same as that of the activated sludge from the wastewater treatment facility. Since the property of the sludge is an important factor for the amount of biogas generated, tipping fee can change with different sludge characteristics. This will be discussed in the sensitivity analysis in the next part.

4.2.1 Calculation of the tipping fee through big-M method

Step 1) Benchmarking

Min (TAC)

Step 2) Tipping fee calculation

Min $(\mathrm{TAC}_{\text{with outer bio-waste}} + M(Price_{BS} - Price_{BS}^{0}))$

constraint 1: $\mathrm{TAC}_0 \geq TAC_{with\ outer\ bio-waste}$

constraint 2: $\mathrm{Price}_{\mathrm{BS}} \geq Price_{BS}^{0}$

constraint 3: $\mathrm{Volume}_{\mathrm{OB}} \leq 0.2(Volume_{PS} + Volume_{WAS})$

Two-step optimization problem was formulated to calculate the tipping fee for the outer bio-waste. First, the wastewater treatment system with a certain capacity and pollutant content is optimized to minimize the total annualized cost (TAC), and the optimum value is used as a benchmark cost. In the second step, modifying the objective function and imposing additional constraints are conducted to get better or same TAC with outer bio-waste with minimum tipping fee.

In the second phase, the objective function is changed to utilize 'Big M method' to penalize the unlimited increase of the tipping fee and find minimum tipping fee for a better solution with outer bio-waste. The first additional constraint is to ensure better solution (less than benchmark TAC value). The second additional constraint is to utilize the big-M method. $\mathrm{Price}_{\mathrm{BS}}^{0}$ is introduced to make the big-M method work well because the performance of this approach depends on the selection of numerical scale of the first part (TAC) and the second part (big-M) of the objective function. With this method, the minimum tipping fee that can improve the solution can be obtained for different scales of wastewater treatment facilities.

4.2.2 Tipping fee result

The result of tipping fee calculation shows that it is possible to treat the outer bio-waste in a reasonable tipping fee which is around \$30~62/wet ton. Considering that typical contract price for the sludge hauling to landfill site is around \$50~100/wet ton, it is in the feasible region. One of the potential issues is the transportation cost, which can increase significantly depending on the location of the bio-waste source and wastewater treatment facility. This result also shows that the capacity of wastewater treatment facility and pollutant content in it are important factors for the tipping fee. Even if the pollutant content of wastewater is same, tipping fee for outer bio-waste has \$11 ~\$19/wet ton difference depending on the pollutant concentration. This confirms the previous postulation that large wastewater treatment facility can have more advantage by using its economy of scale in the waste treatment. In addition, the degree of advantage with increasing capacity can be assessed, which gave a valuable insight to investigate opportunity in this strategy.

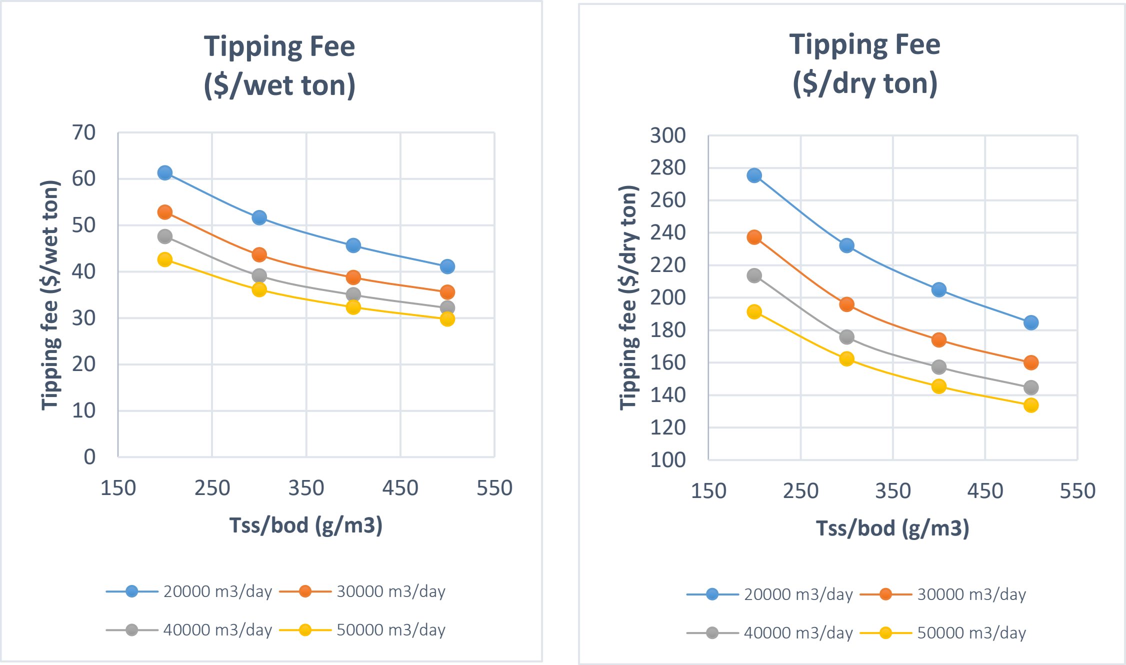

Figure 26. Minimum tipping fee for outer bio-waste

4.2.3 The impact of the carbon credit on the tipping fee

The reduction of GHG emission with outer bio-waste is significant potential revenue source due to the carbon tax. Therefore, analyzing the impact of carbon tax on the tipping fee is important the potential of this strategy under the future scenario. Therefore, a carbon tax at $10/ton eCO$_2$ was assumed, and the tipping fee was estimated. Under this scenario, the tipping fee can be decreased by $10~12/wet ton. The impact of carbon credit can change with a different characteristic of bio-waste from outside because biogas generation is highly dependent on the biochemical property of the bio-waste. However, based on the substantial impact of the carbon tax on the tipping fee in this analysis, the potential of large-scale wastewater treatment system as a sustainable center will substantially increase under the carbon tax era.

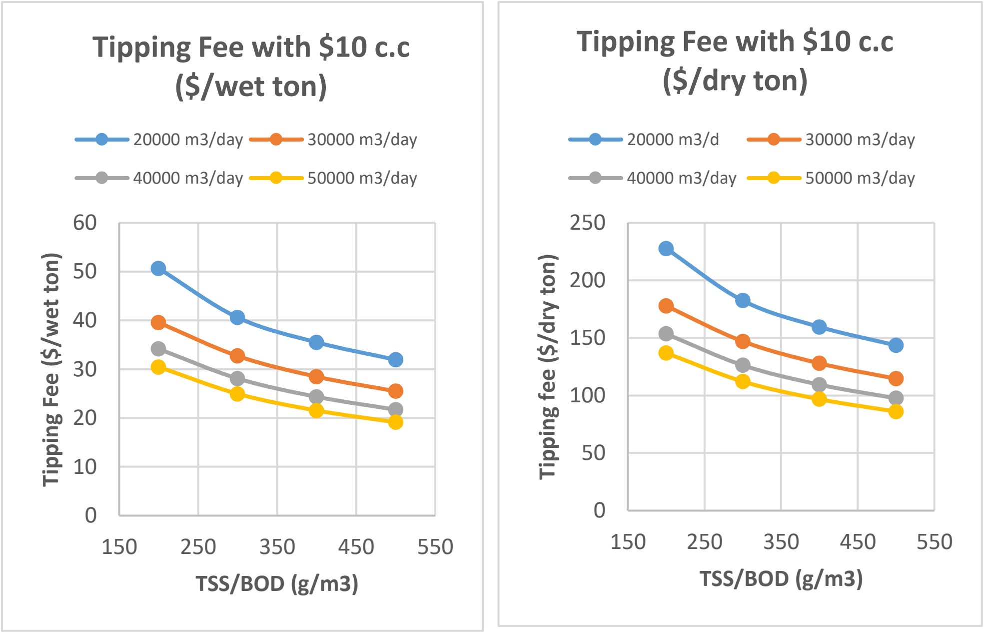

Figure 27. Minimum tipping fee for outer bio-waste with carbon tax ($10/ton CO_2)

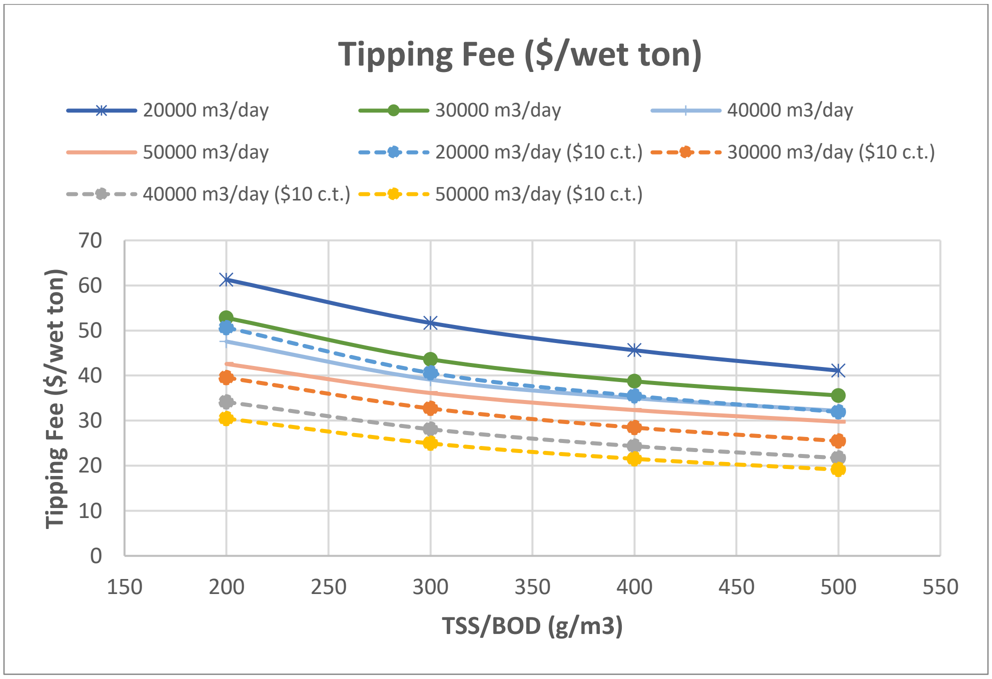

Figure 28. Minimum tipping fee with/without carbon tax

4.2.4 Sensitivity analysis of bio-waste characteristics

4.2.4.1 Chemical characteristics (initial biodegradability, bio-methane potential)

As the economy of the anaerobic digester is highly dependent on the amount of the biogas generated, the biochemical property of the sludge is critical and should be considered. In this analysis, sludge has mainly two variables: initial biodegradability and bio-methane potential. As we can see in the difference between primary sludge and activated sludge, if bio-waste has a higher initial biodegradability, it means less impact by the THP. Also, if the bio-methane potential is low, the increment in the biodegradability with THP cannot have sufficient effect on the economy of the anaerobic digestion.

When we can get bio-waste from outside with a tipping fee, it is more beneficial if the bio-waste has a high bio-methane potential with a moderately low initial biodegradability. If the initial biodegradability is too low, the biogas from the sludge can be very low even though the increment in biodegradability is high. Therefore, there is an optimal initial biodegradability of the bio-waste to be treated in THP. For the purpose of finding the best initial biodegradability and confirm the impact of sludge characteristic on the economy of this strategy, the sensitivity analysis of the initial biodegradability on the tipping fee was conducted. The maximum volume that can be gathered from outside was set as the same amount of the sludge from the wastewater treatment facility that has 50,000 m^3/day capacity and 300 g/m^3 pollutant (TSS, BOD) concentration.

By optimizing the wastewater treatment system with THP, the best initial biodegradability was found to be 0.4 in 200 °C of THP operating temperature as shown in Figure *29.* below. The optimal initial biodegradability can be changed if we change the operating temperature of the THP. When we have a low operating temperature, it is more economical to have a more biodegradable bio-waste because the increment is not as large as that in the high operating temperature.

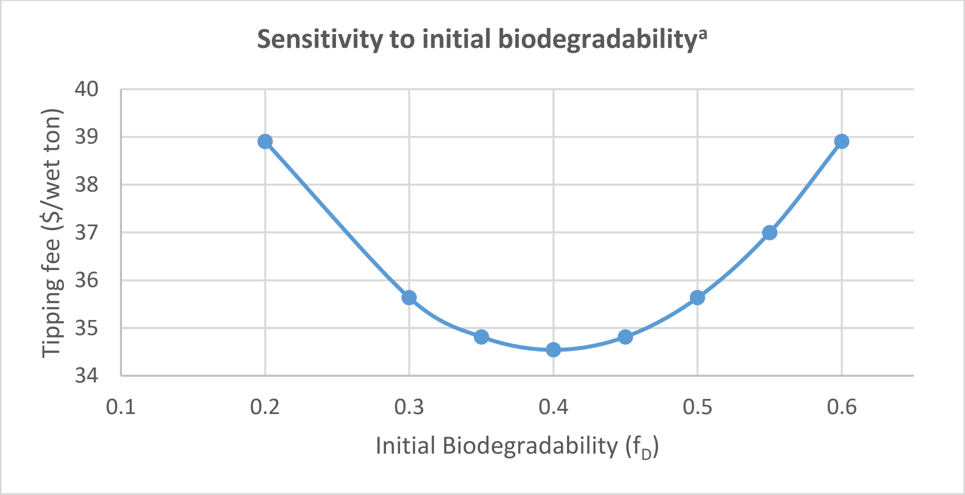

Figure 29. Sensitivity of initial biodegradability on the minimum tipping fee

In addition to the initial biodegradability, bio-methane potential, which is set by the chemical composition of the sludge, is important to find the best sludge to treat with the thermal hydrolysis process. Several sludges with different chemical compositions were used for the calculation of the tipping fee to analyze the impact of the biomethane potential on the economy of the structure. The result from this analysis shows that if the bio-methane potential is high, it is more attractive to treat with thermal hydrolysis process and the impact of THP is greater for the sludge with low biodegradability and high bio-methane potential.

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[a] Using the same chemical composition as the model activated sludge in 50,000 m^3/day wastewater and 300 g/m^3 pollutant concentration

Sludge Characteristics from different industries					
	Paper bleaching	**Chemical**	**Petro chemical**	**Automobile**	**Food processing**
C	12.6	8.9	15.3	9.3	15.5
H	21.9	113.7	7.2	19.2	20.3
O	14.7	33.7	7	5.5	8.7
N	1	1	1	1	1
Biomethane Potential (L/g VS)	0.2646	0.2855	0.4543	0.5100	0.4821

Table 5. Sludge characteristic from different industries (Mahanty et al. 2014)

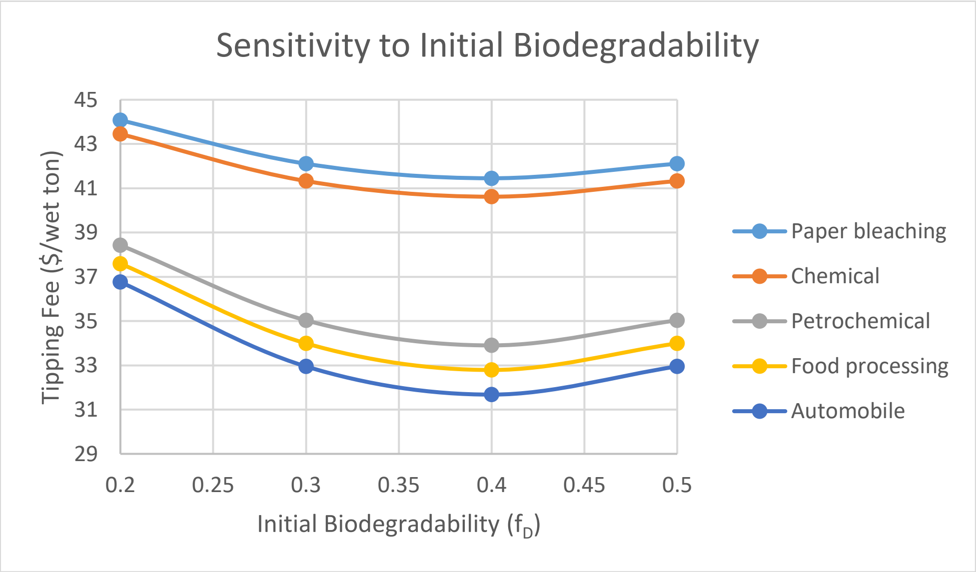

Figure 30. Sensitivity analysis of initial biodegradability on the minimum tipping fee

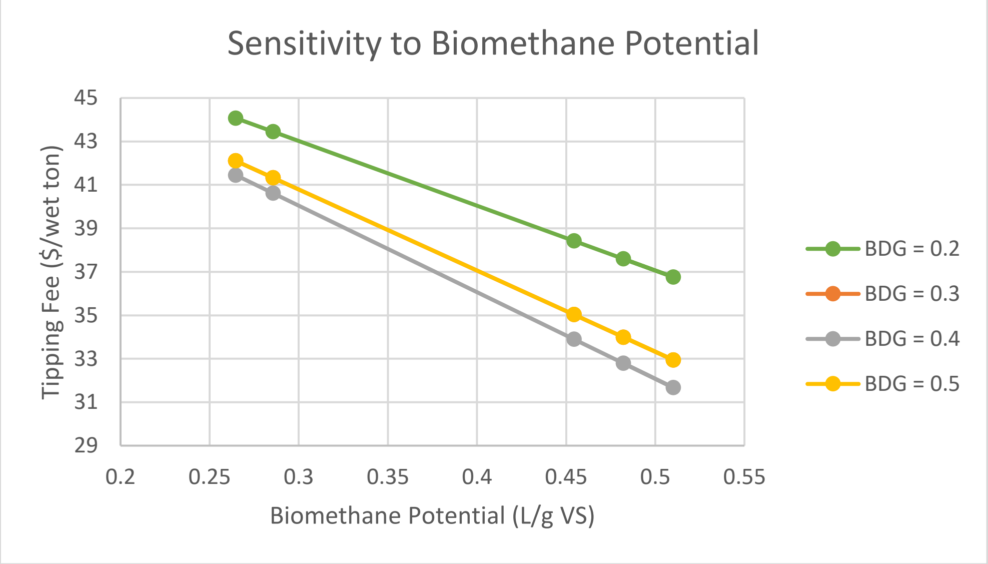

Figure 31. Sensitivity analysis of bio-methane potential on the minimum tipping fee

From the sensitivity analysis of the two most important biochemical properties of the sludge, the difference in the tipping fee according to them was estimated to be around $5/wet ton. Also, from the literature (Labatut, Angenent, and Scott 2011), some of the biomass that can be promising candidates for the treatment in the wastewater plant with THP unit were found. As the best biodegradability of the biomass is around 0.4, the promising candidates for the treatment will be manure, manure having a certain mixing ratio with food waste, and FOG (fat, oil, and grease). For the manure, high cost along with difficulties in the efficient use of methane from on-site anaerobic digestion makes it less attractive for farmers to install digester in their farm individually. This suggests the promising potential of the centralized waste treatment system with the wastewater treatment facility, which can have the infrastructure to deal with biogas generation from the waste.

Biomass Type	Manure ratio	Biomethane potential	Biodegradability
Manure	-	242.7	0.55
Manure+Meat pasta	75.00%	285.6	0.48
Manure+Plain paste	90.00%	224	0.48
Settled FOG	-	413.4	0.46
Manure+Cola	75.00%	235	0.46
Manure+Whey	90.00%	237.6	0.45
Suspended FOG	-	402.3	0.44
Plain paste	-	326.1	0.41
Manure+Whey	75.00%	252.4	0.41
Manure+Switchgrass	75.00%	207.8	0.41
Manure+Meat pasta	90.00%	232.1	0.39
Meat pasta	-	216.2	0.37

Table 6. Biomass biomethane potential and biodegradability (Labatut, Angenent, and Scott 2011)

4.2.4.2 Physical characteristics (solid content)

In addition to the chemical property of the sludge, physical property (density, solid content, etc.) might affect the minimum tipping fee. Among the many variables, solid content is one of the main concerns when we consider the bio-waste to treat because of the transportation cost, additional heating requirement, and increased expenses for solid treatment. Therefore, sensitivity analysis of the solid content of the bio-waste was conducted by using the same biochemical property of the activated sludge. In this analysis, Figure 32 shows that if the solid content of the sludge is higher, tipping fee for wet sludge should be higher. It is because even though transportation cost is higher for the low solid content sludge due to the high volume, the cost of sludge treatment is mainly governed by the amount of solid. Therefore, high solid content sludge should have higher tipping fee because of the higher additional treatment cost. This trend can change if we can sell the sludge after the treatment because we can gain profit from the solid content in the sludge with this option.

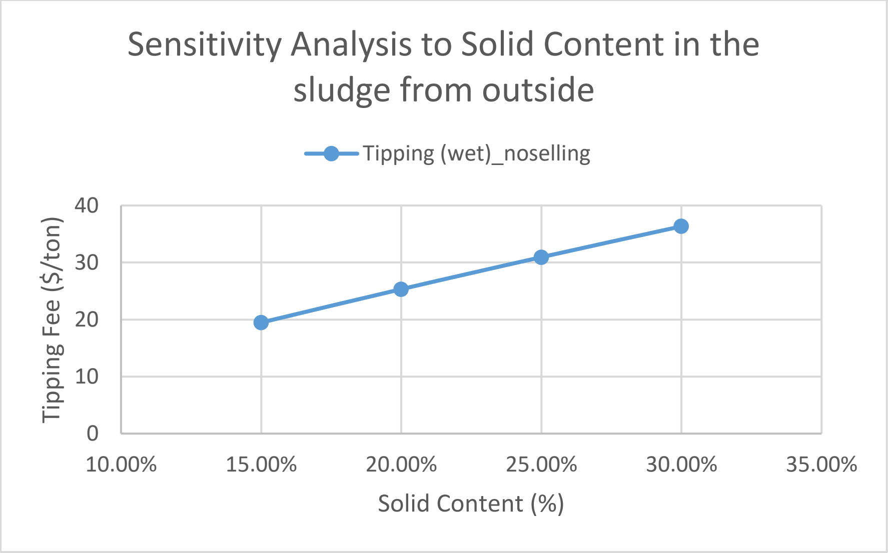

Figure 32. Sensitivity analysis of solid content on the minimum tipping fee

4.2.5 Sludge selling scenario

As stated in the previous part, sludge selling option is one of the key element that determines the feasibility of the transformation of combined wastewater facility into the sustainable center. Since it is possible to make 'Grade A' or 'EQ (Exceptional Quality) sludge with THP, treated sludge can be sold for various purposes including agricultural nutrient, site recovery, and feedstock for the renewable fuel production.

In the base scenario, the hauling cost of the sludge is set to $50/wet ton for grade A sludge and $70/wet ton for grade B sludge without THP. This reflects the preference by the contractor to grade A sludge due to the easiness to be used for other purposes such as agricultural usage while grade B sludge has restricted usage for that.

However, if we can sell grade A sludge at a certain price to the customer directly without having contractor between, it is possible to transform this hauling cost to revenue with the treated sludge. With this option, it is also possible to have less tipping fee for the sludge from outside. It is because of the additional revenue on the top of the revenue from biogas.

Therefore, to see the impact of sludge selling on the economy of the wastewater treatment facility, tipping fee for outside bio-waste was calculated with different selling prices. According to the calculation, we can reduce the tipping fee by half compared to the base case if we can sell the treated sludge at \$10/wet ton. It shows that the significant influence of the selling option when we consider the treatment of the outside bio-waste.

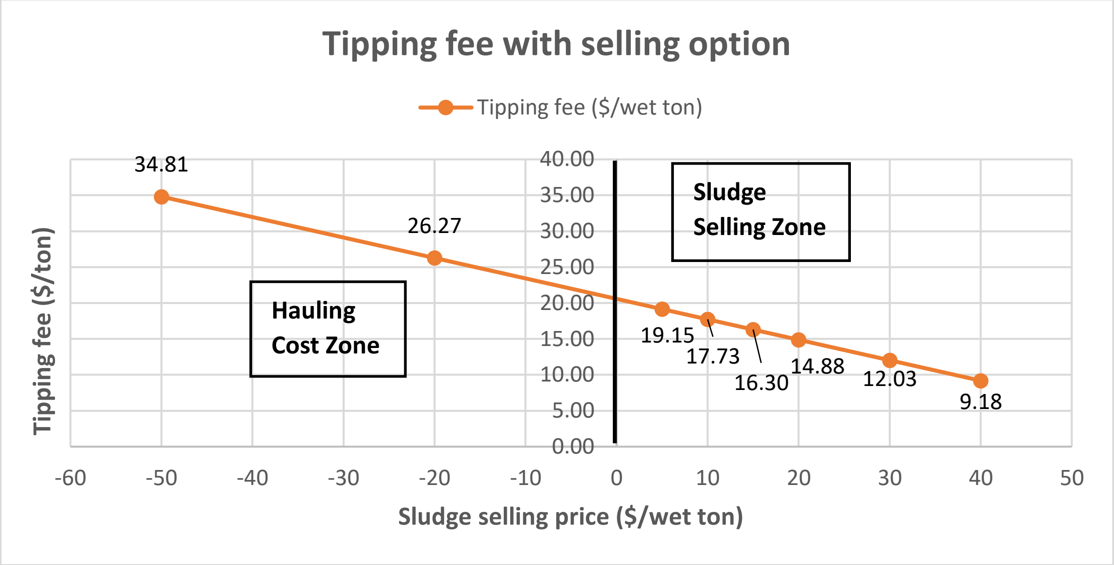

Figure 33. Impact of selling price on the minimum tipping fee

Furthermore, the relationship between sludge selling price and solid content of the bio-waste is investigated because the best bio-waste to collect from outside will change according to different scenarios. From this analysis, it was shown that treating a high-solid content biomass is more attractive than treating a low-solid biomass only if we can sell our treated sludge at a high price that is above a \$50/wet ton.

Therefore, if there is an opportunity to sell the treated sludge, it might be more profitable to have bio-waste with high solid content. With this analysis, it is possible to see the impact of sludge selling price on the strategy of deciding the best candidate for biogas generation with THP.

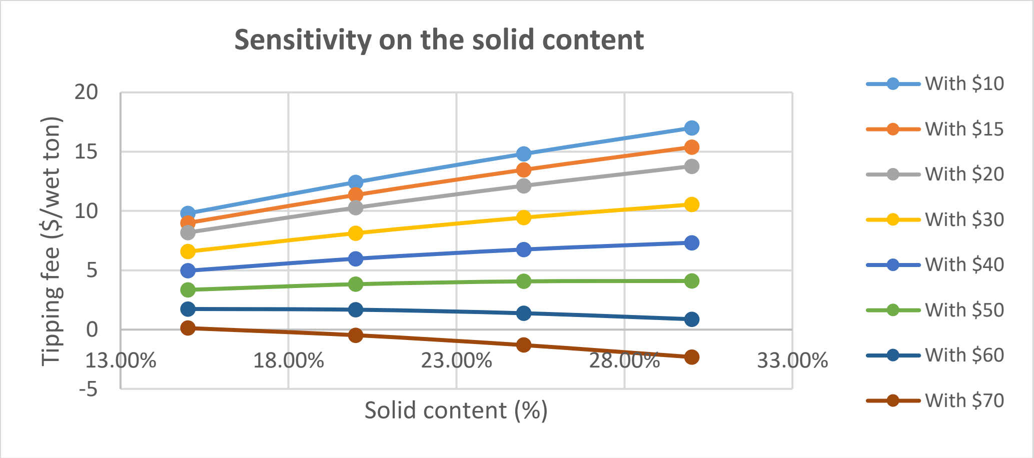

Figure 34. Sensitivity of sludge minimum tipping fee by sludge selling price

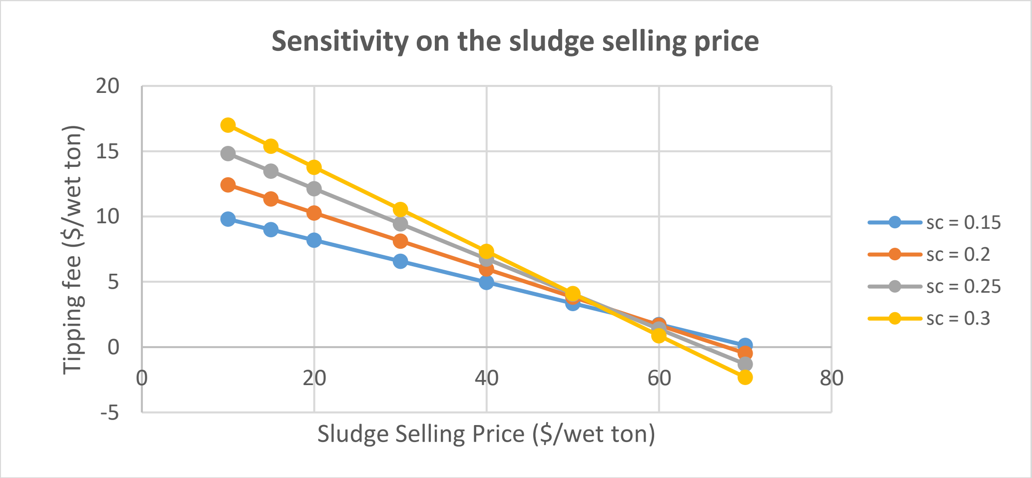

Figure 35. Sensitivity of sludge minimum tipping fee by solid content

4.3 Potential of EIP as a Sustainable Center

In EIP, one of the major interest is the water exchange network (WEN) that enables the optimal exchange and reuse of the wastewater from processes in order to minimize the cost and sustainability of the water network. The special feature of water network in EIP is centralized water interception network including treatment units, and this centralized structure enables to take advantage of the economy of scale in wastewater treatment to relieve the stress of high initial capital cost otherwise very costly for small-scale plants that need treatment. Along with this, as analyzed in the previous part, the economy of scale is also a crucial element for THP. By combining these two points, it is possible to infer that there should be some synergetic effects between THP and EIP due to their inherent characteristics. For example, the benefit of THP can be maximized with the optimal water exchange network of EIP that has centralized large scale treatment units. In the other way, EIP can enhance its sustainability by having measures to reduce waste treatment cost and even generate revenue from THP. In other words, centralized water treatment unit in EIP can be combined with large-scale waste treatment facility having THP to maximize the profit from it. With this strategy, EIP can be transformed into the sustainable center, enhancing the sustainability of EIP further.

For the purpose of analyzing the feasibility and potential of this option, a case study was conducted through the steps in the previous methodology part.

4.4 Case Study

In this case study, the impact of having THP unit within the water exchange network in EIP is investigated. The main interests are mainly four aspects.

1) Improvement of the economy of the water exchange network in eco-industrial park with THP
2) Reduction of GHG emission with THP and impact of carbon tax on the economy
3) Synergetic effect between EIP and THP and potential opportunity

The major difference from the previous analysis is that level and cost of the steam are set by the result from total site analysis (TSA). In addition, the concentration of pollutant and the wastewater load into the treatment units are optimized while considering the sludge treatment facility simultaneously. Furthermore, as it is possible to estimate the GHG emission reduction in the biological treatment system, we can understand the impact of the carbon tax on the integrated water exchange network as well. Therefore, the objective of this analysis is to investigate the impact of THP on EIP under optimized water exchange network in the various scenario where carbon credit, selling option or treating outside bio-waste option to enlarge capacity may exist.

In EIP, pulp & mill plants, chemical plant (Gas to Liquid), dyeing & finishing plants and washing plants are included. The selection criterion was the level of water-intensity and availability of surplus steam, which are crucial elements for this approach. Pulp & mill plants and dyeing & finishing plants use a lot of water and emit highly polluted water (high BOD and TSS) due to the characteristic of the industry. In addition, the chemical plant has a lot of surplus heat from the processes because of the high-temperature operating condition. This surplus heat can be used for steam generation that can be employed for the treatment of the sludge from wastewater treatment facility.

4.4.1 Total site analysis to select steam level and availability

4.4.1.1 Data extraction

For the data extraction of the heat source-sink, process stream of finishing & dyeing and washing plant are ignored. It is because although they are a high consumer of freshwater and emit highly polluted wastewater, they are not major players in the energy aspect compared to Kraft pulping process and GTL process. Heat source-sink data is in Appendix B.

4.4.1.2 Grand composite curve

By using the pinch analysis, grand composite curves were constructed to analyze utility requirement for each site. In GTL process, a very high load of cooling is observed in site 2, which is syngas conditioning process. For Kraft pulping process, a significant amount of heating requirement is observed. The primary heating duty is around medium pressure steam range (100~200 °C).

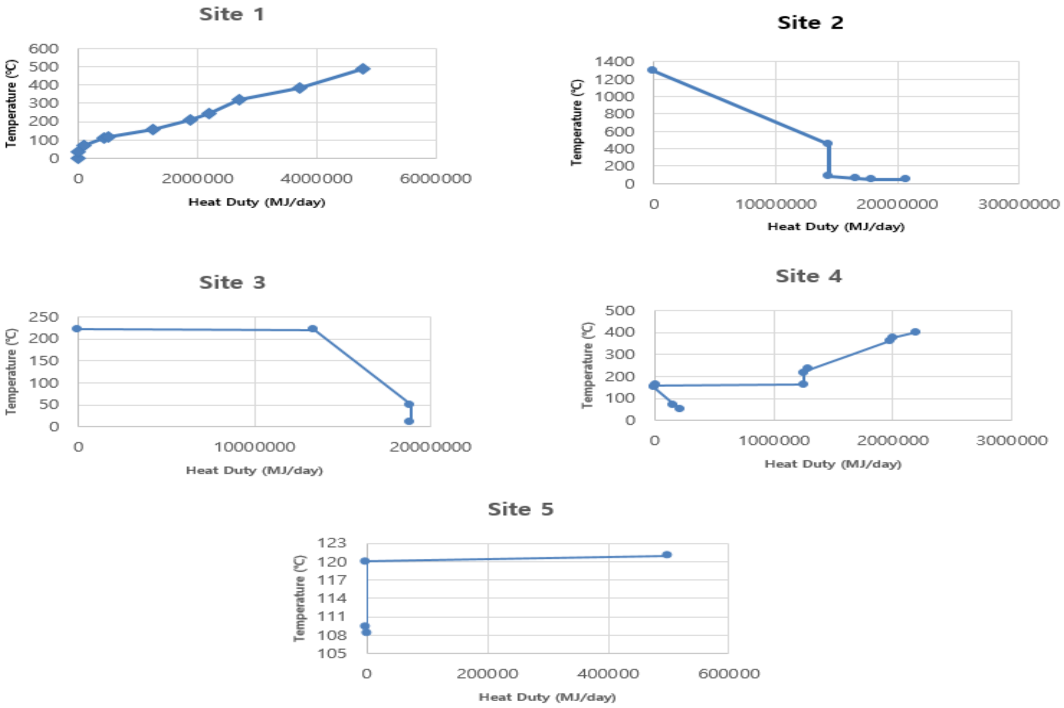

Figure 36. Grand composite curve of each site in GTL process

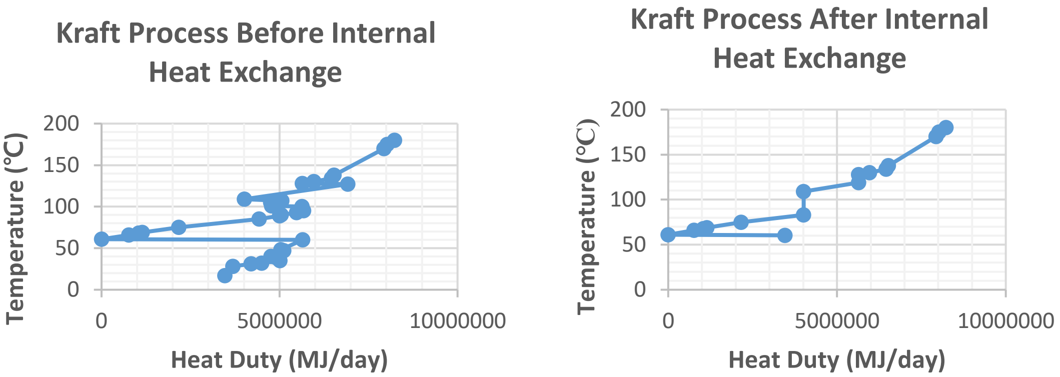

Figure 37. Grand composite curve of Kraft pulping process (Left: without internal heat exchange, Right: with internal heat exchange)

4.4.1.3 Total site profile

By using the grand composite curve for each site, total site profile was constructed. Total site profile is utilized for the steam level selection. There can be many methods to select optimum steam levels such as graphical method, or mathematical programming method. However, in this analysis, the steam level is selected by the heuristic method to simplify the procedure. However, this steam level selection procedure can be improved by the other methods such as mathematical programming, and to incorporate that algorithm in the integrated methodology can be one of the future work.

For selected steam level, steam generation potential and requirements are estimated. The heating requirement that needs the condition above robust steam distribution level is removed from the analysis and treated as a heating requirement. Its duty is estimated as 694.57 MWh/day. Also, heat sources that cannot be used for a steam generation due to the low temperature are treated with cooling water, and its duty is estimated as 3722.94 MWh/day. From this analysis, we can see that there is a lot of surplus heat in the industrial park. This surplus heat is converted to steam and used for THP and MED in water exchange network.

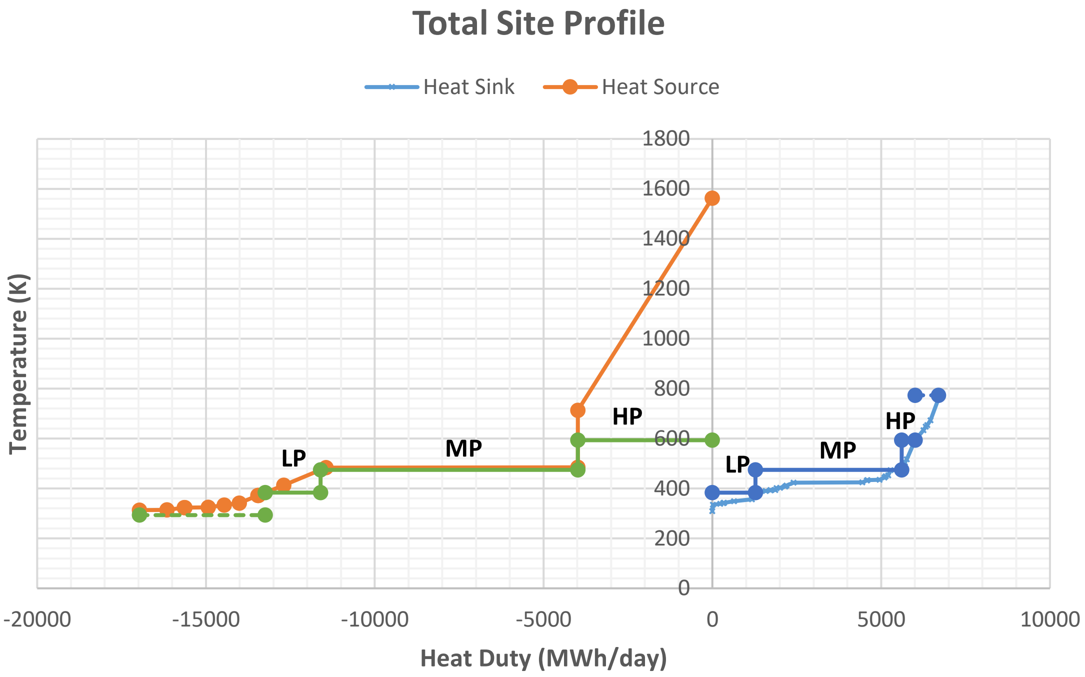

Figure 38. Total site profile of eco-industrial park

Steam Property & Availability					
Steam Type	Temp (K)	Pressure (bara)	Generated (MWh/day)	Required (MWh/day)	Net (MWh/day)
HP	593.15	108.85	3987.3	400.542089	3586.765811
MP	474.15	16.34	7613.7	4327.43477	3286.25621
LP	383.15	1.56	1644.4	1279.27623	365.16489
Heating	>700	-	-	694.57	-694.57
Cooling	293.15	-	3722.94	-	3722.94

Table 7. Steam profile from the total site profile

Cost of Steam		
HP	0.0104	$/kg
MP	0.00742	$/kg
LP	0.00389	$/kg

Table 8. Steam cost information based on the electricity potential

Source						Sink					
		Flowrate (m3/day)	BOD (g/m3)	TSS (g/m3)	TDS (g/m3)			Flowrate (m3/day)	BOD (g/m3)	TSS (g/m3)	TDS (g/m3)
Kraft process											
Washer filtrate (bleaching)	1	26000	439	500	2007	Recausticising	1	4550	50	50	500
White water (drying)	2	10400	40	50	200	Washing	2	11050	10	20	200
Condensate (evaporation)	3	9360	30	30	10	Bleaching	3	26000	10	10	10
						Drying	4	2600	10	10	50
Papermaking	1	39000	218	708	800		1	39000	30	30	50
DFP 1	1	844	1200	450	1250		1	1200	20	30	400
	2	342	28	30	1300		2	282	20	10	500
	3	280	180	60	400		3	100	32	20	430
	4	220	10	7	800						
DFP 2	1	1407	1400	600	1290		1	2200	20	30	300
	2	864	32	50	1270		2	812	20	10	270
	3	800	160	70	500		3	220	32	20	240
	4	490	10	7	600						
DFP 3	1	954	1000	400	1300		1	1330	20	30	400
	2	412	32	40	300		2	402	20	10	300
	3	400	240	70	140		3	120	32	20	200
	4	250	10	7	400						
Washing Plant 1	1	200	220	100	1200		1	200	20	30	300
Washing Plant 2	2	280	244	140	1600		2	280	20	30	300
Washing Plant 3	3	250	208	120	2000		3	250	20	30	300
GTL											
MED treated water	1	a*	0.1	0.1	2	Natural Gas Saturator	1	1224	5	5	2
Biologically treated water	2	a*	20	25	b*	Cooling Tower	2	14568	5	5	500
						CO2 removal unit	3	144	5	5	500
						Natural gas reformer	4	1344	5	5	2

Table 9. Water source-sink data profile in EIP

a* : Water supply from the treatment unit and fresh water only

b* : TDS concentration is same as the input concentration into the biological unit

Environmental Limitation		
BOD (g/m^3)	TSS (g/m^3)	TDS (g/m^3)
50	60	20000

Table 10. Environmental limitation for water disposal

Freshwater property				
Water Type	**BOD (g/m^3)**	**TSS (g/m^3)**	**TDS (g/m^3)**	**PRICE ($/m^3)**
Pretreated water	0.1	0.1	0.1	2.5
River raw water	15	15	50	0.8

Table 11. Properties of fresh water sources

From this information, the steam cost is calculated according to the methodology under the assumption that there is a condensing turbine within the industrial park.

4.4.2 Water sink-source data

Pulp & Paper Mill is one of the water-intensive industries with effluent having a high concentration of suspended solid (SS) and biological oxygen demand (BOD). Dyeing & finishing plant is also water-intensive industry so that they are chosen as a participant of the eco-industrial park. In addition, GTL process needs a significant amount of water for the processes including natural gas saturator, cooling tower, a CO_2 removal unit, and natural gas reformer.

From the process data, water sink-source data is constructed. For the Kraft Pulping process, the primary source of process water is washer filtrate in the bleaching process. This wastewater has a high dissolved solid content that limits direct reuse in the process. In addition, there is condensate from evaporators, and white water from drying process, which are relatively easier to be reused in the process due to the low pollutant in them.

For papermaking plant, a significant amount of water is used for the papermaking with market pulp. The water usage and pollutant content were obtained from the literature.

Dyeing and finishing plants (DFP) and washing plants (WP) are not included in the total site analysis due to the little impact on the energy consumption and surplus steam for the industrial park. However, they emit a considerable amount of water that has high pollutant concentration, so it is considered in the water-exchange network. For GTL process, there is no significant water source within the process, but they need clean water to operate process units. With these data, water exchange network is optimized to minimize the total annualized cost for the water-exchange network with the treatment unit (biological unit and multi-effect distillation unit).

Environmental limit from the regulation of water disposal is set by the effluent standard (EPA), for pulping & paper mill. Freshwater property and price are assumed. The first freshwater is pre-treated water from the fresh water source and the other freshwater is raw water from the water source.

4.4.3 WEN optimization

4.4.3.1 Conventional biological treatment system (without THP)

WEN with the conventional system does not have THP in its biological treatment unit. Therefore, this optimization is base-case to be compared with the case where the eco-industrial park has THP in it under different scenarios. The table below shows the cost allocation for the optimized WEN for the conventional system case. Total annualized cost for the WEN is estimated as \$38.26 million while \$13.32 million for freshwater and \$23.89 million for the treatment of wastewater. Among the treatment cost, biological treatment accounts for \$5.43 million and \$18.46 million for MED. The wastewater load for BG is estimated 75021 m^3/day and 67267 m^3/day for MED. The most important factor in this optimization is the wastewater load and pollutant concentration to the biological unit because they will decide the cost of the biological treatment and sludge production that is the focus of this research. As the concentration of suspended solid (SS) is higher than BOD, primary sludge, mainly from suspended solid, is produced more compared to the activated sludge generated from BOD removal during the activated sludge treatment.

Result of optimized WEN		
Variables	**Value**	**Unit**
Total Annualized cost for WEN	38.257	M$/yr
Freshwater cost	13.317	M$/yr
Total Cost for treatment	23.888	M$/yr
Biological Treatment Cost	5.426	M$/yr
MED treatment cost	18.462	M$/yr
Wastewater load for BG	75020.9	m^3/day
Wastewater load for MED	67267.2	m^3/day

Table 12. Result of WEN optimization

Biological Treatment		
Input variables	**Value**	**Unit**
Wastewater load	75020.9	m3/day
BOD	325.77	g/m^3
SS	567.96	g/m^3
TDS	1213.4	g/m^3

Table 13. Input variables to the biological treatment system

Result from BG		
Unit cost	0.201	$/m^3
Hauling cost	1.855	M$/yr
Sludge disposal volume	70.5	m^3/day
Biogas total volume	7959.96	m^3/day
CH4 % in biogas	66.1	%
CH4 from PS	4801.366	m^3/day
CH4 from WAS	460.354	m^3/day
Biogas to MP	33186.1	MJ/d
Biogas to LP	44898.8	MJ/d
Revenue from biogas by heat	0.056	M$/yr
Revenue from biogas by electricity	0.515	M$/yr
GHG Reduction from CH4	29345.5	eco2 ton/yr

Table 14. Results of important variables from sludge treatment system

MED		
Steam for MED	3626818	kg/day
EOR	11.128	
Unit cost	1.271	$/m^3

Table 15. Information about MED

4.4.3.2 THP in the biological wastewater treatment unit

Secondly, the optimization of WEN with THP has been conducted. In this case, it was assumed that the sludge after THP and anaerobic digestion can be sold at $10/wet ton to farmers due to its preferable quality and non-pathogenic property. This value was calculated based on the price of urea fertilizer and nitrogen content in the textile plant sludge (Islam et al. 2009). With $353/ton of urea fertilizer price containing 46% of nitrogen, the value of the sludge as a fertilizer is $15.34/ton sludge with 2% nitrogen content. As the solid content of dewatered sludge with THP is higher than other conventional dewatered sludge, nitrogen content in the sludge can be greater than conventional sludge. Therefore, the range of possible sludge price is set to $7.67/wet ton (1%) and $30.68/wet ton (4%), and these values were used through this study.

Therefore, in this case, the eco-industrial park does not have a contract with landfill tipping company, and they possess own trucks and facilities for hauling in itself. Under this assumption, it is important to assess the cost of transportation including trucks and loading facilities. Therefore, capital cost and related operating expenses (labor, operation & maintenance, fuel) are estimated by adjusting EPA standard calculation (Stein et al. 1995) to the current value.

In this analysis, this eco-industrial park is assumed to be located on the Gulf coast near the petrochemical plant and chemical plant. By assuming this, the distance from the eco-industrial park and farms are found as below. By using this distance information, the hauling cost is calculated. The distance between the eco-industrial park and sludge consumer (farms) is critical because the transportation cost is critical to the economic feasibility of sludge selling.

Name	One-way distance (mile)	Round-trip distance (mile)
A&W Christmas tree farm	16.5	33
Oak Hill Tree Farm & produce	19.9	39.8
Blue Moon farm	23.1	46.2
To the moon farm	22.4	44.8
Session farm	17.1	34.2
Ken Buck farm	25.4	50.8
Driskell Turf farm	21.6	43.2
Average	20.86	41.71

Table 16. Distance from farms (consumer for treated sludge) to EIP

Benefits of having THP is similar to the previous analysis with THP unit assuming the certain capacity of the wastewater plant. Due to the improvement of dewaterability of the sludge, it is possible to reduce the final sludge volume by 51.10%, and unit cost for biological treatment by 10.79%. In addition, biogas yield is increased by 44.4% compared to the conventional system. Due to this increase in biogas, it is possible to enhance the carbon credit within the eco-industrial park.

An important result from this step is steam consumption for THP and MED that will be used for adjusted steam balance and the cogeneration potential targeting. From the result, steam consumption for THP is far less than the steam requirement for MED. It means that with only a small amount of steam, it is possible to generate electricity, MP steam, and LP steam due to the increased biogas yield by hydrolysis. Also, we can reduce a significant amount of carbon emission, so THP can be beneficial to both sustainability and economy of the eco-industrial park.

Result of optimized WEN			
Variables	**Value**	**Unit**	**Difference with conventional system**
Total Annualized cost for WEN	37.304	M$/yr	-2.49%
Freshwater cost	13.350	M$/yr	-
Total Cost for treatment	22.902	M$/yr	-4.13%
Biological Treatment Cost	4.460	M$/yr	-17.81%
MED treatment cost	18.442	M$/yr	-
Wastewater load for BG	75331.5	m^3/day	-
Wastewater load for MED	67187.9	m^3/day	-

Table 17. Results of WEN optimization with THP

Biological Treatment		
Input variables	Value	Unit
Wastewater load	75331.5	m^3/day
BOD	324.50	g/m^3
SS	565.72	g/m^3
TDS	1213.99	g/m^3

Table 18. Input variables to the biological treatment system

Result from BG			
Input variables	**Value**	**Unit**	**Difference with conventional system**
Unit cost	0.164	\$/m^3	**-18.15%**
Hauling cost	0.188	M\$/yr	**-89.87%**
Sludge disposal volume	34.477	m^3/day	**-51.10%**
Biogas total volume	11493.69	m^3/day	**44.40%**
CH4 from PS	6540.012	m^3/day	36.23%
CH4 from WAS	1045.129	m^3/day	127.73%
Biogas to MP	47841.9	MJ/d	44.16%
Biogas to LP	64727.3	MJ/d	44.16%
Revenue from biogas by heat	0.08	M\$/yr	44.16%
Revenue from biogas by electricity	0.743	M\$/yr	44.16%
GHG Reduction from CH4	42305.23	eco2 ton/yr	44.16%

Table 19. Results of important variables from sludge treatment system with THP

Steam Consumption		
Steam usage for THP (MP)	39.61	ton/day
Steam for MED (LP)	3622.54	ton/day

Table 20. Steam requirement for THP and MED

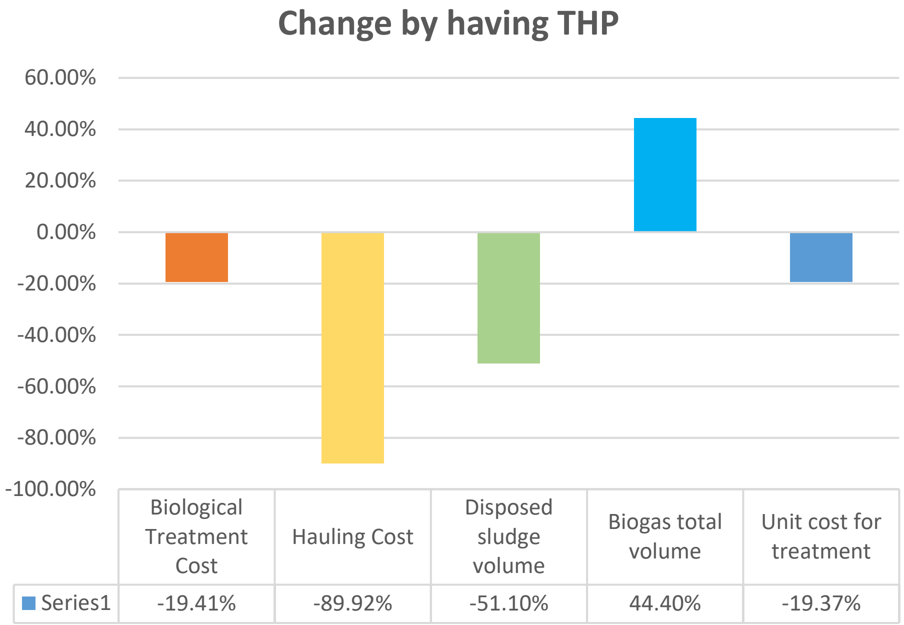

Figure 39. Difference by having THP in the WEN

The main advantage of having THP is that surplus MP can be used for: 1) reducing hauling cost by monetizing sludge, 2) generating steam (MP, LP) and electricity, and 3) earning carbon credit from biogas. One additional important feature of THP in EIP is that low-grade heat from CHP using biogas can be utilized not only for electricity generation but also for clean water production with MED. In particular, LP steam from biogas can be more valuable in EIP with MED because LP steam can be used for water production, and it can be sold to consumers. In this case, the revenue from the heat using biogas can be represented as

$$\mathrm{Revenue_{heat}} = \eta_{eff}(H^{MP} - H^{LP})m_{mp}P_{elec} + \frac{\Delta \mathrm{H^{LP}}(\mathrm{m_{mp}} + m_{lp})}{\dot{\hat{E}}_{MED}}(P_{water} - Cost_{water})$$

The first part of the revenue from heat is about the electricity co-generated from MP steam in the steam turbine. η_{eff} is extractable energy efficiency defined from extractable energy analysis, and it is assumed to be 0.7. The second part is revenue from water with MED. LP steam from cogeneration of MP steam is combined with LP steam from engine cooling of CHP, and it is used for the water production. $\dot{\hat{E}}_{MED}$ is unit thermal energy consumption for MED, and it is set to 200MJ/m^3 according to the literature (Al-Karaghouli and Kazmerski 2013). $\mathrm{P_{water}}$ is an available price for clean water from MED, and $\mathrm{Cost_{water}}$ is unit cost for the MED.

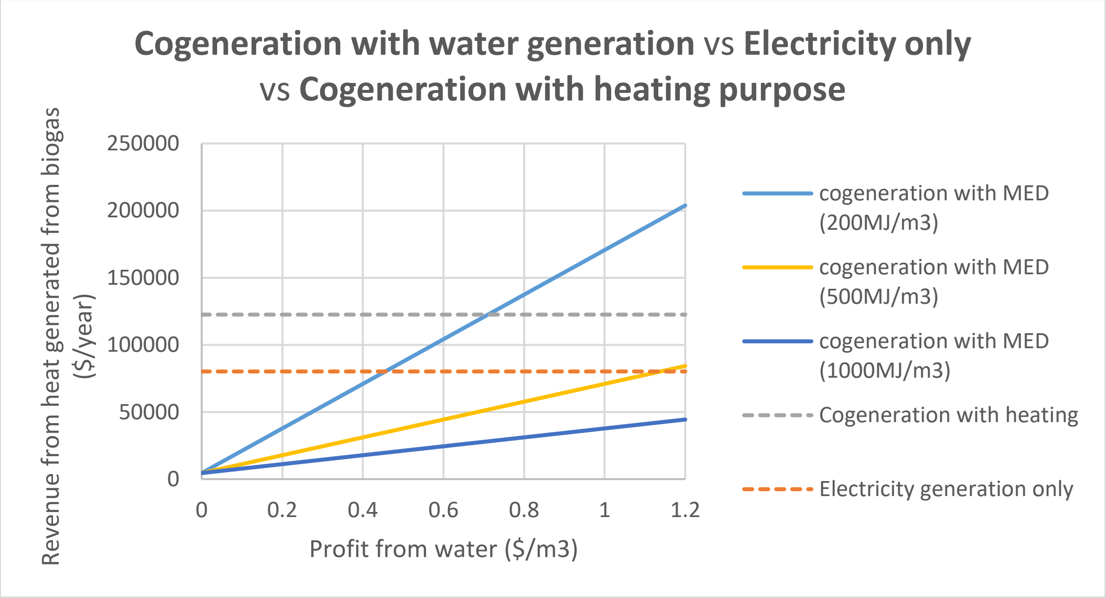

Figure 40. Synergetic effect between MED and CHP with biogas

Figure 39 shows the revenue from the steam generation in CHP using biogas based on the WEN optimization with THP. The gray line is the revenue when EIP has a heat sink for LP steam, and the orange line is when MP and LP steam from biogas are only used for electricity generation without cogeneration. When the profit from the water selling is more than \$0.45/m^3, we can gain more revenue by using cogeneration of water with the steam from the CHP. When it is possible to have \$0.93/m^3 profit from the water generation, revenue from the steam generated with biogas can be increased by 100% compared to the strategy where all the steam is used for electricity generation. Therefore, with proper amount of profit from water selling, the revenue from the steam generated during the CHP process can be increased so that it is profitable for THP.

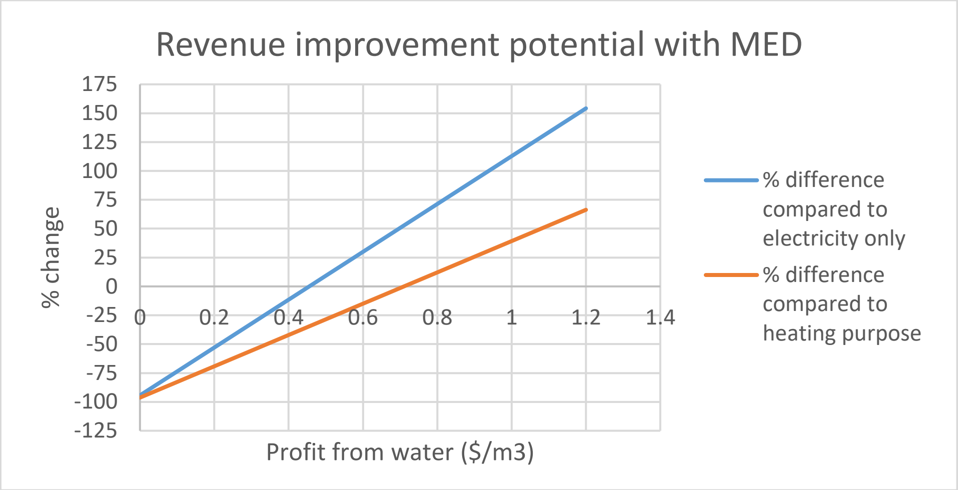

Figure 41. Percentage advantage of water generation compared to electricity generation with low-grade steam

In EIP, surplus heat can be utilized through THP for pollution reduction, electricity generation, and water generation simultaneously. Therefore, good synergetic effect can be achieved between centralized EIP having MED and THP unit for sludge treatment.

4.4.4 Impact of carbon tax on the integrated structure

In the integrated structure, the impact of carbon tax is significant due to the large GHG factor of methane in biogas generated from the sludge. When carbon tax is $10/ton eco2, the revenue from a carbon tax can reach $ 0.423M/year. However, the cost of electricity from biogas without carbon tax is estimated 23.7cents/kWh, which is far higher than the usual price of electricity ($6~15 cents/kWh for the large industry). Even if there is a carbon tax at $30/ton co2, it is not competitive enough to cope with electricity from other fossil fuel.

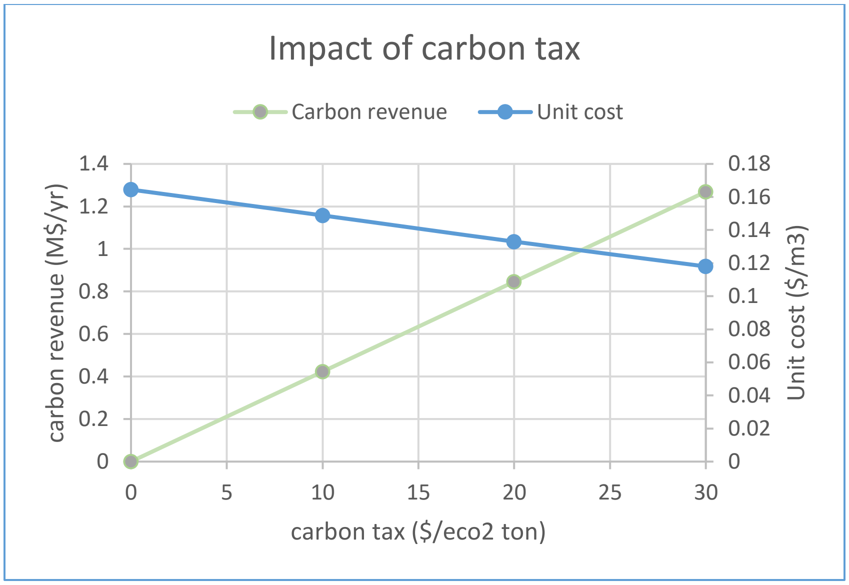

Figure 42. Impact of carbon tax on the EIP's biological treatment system

It shows that even though THP can improve the competitiveness of electricity from biogas by increasing biogas yield and reducing hauling cost, this EIP needs more subsidies or other strategies to have sufficient economic incentive from biogas. One of the strategies is collecting bio-waste from adjacent communities to treat in EIP by using economy of scale due to the centralized structure and surplus heat from other processes. As studied in the previous analysis, adequate amount of tipping fee from outer bio-waste can be a powerful incentive that enables EIP to make biogas more competitive and to maximize the benefit of THP.

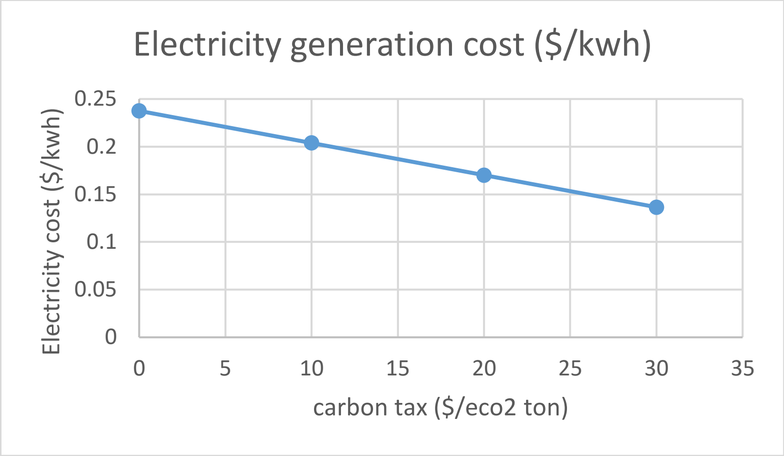

Figure 43. Electricity generation cost from biogas with internal sludge only

4.4.5 Optimization with outer sludge with tipping fee

As shown in the previous analysis about power generation cost, earning sufficient profit with the sludge only from internal wastewater treatment facility is not promising. However, as EIP already needs a large capacity of wastewater treatment and sludge treatment facilities, EIP can take advantage of economy of scale by acting as a waste treatment center for outer bio-waste. Moreover, since EIP has a significant amount of surplus heat from the processes, EIP has an advantage compared to other separated organic waste treatment companies that might have to use natural gas to utilize THP process. These bio-wastes collected with tipping fee can be utilized for energy recovery and as measures to obtain carbon credit for EIP. In addition, as the population grows rapidly, the price of fertilizer goes up due to the high demand for food. As the treated organic waste can be used as an alternative for the fertilizer, the value of treated organic waste is expected to increase. Therefore, it is attractive enough to treat the bio-waste from outside within EIP by using surplus heat and large scale of a treatment facility in order to produce more biogas and sell the treated sludge to farmers as an alternative to fertilizer.

Number	**1**	**2**	**3**	**4**	**5**	**6**
Bio-waste source	Chemical sludge	Petro-chemical sludge	FOG	Animal Manure	Food waste	Animal Dung
Bio-methane potential (m^3/g VS)	0.2897	0.4543	0.4458	0.2534	0.3363	0.2280
Biodegradability	0.25	0.25	0.46	0.55	0.37	0.5
Solid content (%)	0.25	0.25	0.4	0.15	0.3	0.2
Maximum volume (m^3/day)	15.7	14	3.33	114.97	20.72	80
Distance to eco-industrial park (mile)	10	6	80	73.4	80	131.6
Tipping fee ($/wet ton)	50	50	50	50	50	50

Table 21. Properties of bio-waste from adjacent sources

Several organic waste characteristics are set to analyze the impact of outer bio-waste on the EIP. This bio-waste information is adopted and modified from literature (Scheftelowitz and Thrän 2016; Mahanty et al. 2014; Labatut, Angenent, and Scott 2011), and distance information was inferred from the location of virtual EIP in the gulf coast. Industrial sludge is dewatered before being transported to the EIP in order to reduce the volume. Animal manure and dung come from dairy farms, and FOG and food waste are from the city 'Mobile' that has 198,915 population. The amount of maximum FOG and food waste are calculated by using food waste loss data (Buzby, Farah-Wells, and Hyman 2014) while assuming 30% of total loss is our target waste. Tipping fee for the bio-waste is set as a $50/wet ton, which is usual landfill tipping contract fee for the waste. The price of treated sludge is set as a $10/wet ton to compare with the previous analysis.

4.4.6 Impact of maximum sludge volume on the strategy

When the maximum volume of bio-waste from the outside is limited as 20% of the internal wastewater treatment facility's sludge, chemical and petrochemical sludge are selected. Based on the volume collected, the first preference is petrochemical sludge that is the closest to the EIP. This shows that the sensitivity of the cost by the change in the transportation cost (distance) is crucial in deciding which bio-waste to be treated in EIP. Even though each bio-waste has different characteristics such as biomethane potential, biodegradability, and solid content, distance might be the most critical criterion due to its higher impact on the feasibility of this strategy. In another word, this demonstrates that even if there are good bio-waste to be treated, it is not economically preferred to transport the bio-waste from too far away since transportation cost exceeds the benefit of advantage from the quality of the bio-waste. After collecting bio-waste around, next targets are FOG and food waste from the city. Interestingly, although the distance from the city to EIP is greater than that from the dairy farms, bio-wastes from the city are selected. It is because these bio-wastes have higher bio-methane potential than the manure, which is sufficient to overcome the disadvantage in the distance. This shows that different pricing strategy might be needed to incorporate various kind of bio-waste and stabilize the economy of organic waste treatment.

Bio-waste	**Max (m3/day)**	**Distance (mile)**	**Maximum volume ratio of bio-waste from outside (V_{out} : V_{inside})**					
			0.2	**0.4**	**0.6**	**0.8**	**1**	**2**
Chemical	15.7	10	7.76	15.7	15.7	15.7	15.7	15.7
Petrochemical	14	6	14	14	14	14	14	14
FOG	3.33	80	-	3.33	3.33	3.33	3.33	3.33
Animal Manure	114.97	73.4	-	-	11.53	33.29	55.05	100.83
Food waste	20.72	80	-	10.49	20.72	20.72	20.72	20.72
Animal Dung	80	131.6	-	-	-	-	-	62.86

Table 22. Change in bio-waste selection with increasing capacity of the plant

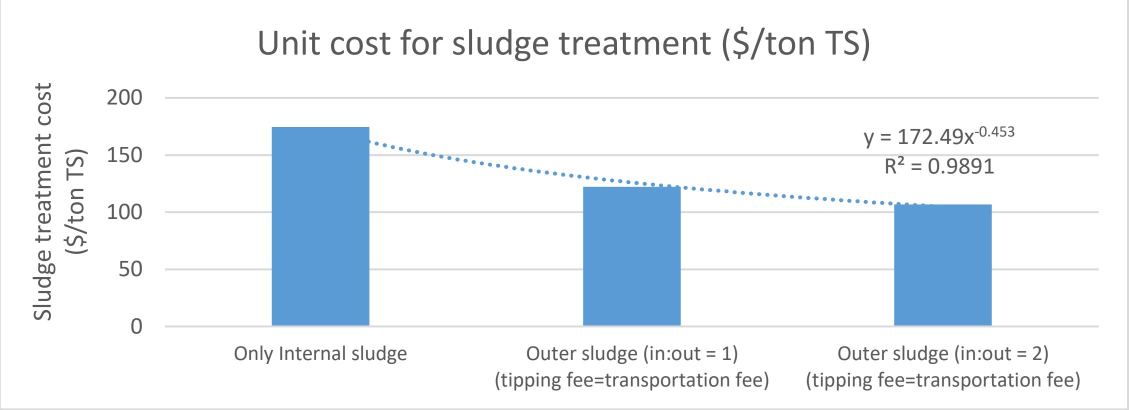

Figure 44. Economy of scale in the bio-waste treatment system

As stated in the previous section, the economy of scale is an important advantage of EIP. The graph below shows that the solid waste treatment cost per ton of solid can decrease significantly with the increasing volume of organic waste even if tipping fee is same as transportation cost, which means no revenue from tipping fee. When EIP treats only the internal sludge, unit treatment cost for the sludge is about $174.4/ton TS. However, by increasing its capacity with outer organic waste, unit cost can decrease to $122.2 for double (29.93% reduction), $106.8 for triple volume (55.32% reduction) of the internal sludge. This result justifies collecting organic waste from outside to maximize economy of scale within the centralized structure in EIP. Electricity generation cost from biogas shows u-shape with the increased capacity. It is because of the low biomethane potential of manure. It indicates the sensitivity of the electricity generation cost according to the biochemical property of the bio-waste.

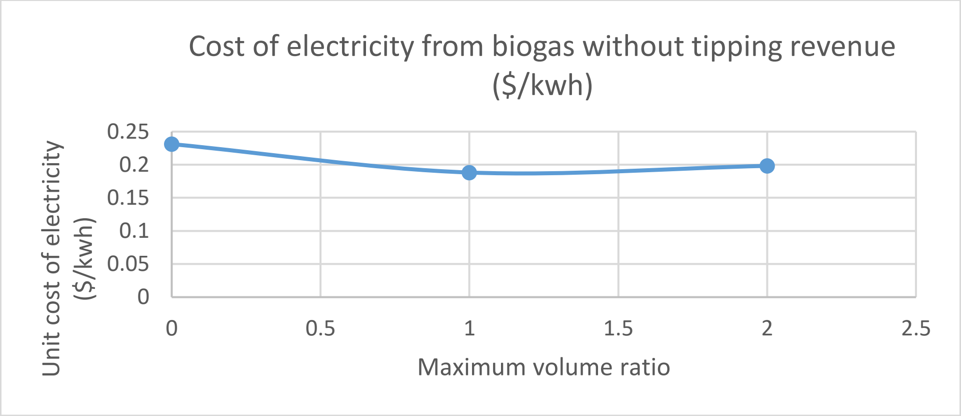

Figure 45. Cost of electricity generation without tipping fee revenue

4.4.7 Impact of tipping fee

The economy of scale in EIP can be improved further with the adequate amount of tipping fee. With a $50/wet ton of tipping fee, which is general landfill tipping fee in the US, it is possible to reduce unit treatment cost and electricity generation cost significantly. Compared to the unit cost for sludge treatment of no outer bio-waste, the unit cost can be lessened by 66.06% in doubled capacity, 83.9% in tripled capacity. Therefore, if EIP can have sufficient capacity for bio-waste treatment with a certain amount of tipping fee, it can successfully serve as solid-waste treatment center with its economy of scale and surplus heat. Electricity generation cost is estimated $0.096/kwh in tripled capacity, which has potential to cope with the electricity from natural gas.

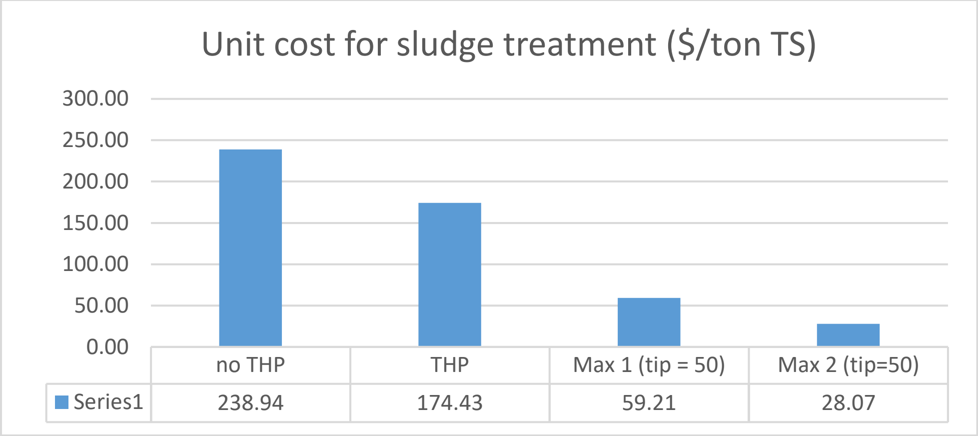

Figure 46. Unit cost of bio-waste treatment with tipping fee revenue

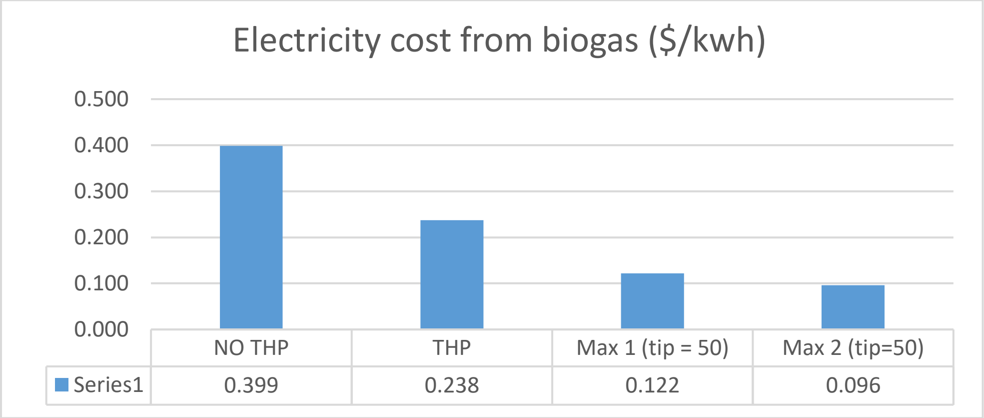

Figure 47. Cost of electricity generation with tipping fee revenue

Moreover, one of the major benefits of this strategy is that EIP can reduce GHG emission with biogas and can earn carbon credit from it. Therefore, if a carbon tax or credit is available, benefit from bio-waste treatment in EIP can increase proportionally, which improves the economy of waste treatment significantly. As shown in Figure *47*, the cost of electricity generation from biogas can reach $0.062/kwh with tripled capacity and $10/ton co2 carbon tax, which is in the reasonable range with a modest level of the carbon tax.

Considering that the continuous increase of the population will increase the price of fertilizer, the value of treated sludge as a fertilizer will increase as well. If the price of treated sludge increases, it can improve the economy of waste treatment substantially. As shown in Figure *47*, when the price of treated sludge is increased to the $20/wet ton, the unit cost of electricity can be reduced by around $0.013/kwh, which makes the electricity from biogas more competitive to the electricity from natural gas.

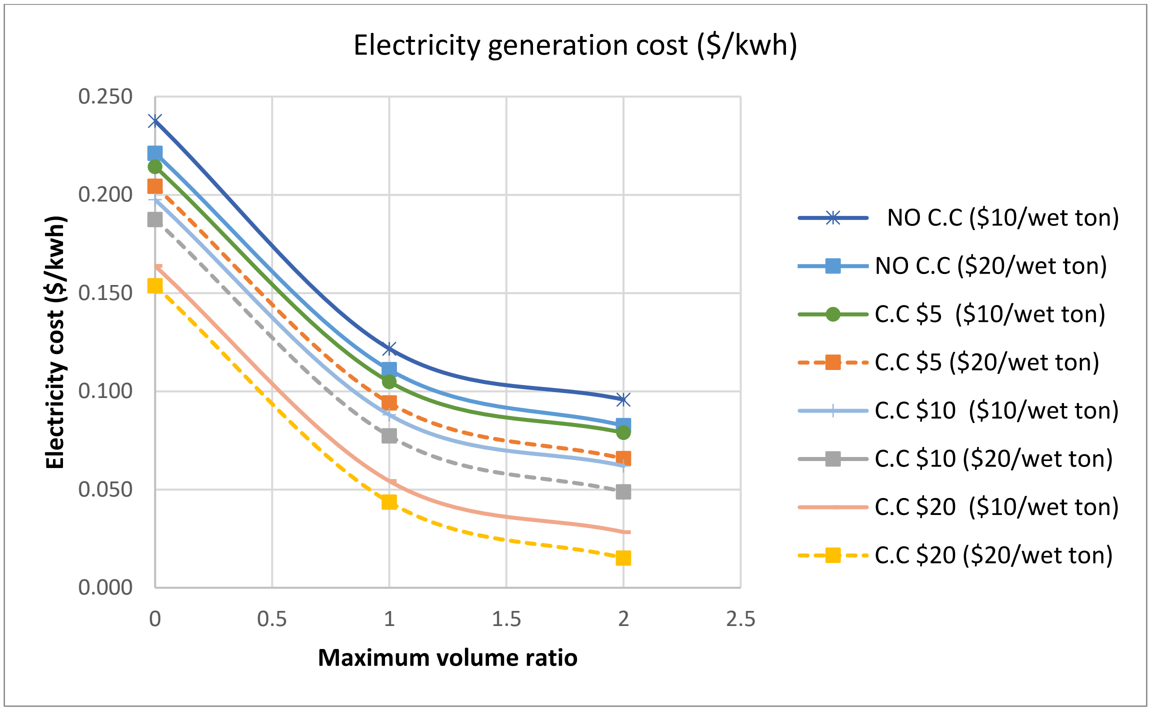

Figure 48. Electricity generation cost with carbon tax and sludge selling

4.4.8 Impact of GHG emission from transportation

One of the important advantages of treating bio-waste in the EIP is the reduction of GHG emission due to the biogas recovery from the waste. However, this strategy requires transportation of the bio-waste from external sources to EIP so that it might be detrimental in the sense of total GHG emission if more GHG is emitted during the transportation than the amount of reduction from biogas recovery. However, landfill site is generally far from the waste sources because of the regulation, so net GHG emission from the transportation to EIP would be less than landfilling option. Also, due to the higher greenhouse impact factor of methane than diesel fuel, emission from diesel fuel during the transportation can be compensated from the biogas recovery in the EIP. To illustrate, virtual distance from sources to EIP and to landfilling site are assumed, and GHG emission from transportation is calculated. The distance from sources to landfill site is assumed from the average distance data for the landfill site. As shown in the table, the contribution of GHG emission reduction from biogas is much higher than that from the transportation. It means that even though the distance from the source to EIP is longer than that to the landfill site, recovery of biogas has a higher value in the sense of GHG emission reduction, resulting in justification of transporting bio-waste to reduce GHG emission.

Source Number	1	2	3	4	5	6	EIP
Distance from Landfill site (mile)	80	70	120	100	120	120	121.44
Distance from EIP (mile)	10	6	80	73.4	80	131.6	41.71 (to farmer)

Table 23. Distance between landfill site and bio-waste sources including EIP

CO2 from source to Landfill site (ton co2/year)	616.428
CO2 from source to EIP (ton co2/year)	483.499
CO2 from EIP to Landfill site (ton co2/year)	248.475
CO2 from EIP to farmer (ton co2/year)	85.3418
Net GHG reduction from transportation (ton co2/year)	296.0622
GHG reduction from biogas (ton co2/year)	70323.75

Table 24. GHG emission reduction comparison between transportation (diesel) and biogas recovery (methane)

5. CONCLUSIONS AND DISCUSSIONS

5.1 Conclusions

Through the methodology and model proposed, the economy of THP with/without water exchange network was successfully estimated, and some valuable insights could be obtained.

First, waste treatment unit shows significant sensitivity by the capacity of the plant. This indicates that there might be an opportunity for EIP to include centralized large-scale waste treatment facility in it because the economy of scale in the centralized wastewater treatment facility in EIP can have a synergetic effect with it due to a large amount of sludge from the centralized wastewater treatment units.

Second, by using surplus heat from the processes in EIP to generate steam, it is possible to reduce the cost of the steam for THP and MED. The cost of MP steam which is the main operating steam for THP can be decreased from \$0.01/kg to \$0.007/kg, which is 30% less than the general cost. This reduction in cost can be higher if EIP does not have adequate equipment that can use the surplus MP steam. This advantage of EIP can contribute to reducing the operating cost of waste treatment facility further.

Third, the synergetic effect of THP with EIP in respect of low-grade heat utilization can be achieved; low-grade heat from CHP using biogas can be utilized for the clean water production using MED in EIP, increasing the revenue from biogas. In this particular case study, if we can earn a profit above \$0.93/m^3 from the treated water, the income from heat using biogas can be increased by more than 100%. Therefore, the economy of THP can be improved with the clean water generation in MED if there are a consumer for the clean water.

Fourth, if the capacity of the waste treatment block can be increased with outer bio-waste, a significant advantage of economy of scale can be taken even without tipping fee. In the case study, it was possible to reduce the unit cost for the waste treatment from \$174.42/ton TS to \$122.22/ton TS with doubled capacity, and to \$106.83/ton TS with tripled capacity by treating outer bio-waste without tipping fee. Furthermore, with the proper amount of tipping fee, it is possible to reduce the cost further, and the electricity generation cost can be competitive with the electricity from fossil fuel. The cost of the electricity with biogas can be reduced from \$0.238/kwh to \$0.096/kwh by treating outer bio-waste with tipping fee.

Fifth, the impact of carbon credit is substantial due to the high Global Warming Potential (GWP) of methane so that this integration will be more promising with the carbon tax. Even with a reasonable range of carbon tax, it is possible to be competitive with the electricity price from fossil fuel. With \$10/ton eco2 carbon tax, the cost of electricity can be decreased to \$0.062/kwh in the waste treatment system with three times the capacity, which is very competitive cost. Furthermore, with a carbon tax at \$20/ton co2, the cost is \$0.0283/kwh so that EIP might be able to generate net profit from the biogas within the waste treatment plant.

Finally, availability and willingness of consumers to whom EIP can sell the treated sludge are critical to the feasibility and profitability of EIP as a sustainable center. By increasing the selling price by the \$10/wet ton, it is possible to reduce the electricity cost by \$0.004~\$0.014/kwh depending on the capacity of the waste treatment plant. With a \$20/wet ton of selling price, it is possible to have competitive electricity price (\$0.066/kwh) with the \$5/ton eco2 of a carbon tax in tripled-capacity of the plant.

In sum, by having THP, the spectrum of the optimization of water exchange network in EIP can be expanded and combined with the waste treatment block which enables EIP to reduce the greenhouse gas emission and to generate revenue with biogas; EIP can cope with the stricter regulation on the waste disposal and carbon emission simultaneously while finding a new opportunity coming along with this change. As the concern about the GHG emission and efforts to apply carbon tax increases, this strategy will become more important and more economically and environmentally favored in the near future. By transforming EIP to sustainable center, we can improve the sustainability of its own and adjacent communities as well, driving us toward the world with more sustainability.

5.2 Discussions

5.2.1 Limitation of the study

Even though this study can provide useful insight of key variables to estimate the potential of THP, this study does not consider dynamic behavior or a detailed model of the treatment units. Due to this limitation, the performance of each unit can be considerably different from the design value assumed in this study. In addition, due to the limited information about THP process, it was difficult to assess the kinetics of sludge during the THP process. Therefore, the effect of THP on bio-waste can be different from the result obtained in this study. This can be improved with real experimental data of bio-waste that has enough potential to be used for biogas generation with THP. Transportation cost and landfill tipping fee can be remarkably different from each region due to the sensitivity of the transportation cost from the geographical characteristics or infrastructure around the EIP. This issue can be relieved by considering region-specific approach or using stochastic optimization to incorporate uncertainty in the optimization model.

5.2.2 Future work

First, this methodology can be expanded by including other waste-to-energy technologies such as drying or pelletizing of sludge. In this situation, more energy is required, but more energy can be recovered. Therefore, there might be an optimal ratio of sludge treatment with different methods in EIP depending on the characteristic of EIP.

With the detailed model of wastewater characteristic and performance of each unit, it will be possible to estimate the chemical and physical property of sludge from wastewater treatment system. This will increase the scalability of this approach to the more general situation, and improve the accuracy of the cost estimation.

In addition, as one of the main advantage of THP is reducing GHG emission significantly, Life cycle analysis can be adopted to analyze the benefit of THP in the life cycle base. This will highlight the potential and advantage of this option further.

Finding new application of the treated sludge would be one of the interesting future works. Resource recovery from the sludge or using it as a feedstock within EIP will open a new horizon for EIP as a sustainable center.

Finally, if it is possible to incorporate nitrogen balance in the system, estimation of cost for treated sludge as a fertilizer can be conducted in a systematic way. This will provide another optimization variable that can be used for the criterion in certain circumstances and help estimation of the optimal candidate to treat in EIP.

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APPENDIX

A. Process Design Parameters

Unit	**Grit Chamber**		**Reference**
n_{BOD}	0		Removal rate of BOD
n_{TSS}	0.1		Removal rate of TSS
n_{VSS}	0.1		Removal rate of VSS
VSS fraction	0.67		Volatile fraction in inlet stream
Unit	**Primary settler**		**Reference**
n_{BOD}	0.3		Removal rate of BOD
n_{TSS}	0.7		Removal rate of TSS
solid content	0.05		sludge solid content from primary settler
BDG_{PS}	0.5		Initial biodegradability of primary sludge
SOR	800~1200	gal/(ft^2 day)	Surface overflow rate
Unit	**Aeration Basin**		**Reference**
SRT	8~15	day	Solid retention time
MLSS	3000/4000	g/m^3	Mixed Liquor Suspended Solids concentration (conventional/THP)
Y	0.5	gBOD/gBOD	Uptake coefficient for sludge production
b	0.06	d^{-1}	Endogenous decay coefficient
VSS fraction	0.8		Volatile fraction in mixed liquor
Temperature	15	℃	Operating Temperature
SRT	8~15	day	Solid retention time
Unit	**Secondary Settler**		**Reference**
HRT	2~6		Hydraulic Retention Time
Depth	10	ft.	Settler Depth
X_W	10000	g/m^3	Thickened waste sludge from secondary settler
BOD_{eff}	20	g/m^3	Effluent from secondary treatment
TSS_{eff}	25	g/m^3	Effluent from secondary treatment
BDG_{WAS}	0.35		Initial biodegradability of WAS
sBOD	5	g/m^3	
Unit	**THP**		**Reference**
T_{sup}	15	℃	Supplement water temperature
T_{ref}	0	℃	Reference temperature
T_{THP}	150~200	℃	Operating temperature
C_{PW}	4.18	J/kg	Pure water heat capacity

C_{SW}	4.18	J/kg	Supplemental water heat capacity
C_{Sludge}	1.5	J/kg	Sludge heat capacity
Solid content	0.08		Solid content after THP & before AD
T_{after}	60~100	℃	Temperature of outlet stream after heat exchange
Unit	**Anaerobic Digestion**		**Reference**
$n_{VSS,\ w/o\ THP}$	0.4		Removal rate of volatile suspended solid without THP
$n_{VSS,\ w/\ THP}$	0.6		Removal rate of volatile suspended solid with THP
$SRT_{AD,\ w/o\ THP}$	12	day	Solid Retention Time of AD without THP
$SRT_{AD,\ w/\ THP}$	20	day	Solid Retention Time of AD with THP
Solid content	0.05		Solid content after AD
Temperature	35	℃	Mesophilic operating temperature
C_{WAS}	4.1	J/K	Heat capacity without dewatering (w/o THP)
ρ_{CO2}	1.84485	kg/m^3	Density of CO_2 in anaerobic digester
ρ_{CH4}	0.61122	kg/m^3	Density of CH_4 in anaerobic digester
Unit	**Belt Press Dewatering**		**Reference**
$Solidcapture_{primary}$	0.9		Solid capture in dewatering
$Solidcapture_{Secondary}$	0.9		Solid capture in dewatering
$Solidcapture_{final}$	0.93		Solid capture in dewatering
Solid $content_{w/o\ THP}$	0.25		Solid content in the sludge after dewatering without THP
Solid $content_{w/\ THP}$	0.45		Solid content in the sludge after dewatering with THP
Unit	**Gravity Thickener**		**Reference**
Solid capture	0.9		Solid capture after thickening
Solid content	0.05		Solid content in the sludge after thickening
SLR	10	day	Solid loading rate
Unit	**CHP**		**Reference**
n_{elec}	0.44		Electrical conversion efficiency in CHP
n_{MP}	0.17		High-grade heat conversion efficiency in CHP
n_{LP}	0.23		Low-grade heat conversion efficiency in CHP

B. Miscellaneous parameters

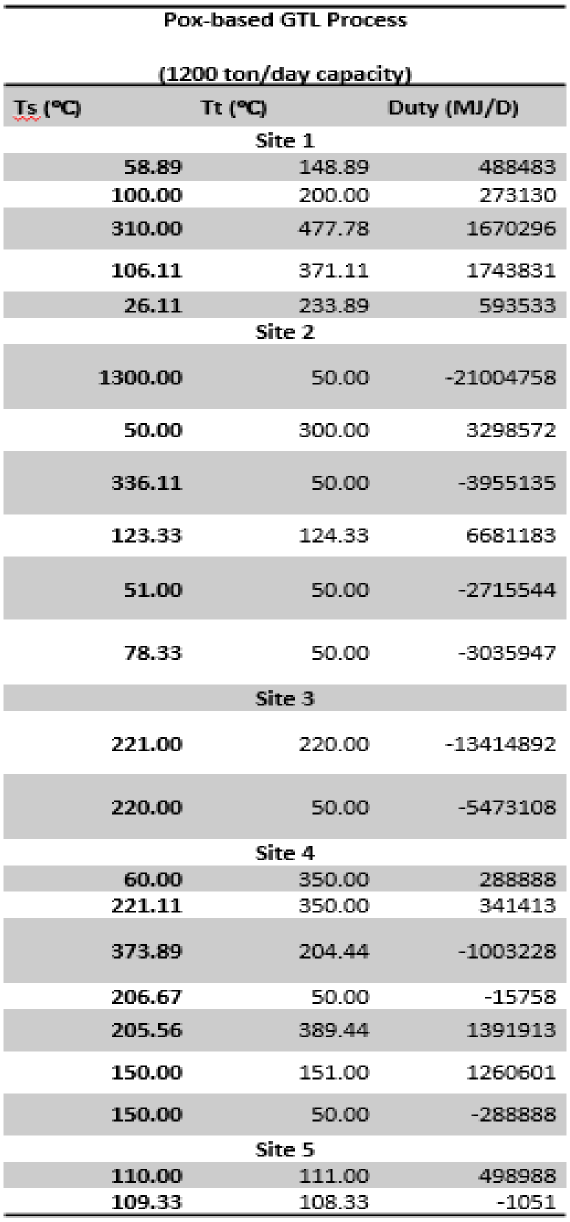
Parameter	Value	Unit	Reference
EC	0.1	\$/m^3	Disposal pumping cost
CUW1	2.5	\$/m^3	Fresh water cost (pre-treated)
CUW2	0.8	\$/m^3	Fresh water cost (raw)
CEPCI	550		Chemical Engineering's Plant Cost Index
$CO_{2\ diesel}$	10.21	kgCO$_2$/gal	GHG emission factor of diesel fuel
P_{diesel}	2.016	\$/gal	Price of diesel fuel
LT	0.4	hr	Loading time for hauling
ULT	1	hr	Unloading time after hauling
HPD	6	hr/day	Hours per day of driver's labor
DPY	120	day/year	Days per year of driver's labor
V_{truck}	35	mile/hr	Velocity of truck
P_{NG}	3	\$/MMBTU	Price of natural gas
$N_{turbine}$	0.65		Iso-entropic efficiency of turbine
P_{elec}	0.06	\$/kwh	Electricity price
$S_{cond,w}$	707.062	J/kg K	Entropy of condensed water at condensing turbine
$S_{cond,g}$	8070.19	J/kg K	Entropy of condensed steam at condensing turbine
$H_{cond,w}$	210.418	kJ/kg	Enthalpy of condensed water at condensing turbine
$H_{cond,g}$	2591.67	kJ/kg	Enthalpy of condensed steam at condensing turbine
$Heatingvalue_{methane}$	39820	kJ/m^3	Heating value of methane at 0 °C

	Capital cost	x	unit
Primary settler	170.84 x+66558	Surface area	ft2
Aeration tank	2231.9 x+291068	Volume	ft3
Secondary settler	170.84x+66558	Surface area	ft2
Belt filter press	21016x+173832	Flow	gpm
Thickener	5633.2x+26871	Diameter	ft
THP	6754.696x^0.6	solid loading rate	kg/d
AD	18063.46x^0.6	Volume	m^3
CHP	1670.5x^0.8409	Electricity generation capacity	kw
Unthickened Sludge pumping	x^3-0.0246x^2+174.33x+89824	flowrate	gpm
Thickened sludge pumping	0.0004*x^3-0.7412*x^2+494.82x+22130	flowrate	gpm
Management	69196x^0.5523	total capacity	MGD

C. Cost function

	Operating cost	**x**	**unit**
Primary settler	4.1011x+7861.9	Surface area	ft2
Aeration tank	690.65x+76673	Volume	ft3
Secondary settler	4.1011x+7861.9	Surface area	ft2
Belt filter press	1867.7x+33960	Flow	gpm
Thickener	1211.8x+55302	Diameter	ft
THP	0.1x+steam_cost	capital cost	kg/day
AD	0.1x+heatingcost	capital cost	m^3
CHP	0.008x	Electricity generation capacity	kw
Unthickened Sludge pumping	3*(10^-7)x^3-0.0055x^2+40.98*x+10803	flowrate	gpm
Thickened sludge pumping	-0.0443x^2+117.88x+6447	flowrate	gpm
Management	88589x^0.4529	total capacity	MGD

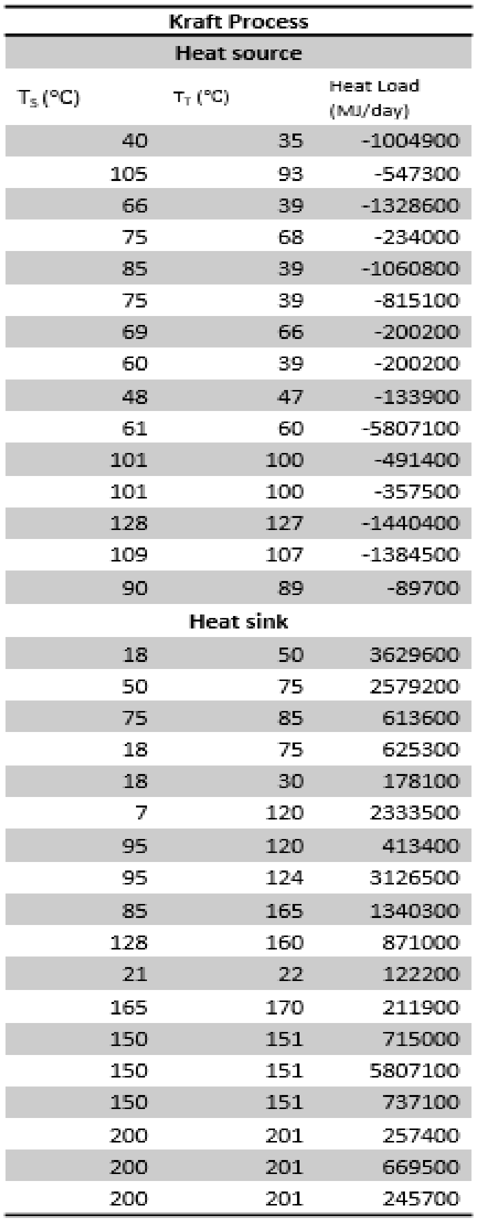
D. Heat source-sink data



Pox-based GTL Process

(1200 ton/day capacity)

Ts (°C)	Tt (°C)	Duty (MJ/D)
	Site 1	
58.89	148.89	488483
100.00	200.00	273130
310.00	477.78	1670296
106.11	371.11	1743831
26.11	233.89	593533
	Site 2	
1300.00	50.00	-21004758
50.00	300.00	3298572
336.11	50.00	-3955135
123.33	124.33	6681183
51.00	50.00	-2715544
78.33	50.00	-3035947
	Site 3	
221.00	220.00	-13414892
220.00	50.00	-5473108
	Site 4	
60.00	350.00	288888
221.11	350.00	341413
373.89	204.44	-1003228
206.67	50.00	-15758
205.56	389.44	1391913
150.00	151.00	1260601
150.00	50.00	-288888
	Site 5	
110.00	111.00	498988
109.33	108.33	-1051



Kraft Process

	Heat source	
T_S (°C)	T_T (°C)	Heat Load (MJ/day)
40	35	-1004900
105	93	-547300
66	39	-1328600
75	68	-234000
85	39	-1060800
75	39	-815100
69	66	-200200
60	39	-200200
48	47	-133900
61	60	-5807100
101	100	-491400
101	100	-357500
128	127	-1440400
109	107	-1384500
90	89	-89700
	Heat sink	
18	50	3629600
50	75	2579200
75	85	613600
18	75	625300
18	30	178100
7	120	2333500
95	120	413400
95	124	3126500
85	165	1340300
128	160	871000
21	22	122200
165	170	211900
150	151	715000
150	151	5807100
150	151	737100
200	201	257400
200	201	669500
200	201	245700