EVALUATION OF DEWATERED AND PARTIALLY DRIED SEWAGE SLUDGE COMBUSTION BASED ON ENERGY BALANCE AND CARBON FOOTPRINT

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ABSTRACT

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Aim of this thesis is to evaluate dewatered (wet) and partially dried sludge combustion, based on energy balance, carbon footprint and cost estimations. Thermal processes have advantage of converting sludge into energy. Transition from environmentally risky disposal methods to environmentally friendly innovative thermal processes is crucial. Until innovative technologies are proven to be robust and efficient, mono-incineration is evaluated as the transition technology in sludge management. Sufficient data and easy operation due to being conventional makes mono-incineration an available and applicable thermal process for sewage sludge. Besides, electricity generation has potential to avoid carbon dioxide (CO_2) emissions.

Only mono-incineration is evaluated in this study because in co-combustion applications, sludge disposal is directly dependent on the sectoral dynamics of cement plants or power plants where co-combustion occurs. In this study, six different mono-incineration scenarios are developed. Generally, an autogenous combustion, combustion of a substance without external fuel supply, cannot be achieved for dewatered sludges. Therefore, scenarios are differing by additional fuel consumption in furnaces or partial drying application prior to furnaces. Besides, electric generation is applied in half of the scenarios. For each scenario and each sludge selected, mass and energy balances, carbon footprints and initial cost estimations are conducted. Evaluation criteria are; fossil fuel consumptions, electric consumptions, electricity generations, net CO_2 emissions and initial cost estimations. Scenarios including direct combustion of dewatered sludge with natural gas or partial drying by recovered energy from combustion are advantageous regarding the evaluation criteria. Scenarios including partial drying with external fuel supply do not show any advantage for any of the evaluation criteria.

Keywords: autogenous combustion, auto thermal point, carbon footprint, combustion, energy, lower heating value, mono-incineration, partial drying, sludge

ÖZ

SUSUZLAŞTIRILMIŞ VE KISMİ KURUTULMUŞ ARITMA ÇAMURU YAKMANIN ENERJİ DENGESİ VE KARBON AYAKİZİ BAZINDA DEĞERLENDİRİLMESİ

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Bu tezin amacı susuzlaştırılmış (yaş) ve kısmi kurutulmuş atıksu çamuru yakmanın, enerji dengesi, karbon ayakizi ve maliyet tahminleri yönünden değerlendirilmesidir. Termal prosesler çamuru enerjiye çevirmesi sayesinde avantajlıdır. Çevresel açıdan riskli yöntemlerden çevre dostu yenilikçi termal yöntemlere geçiş çok önemlidir. Yenilikçi teknolojilerin güçlü ve verimli oldukları kanıtlanana kadar, çamur yönetiminde geçiş teknolojisi olarak tek başına yakma değerlendirilmiştir. Konvansiyonel olması dolayısıyla yeterli veri ve kolay işletme, tek başına yakmayı arıtma çamuru için hazır ve uygulanabilir bir termal proses yapmaktadır. Bununla birlikte, elektrik üretimi karbondioksit (CO_2) salınımlarını önleme potansiyeline sahiptir.

Bu çalışmada yalnızca tek başına yakma değerlendirilmiştir çünkü beraber yakma uygulamalarında çamur bertarafı beraber yakmanın gerçekleştiği çimento fabrikaları veya termik santrallerinin sektörel dinamiklerine doğrudan bağlıdır. Bu çalışmada, altı farklı tek başına yakma senaryosu geliştirilmiştir. Genelde, kendi kendine yanma, harici yakıt temini olmaksızın bir maddenin yanması, susuzlaştırılmış çamurlarda erişilememektedir. Dolayısıyla, senaryolar, fırın içerisinde ek yakıt tüketimi veya fırın öncesi kısmi kurutma uygulaması açısından farklılık göstermektedir. Bununla birlikte, senaryoların yarısında elektrik üretimi uygulanmaktadır. Her bir senaryo için, kütle ve enerji dengeleri, carbon ayak izleri ve ilk yatırım maliyet tahminleri yapılmıştır. Değerlendime kriterleri; fosil yakıt tüketimleri, elektrik tüketimleri, elektrik üretimleri, net CO_2 salınımları ve ilk yatırım maliyet tahminleridir. Doğrudan susuzlaştırılmış çamurun doğalgaz ile yakıldığı veya geri kullanılan yakma enerjisi ile kısmi kurutmanın uygulandığı senaryolar değerlendirme kriterleri açısından avantajlıdır. Harici yakıt temini ile kısmi kurutmanın uygulandığı senaryolar hiç bir değerlendirme kriterinde herhangi bir avantaj göstermemektedir.

Anahtar Kelimeler: alt ısıl değer, çamur, enerji, karbon ayakizi, kendi kendine yanma, kısmi kurutma, oto termal nokta, tek başına yakma, yakma

To my family with endless love.

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ABBREVIATIONS

a	: Molar Amount of C in Sludge Feed into Furnace
b	: Molar Amount of H in Sludge Feed into Furnace
c	: Molar Amount of O in Sludge Feed into Furnace
C	: Carbon
CH_4	: Methane
c_{nvm}	: Specific Heat of Non-Volatile Matter
CO_2	: Carbon Dioxide
c_{vm}	: Specific Heat of Volatile Matter
c_w	: Specific Heat of Water
d	: Molar Amount of N in Sludge Feed into Furnace
DM	: Dry Matter
e	: Molar Amount of Sin Sludge Feed into Furnace
E_b	: Thermal energy transferred to steam
$E_{ba,850°C}$	: Energy of Bottom Ash at 850°C
E_{cw}	: Output Energy by Condensed Water
E_{cool}	: Energy Lost Due to Cooling of Sludge and Evaporated Water
E_d	: Thermal Energy Required for Drying
$E_{fg,850°C}$	: Energy of Flue Gas at 850°C
$E_{hl,c}$	: Heat Losses In Combustion Furnace Due To Thermal Efficiency
$E_{hl,b}$	: Heat Losses From Waste Heat Boiler
$E_{hl,d}$	: Heat Losses Of Dryer
E_{MAF}	: Energy of MAF Part of Sludge
$E_{ng,c,25°C}$	: Energy Of Natural Gas Input To Combustion
E_{ss}	: Input Energy by Superheated Steam
f	: Molar Amount of H_2O Content of Sludge Feed into Furnace

g : Molar Amount of CH_4 Feed into Furnace

GHG : Greenhouse Gas

H : Hydrogen

H_2 : Hydrogen Gas

H_2O : Water

H_2S : Hydrogen Sulfide

HCL : Hydrogen Chloride

h_{cw} : Enthalpy of pump inflow condensed water

HF : Hydrogen Floride

h_{fw} : Enthalpy of Pump Outflow Feed Water

HHV : Higher Heating Value

h_{ss} : Enthalpy of Boiler Outflow Superheated Steam

$h_{ss,out}$: Unit Enthalpy Of Steam At Outlet From Turbine

$h_{v,T2}$: Enthalpy of Vapor at 100°C

$h_{v,T2}$: Enthalpy of Water at 100°C

LHV : Lower Heating Value

LHV_{MAF} : Lower Heating Value of MAF Part of Sludge

LHV_{ng} : Lower Heating Value of Natural Gas

LH_w : Vaporization Energy of Water in Total Sludge Feed into Furnace

MAF : Moisture and Ash Free

m_{air} : Total Air Supply into Furnace

m_{ash} : Ash Part of Sludge

m_{ba} : Bottom Ash Formed in Furnace

m_{CO2} : Mass Flow of CO_2 in Flue Gas

m_{fa} : Mass Flow of Fly Ash in Flue

m_{fg} : Flue Gas Outflow from Furnace

$m_{fg,b}$: Mass Flow Of Flue Gas Output From Waste Heat Boiler

m_{fw} : Mass Flow of Feed Water Into Boiler

m_{MAF} : Moisture and Ash Free Mass Of Sludge Flow Into Furnace

$m_{H2O, formation}$: Water Formed by Combustion Due to The H Content of Fuels

$m_{ng,c}$: Natural Gas Consumption In Furnace

$m_{N2, air}$: Mass Flow of N_2 in Combustion Air

$m_{N2,fg}$: Mass Flow Of N_2 In Flue Gas

m_{nvm} : Mass Flow of Non-Volatile Matter of Sludge

$m_{O2, air}$: Mass Flow of O_2 in Combustion Air

$m_{O2,fg}$: Mass Flow Of O_2 In Flue Gas

m_s : Total Sludge Amount Fed into Furnace

m_{SO2} : Mass Flow of SO_2 in Flue Gas

m_{ss} : Mass Flow of Superheated Steam Produced in Boiler

m_{vm} : Mass Flow of Volatile Matter of Sludge

$m_{w,c}$: Water Amount In Total Sludge Fed Into Combustion Furnace

$m_{w,d}$: Mass Flow Of Water Content Of Sludge Feed Into Dryer

$m_{w,e}$: Mass Flow Of Water To Be Evaporated

N : Nitrogen

N_2 : Nitrogen Gas

N_2O : Nitrous Oxide

O : Oxygen

O_2 : Oxygen Gas

P_{cw} : Pressure of Condensed Water

P_{fw} : Pressure of Feed Water of Boiler

S : Sulphur

$SE_{fg,850°C}$: Sensible Energy of Flue Gas at 850°C

SO_2 : Sulphur Dioxide

T_1 : Feed Temperature of Dryer

T_2 : Dryer Operation Temperature

W_p : Work Required for Pump

W_T : Work Output from Turbine Per Unit Steam İn Cycle

V : Volume of The Condensed Water

x : Percentage of Excess Air

CHAPTER 1

INTRODUCTION

Management of sewage sludge is a critical issue regarding environmental pollution and energy management as sludge contains a significant energy value (Werther and Ogada, 1999; Houillon and Jolliet, 2005). Sludge amounts are increasing by increasing population and sustainable sludge management gets more difficult and crucial by time. Through a rough estimation, Adar (2016) mentions that daily municipal/domestic sewage sludge production amount is between 1700 and 2600 ton dry matter in Turkey. Nowadays, studies on sludge management focus on comparing various sludge management approaches as incineration, pyrolysis, gasification, combustion, oxidation, anaerobic digestion, land application or landfilling, etc. (Adar, 2016; Samolada and Zabaniotou, 2014; Houillon and Jolliet, 2005). Although comparing these conventional and innovative approaches is important, focusing on a key technology in transition should have been furtherly evaluated because sewage sludge management problem requires not only sustainable but also a rapid solution. In this study, scenarios to be evaluated are created only for mono-incineration, which is selected to be key technology in sludge management transition, while considering dewatered and partially dried sludges having different heating values.

Due to the legislative limitations and efforts on reducing environmental impacts, sewage sludge disposal approaches are being shifted from dumping to recovering the energy and material content (Horttanainen et al., 2010). Agricultural use leads to benefiting from the nutrient value of sludge, yet, there is a risk on environment and human food chain due to unwanted substances. Besides, thermal approaches are used to recover the energy value of sludge (Fytili and Zabaniotou, 2007). Some conventional and developing thermal management technologies as combustion, pyrolysis, gasification, etc. become more common currently. Worldwide technological progresses show that sewage sludge can be regarded as waste, and a potential source of energy at the same time (Werther and Ogada, 1999; Adar et al., 2016).

Carbon content of sludge is stated as biogenic in the Guideline of IPCC Intergovernmental Panel on Climate Change (IPCC, 2006b) and municipal and non-hazardous industrial sludges are considered as biomass according to the Turkish Regulations. These international and national statutes create opportunity for considering sludge as a local and renewable energy source. Currently, climate change is a significant threat and main contributor of global warming is greenhouse gas emissions due to fossil fuel utilization. Share of alternative non-fossil energy sources should be substituted for fossil fuels as soon as possible to control this global threat (IPCC, 2006b). Energy balance and contribution to climate change should be analyzed as well while evaluating sewage sludge management approaches. Energy recovering sludge management technologies such as combustion, pyrolysis or gasification methods have potential to decrease the share of fossil fuels in energy generation.

Although there have been worldwide progresses in thermal technologies, landfilling and agricultural use of sludge, such as land application, are still among common applications. Gasification and pyrolysis are not new technologies but they are still in progress and have not been commercialized enough. On the other hand, incineration is also a common application but it is not applied in every country (Adar et al., 2016).

In this study, sludge is considered as an alternative and local energy source. Sludge is produced in most of the wastewater treatment plants and should be managed effectively. Although pyrolysis, gasification and other innovative technologies are being developed to make use of the energy content of sludge, these technologies have not been fully commercialized yet. A robust and well known technology is required to be evaluated as a transition technology in sustainable sludge management. Therefore, incineration or combustion based technologies are still favorable and constitute the conventional technologies until other above mentioned technologies are proven to be robust and efficient for various sludge types, management conditions etc. As transition in sludge management from conventional to future promising applications may take some time, there is need for improvement in the efficacy of combustion based sludge management technologies. Numerous accurate data and qualified labor can be found regarding combustion. Especially in Turkey, currently, sufficient know-how and labor is available. Three sludge incineration plants are being operated in Bursa, two more are under construction in Kocaeli and there are also co-combustion applications in some cement factories. In this study, rather than co-combustion in a readily built cement or power plant, on-site mono-incineration applications are evaluated. Objectives of this study are to;

- develop mono-incineration scenarios and create a calculation methodology for these scenarios,
- compare the wet and partially dried sludge incineration with respect to the energy balance and carbon dioxide (CO_2) emissions,
- find the electricity generation potential by different mono-incineration scenarios for sludges having different heating values,
- find the critical sludge heating values where scenarios get carbon neutral or save CO_2,
- find the best scenarios regarding energy balance, C footprint, initial cost estimations and flue gas amounts for different sludges.

Towards these objectives, different from the other comparison studies remaining in literature, six different sludge characteristics are selected and evaluated by six different fluidized bed mono-incineration approach. Scenarios are differing by; dewatered or partial dry sludge combustion, electric generation and/or heat recovery for partial drying. Equations and assumptions are taken from literature and an Excel Goal Seek function based calculation tool is developed and evaluation done by using the calculation tool developed in this study.

CHAPTER 2

LITERATURE REVIEW

2.1.Sewage Sludge

Sewage sludge is a waste from various chemical, physical and biological treatment processes of municipal wastewaters. It can be described as the concentrated residual of wastewater treatment. It contains many constituents harmful to environment and human life. Besides harmful characteristics, raw sewage sludge has nutrients, heavy metals, energy value and significant water content. Therefore, sludge can be a potential source in energy, industry and agriculture sectors (Tchobanoglous et al., 2004; Arjona and Cisneros, 2005). Energy value of sewage sludge is stated in detail in section 2.3.

Composition of sewage sludge is pretty complex (Wasielewski et al., 2013). It differs by the season and weather conditions, treatment methods, location and sources of wastewaters (EIPPC Bureau, 2006). sewage sludge is generally composed of water, organics, pathogens and indicator microorganisms, nutrients, heavy metals and other inorganic (Tchobanoglous et al., 2004; Sanin et al., 2011).

Raw sewage sludge mainly consists of water. Dry content range of raw, mixed primary and secondary sludge is 0.5 - 1.5 % by weight (Tchobanoglous et al., 2004). Organic content range changes as around 60 to 90 % of dry matters (Tchobanoglous et al., 2004). Organic part of the sewage sludge is originating from biological sludge microbial cells and other organic compounds (Tyagi and Lo, 2013). Harrison et al. (2006) states that over 500 organic chemicals are detected in sewage sludge and some portion of this is among the priority pollutants. Some toxic organics remained in non-stabilized sludge are; PCB, PAH, dioxins, pesticides, endocrine disrupters and nonyl-phenols. Moreover, organics are in two forms as biodegradable and non-biodegredable (Tyagi and Lo, 2013Moreover, microbial growth due to the organic part of sludge leads to pathogenic formations, odor and biological decay (Tchobanoglous et al., 2004). Besides, sewage sludge includes nitrogen, phosphorus, potassium and other nutrients in the proteinaceous form, which give sludge a fertilizer value (Tyagi and Lo, 2013).

Table 1– Typical pathogens and indicator microorganisms present in Wastewater sludge (Sanin et al., 2011)

Type	Organism
Virus	Various enteric viruses
Bacteria	Total coliforms Fecal coliforms Fecal streptococci Salmonella sp.
Parasites	Ascaris sp. Trichus Toxocara sp. Helminth eggs

Typical nutrient values for fertilizer and sewage sludge are given in Table 2. Depending on the type of wastewater, sewage sludge contains heavy metals. Presence of them are mostly due to industrial and commercial connections to treatment system (Sanin et al., 2011; Stasta et al., 2006). Metals present in sewage sludge and their typical amounts are given in Table 3. Other inorganics remained in sewage sludge are compounds of silicates, aluminates, calcium and magnesium (Tyagi and Lo, 2013).

Table 2 – Nutrient levels by percentage of typical fertilizer and stabilized sewage sludge based on total solids (Sanin et al., 2011; Tchobanoglous et al., 2004)

	N (% of total solids)	P (% of total solids)	K(% of total solids)
Typical Fertilizer	5	10	10
Sewage sludge after Stabilization	3.3	2.3	0.3

Table 3 - Typical metals present in sewage sludge and their average amounts (Sanin et al., 2011)

Metal	Typical average amount (mg/kg)
Arsenic	10
Cadmium	10
Chromium	500
Cobalt	30
Copper	800
Iron	17000
Lead	500
Manganese	260
Mercury	6
Molybdenum	4
Nickel	80
Selenium	5
Tin	14
Zinc	1700

2.2.Sludge Management

Ensuring environmental sustainability through sanitation is one of the targets in 'The Millennium Development Goals Report' (2013) of United Nations. Sewage sludge management has a significant importance and difficulty in environmental protection (Nadziakiewicz and Koziol, 2003). Sludge should be managed well with respect to the ethical and environmental perspective. Improper disposal has the potential to; harm the environment permanently, affect ecosystems negatively, create hazardous conditions for human health, lead to fire or explosions, create odor and aesthetical problems and cause water, energy, material and financial losses. Sustainable sewage sludge management can be achieved by eliminating the factors affecting environment and by recovering the energy, nutrient and/or material from it. There occurs an opportunity to consider the sludge as a potential source (Sanin et al., 2011; Tchobanoglous et al., 2004; Olajire, 2009).

There are some important applications in the perspective of sludge management issues. First of all, production of sludge should be prevented. Secondly, produced sludge should become suitable for disposal by treatment. Finally, a proper disposal method should be found which can tolerate the disposed sludge without creating negative impacts (Sanin et al., 2011). In addition, Fytili and Zabaniotou (2008) describes five different sludge handling concepts as; prevention, reuse, convert, contain and disposal. As from the waste hierarchy or other studies, 'prevention' of a waste source is the target step to achieve. Secondly, 'reuse' option includes the usage of chemicals or nutrients for other purposes. The step 'convert' is conversion of the substances in sludge for recovery of energy or proper disposal. 'Contain' option is to eliminate the hazardous properties of sludge prior to disposal by treatment of sludge. Finally, proper 'disposal' is to disperse sludge into environment by ensuring that the long term negative effects are eliminated.

Since water has the major share in amount, water removal is crucial for management approaches. Decreasing the content of water leads a reduction of sludge volume. By that way transportation and further treatment costs get less due to reduction of; amount, energy, chemical and bulking agent requirements, leachate production, decomposition and odor problems. Removal of water can be achieved by three main operations; thickening (almost compulsory for all other further treatment approaches), dewatering and drying(Tchobanoglous et al., 2004; Arjona and Cisneros, 2005). By thickening, mostly a gravitational approach for water-solid separation, 10 % dry matter content can be achieved. Mechanical dewatered sludge (wet sludge) typically has 25 % dry matter content and if conditioning (thermal or chemical process used to increase the effectivity or dewatering or stabilization processes) is applied dry matter can be increased up to 35 %. By a thermal drying (evaporation), sludge can be dried up to over 90 % dry matter content (Werther, 1999). Typical dry matter and water contents of sewage sludge after these water removing processes are given in Figure 1.

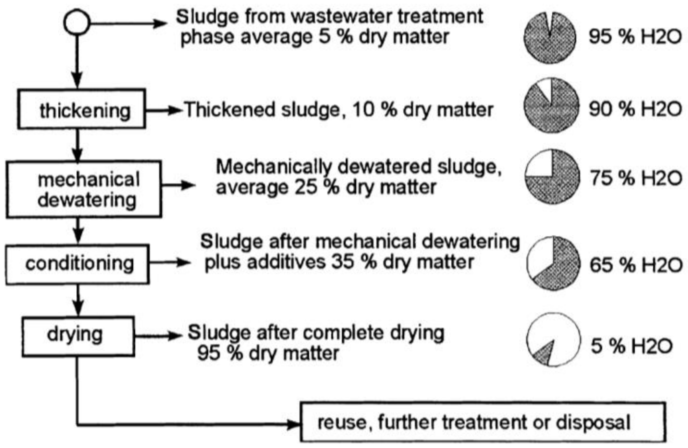

Figure 1– Typical dry matter and water contents of sewage sludge after different water removing processes (Werther, 1999)

Sludge should also be stabilized according to final disposal method. Stabilization may be occurred through enabling bioactivity by degrading organics or destruction of pathogens. While digestion can reduce organics between 30 to 60 %, almost all of the volatile/organic content is oxidized in incineration (Tchobanoglous et al., 2004; Stasta et al., 2006). Also, 45 % of organic solids content is decomposed in composting (Suh and Rousseaux, 2002). Alkaline stabilization has no effect on organic content but pathogen destruction occurs due altered pH. Moreover, increased temperatures in thermal drying method also destructs pathogens (Tchobanoglous et al., 2004; Stasta et al., 2006). Stabilization of sludge may be done in some levels through the methods given in Table 4.

Anaerobic treatment of wastes one of the most common and old treatment methods (McCarty, 1988). Digestion improves the feasibility of further treatment approaches as it decreases the sludge volume, increases the dewaterability and provides stabilization and partial storage (Werther and Ogada, 1999). By anaerobic digestion, organic part is partially converted into biogas and digestion leads decrease in dry matter, as well as in amount of sludge. (Tchobanoglous et al., 2004). On the other hand, decrease in organic matter due to digestion leads to decrease in energy value of remaining sludge, which creates a disadvantage in combustion of sludge (Çelebi, 2015).

Table 4- Common approaches that stabilizes sludge (Fonda and Lynch, 2009; Tchobanoglous et al., 2004; Stasta et al., 2006)

Treatment Method	Stabilization Achieved
Aerobic/Anaerobic Digestion	Partial biodegradation of volatile matter by aerobic or anaerobic bacteria
Composting	Partial biodegradation of volatile matter with bulking agent addition
Alkaline Stabilization	Destruction of pathogens by creating unsuitable medium for bioactivity by increasing the pH
Thermal Drying	Destruction of pathogens by creating unsuitable medium for bioactivity by increasing the temperature and removing significant amount of water
Thermal Processes (combustion, pyrolysis, gasification, etc.)	Oxidation or thermal conversion of organics, destruction of pathogens

After proper treatment of sludge (water removal, stabilization, etc.) disposal method should be selected. There are several final disposal approaches that have been implemented as given below (Werther and Ogada, 1999; Sanin et al., 2011; Tyagi and Lo, 2013);

- Dumping into sea/ocean

- Disposal into landfill
- Agricultural, silvicultural and horticultural usage
- Mono-incineration
- Co-combustion in waste treatment, energy production or building material manufacturing (cement, concrete, etc.) sectors
- Other thermal processing alternatives like pyrolysis, gasification, etc.

Currently, dump into sea/ocean method has been banned in many countries (U.S.A., England, EU countries, Turkey, etc.). Landfilling is not a promising solution because landfilling increases the risks of groundwater pollution due to leachate. Also, in landfills anaerobic decomposition of sludge produces landfill gas (main components are CH_4 and CO_2), creates fugitive emissions and increases explosion risks. Although being a renewable energy source while recovered, unrecovered landfill gas is a significant greenhouse gas source. Thus, limitations are mostly based on volatile matter and dry matter content of sludge(Werther and Ogada, 1999; Sanin et al., 2011; Tyagi and Lo, 2013).

Agricultural usage of sludge is a method for recycling the nutrients back to the nature and for soil conditioning. In that case, heavy metals, pathogens and some other toxic characteristics are the major concern. Sewage sludge nutrient value is similar to typical fertilizer. Land usage of sludge can also be assessed as a soil conditioning process especially in semi-arid, arid and disturbed areas. Water content, organic content and soil porosity can be enhanced by sewage sludge application to soil (Sanin et al., 2011). On the other hand, agricultural usage of sewage sludge is expected to decrease in future despite the increasing amounts of sludge and wastewater production. Main reason for this is the concerns of creating a direct contact of sludge with environment and regulatory restrictions based on this application (Stasta et al., 2006). Pathogens or disease causing microorganisms are hazardous for human health. Also, decomposition of organic part leads to a decrease in O_2 levels in receiving bodies. As mentioned previously, stabilization processes are commonly used for dealing with these adverse impacts (Tchobanoglous et al., 2004; Werther and Ogada, 1999). Heavy metals are also critical when sludge is applied in agriculture since their adverse impacts on environment according to their disposal types. They are toxic for human health, animals and plants. Some heavy metals, on the other hand, provide plant growth even in trace amounts (Sanin et al.,2011). Nevertheless, heavy metal accumulation in soil creates important problems. (Yaman, 2009; Sanin et al., 2011). Additionally, agricultural fertilization takes place at most twice in a year to a land, yet the sludge is being produced daily during the year. Thus, storage of sewage sludge is required (Fytili and Zabaniotou, 2008). Also, ethical problems in society occur due to land application. Public acceptance should be provided while applying this disposal method (Stasta et al., 2006).

Besides those, thermal processing is another approach for sludge disposal. It has beneficial consequences as; stabilization of sludge, volume reduction and energy recovery possibility. Common methods; mono-incineration and co-combustion technologies, are stated to emit less GHG with respect to the landfilling of sludge. Those processes; emit zero CH_4 emissions, odorless, suitable for energy recovery and have fossil fuel reduction potential. Provided emission control sections are included to these technologies, thermal processing of waste contributes positively to sustainable development (Bogner et al., 2008). Thermal processes are mentioned in detail in section .

2.3.Evaluation of Sewage Sludge as an Alternative Energy Source

Sewage sludge is generated locally and accepted to contain no fossil carbon within (IPCC, 2006b). Energy of sludge can be harvested as heat from incineration (solely or with other fuels/wastes), biogas, landfill gas, microbial fuel cells or bio-fuel production through several management methods (Tyagi and Lo, 2013).

Sludge is considered as local and alternative energy source in this study. To maintain the energy security and decrease the dependency rate on foreign sources, policy makers are targeting efficient domestic energy source usage (Ozturk, 2014). Therefore, energy production from sludge also contributes to energy security.

High energy is consumed during treatment, transportation and disposal of sludge, as well as production of chemicals to be used in wastewater and sludge treatment. Thus, the energy balance should be evaluated carefully to sustain an effective solution (Remy et al., 2011). For instance, the highest heating value of sludge can be achieved after water removal by thermal drying, while that is a significant energy consuming approach (Arjona and Cisneros, 2005). If sewage sludge management approaches are assessed and chosen properly, wastewater treatment plant can be energy independent, furthermore, produce excess energy to make profit (Houdkova et al., 2008).

There is a non-negligible energy production potential from sewage sludge. Calorific value and composition of sludge are among the most important decision criteria in sludge management (Stasta et al., 2006). Water content is a very important parameter for calorific value. According to the data available in the study of Stasta et al. (2006), as water content increases, heating value per total sludge mass decreases linearly, which means, heating value per dry mass decreases ascendingly. Therefore, dehydration processes as dewatering or drying contribute to increase the heating value of total sludge per mass (Li et al., 2012; Stasta et al., 2006).

Some stabilization methods affect the calorific value of sludge directly. Lime addition, for instance, increases the inorganic amount and decreases the heating value based on total mass. Furthermore, digestion decreases the amount of organics, correspondingly the heating value of sludge. On the other hand, biogas, produced by utilization of biodegradable organics through anaerobic digestion, has also a significant heating value. (Werther and Ogada, 1999)

Digested dry sludge have similar lower heating value with brown coal (21 MJ/kg), (Stasta et al., 2006). Werther and Ogada (1999) also states that after digestion, lower heating value of sludge decreases from 17.5 to 10.5 MJ/ dry kg (Werther and Ogada, 1999).

Table 5 shows the typical lower heating values of several fossil fuels, sludge and biogas.

Table 5– Lower heating values (LHV) of several fuels and sewage sludge (IPCC, 2006a; Arjona and Cisneros, 2005; Turovski and Mathaiy, 2006; Werther and Ogada, 1999)

Fuel Name	Lower heating value (MJ / dry kg)
Anthracite Coal	21.6 – 32.2
Lignite	5.5 – 21.6
Petroleum Coke	29.7 – 41.9
Diesel	41.4 – 43.3
Crude Oil	40.1 – 44.8
Liquefied Petroleum Gas	44.8 – 52.2
Wood/Wood Waste	7.9 – 31.0
Natural Gas	46.5 – 50.4
Biogas	25.4 – 100
Non-Digested Primary Sludge	20 – 28
Non-Digested Secondary Sludge	16 – 22
Digested Sewage sludge	10 – 15
Pyrolysis Oil	29 – 38

2.3.1. Thermal Processes

Thermal processing enables a significant volume reduction by conversion of organic substances into gas, liquid and solid end products by supplying high temperatures and suitable process-specific medium. Energy can be recovered by thermal processes by produced heat or by utilization of some end products as syngas, bio-oil, etc. Treatment alternatives are differing mainly based on the most important two parameters: temperature and the characteristics of the medium provided (Bilitewski et al., 1996; White et al., 1995). Common alternative thermal processing temperatures and descriptions are given in Table 6.

Table 6 – Common thermal processing options and operation temperatures (Sanin et al., 2011; Werther and Ogada, 1999; McKendry, 2002; Bilitewski et al., 1996; Bilitewski et al., 1985; White et al., 1995)

Name of Process	Temperature of Process (^0C)	Definition
Wet oxidation	150 – 330	Oxidation of organics in aqueous medium with oxygen or air supply.
Pyrolysis	300 – 900	Decomposition of organic matter in inert atmosphere with no oxygen.
Gasification	800 – 900	Conversion of organic matter with steam or air into gaseous products.
Combustion	800 – 1500	With air supply, oxidation of all burnable content by mono-incineration or co-combustion.

Sewage sludge can be mono-incinerated in scope of waste management and energy production or co-combusted with fossil fuels in power plants or cement factories. Many high energy consumption industries such as cement industry are in the search of alternative clean and low cost fuel sources as sewage sludge (Olajire, 2009; Arjona and Cisneros, 2005; Shih et al., 2005; Stasta et al. 2006). Additionally, heavy metal content of sludge can play a raw material role in cement production (Shih et al., 2005).

Some other thermal processing methods, producing bio-fuels with significant heating values, are still in progress and require more researches and time to be proven, such as gasification and pyrolysis (Tyagi and Lo, 2013). Those methods are being developed since 1970's and they are different from incineration. Rather than energy recovery, chemical value is recovered in pyrolysis and gasification, which can be used for energy production too. There are combinations of pyrolysis, combustion and gasification. Main aim of pyrolysis and gasification are to produce valuable by-products and create a low emission disposal (EIPPC Bureau, 2006). Sludge thermal process applications for EU are given in Table 7.

Table 7 – Thermal Processing applications for sludge (EIPPC Bureau, 2006)

Thermal Process	Technology	Application on Sludge
Combustion	Grate	Not Normally Applied
	Rotary Kiln	Applied
	Fluidized Bed	Widely Applied
	Hearth Furnaces	Not Normally Applied
Pyrolysis		Rarely Applied
Gasification		Rarely Applied

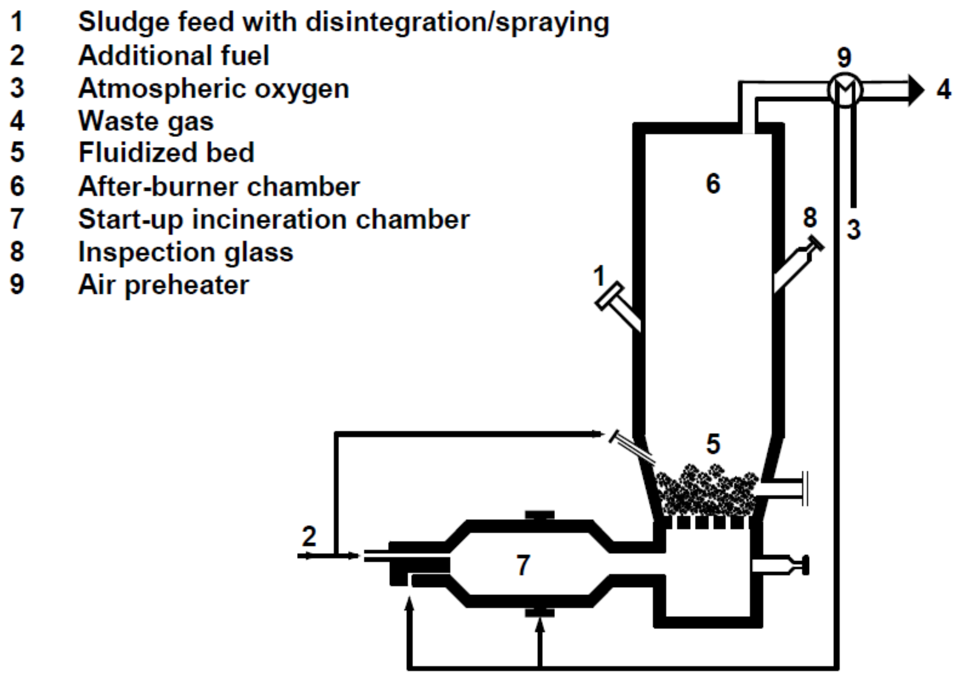

Figure 2 – An Example Fluidized Bed Incineration Flow Scheme

As widely applied technology is fluidized bed incineration according to EIPCC Bureau (2006), an example incinerator configuration is given in Figure 2. Fluidized bed incineration is mentioned furtherly in section 2.3.1.1.1. Also, thermal processes are stated in detail in following sections.

2.3.1.1.Combustion

Combustion is a rapid oxidation of organics by air supply, in a temperature range of 800 to 1500 C. Products of the combustion process are ash and flue gas (Werther and Ogada, 1999). Lasse (2013) states that recent models show even CH_4 combustion has 277 elementary steps and 49 species.

Ragland and Bryden (2011), generalizes the combustion reaction for hydrocarbon fuels including oxygen and by considering the N_2 gas as below:

$$C_aH_bO_c + \left(a + \frac{b}{4} - \frac{c}{2}\right)(O_2 + 3.76N_2) \rightarrow aCO_2 + \frac{b}{2} H_2O + 3.76\left(a + \frac{b}{4} - \frac{c}{2}\right)N_2 \quad (1)$$

Other than CO_2 and H_2O, some possible flue gas components are; heavy metals, solid particles, NO_x, N_2O, SO_2, HCl, HF, hydrocarbons, dioxins and furans. Although those components are harmful for environment and human health, they can be eliminated through efficient burning temperatures, effective combustion process and flue gas treatment. Energy production through combustion is done by the help of flue gas since heat of the flue gas is utilizable and recoverable. (Werther and Ogada, 1999)

Combustion technologies are mature, correspondingly availability of adequate experience is one of the advantages of combustion technologies (Adar et al., 2016). For sewage sludge combustion; fluidized bed, rotary kilns, multiple hearth incinerators and grate-firing systems (for co-combustion) are used in general (EIPPC Bureau, 2006). Two main combustion approaches, mono-incineration and co-combustion are mentioned in below.

2.3.1.1.1. Mono-Incineration

Schwarz (1982) defines common incineration technologies as fluidized bed and multiple hearth furnaces. In 1999, Werther and Ogada predicts that common mono-incineration technologies are going to be fluidized bed and multiple hearth in future. Moreover, incineration of sewage sludge is particularly mentioned in Reference Document on the Best Available Techniques for Waste Incineration of European Commission Integrated Pollution Prevention and Control Bureau - EIPPC Bureau

(2006) as; the best available technique for sewage sludge mono-incineration is mainly fluidized bed technology. The reason is; with respect to the other sludge incineration technologies, fluidized bed incineration is more efficient due to combustion efficiency and lower flue-gas in volume than other combustion processes (EIPPC Bureau, 2006).

Due to legal obligations and process requirements, there are strict process temperature rates for mono-incineration. Flue gas, therefore, is generated at high temperatures. Energy production is possible through waste heat recovery from hot flue gas and also from ash cooling. Recovered energy can be used in several methods such as steam production or feed air pre heating. Produced steam can either be used in processes or for electricity generation. (Werther and Ogada, 1999)

In fluidized bed technologies, quartz sand is used as bed material. Sludge contacts and mixes through the sand and by that way; sludge aggregate fragmentation, rapid drying, organic matter separation, combustion and mineral calcination occurs (Turovski and Mathaiy, 2006). Fluidized bed technology is applicable especially for wastes with low calorific value and high water content such as sewage sludge. Pre-drying of sludge or pre-heating of combustion air is commonly required. Fluidized bed systems have several advantages over other technologies. Turbulence due to mixture of bed material creates an efficient oxidation of combustible matter. Moreover, air-gas turbulence created in freeboard section and thermal stability of bed material leads a very effective combustion. NOx and CO formations are lower in fluidized bed plants than other technologies due to the effective combustion and other design properties (Caneghem et al., 2012).

2.3.1.1.2. Co-Combustion

Co-combustion is considered to be benefiting from the heating value of sewage sludge in high-energy consuming industries, municipal waste combustion plants or in power plants. Sludge is combusted together with main fuel or waste source of those plants (Stasta et al., 2006; Werther and Ogada, 1999). Some high energy consuming industries invest on co-combustion of sludge with fossil fuels in order to achieve an environmental friendly and cheap energy management solution. All in all, provision of the marketability of sludge is required for beneficial usage options (Arjona and Cisneros, 2005).

In power plants, by adding sewage sludge as alternative fuel source, thermal output of the boiler, air required for combustion, volume and composition of flue gas, ash and slag amounts and heavy metal emission values is excepted to change (Nadziakiewicz and Koziol, 2003). Hong et al. (2013), indicates that environmental problems and responsibilities of coal fired power plant increase when sludge is co-combusted; due to sludge related emissions and ash, sludge treatment, electric demand. Werther and Ogada (1999) also presents that ash amount increases in a fluidized bed co-combustion of coal and sludge by increasing sludge feed share.

From a different perspective, according to Stasta et al. (2006), if the amount of sewage sludge to be co-combusted be low enough when compared with the original fuel source amount (~5 % of fuel), combustion process does not be affected adversely. By that way, investment cost will be low, combustion temperature will not be adversely influenced and no extra emission control applications will be required except the current control system in plant (Stasta et al., 2006).

Other than power plants, co-combustion is being implemented mostly in cement production plants or in brick producing plants. Cement production process temperatures may be up to 2000 °C. Sewage sludge amount should not exceed 5 % of the clinker produced in weight in order to maintain clinker quality. Emissions – especially SO_2 and HCl – may be affected adversely according to the characteristics of sludge. (Werther and Ogada, 1999)

Stasta et al. (2006) compares the heavy metal content of sludge, raw material and fuel used in cement works. Commonly; coal, heavy fuel oil, coke or natural gas is used in rotary kilns in cement factories. According to their study, by comparing with clinker, sludge contains; higher cadmium and mercury, lower zinc copper and lead and comparable nickel, chromium and arsenic. Fixing of these metals successfully in clinker is part of the process. This can be called as an environmental friendly waste-to-energy disposal option since gaining energy from sewage sludge saves from major fossil fuel source, raw materials and correspondingly the GHG emissions. After combustion process, ash produced by sewage sludge is fixed in clinker and reduces one third of raw material requirements. Non-emitted S, Cl, alkali and heavy metals in sludge ash are bounded while clinker production, though, no solid waste is produced during the co-combustion of sewage sludge in cement plants. (Stasta et al., 2006).

Net energy balance should be assessed well for co-combustion disposal option. To be the process feasible, sludge should be at least 90 % dry for suitability of cement kiln. Therefore, thermal drying, which is also a significant energy consuming process, is a prerequisite for co-combustion. Waste heat from cement works can be used for sludge drying. On the other hand, dried sludge has a potential to substitute some amount of the required fossil fuel because it is an alternative energy source and can lead to fossil fuel savings by co-combustion. (Stasta et al., 2006; Arjona and Cisneros, 2005).

2.3.1.2.Pyrolysis

Pyrolysis is the thermal decomposition of organic matter in an O_2 free atmosphere with a temperature range between 300 °C up to 900 °C. Through complex thermo-chemical reactions, organic matter converts into pyrolysis gas, char and oil from sludge (OFS). These products can be used as a fuel or raw material source in energy production or petrochemical production sectors. Main components in pyrolysis gas are; H_2, CO, CO_2, CH_4 and hydrocarbons. Process temperature and sludge characteristics affect the share of these components and amount of pyrolysis gas. (Sanin et al., 2011; Werther and Ogada, 1999)

Pyrolysis technologies have not been fully commercialized yet. Therefore, there are many uncertainties in market for pyrolysis technology. But still, there is a significant progress in researchs and applications. Also, like most thermal treatment methods, pyrolysis has a potential to increase the energy independency. Bio-oil from pyrolysis is a promising source of renewable energy (Adar et al., 2016). Oil obtained from pyrolysis has a high heating value in the range of 29-38 MJ/kg (Werther and Ogada, 1999). Solid by-producs, in addition, are available to landfill, incinerated or used as fertilizer. Another advantage of pyrolysis is flue gas treatment requirements are much lower than incineration (Adar et al., 2016).

2.3.1.3.Gasification

Gasification is a chemical reaction series under high temperature. Solids are converted into gaseous form. Generally, products are; H_2, CO, CH_4, CO_2, $H_2O$and N_2 (in case of air usage rather than Oxygen) and ash. % 90 dry sludge gasification is more efficient than wet sludge gasification where process is designed for dewatered sludge (Sanin et al., 2011).

Different from combustion, air is used in gasification is lower than stoichiometric requirement. Since the formed gas is aimed to be burned in gasification; H_2, CO and CH_4 formation enhances the generated energy amount, where, CO_2 and H_2O reduces. (Ragland and Bryden, 2011)

Ash generation is a handicap. Also, there is a risk of pollutant remaining at gas. Gasification is not a mature technology, thus, there are not sufficient information and qualified stuff when compared with incineration. However, many researches and proven applications are available. There are several gasification technologies combined with incineration and pyrolysis. Gasification gas has a calorific value around 4 MJ/m3 where the potential for renewable energy production is high. (Adar et al., 2016)

2.3.2. Effect of Drying on Thermal Processes

Commonly, external sludge drying before incineration process or additional fuel supply may be essential in order to eliminate the negative effect of sludge water content on incineration (EIPPC Bureau, 2006). For combustion without additional fuel, states Werther and Ogada (1999), dry matter content should be much more than the amount achieved after dewatering.

According to Oleszkiewicz and Mavinic (2001), for the best management solutions while targeting energy recovery, optimum sludge should have 90 to 95 % dry solids content, maximum heating value and minimum transportation route distance to the sludge utilization facility. Additionally, Arjona and Cisneros (2008) mentions that water amount should be 10 % by total mass in order to consider sludge as a fuel.

Moreover, if external drying is going to be applied prior to incineration, the generated heat from incineration process should be used while considering the best available technic. (EIPPC Bureau, 2006). Especially, co-combustion, pyrolysis and gasification processes require drying (Werther and Ogada, 1999).

Çelebi (2015), states that the highest energy can be gained with thermal drying and mono-incineration of non-stabilized sludge. In their study, indeed, direct incineration of non-stabilized, dewatered sludge is not considered in scenarios.

In combustion, moisture due to wet (dewatered) sludge burning causes a temperature decrease (especially in cement processes) and increases the flue gas amount, correspondingly the flue gas treatment costs (Stasta et al., 2006). However, flue gas is the energy source obtained from combustion (Murakami et al., 2009; Houillon and Jolliet, 2005). Therefore, the increased hot flue gas amount due to wet sludge combustion can also be considered as increased energy recovery potential.

According to EIPPC Bureau Guidelines, contrary to other processes, it is suitable to feed wet sludge into the mono-incinerators, especially if sludge is at auto-thermal point. While depending on characteristics of sludge, auto thermal point can be achieved in around 35 % dry matter content Therefore, external drying is not a necessity provided the sludge is thermally suitable for mono-incineration (EIPPC Bureau, 2006). If sludge is not at its auto-thermal level, in other words if combustion cannot be done autogenously, there is still no strict requirement for drying since auxiliary fuel supply into process is applicable. Dewatered or semi-dried with 20 to 60 % dry content sludge feeding is common in mono-incineration. In fact, Multiple hearth furnaces are commonly operated with wet sludge and fluidized bed reactors are with both wet and partially dried sludge (Werther and Ogada, 1999). Moreover, Murakami et al. (2009) states that 70 % of dewatered sludge with 20 % dry matter content in Japan are incinerated in bubbling fluidized bed reactors without external drying and flue gas is used for energy exchange.

Besides the technical applicability and energy efficiency criteria, moisture content plays a role as a buffer. In co-combustion with high calorific valued wastes, water in dewatered sludge has a potential to maintain the high temperature peaks during operation (EIPPC Bureau, 2006).

2.3.3. Biogas

Biogas is produced from partial digestion of organic part of sludge by microbiological activities in anaerobic digesters. In other words, biodegradable part of the organics is converted into biogas through anaerobic bacteria. (Tchobanoglous et al., 2004)

Biogas, produced from anaerobic digestion, has a lower heating value as 22400 kJ / m^3 (Tchobanoglous et al., 2004). Main components of biogas are CH_4, CO_2 and trace amounts of H_2 gas, NH_3, N_2, O_2, CO, H_2S and Cl^- (Tyagi and Lo ,2013).

Through the biogas energy; heat, steam, electricity and mechanical vehicle energy production are common. Also, since biogas is a renewable energy source, all those applications can be invested in carbon credit systems or renewable energy incentives. Combined Heat and Power (CHP) cogeneration systems, production of electricity and heat at the same time from an energy source (biogas, natural gas, etc.), can be adapted to anaerobic digesters to enhance the energy recovery through biogas produced (Tyagi and Lo, 2013).

On the other hand, anaerobic digestion does not provide a complete sustainable disposal. This technology has many benefits regarding energy and stabilization, yet, only some part of organic (30-60 % of organics) is converted into gas and remaining major portion requires further treatment (Adar et al., 2016). Also, converting the volatile part into biogas decreases the energy content of remaining mass. As mentioned before, water and inert parts should be minimized and volatile part should be high in amount for a remarkable calorific value (Tyagi and Lo, 2013). For reduction of water content, thermal treatment methods require significant energy. There occurs an inefficient management when sludge is digested, thermally dried by external fuel and combusted. Then, there is a risk of resulting in negative energy balance (Arjona and Cisneros, 2005). Çelebi (2015), has fully studied the effect of anaerobic digestion on calorific value and found out that incineration without anaerobic digestion provides the highest amount of energy gain. Thus, besides the energy of biogas; remaining sludge calorific value and energy consumptions of treatment methods are critical with regard to energy balance (Tyagi and Lo, 2013).

2.3.4. Landfill Gas

Disposing into landfill creates anaerobic atmosphere for wastes and and there occurs landfill gas release (Tyagi and Lo, 2013). CH_4 ratio in landfill gas is 50 % in general and generation of methane decreases if the disposal site is not anaerobically managed. Furthermore, in soil or compost covered landfills, some part of methane is being oxidized. Methane recovery, on the other hand, is another approach in landfills with a large recovery percentage range of 9 to over 90 %. IPCC Guidelines, indeed, agrees on estimating the recovery as 20 % by considering the numbers of disposal sites and recovery percentages in application. Recovered methane is used for energy production. (IPCC, 2006b)

For many wastes including sludge, a rapidly degrading waste, methane generation may not occur for months after disposal. Also, wastes do not decay linearly. Thus, there are many uncertainties and assumption requirements in estimation of landfill gas generation. (IPCC, 2006b)

2.3.5. Other Products

According to the management alternatives, there are also some bio-fuels (bio-hydrogen, synthetic gas, bio-oil, bio-diesel, etc.) can be produced from sludge and have energy potential (Tyagi and Lo, 2013).

2.4.Basic Review on Sludge Management Methods Comparison Studies

Houillon and Jolliet (2005), evaluated some sludge management scenarios with respect to the energy and GHG emissions through a life cycle assessment study. Assessment is done for 87.6 ton/day wet sewage sludge in France. Evaluated methods are;

agricultural application, wet sludge fluidized bed incineration, wet oxidation, pyrolysis, co-combustion in cement kiln and landfilling. According to the study mentioned above, thermal oxidation processes (wet sludge incineration, co-combustion in cement kiln and wet oxidation) are the most favorable methods with respect to the GHG emissions. Co-combustion, furthermore, is the only method which saves GHG. Emissions from wet oxidation and wet sludge incineration are low with respect to the pyrolysis. Main disadvantage of pyrolysis is the requirement for drying. Although high energy is recovered in pyrolysis, drying consumes the main energy and produces a significant GHG. Land application GHG emissions are higher than pyrolysis and the highest value is for landfill without gas recovery. Regarding the energy balance, all of the methods are energy negative. Land application and wet sludge incineration with heat recovering methods have the lowest net energy demand.

Samolada and Zabaniotou (2014) conducted a SWOT analysis for Greece to compare sludge incineration, pyrolysis and gasification. Four comparison criteria are used for assessment as; solution to the problem, GHG emissions, technology maturity and legislation. Result of the study of Samolada and Zabaniotou (2014) is summarized in Table 8.

Table 8 – Comparison results of the study of Samolada and Zabaniotou (2014) done for Greece

Criteria	Incineration	Pyrolysis	Gasification
Solution to Problem	Very Poor	Very Good	Very Good
GHG Emissions	High	Low	Moderate
Technology Maturity	Large Pilot Scale	Pilot Scale	Pilot Scale
Legislation	Advanced	Advanced	Acceptable

Study of Samolada and Zabaniotou (2014) is done for Greece and pyrolysis is determined to be the most promising method. Major differences between incineration and other processes are; incineration can be energy deficit and it is not a zero waste method.

Significant amount of sludge produced in Greece is exported to be incinerated (Kelessidis and Stasinakis, 2012). This might be the reason that Samolada and Zabaniotou (2014) states the incineration application is ‘large pilot scale’. Many researches (Turovski and Mathaiy, 2006; Murakami et al., 2009; Kelessidis and Stasinakis, 2012) show that sludge incineration is a widely applied plant scale method in many countries.

In their study, Adar et al. (2016), compared five energy recovering methods; anaerobic digestion, incineration, pyrolysis, gasification and supercritical water gasification for Turkey. Comparison is done through combination of SWOT with Fuzzy analytical hierarchy process. Four criteria are used and weighted for this assessment; problem solving, greenhouse gas emissions, technological development and legal. Regarding problem solving and greenhouse gas emissions criteria, supercritical water gasification is stated to be the best method. Weight value (value given by author to each criteria for comparison) given for other methods are very low, even incineration has no weight value for these criteria. Adar et al. (2016) states that incineration efficiency is dependent to sludge characteristics and emissions from incineration are harmful. Regarding technological development, anaerobic digestion and incineration are two methods only have weight. This is because other methods are still in progress and not mature enough. Weight values of all methods for legal criterion are low since it is stated that in Turkey all of those methods are linked to same regulation. However, supercritical water gasification has a higher weight value for this criterion. In result, although it is mentioned that the technology is still lab-scale, supercritical water gasification is decided to be encouraged due to low GHG emissions, high efficiency, clean by-products and high energy recovery potential.

2.5.Sewage sludge and Climate Change

2.5.1. Climate Change; Sources, Impacts and Acts

Climate change is defined by Intergovernmental Panel on Climate Change (IPCC) as the change in average or various climate characteristics for longer than 10 years due to the natural or artificial effects. United Nations Convention on Climate Change (UNFCCC), however, defines it as the change of global atmospheric characteristics and variability for the comparable time slots due to the artificial reasons (IPCC, 2007). Average global temperature has been observed to have an increasing trend due to increasing greenhouse gas (GHG) levels in atmosphere since 1750's, hence; the threat that humanity is currently face-to-face is global warming (IPCC, 2007). CH_4 and N_2O have much greater global warming potential than CO_2. Yet, the quantity of CO2 corresponds the 77% of the anthropogenic GHG emissions with respect to the 2004 data. As long as the artificial GHG emissions are being emitted, the change of the global climate will be continued and impacts will be observed more obviously at the end of 21th century (IPCC, 2007).

Table 9 – Some Important Progress Regarding Climate Change by date (Sayman et al., 2014; UNFCCC, 2018)

Date	Event / Act
Before 1950	CO_2 has been estimated to increase 40 ppm since 1950's
1975	'Global Warming' notion has been created
1988	CO_2 have reached a very critical value; 350 ppm
1990	1st IPCC Report has been published
1992	UNFCCC has been signed
2005	Kyoto Protocol have become valid
2009	2^0C global temperature limit has been decided (COP15)
2013	CO_2 have reached ~400 ppm
2015	Intended Nationally Determined Contributions submissions are done for Paris Agreement (COP21)

While the annual average CO_2 amount in the atmosphere was around 356 ppm in 1992, global amount in 2012 was increased to 394 ppm and got close to 400 ppm in May 2013 (Olivier et al., 2013). Official website of U. S. Department of Commerce / National Oceanic & Atmospheric Administration reports the global CO_2 data is over 400 ppm at the end of 2017 (URL 2). Worldwide important issues about climate change are listed in Table 9.

2.5.2. Relationship Between Sludge Management and Climate Change

Biologically based wastes are categorized as Carbon-neutral in 'Guidelines for the use of LCA in the waste management sector' of Bjarnadottir et al (2002). Correspondingly, Carbon in sewage sludge is treated as non-fossil based in IPCC Guidelines (2006b). CO_2 emissions from sewage sludge management approaches are divided into two; fossil and non-fossil (biogenic) emissions. Fossil based CO_2 is emitted due to utilization of fossil fuels and biogenic CO_2 is due to degradation of sewage sludge (Houllion, 2005).

Biomass is accepted to consume the non-fossil C, such as atmospheric CO_2, during the growth. Therefore, emitted CO_2 during the utilization process is stated to be already in the carbon cycle. Net effect of these emissions on global CO_2 amounts is negligible at long scale. Sewage sludge, for instance, is stated to have zero fossil carbon content. CO_2 emissions from these carbon-neutral resources are called biogenic CO_2 emissions. Sewage sludge is a renewable, domestic and non-fossil energy source, which makes it a suitable source for climate change action plans. Also by that way energy production from sludge has a contribution to energy security and energy source diversification (Murray and Price, 2008; Frijns, 2012; IPCC, 2006a; Lim, 2012).

2.6. Regulations and Applications on Sewage Sludge Management

It is mentioned in regulatory report on disposal and recycling routes for sewage sludge, that, agricultural use of sewage sludge has specific national and European legislations, while other disposal options are discussed in general laws (European Communities, 2001).

According to EU laws, suitable reuse of wastewater sludge must be implemented when possible, through disposal options having minimum negative environmental impacts. EU laws enable different sludge disposal methods with specific limits. Sewage sludge is considered to be an alternative fertilizer. Sludge can be applied on lands only if it does not harm the soil and agricultural products. There are strict limitations the heavy metal concentrations. Also it is mandatory to monitor sludge and soil and reduce the fermentability of sludge before agricultural usage. Besides, it is forbidden to apply sludge on certain types of crops and let grazing animals access to the lands before 3 weeks after land application of sludge. Biodegradable waste disposal by landfill method is also considered in EU laws. By 2016, 35 % reduction in weight is mandatory based on the amounts of 1995. In order to ensure environmental safety, there are also strict limits for emissions from incineration of wastes.

According to the German 'Technical Guide on the Treatment and Recycling Techniques for Sludge from municipal Wastewater Treatment with references to Best Available Techniques (BAT)' (2014), document, landfilling shall be the last option if no other disposal methods are appropriate. Also, for agricultural usage, national limits shall not be exceeded, soil shall be tested for sludge application suitability and monitored after sludge application. Share of the sludge management alternatives for 15 EU old member countries for 1992 to 2005 are given in Figure 3.

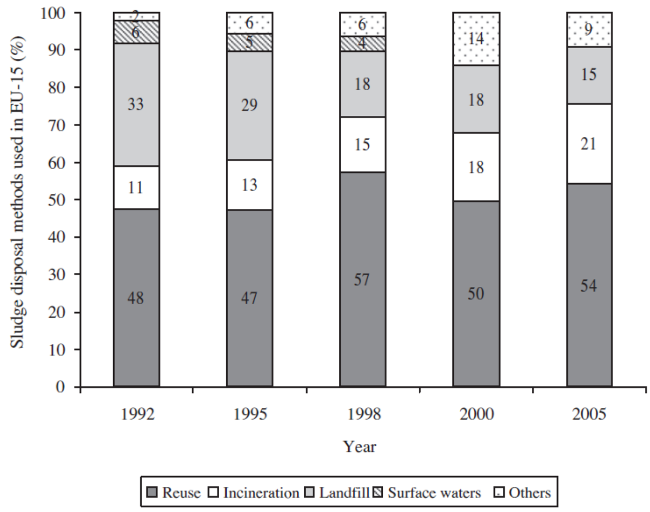

Figure 3 – Sludge management methods shares for 15 EU member countries between 1992 – 2005 (Kelessidis and Stasinakis, 2012).

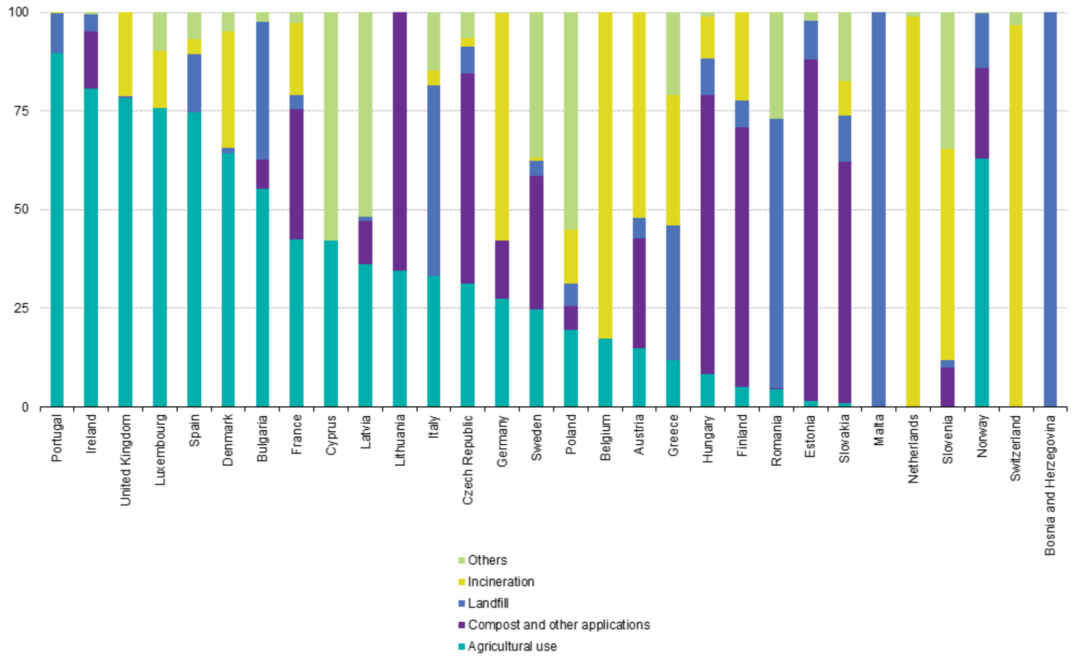

Figure 4 – EU sludge management alternatives percentage share by sludge amount handled (2010, 2012 and 2013 data for some countries) (Eurostat, 2018)

According to the Figure 3, for a wide time range, share of incineration is increased and landfilling decreased. Reuse in agriculture percentages are significant between 1992 and 2005. Furthermore, Surface water disposal is no longer a sludge management method after 1998 due to prohibitions. (Kelessidis and Stasinakis, 2012) Through the information obtained by Figure 4, EU Countries are listed according to their sludge incineration statistics in Table 10.

Table 10 – EU Countries and Their Sludge Incineration Percentages according to the data from 2010, 2012 and 2013 (Eurostat, 2018)

Percentages of Sludge Incineration by Produced Total National Urban Sludge	Countries
≥ 90 %	Netherlands, Switzerland
≥ 75 %	Belgium
≥ 50 %	Germany, Slovenia, Austria
≥ 25 %	Denmark, Greece
< 25 %	United Kingdom, Luxembourg, France, Poland, Hungary, Finland, Slovakia
Very Low Share or No Application	Portugal, Ireland, Spain, Bulgaria, Cyprus, Latvia, Lithuania, Italy, Czech Republic, Sweden, Romania, Estonia, Malta, Norway, Bosna and Herzegovina

By data 2013 of Eurostat, Germany produced 1.8 million ton urban sludge annually and incinerated around 1 million ton/year, which is the largest amount in Europe. Turkish regulations are mostly same with EU directives about environmental management. For instance, sludge incineration, flue gas should remain at 850°C for non-hazardous and 1.100^{0}C for hazardous wastes in secondary combustion at least for

2 seconds in both EU and Turkish regulations. Also, there are limitations of total organic carbon and dissolved organic carbon parameters until 2020. Also, sludge cannot be disposed into landfills if dry matter ratio is under 30 %. Besides, Turkish regulations consider municipal and industrial sewage sludge as biomass, therefore a renewable energy source. Adar (2016) calculates the daily municipal/domestic sludge production as between 1700 and 2600 ton dry matter for Turkey. In recent years, sludge incineration plant investments are increased in Turkey (INEVA Çevre Teknolojileri, 2018; Kuzu Grup, 2018):

- Demirtaş Organized Industrial District (DOSAB) WWTP 93 ton/day dewatered sludge incineration plant, Bursa (operation)
- S.S. Yeşil Çevre Treatment Plant Operation Cooperative 60 ton/day dewatered sludge incineration plant, Bursa (operation)
- BUSKI 400 ton/day dewatered sludge incineration and 2.5 MW electric Generation Plant, Bursa (operation)
- Kullar WWTP 95 ton/day dewatered sludge incineration and 1 MW electric Generation Plant, Kocaeli (under construction)
- Gebze WWTP 95 ton/day dewatered sludge incineration 1 MW electric Generation Plant, Kocaeli (under construction)
- Gazintep Organized Industrial District 240 ton/day dewatered sludge incineration and 2.5 MW electric generation plant (GAOSB), Gaziantep (under construction)

According to the final report of TÜBİTAK-KAMAG Domestic/Municipal Sewage Sludge Management Project, announced at official website of T.C. Ministry of Environment and Urban Planning, S.S. Yeşil Çevre, BUSKİ, Kullar and Gebze plants are stated as municipal or domestic wastewater treatment plants.

Total capacity of incineration plants listed above (by considering also the plants under construction) in Turkey is daily 983 ton dewatered sludge per day, where, 650 ton of this amount is municipal/domestic and 333 ton is industrial sludge. By assuming that dry matter contents are around 25 %, roughly dry mater amount of municipal/domestic sludge to be incinerated is 162.5 ton/day. Therefore, listed municipal/domestic sludge incineration capacities corresponds to 6.25 – 9.55 % of total dry matter production estimation of Adar (2016).

Table 11- Regulations on Sludge Management and Incineration (T.C. Başbakanlık, 2018; European Union, 2018)

Country	Regulations
Turkey	• Waste management regulation (Atık yönetimi yönetmeliği, official gazette date 02.04.2015, issue 29314) • regulation on landfilling of wastes (Atıkların düzenli depolanmasına dair yönetmelik, official gazette date 26.03.2010, issue 27533) • Regulation on the incineration of wastes (Atıkların yakılmasına ilişkin yönetmelik, official gazette date 06.10.2010, issue 27721) • Regulation on certification and support of renewable energy sources (Yenilenebilir enerji kaynaklarının belgelendirilmesi ve desteklenmesine ilişkin yönetmelik, official gazette date 01.10.2013, issue 28783) • Law on the use of renewable energy resources for electricity generation (Yenilenebilir enerji kaynaklarının elektrik enerjisi üretimi amaçlı kullanımına ilişkin kanun, official gazette date 18.05.2005, issue 25819, No. 5346) • Law on the amendment of the electricity market law and some laws (Elektrik piyasası kanunu ile bazı kanunlarda değişiklik yapılmasına dair kanun, official gazette date 17.06.2016, issue 29745, No. 6719) • Regulation on the use of domestic and urban sewage sludge in the soil (Evsel ve kentsel arıtma çamurlarının toprakta kullanılmasına dair yönetmelik, official gazette date 03.08.2010, issue 27661) • Regulation on water pollution control (Su kirliliği kontrolü yönetmeliği (official gazette date 31.12.2004, issue 25687) • Notification of technical procedures of wastewater treatment plants (Atıksu arıtma tesisleri teknik usuller tebliği (official gazette date 20.03.2010, issue 27527) • Regulation on control of soil pollution and point pollution contaminated territory (Toprak kirliliğinin kontrolü ve noktasal kaynaklı kirlenmiş sahalara dair yönetmelik, official gazette date 08.06.2010, issue 27605) • Notification of refuse derived fuel, additional fuel and alternative raw material (Atıktan türetilmiş yakıt, ek yakıt ve alternatif hammadde tebliği, official gazette date 20.06.2014, issue 29036) • Regulation on municipal wastewater treatment (Kentsel atıksu arıtımı yönetmeliği, official gazette date 08.01.2006, issue 26047)
EU	• Council Directive 91/271/EEC concerning urban waste water treatment • Council Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture • Council Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) • Council Directive 99/31/EC on the landfill of waste

CHAPTER 3

METHODOLOGY

3.1.Overview

The methodology given in this chapter is used as a tool for calculation, evaluation and comparison of six combustion scenarios for six different sludges based on energy balances and C footprints. At the beginning, excess air ratio, combustion temperature, heat losses and all other assumptions are done. Combustion furnace is assumed to be fluidized bed because as aforementioned, fluidized bed technology is more favorable for sewage sludge rather than other combustion technologies as rotary kiln or grate furnace regarding combustion efficiency and emissions (EIPPC Bureau, 2006). Typical furnace temperature for fluidized bed sludge combustion is 850 °C (EIPPC Bureau, 2006). Besides, according to Turkish legislation, it is mandatory to sustain the flue gas from combustion of non-hazardous waste at 850 °C for 2 seconds in minimum to minimize emission risks. Therefore, it is assumed that sewage sludge is non-hazardous and the combustion and flue gas temperature is 850 °C. Also, excess air ratio is taken as 1.4 (Schwarz, 1982) of required theoretical air for combustion. Then, six different sludges are selected and their ultimate analysis, dry matter content, volatile matter content and LHV values are calculated and/or defined. Regardless of the scenario number, combustion reactions of all sludges are written and initial mass balances are calculated. After mass balance, the required energy for combustion of the selected sludge at desired temperature is calculated. By knowing the LHV and amount of sludge, input energy is also calculated. If the difference between energy required for 850 °C combustion and energy input is not positive, the selected sludge can be autogenously combusted at desired temperature since input energy is sufficient. However, if the gap is positive, then the selected sludge cannot be combusted at the desired temperature since required energy for this is higher than input energy. These calculations are only done for combustion furnace and regardless of scenarios. Aim is to observe if dewatered sludge energy is enough to achieve 850°C combustion temperature or not. After this, for sludges that input energy is lower than required energy, energy and mass balances are recalculated, by considering the scenarios this time.

Until this step, sludges are evaluated if they can be combusted auto thermally at 850°C. For sludges which are not at their auto thermal point, six scenarios are applied. In scenarios 1 and 2, additional natural gas is fed into furnace to increase the input energy. In scenarios 3, 4, 5 and 6, partial drying is applied in order to remove the adverse effect of water in sludge and decrease the required energy to achieve autogenous combustion. Therefore, two main energy improvements are applied by scenarios.

For scenarios 1 and 2, amount of natural gas and for other scenarios desired drying levels are obtained for each sludge. Either adding natural gas to furnace or removing water from sludge prior to furnace; both leads to differences in energy balance. An iterative calculation method seems to be required but, Excel Goal Seek tool is applied rather than applying manual iterations. Goal Seek is a tool of Microsoft Excel which conducts iterations until the sought value is achieved by changing a selected data (Morris et al., 2011). The target sought value is 0 for the energy gap in this study. For scenarios 1 and 2 changing data is natural gas amount. By obtaining this data, combustion reaction is rewritten. For scenarios 3 to 6, changing data is dry matter content. For these scenarios, combustion reaction is also rewritten. Then for each sludge, mass and energy balances are recalculated for furnace and then calculated for waste heat boiler to find the steam production.

Steam is used in several points in scenarios. In scenarios 2, 4 and 6, electricity generation units are used. Methodology diagram splits into three. In scenario 1, steam is only condensed and recycled to the boiler. Therefore, after waste heat boiler calculations, energy balance and C footprint is completed for overall scenario. In scenario 2, produced steam is used for electricity generation, thus, electricity productions are calculated first and then energy and C footprint of scenario 2 is calculated. For scenarios 3 to 6, energy requirements of drying are calculated. Following step furtherly splits into two, for scenarios 4 and 6, electricity generation is calculated first and then overall calculations are done. For scenarios 3 and 5, after dryer calculations, directly energy balance and C footprint calculations are completed since these scenarios do not include electricity generation application. This calculation methodology is illustrated in Figure 5 briefly.

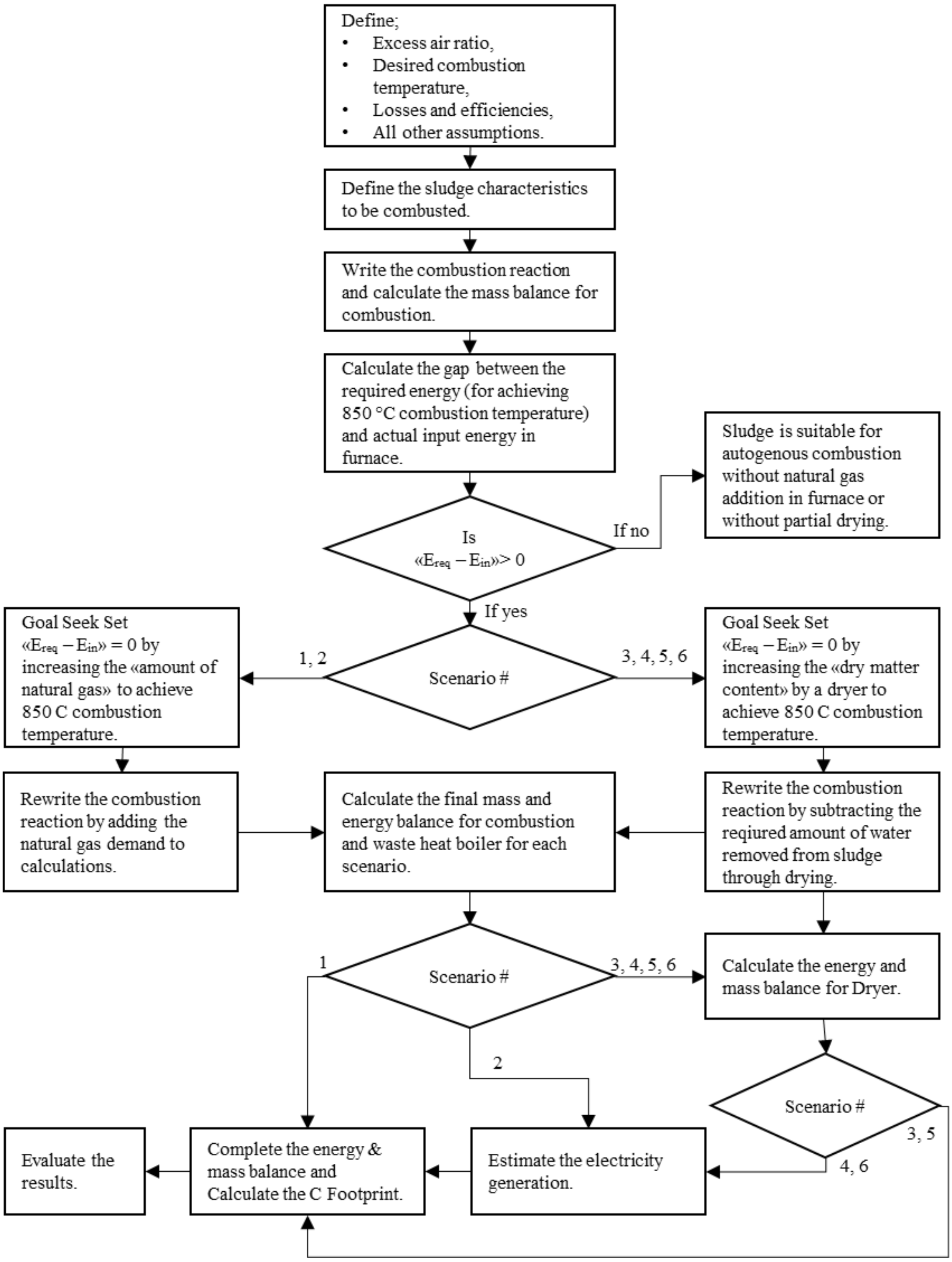

Figure 5 – Calculation Tool Application Scheme

3.2. Scenario Development

In this section, in order to evaluate the theoretical carbon footprint and energy balances of different sludge combustion applications, some scenarios are developed. Only basic flow schemes of scenarios are illustrated regardless of their design details, auxiliary equipment, dimensioning, P&I, etc. These detailed engineering calculations are out of scope of this study. In all scenarios outflow of dewatering unit is considered as the initial evaluation point in the process flowcharts in evaluation of energy balance and carbon footprint.

In general, components of sludge mono-incineration plants are; furnace (where combustion takes place), waste heat boiler, turbocharger or air pre-heater (where flue gas cooling takes place), flue gas treatment system, exhaust stack and bottom and fly ash collectors (Werther and Ogada, 1999; Veli et al., 2008). In this study, air pre heating is not evaluated in scenarios and common components for all scenario are accepted as; furnace, waste heat boiler, flue gas treatment, stack and bottom and fly ash collection.

Some scenarios include wet sludge incineration but some include drying unit prior to combustion in order to evaluate the impact of dry matter content on results. Besides, scenarios including dryer are further diversified through source of energy. Energy supply to dryer can be done by either external fuel or the heat recovered from combustion process. Electric generation is also evaluated in some scenarios.

To sum up; wet and partially dried sludge incineration with no energy recovery are two initial alternatives. As a third alternative, energy for dryer is supplied by the steam produced in flue gas cooling boiler. Numbers of alternatives are doubled when electricity generation options are also considered. Thus, six different scenarios are developed by considering those conditions.

Scenario 1 and 2 has no drying unit is applied and wet sludge is incinerated. While, Scenario 1 includes no heat recovery, in Scenario 2, the steam generated in boiler is used for electricity generation. In Scenario 1 and 2, additional natural gas is going to be utilized in furnaces if necessary to achieve desired combustion temperature.

Scenarios 3, 4, 5 and 6 include partial drying units. Main aim of drying is to increase the dry matter content of sludge to an auto-thermal point. In other words, drying units are going to evaporate some amount (calculated in each scenario) of water remained in dewatered sludge and remove the natural gas demands in furnace for an autogenous sludge combustion.

Drying unit also requires energy. In scenarios 3 and 4 this energy is satisfied by external fuel and in scenarios 5 and 6, heat from combustion is recovered to drying unit. Scenarios 4 and 6 includes electric generation systems. Components of 6 scenarios are given in Table 12.

Table 12 – Components of 6 Scenarios

Components	Scenario #					
	1	2	3	4	5	6
Partial Drying	-	-	✓	✓	✓	✓
Heat Recovery for Partial Drying	-	-	-	-	✓	✓
Combustion	✓	✓	✓	✓	✓	✓
Flue Gas Cooling, Treatment and Exhaust	✓	✓	✓	✓	✓	✓
Ash Collection	✓	✓	✓	✓	✓	✓
Electricity Generation	-	✓	-	✓	-	✓

"✓": Applied in stated scenario

"-": Not applied in stated scenario

In drying unit, partially drying is applied until the sludge reaches a dry matter content, which is sufficient for autogenous combustion without additional fuel consumption in furnace. Energy source of drying unit is either steam from flue gas cooling (Scenario 5 and 6) or heat supplied by an external fuel (Scenario 3 and 4). To be comparable, drying unit is accepted to be superheated steam dryer in scenarios 3 to 6. The steam heats a surface and by heat transferred from this surface, sludge is dried (conduction). Steam drying is applied in different technologies for different products drying (Jensen, 1995; Fitzpatrick,1998; Li et al., 2016). Evaporated water from sludge is assumed to be condensed and discharged to wastewater treatment plant. In scenarios 3 and 4, steam is produced in an additional boiler for drying which is operated by natural gas. In scenario 5, steam used in drying is assumed to be condensed in dryer and fed into the flue gas cooling boiler in order to be more efficient. In scenario 6, the surplus steam remaining which is not used by dryer is fed into electric turbine. Thus, in this scenario dyer outlet and turbine condenser outlet waters are fed into boiler. Dryer technical capabilities regarding high pressure and temperature superheated steam feed or sludge sticky phase situations are not considered in this study.

Combustion furnace is assumed to be a fluidized bed system due to its efficiency and low emission potential, which are also stated by Werther and Ogada (1999). Sludge, air and natural gas (if necessary) are fed into the furnace. Waste heat boilers are commonly used in incineration systems in order to recover the heat and/or cool the flue gas before the flue gas treatment (Niessen, 2010). Energy recovery (if applied) is done through the waste heat boiler. Electric generation potential increases when the steam fed into turbine is superheated (Sandler, 2006). Thus, in order to be comparative, boilers of all scenarios are assumed to produce superheated steam even if energy is not recovered. Energy is produced by electric generation system, operated as Rankine Cycle as stated by Sandler (2006). In Rankine Cycle, superheated steam from boiler is fed into a steam turbine and the work of turbine is converted into electricity in an electric generator. Exhaust steam from the turbine is fed into a condenser and condensed water pressure is increased by a pump. Pump feeds the water in high pressure into the boiler (Sandler,2006). Water mass losses in steam cycle and/or in dryers are neglected in this study. No energy recovery is applied in flue gas treatment and exhaust stack in this study. Fly ash is removed from flue gas treatment system. Performance of treatment units and dose of chemicals are not investigated and out of the scope of this study. Basic flow schemes and input and output tables are given in following sections for different scenarios.

3.2.1. Scenario 1

In scenario 1, dewatered sludge is directly incinerated without energy recovery. Aim is to observe the energy balance and carbon footprint of dewatered sludge thermal disposal where energy recovery is not an option. Air, natural gas and dewatered sludge is fed into combustion furnace. Flue gas, the product of combustion is cooled in boiler. Energy of flue gas is transferred into the water and by this energy water is converted into steam. In this scenario, produced steam is not used for any energy production but condensed and reused in boiler for better energy efficiency. Bottom ash is collected in fluidized bed and fly ash is collected from flue gas treatment system. Inputs and outputs to the system boundary are listed in Table 13. Process flow scheme of scenario 1 is illustrated in Figure 6 where the colored lines are used to illustrate the mass and energy inputs and outputs.

Table 13 – Inputs and Outputs of Scenario 1

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Natural Gas • Air	• Bottom Ash • Fly Ash • Flue Gas	• LHV of MAF Sludge • LHV of Natural Gas • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge and mechanical losses)

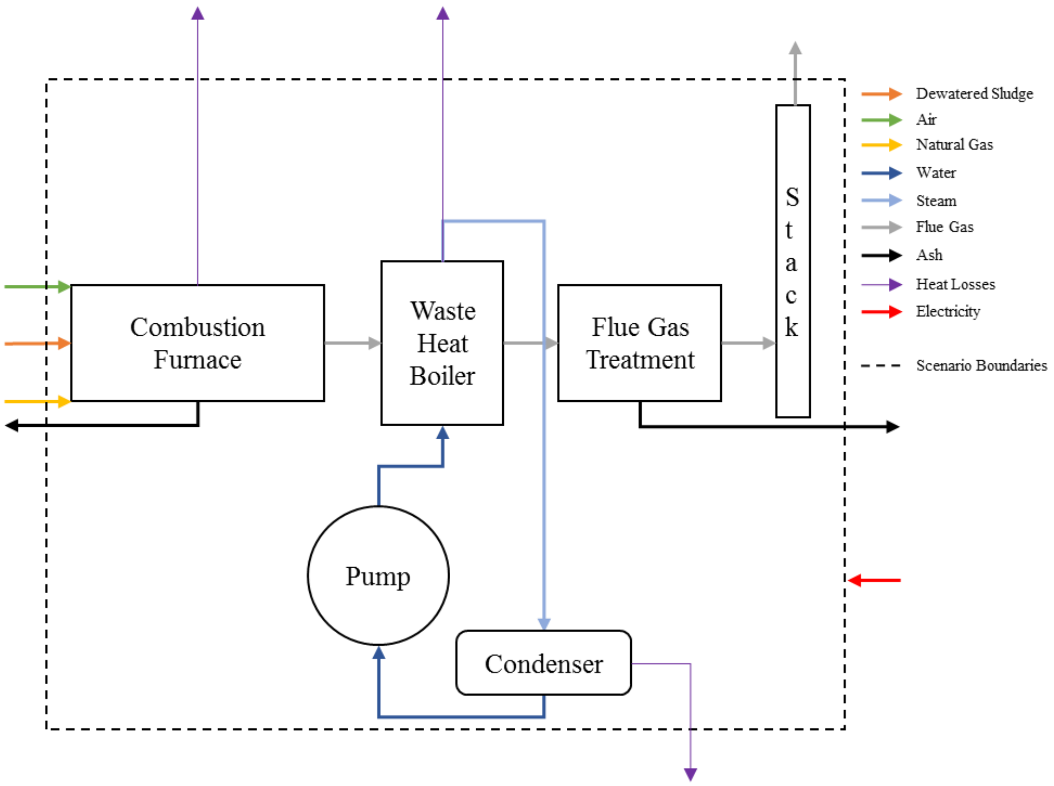

Figure 6 – Process Flow Scheme of Scenario 1

3.2.2. Scenario 2

Scenario 2 is developed under consideration of electricity generation from dewatered sludge combustion. Scenario 2 also do not include a dryer. The only difference from Scenario 1 is the addition of electric generation. For this, there are turbine, condenser and pump operating as a closed Rankine Cycle. Boiler feed water is not supplied externally but as a part of the steam cycle of electricity generation units. Superheated steam, produced by boiler, is fed into the turbine and work of turbine is converted into electricity by a generator. Exhaust steam of turbine is condensed in a condenser and this water is pumped into the boiler under high pressure. Inputs and outputs to system boundary are given in Table 14. Process scheme of scenario 2 is illustrated in Figure 7.

Table 14 – Inputs and Outputs of Scenario 2

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Natural Gas • Air	• Bottom Ash • Fly Ash • Flue Gas	• LHV of MAF Sludge • LHV of Natural Gas • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge and mechanical losses, generator inefficiency) • Electricity Generated

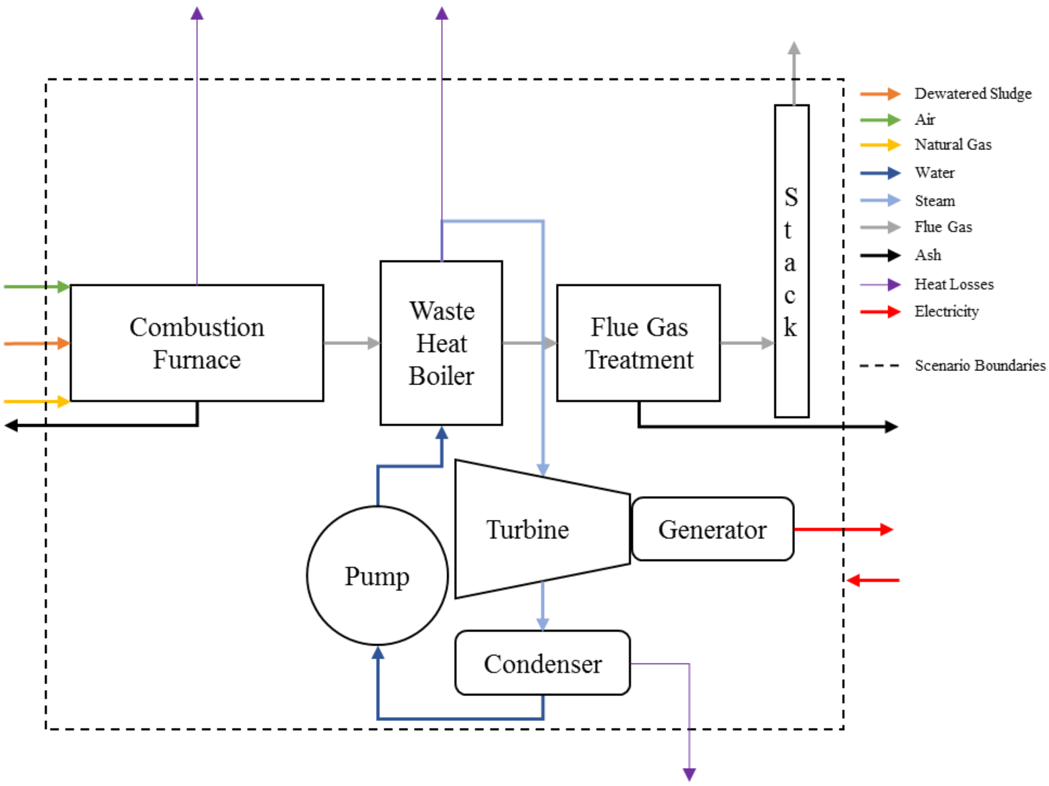

Figure 7 – Process Flow Scheme of Scenario 2

3.2.3. Scenario 3

In Scenario 3, some amount of water is evaporated by a dryer prior to combustion furnace. Sludge is partially dried until no external fuel is required for combustion. Scenario 3 is developed to observe the results when partial drying is applied prior to combustion. Dryer energy is satisfied by an additional boiler, consuming natural gas and producing steam. In other words, natural gas demand is minimized for combustion process by partial drying but the drying energy demand is then satisfied by natural gas. The energy required for drying is supplied externally, not from the energy of combustion.

For that reason, the steam produced in waste heat boiler is condensed and recycled to the boiler just as in Scenario 1. Drying unit has its own additional boiler, utilizing natural gas prior to dryer. Steam from this additional boiler is fed into the dryer and saturated water is recycled to the boiler. The evaporated water from sludge is exhausted as condensed and cooled, therefore the energy of this vapor is lost. Besides, partially dried sludge is assumed to be cooled after drying. Natural gas is burned and resulted flue gas is fed into flue gas treatment system and exhausted. This boiler has also heat loss. In other words, the energy input of additional boiler is transferred into dryer and used to evaporate some amount of water from sludge. But this water is not used and discharged as condensed water. Scenario 3 input and output list is given in Table 15 – Inputs and Outputs of Scenario and process flow scheme is illustrated in Figure 8.

Table 15 – Inputs and Outputs of Scenario 3

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Natural Gas (for drying) • Air	• Bottom Ash • Fly Ash • Flue Gas • Flue Gas (of additional boiler) • Water removed from sludge	• LHV of MAF Sludge • LHV of Natural Gas • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge and mechanical losses) • Drying system losses (heat loss, removed water discharge, flue gas exhaust)

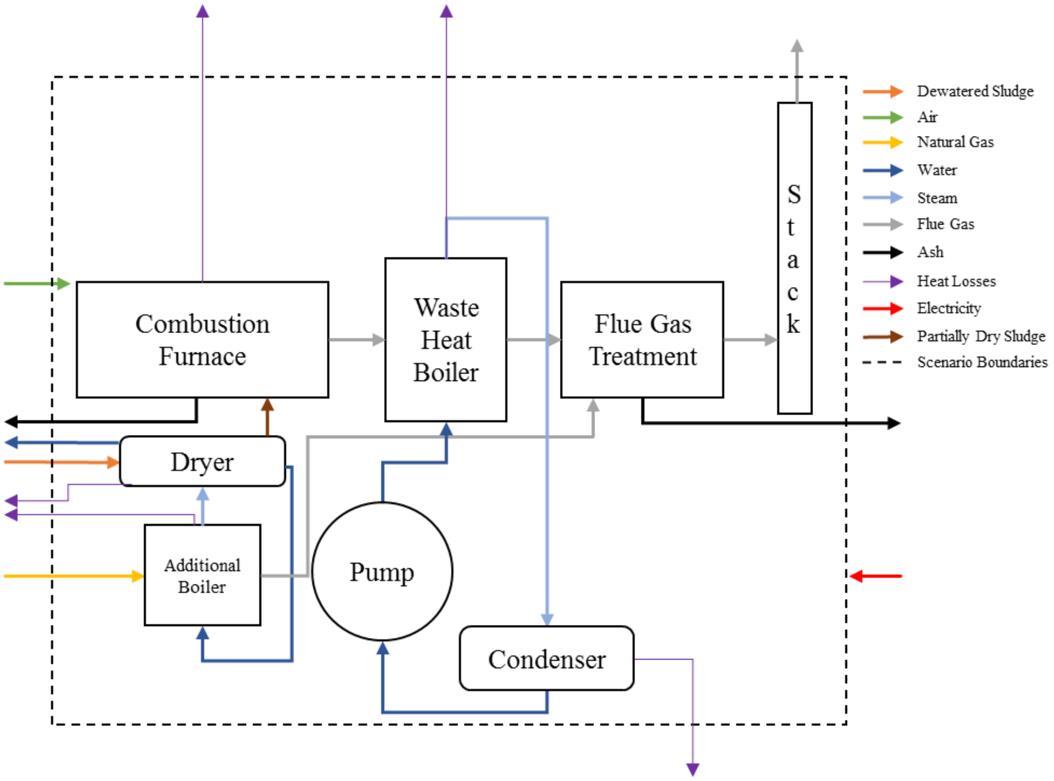

Figure 8 – Process Flow Scheme of Scenario 3

3.2.4. Scenario 4

Scenario 4 is developed by upgrading Scenario 3 by addition of a Rankine Cycle electric generation system, run by the steam generated by waste heat boiler. For drying, steam is still produced by an additional boiler as in Scenario 3 but the steam from waste heat boiler is used for electricity generation. Therefore, Scenario 4 is differing from Scenario 2 by a drying unit and from Scenario 3 by electricity generation system. Drying unit is externally fueled and the steam from flue gas cooling is completely used for electricity generation. Operation and flowscheme of drying is the same as for Scenario 3 and electric generation cycle is similar to the one in Scenario 2. Mass and energy inputs and outputs are given in Table 16 and process flow scheme of Scenario 4 is illustrated in Figure 9.

Table 16 – Inputs and Outputs of Scenario 4

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Natural Gas (for drying) • Air	• Bottom Ash • Fly Ash • Flue Gas • Flue Gas (of additional boiler) • Water removed from sludge	• LHV of MAF Sludge • LHV of Natural Gas • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge, mechanical losses and generator inefficiency) • Drying system losses (heat loss, removed water discharge, flue gas exhaust) • Electricity Generated

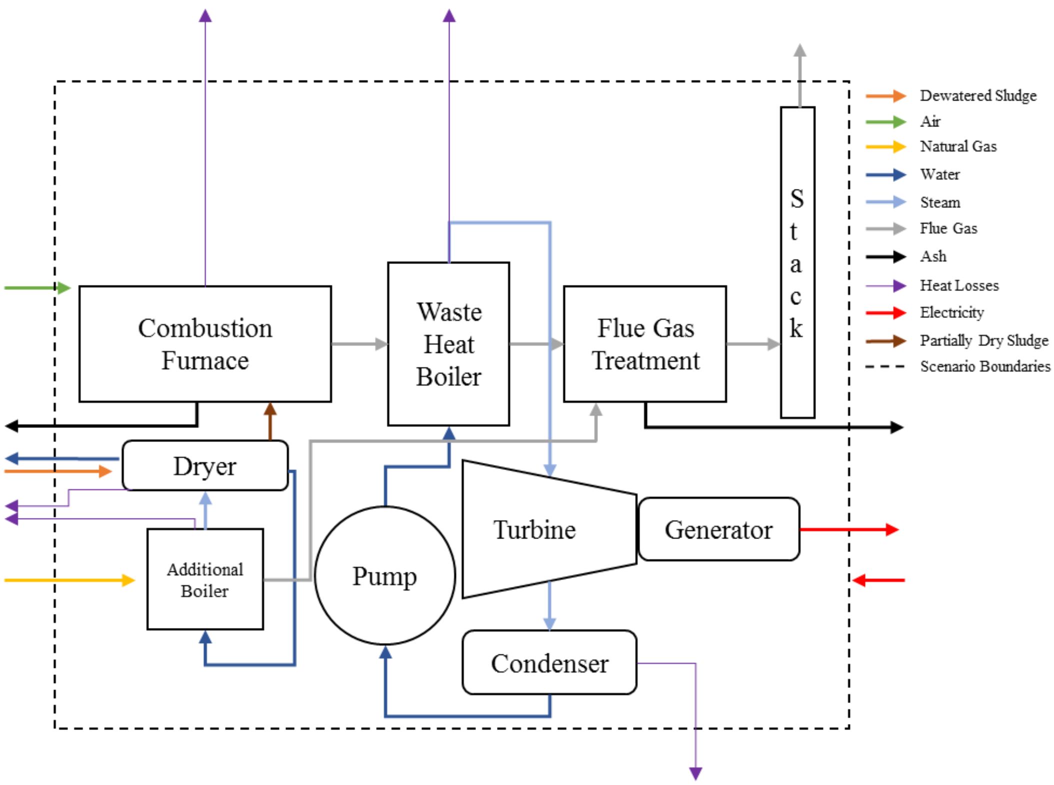

Figure 9 – Process Flow Scheme of Scenario 4

3.2.5. Scenario 5

In Scenario 5, partial drying is applied and the required energy for drying is satisfied by the steam produced from a waste heat boiler. Thus, this scenario includes energy recovery from sludge combustion. No additional fuel is used since dryer energy is taken from the steam produced by flue gas cooling and sludge is combusted without natural gas since it is dried up to its auto thermal point. Since drying demand is dependent on the calorific value of sludge (for auto thermal combustion), steam requirements differ by different sludges. Therefore, for the cases that produced steam is more than the required, the excess steam is condensed and recycled into the boiler. Steam sent to dryer is recovered as condensed water and pumped back to the boiler. Input and output mass and energy are given in Table 17 and process flow scheme of scenario 5 is illustrated in Figure 10.

Table 17 – Inputs and Outputs of Scenario 5

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Air	• Bottom Ash • Fly Ash • Flue Gas • Water removed from sludge	• LHV of MAF Sludge • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge and mechanical losses) • Drying system losses (heat loss, removed water discharge)

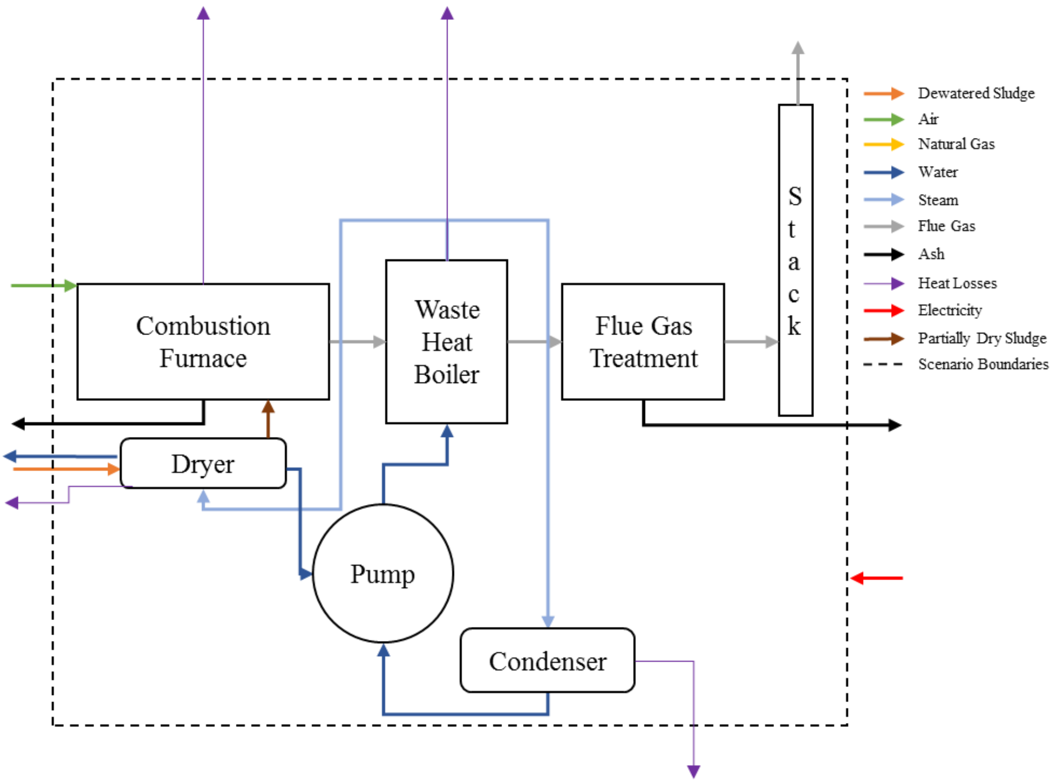

Figure 10 – Process Flow Scheme of Scenario 5

3.2.6. Scenario 6

Scenario 6 is the last scenario. Steam produced by flue gas energy is used both for electricity generation and partial drying of sludge. Like in scenario 5, the dryer requirements (specific for each sludge) are satisfied by the produced steam and the remaining excess steam, which is not used in dryer, is used in Rankine cycle. Input and output mass and energy are given in Table 18 and process flow scheme of scenario 6 is illustrated in Figure 11 – Process Flow Scheme of Scenario 6Figure 10.

Table 18 – Inputs and Outputs of Scenario 6

Input Mass	Output Mass	Input Energy	Output Energy
• Dewatered Sludge • Air	• Bottom Ash • Fly Ash • Flue Gas • Water removed from sludge	• LHV of MAF Sludge • LHV of Natural Gas • Electricity	• Losses (heat losses, bottom ash, fly ash, flue gas discharge, mechanical losses and generator inefficiency) • Drying system losses (heat loss, removed water discharge) • Electricity Generated

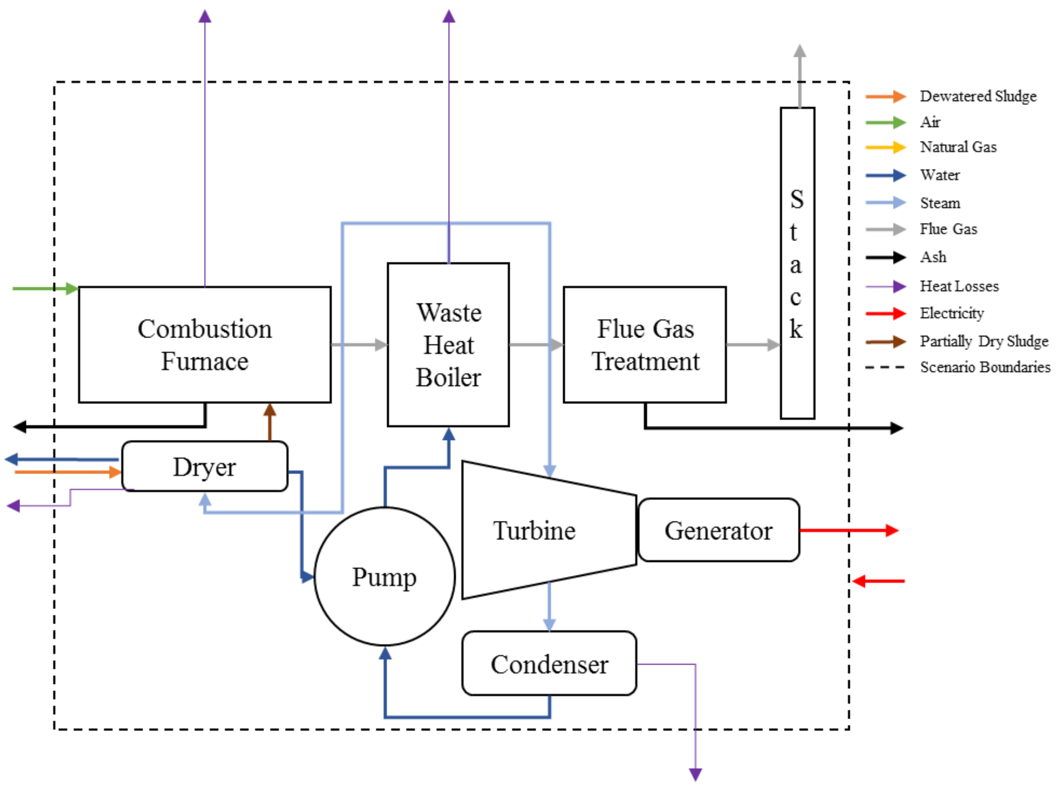

Figure 11 – Process Flow Scheme of Scenario 6

3.3.Calculation Tool Development

Scenarios are evaluated by a calculation tool developed under Excel. Principle of the tool is to conduct mass and energy balances. Moreover, the tool calculates carbon footprint as amounts of CO2 releases. All calculations are done for the operation phase. Start-ups and shut downs of processes are not considered.

3.3.1. Sludge Characteristics

Six different scenarios are applied for different sludge types. Characteristics of different sludges from Turkey are taken from the final report of TÜBİTAK-KAMAG Domestic/Municipal Sewage Sludge Management Project, announced at official website of T.C. Ministry of Environment and Urban Planning (2018). In the report, there are ultimate proximate analysis results for many sludges from Turkey for samples taken during both winter and summer. It is observed from the report that analysis results are differing by season.

From the mentioned report, six sludges with different calorific values and different ultimate analysis are randomly selected. Averages of winter and summer values are used in calculations. These are provided in Table 19. Sludge A to C is defined in the report as non-stabilized and sludges D to F are as anaerobically digested. Sludge A has the highest LHV and Sludge F has the lowest LHV, based on winter and summer averages, when all sludges in the report (Ministry of Environment and Urban Planning) are considered. Although the heating values are given in the report, they are not used and LHV data of sludges are calculated in the following sections by own calculations through the ultimate analysis given in table below.

Table 19 - Summer, winter and calculated average characteristics of sludges given in the final report of TÜBİTAK-KAMAG Domestic/Municipal Sewage Sludge Management Project (Ministry of Environment and Urban Planning).

Sludge	Stabilization	Season	% by Dry Weight of Substance						kcal / kg - dry
			C	H	N	S	O	Ash	Lower Heating Value
A	Non Stabilized	Winter	38.6	6.7	6.2	1.3	18.5	28.6	3408.6
		Summer	41.9	7.7	7.9	1.3	31.5	9.8	4243.4
		Average*	**40.3**	**7.2**	**7.0**	**1.3**	**25.0**	**19.2**	**3826.0**
B	Non Stabilized	Winter	40.3	6.5	6.8	1.1	22.6	22.7	3775.3
		Summer	38.5	6.8	6.7	0.9	30.1	17.0	3780.7
		Average*	**39.4**	**6.6**	**6.7**	**1.0**	**26.4**	**19.9**	**3778.0**
C	Non Stabilized	Winter	42.9	7.1	6.2	0.8	18.7	24.2	3828.7
		Summer	30.2	5.3	3.8	1.1	24.7	34.9	2854.2
		Average*	**36.6**	**6.2**	**5.0**	**1.0**	**21.7**	**29.6**	**3341.5**
D	Anaerobic Digestion	Winter	37.9	6.0	4.6	1.2	21.0	29.3	3381.2
		Summer	35.0	5.7	3.7	1.1	25.1	29.4	3307.1
		Average*	**36.5**	**5.8**	**4.2**	**1.1**	**23.0**	**29.3**	**3344.2**
E	Anaerobic Digestion	Winter	28.0	4.5	4.0	1.2	15.3	47.1	2511.5
		Summer	27.2	4.7	3.1	1.1	20.0	43.9	2452.1
		Average*	**27.6**	**4.6**	**3.5**	**1.1**	**17.6**	**45.5**	**2481.8**
F	Anaerobic Digestion	Winter	25.8	3.9	2.9	1.2	18.7	47.6	2168.7
		Summer	28.8	5.0	4.0	1.0	25.2	35.9	2684.1
		Average*	**27.3**	**4.4**	**3.4**	**1.1**	**21.9**	**41.8**	**2426.4**

*Averages are calculated in this study

Energy value of sludge is calculated on MAF basis. After calculating the HHV or LHV of MAF heat value, dry matter based heating value can be calculated given the ash content. The percentages of C, H, N, S and O are converted into MAF percentages. MAF and dry matter LHV is calculated. Therefore, percentages are calculated for MAF basis by using the ash free amount. All sludges are assumed to be dewatered up to 25 % dry matter content initially in all scenarios. Evaluation is done for 5 ton/day dewatered sludge.

3.3.2. Combustion Process

Calculation tool starts with the combustion energy and mass balance as succeeding systems in the process flow are dependent on the operation of combustion. For instance, in some scenarios, prior to furnace drying is applied, but, the desired drying levels are directly related with the combustion characteristics of sludge. For that reason, calculation tool starts with combustion calculations.

In Scenarios 1 and 2, dewatered sludge is directly fed into the furnace. If the sludge has insufficient calorific value, then the tool quantifies natural gas addition. For scenarios 3 to 6, it is aimed to achieve an autogenous combustion with no need of additional fuel. Thus, for these scenarios, combustion calculations provide drying level requirements.

Combustion process is the oxidation of reactants. Amounts, contents and temperatures of waste, fuel, air and flue gas are directly related to each other. Ragland and Bryden (2011), generalizes the combustion reaction for hydrocarbon fuels, as given in Equation 1 in section 2.3.1.1 Combustion. However, besides C, H and O, combustible part of sludge comprises of S and N too. In this study, according to the ultimate analysis of sludges given in Table 19, N and S elements also remained in sludge. Also, as mentioned before, it is assumed that moisture content of sludge is 75 %. Niessen (2010) states the elemental and organic C oxidizes to CO_2 with a portion of CO; inorganic C may result in CO_2 and/or remain in ash; Elemental and organic H converts into H_2O where H in water and inorganic H may show different patterns dependent on temperature level; oxygen at non-metallic elements behave as O_2 in air where other forms of O can lead to different conversions; N leaves as N_2 with trace amounts of NO_x; organic and inorganic Sulphur usually form SO_2 with some amounts of SO_3.

NO_x formation due to the combustion of sewage sludge is a critical issue. Many parameters can affect the formation of NO_x. Temperature, air ratio, volatile matter content, water content of combusted sludge and even the combustion approach can change the N to NO_x conversion mechanism. Nevertheless, there is no certain mechanism for sewage sludge since each sludge type and combustion conditions cn result in different amounts of emissions. In general, fluidized bed sludge incineration is known to emit low amounts of NO_x if a proper design and an efficient combustion is achieved (Werther, 1999). Therefore, NO_x emissions are assumed to be insignificant in this study. As aforementioned, there are more products formed depending on temperature and components of fuel but this study aims to evaluate the different applications and it is assumed that flue gas products are mainly CO_2, H_2O, O_2, N_2 and SO_2. In this study, sludge is assumed to have water, ash, organic C, H, N, O, S and fixed C contents. By considering the assumptions given above, Equation 1 is modified to include natural gas input and excess ratio of air (x) and embedded in the calculation tool as given in below equation in order to calculate mass balance of furnace.

$$C_aH_bO_cN_dS_e + fH_2O + gCH_4 + (1+x)\left(a + \frac{b}{4} - \frac{c}{2} + e + 2g\right)(O_2 + 3{,}76N_2) + ash \rightarrow (a+g)CO_2 + \left(f + \frac{b}{2} + 2g\right)H_2O + (1-x)O_2 + 3{,}76\left(a + \frac{b}{4} - \frac{c}{2} + e + 2g\right)N_2 + eSO_2 + ash \qquad \textbf{(2)}$$

Where;

a: molar amount of C in sludge feed into furnace (kmol/h),

b: molar amount of H in sludge feed into furnace (kmol/h),

c: molar amount of O in sludge feed into furnace (kmol/h),

d: molar amount of N in sludge feed into furnace (kmol/h),

e: molar amount of S in sludge feed into furnace (kmol/h), f: molar amount of H_2O content of sludge feed into furnace (kmol/h),

g: molar amount of CH_4 feed into furnace (kmol/h),

x: percentage of excess air (40%) (Schwarz, 1982),

Amounts and contents of reactants and products are functions of each other. Besides, fly ash is considered to remain in flue gas and bottom ash is assumed to be 80 % of the total ash content by mass. Basic configurations of mass balance are given below:

$$\boldsymbol{m_s + m_{air} + m_{ng} = m_{ba} + m_{fg}} \quad \textbf{(3)}$$

Where;

m_s: Total sludge amount fed into furnace (kg/h),

m_{air}: Total air supply (theoretical + excess) into furnace (kg/h),

$m_{ng,c}$: Natural gas consumption in furnace (if applied) (kg/h),

m_{ba}: Bottom ash formed in furnace (kg/h),

m_{fg}: Flue gas outflow from furnace (kg/h),

$$\boldsymbol{m_s = m_{MAF} + m_{w,c} + m_{ash}} \quad \textbf{(4)}$$

Where;m_{MAF}: Moisture and ash free mass of sludge flow into funace (kg/h),

$m_{w,c}$: Water amount in total sludge fed into combustion furnace (kg/h),

m_{ash}: Ash part of sludge (kg/h),

$$\boldsymbol{m_{air} = m_{O2,air} + m_{N2,air}} \quad \textbf{(5)}$$

Where;

$m_{O2,\ air}$: Mass flow of O_2 in combustion air (kg/h),

$m_{N2,\ air}$: Mass flow of N_2 in combustion air (kg/h),

$$\boldsymbol{m_{fg} = m_{CO2} + m_{H2O,formation} + m_{w,c} + m_{O2,fg} + m_{N2,fg} + m_{SO2} + m_{fa}} \quad \textbf{(6)}$$

Where;

m_{CO2}: Mass flow of CO_2 in flue gas (kg/h),

$m_{H2O,\ formation}$: Water formed by combustion due to the H content of fuels (kg/h),

$m_{O2,fg}$: Mass flow of O_2 in flue gas (kg/h),

$m_{N2,fg}$: Mass flow of N_2 in flue gas (kg/h),

m_{SO2}: Mass flow of SO_2 in flue gas (kg/h),

m_{fa}: Mass flow of Fly Ash in flue gas (kg/h),

After conducting the mass balance for combustion furnace, energy balance is performed. The energy balance is described as; rate of energy difference between input and output energy which are; heat and work. Change in internal, kinetic and potential energies is assumed to be zero since the combustion process is assumed to be steady-flow process. Input energy is the enthalpy of reactants and output energy is heat losses and enthalpy of products (Çengel and Boles, 2015).

Important issue in energy balance is the desired combustion temperature. Required energy is calculated for output mass to be at the desired temperature. This energy is compared with the actual input energy, which is calculated by multiplying the energy value of input materials with their mass. If the calculated input energy is lower than the requirement, then this means sludge is not at its auto thermal point for combustion at desired temperature. 6 scenarios are developed to combust the sludge at desired temperature. Calculations are done by considering the air as dry air and natural gas as CH_4.

Niessen (2010) describes the energy forms for a waste incineration system as; chemical energy, latent heat, sensible heat, heat losses and usable heat. First of all, chemical energy is described as heat of oxidation reaction and dissociation. In this study dissociation is not considered. Secondly, latent heat is the heat for state changing of materials. In this study, water vapor in flue gas is accepted to have a latent heat since at 850 °C molecules are at gas state. Third is the sensible heat, the heat of products at a temperature with respect to the energy at state reference temperature. Fourth, the heat losses from the walls of system. Fifth and the final, usable heat, which is delivered to boiler.

Chemical energy can be found by the enthalpy of formation for the reactants. This value is the heating value of reactant. (Ragland and Bryden, 2011). Niessen (2010) describes the heat of combustion as the energy released from complete oxidation of C, H and O included in fuels or wastes. They also mention that the N, S, Cl and P containing compounds' heat of combustion can also be evaluated similarly, but this might not be reliable since the products are uncertain. This energy content is found by complete oxidation reaction of substances where reactants and products are at their state temperatures (commonly 25°C) and phases. In other words, this energy is called as the higher heating value of compound. The input energy through the unit of combustible material is, therefore, its higher heating value. In addition to this, since the higher heating value estimation is done for state temperatures of products, heat of formation is found for H_2O at its liquid form. Yet, in combustion furnaces, H_2O is going to remain at vapor phase due to the combustion temperature. Thus, latent heat will be extracted from the total energy input since the HHV is higher than the heat occurred in flue gas. When latent heat is extracted, this value is called lower heating value, and commonly used to obtain the net input energy. In adiabatic conditions, HHV of reactants are equal to the sensible heat of products, heat losses and latent heats. To sum up, net input energy to a combustion system is obtained by the LHV value of fuel and sensible enthalpy of fuel and air. (Niessen, 2010)

Niessen (2011), proposes the Dulong equation for finding the HHV of moisture and ash free (MAF) substance by using the weight percentages of C, H, N, S and O as below (Niessen, 2010);

$$\boldsymbol{HHV\left(\frac{kcal}{kg}\right) = 78.31 \times C + 359.32 \times \left(H - \frac{O}{8}\right) + 22.12\, S + 11.87 \times O + 5.78 \times N} \qquad \textbf{(7)}$$

It is observed from the Equation 7 that C, H, N and S elements increase and O content decreases the higher heating value of substance. Lower heating value, on the other hand is calculated through the formula below, by using the MAF percentage of H by weight (Niessen, 2010);

$$\boldsymbol{LHV}\ \left(\frac{\boldsymbol{kcal}}{\boldsymbol{kg}}\right) = \boldsymbol{HHV} - \mathbf{52.397}\boldsymbol{x}\ (\boldsymbol{H}) \qquad \textbf{(8)}$$

In this study (whether drying is applied or not), all materials (included air) are assumed to be at (or cooled without energy recovery to) 25 oC prior to combustion, which is also the reference state temperature. So, sensible heats of the input substances are zero. Only energy inputs are the LHV of natural gas (if used) and MAF part of sludge. Natural gas LHV is accepted to be 50.05 MJ/kg (Ragland and Bryden, 2011)

In order to create the mass and energy balances, ultimate analysis of sludge to be combusted should be selected. After determining the input energy by using LHV of feed materials, output energy from the combustion furnace is calculated. When sludge characteristics and amounts are known, it is tested whether input energy would be sufficient to achieve the desired combustion temperature. This can be done by obtaining the output energy. Input energy is the LHV and sensible energy of products at initial temperature. On the other hand, output energy is the sensible energies of flue gas components at the desired temperature and the vaporization heat of H_2O due to the water content of fuel.

Vaporization heat of $H_2O_{\text{formation}}$, resulted by H element in sludge content, is extracted and therefore HHV is converted into LHV. Yet, there is still H_2O present in the system; moisture content remaining in total sludge. Therefore, heat of vaporization is considered for moisture content of sludge. In general, by considering the heat loses as well, input energy must be equal to output energy. If not, by Goal Seek additional fuel supply or drying demand is calculated.

For the scenarios excluding a drying unit, i.e. cases the sludge energy is not sufficient for operation at 850 °C, natural gas requirement is the first unknown related to desired operation temperature. Second unknown is the amount of combustion air required for combustion which is related to the amount and content of sludge and natural gas. These two inputs affect the amount and content of flue gas. Therefore, iterations are required to find the fuel and air requirements for combustion of certain sludge at desired temperature.

For the scenarios including a drying unit; first unknown is the dry matter content. Dry matter content shall be increased for an autogenous combustion. This increase does not affect the amount of air but affects the amount of flue gas since H_2O in flue gas is going to decrease. In order to determine mass and energy balances, methodology of this study is similar to Niessen's (2010) calculation methodology.

In their book, Niessen (2010), solves a combustion process of a waste sludge at 15.5°C by pre-heated air. Combustion products are CO_2, O_2, N_2 and H_2O. Initially, they calculate the air requirements. Then they found the input energy by using HHV of waste and sensible heats of waste and air. Since HHV is used, from the total energy, vaporization heats of H2O remaining in sludge and H2O formed by reaction at 15.5 °C are subtracted. In order to find the output energy, they obtained the flue gas content of combustion. Input energy is equal to output energy, and, output energy is the sum of sensible heats of products and latent (vaporization) heat of H2O. By knowing the initial energy and the fraction of ash, CO_2, O_2, N_2 and H_2O in the flue gas; they obtain the adiabatic flame temperature of the combustion. In other words, energy of flue gas is the output energy and must be equal to the input energy. Input energy is taken as reference. By iterations, adiabatic flame temperature of the given reaction is found. After this step, heat losses are considered and flue gas temperature is obtained. Niessen (2010) presents a method to find the pre-heating level of air for desired temperature. First step is determining the desired energy of flue gas, or energy output at adiabatic flame temperature. Second step is considering the heat losses and find the real output energy. Third step is observing the difference between input and output energies. Forth step is calculating the molar heat of air. Finally, fifth step is calculating the pre-heating level to satisfy the energy difference in third step. By this way, air pre-heating level is found to achieve the desired combustion temperature.

In this study, a similar approach is used to achieve 850°C combustion temperature. Instead of air heating, the lacking energy is satisfied by adding natural gas or increasing the dry matter content of sludge through drying. Besides, natural gas amount will increase the flue gas amount and change its content, as well as output energy. For the scenarios with drying rather than additional fuel supply, on the other hand, when water amount of sludge decreases, the flue gas amount will also decrease. Besides, since all input materials are assumed to be at their reference state temperatures, 25 °C, sensible heat of input materials are 0. Since 850° is selected as operation temperature, all products of combustion is assumed to reach 850°C and leave the furnace. Air has no effect on input energy since only energy form is sensible energy for air and it is zero since the temperature of input air is 25 °C (given in Table 20, below). According to the all assumptions and information given above, energy balance formulas are developed as below:

$$\boldsymbol{E_{MAF,25°C} + E_{ng,c,25°C} = E_{fg,850°C} + E_{ba,850°C} + E_{hl,c}} \quad \textbf{(9)}$$

$$\boldsymbol{E_{MAF,25°C} = LHV_{MAF} \times m_{MAF}} \quad \textbf{(10)}$$

$$\boldsymbol{E_{ng,c,25°C} = LHV_{ng} \times m_{ng,c}} \quad \textbf{(11)}$$

$$\boldsymbol{E_{fg,850°C} = SE_{fg,850°C} * m_{fg} + LH_{w,c} \times m_{w,c}} \quad \textbf{(12)}$$

$$\boldsymbol{E_{ba} = SE_{ba,850°C} * m_{ba}} \quad \textbf{(13)}$$

Where;

E_{MAF}: Energy of MAF part of sludge (MJ/h)

$E_{ng,c,25°C}$: Energy of natural gas input to combustion (MJ/h)

$E_{fg,850°C}$: Energy of flue gas at 850°C (MJ/h)

$E_{ba,850°C}$: Energy of bottom ash at 850°C (MJ/h)

$E_{hl,c}$: Heat losses in combustion furnace due to thermal efficiency (95%) (Niessen, 2010),

LHV_{MAF}: Lower heating value of MAF part of sludge (MJ/kg)

LHV_{ng}: Lower heating value of natural gas (50.05 MJ/kg) (Ragland and Bryden, 2011),

$SE_{fg,850°C}$: Sensible energy of flue gas at 850°C (MJ/kg)

LH_w: Vaporization energy of water in total sludge feed into combustion furnace (MJ/kg)

In addition, boiler and furnace thermal efficiencies are also confirmed by INEVA Çevre Teknolojileri San. Tic. A.Ş.

Table 20 – Sensible Enthalpy Values of Flue Gas Parameters (Perry et al., 1997)

Parameter	Sensible Enthalpy(kJ/kmol)			
	@25°C	@827°C	@850°C*	@927°C
CH_4	0	38.89	40.18	44.48
CO_2	0	30.17	31.16	34.48
H_2O	0	30.17	31.16	34.48
O_2	0	24.76	25.53	28.11
N_2	0	26.22	27.03	29.76
SO_2	0	39.91	41.19	45.46

*Obtained by interpolation

Total output energy from furnaces are the energy of flue gas, the bottom ash and heat losses. Oxidation and conversion of ash is ignored. Sensible energy of gases produced by combustion at 850°C is found by multiplying the molar amount of products with the sensible enthalpy. Sensible enthalpy data given in Table 20 are used for this purpose. Sensible enthalpy is not found in literature for ash. Therefore, Niessen's (2010) approach is used only for ash; multiplication of specific heat with temperature difference. Specific heat value is assumed to be 0.25 kcal/kg°C (1,046 kJ/kg°C) (Niessen, 2010). This value is used both for bottom ash removed from furnace and fly as in the flue gas. Besides the sensible energy, H_2O in flue gas has two different source. Some part of the H_2O is formed during combustion of H component of fuel. Since dry LHV of fuels are considered in calculations rather than HHV, formation vapor energy is only occurred by its sensible heat. Yet, water content coming from sludge has sensible energy and also a vaporization energy (or called latent heat). This latent heat amount is accepted as 10507 kJ/kmol of water (44 MJ/kmol) (Niessen, 2010).

As applying the methodology given in this section, E_{req} at 850°C and E_{in} can be obtained. If these two values are equal to each other without drying or natural gas supply, then this means that given sludge input is sufficient for autogenous combustion at 850°C. But if E_{req} - E_{in} is negative, then either natural gas should be added to system or water should be removed from sludge prior to the combustion.

3.3.3. Waste Heat Boiler and Pump

A waste heat boiler is among the common equipment for all scenarios. Aim is to cool the flue gas before the treatment and exhaust. After combustion chamber, flue gas at 850°C enters into boiler for steam generation. Outflow of boiler is assumed to be 180°C which corresponds to 453°K. Flue gas leaves boiler in gas form so vaporization energy of water is not changed. The energy transferred in boiler is the difference between sensible heats of inlet and outlet flue gas at boiler and heat losses of boiler. Sensible heat of boiler outlet flue gas is found by interpolation and result tables are given in Appendix C.

Hot flue gases are fed into steam boiler. Enthalpy difference of flue gas at boiler inflow and outflow temperatures are calculated and the thermal inefficiency of boiler is subtracted from this difference. Obtained value is the energy transferred to feed water (Niessen, 2010). Superheater, boiler and economizer is assumed to be evaluated as one system called; boiler.

In all scenarios, steam is in a cycle and a pump is used for feeding the water in high pressure to the boiler. In scenario 1 and 3, steam from boiler is not used for electricity generation or drying process but condensed and pumped to the boiler. In scenario 2 and 4, produced steam is used for electricity generation in configuration of Rankine Cycle, which is mentioned in next section. In scenario 5, steam is used for drying unit and in scenario 6, for both drying and electricity generation.

Sandler (2006) solves a sample Rankine Cycle with 30 bar, 600 °C with 3682 kJ/kg enthalpy superheated steam outflow from boiler. To be comparable, in all scenarios the pump is accepted to increase the pressure of water at 30 bar and boiler generates the steam at 30 bar and 600 C.

To calculate the amount of steam, heat transfer by flue gas is multiplied by the enthalpy difference between feed water and produced steam. For this, boiler inlet water enthalpy must be calculated first (Sandler, 2006). The enthalpy of outflow water of pump (boiler input) is found by sum of the work of pump and the enthalpy of input water to pump (outflow of condenser or dryers).

Inflow of pump is accepted to be condensed saturated water from condenser at 100 C, 1.0135 bar with 419 kJ/kg enthalpy, and output of pump is water at 30 bar, as given also by Sandler's (2006) Rankine Cycle. These values are used in this study even there is no Rankine Cycle in some scenarios to be comparative. Work required for pump operation is found by multiplication of volume (m^3/kg) and pressure difference of input and output of pump by formula below (Sandler, 2006);

$$\boldsymbol{h_{fw} = h_{cw} + W_p} \tag{14}$$

$$\boldsymbol{W_p = V \times (P_{fw} - P_{cw})} \tag{15}$$

Where;

h_{fw}: Enthalpy of pump outflow feed water at 30 bar (3 MPA) bar,

h_{cw}: Enthalpy of pump inflow condensed water (0.10135 Mpa) (419 kJ/kg) (Sandler, 2006)

W_p: Work required for pump,

V: Volume of the condensed water (0.00104 m^3/kg) (Sandler, 2006),

P_{fw}: Pressure of feed water of boiler (pump outlet) (3 Mpa) (Sandler, 2006),

P_{cw}: Pressure of condensed water (pump inlet) (0.10135 Mpa) (Sandler, 2006),

By the equations above, enthalpy values of condensed water and feed water at given conditions are calculated.

Sandler (2006) finds the enthalpy of feed water is then calculated by adding the W_p value to the enthalpy of condensed water. At this point, the data regarding condensed water, feed water and superheated steam after boiler are known. The difference between the enthalpies of feed water and superheated steam is the energy requirement per one kg of water. Niessen (2010) defines the energy transferred to steam as; the energy difference due to the temperature decrease of flue gas in boiler added by the heat losses in boiler. By this approach, mass and energy balances are formulized in this study as below:

$$\boldsymbol{m_{fg} + m_{fw} = m_{fg,b} + m_{ss}} \tag{16}$$

$$\boldsymbol{E_{fg,850°C} = E_b + E_{fg,180°C} + E_{hl,b}} \tag{17}$$

$$\boldsymbol{h_{fw} = h_{cw} + W_p} \tag{18}$$

$$\boldsymbol{m_{fw} = m_{ss} = \frac{E_b}{(h_{ss} - h_{fw})}} \tag{19}$$

Where;

$m_{fg,b}$: Mass flow of flue gas output from waste heat boiler (kg/h),

m_{fw}: Mass flow of feed water at 30 bar into boiler (kg/h)

m_{ss}, Mass flow of superheated steam at 30 bar 600°C produced in boiler (kg/h)

h_{ss}, Enthalpy of boiler outflow superheated steam at 30 bar 600°C (kJ/kg) (Sandler, 2006)

E_b: Thermal energy transferred to steam(kJ/h),

$E_{hl,b}$: Heat losses from waste heat boiler (5% of total energy) (Niessen,2010),

3.3.4. Turbine and Generator

For scenarios with electric generation, turbine system includes steam turbine, condenser and pump. This system operates as a classical Rankine Cycle with boiler given in previous section. Steam generated in boiler flows into the turbine. Turbine is assumed to be isentropic, therefore the entropy does not change but the input enthalpy is converted into work, output steam has lower enthalpy. Outlet steam outlet of turbine is decreased and fed into condenser. Condenser outflow is saturated liquid. Pressure of this liquid is increased by pump and enthalpy is increased by the given work by pump (Sandler, 2006). This liquid flows into boiler system to become superheated steam. Pump and waste heat boiler is mentioned in previous section. As stated in previous chapter, in all scenarios it is decided that condenser (and/or dryer) outlet is always saturated water at 100 °C, pump increases the pressure of this water up to 30 bar and boiler produces superheated steam at 30 bar and 600 °C. Therefore, turbine inlet is 30 bar and 400°C in scenarios 2, 4 and 6. Steam outlet from the turbine should have same pressure with condensed water since condenser is isobaric and same entropy with turbine inlet superheated steam since turbine is isentropic. These steam data is taken from the Rankine Cycle given in the book of Sandler (2006).

Conditions and energy flow types are given in Table 21 and accepted to be valid for this study also. Besides, the unit work output by turbine is calculated by Equation 20 below. Calculated unit work is multiplied by the efficiency of generator and the amount of steam in Rankine cycle. So, electricity generation capacity is found for the scenario.

Table 21 – Rankine Cycle Units, Conditions and Energy Types (Sandler, 2006)

Rankine Cycle Units	Condition	Energy Type
Pump	Isentropic	Work Input
Boiler	Isobaric	Work Input
Turbine	Isentropic	Work Output
Condenser	Isobaric	Heat Output

$$\boldsymbol{W_T} = \left(\boldsymbol{h_{ss,out}} - \boldsymbol{h_{ss}}\right) \quad \textbf{(20)}$$

Where;

W_T: Work output from turbine per unit steam in cycle (kJ/kg)

$h_{ss,out}$: Unit enthalpy of steam at outlet from turbine (2734.7 kJ/kg) (Sandler, 2006)

3.3.5. Drying Unit

Scenarios 3, 4, 5 and 6 include partial drying unit prior to furnace. Energy demand of drying is satisfied by an external fuel in Scenarios 3 and 4 and by the heat of steam. As aforementioned, waste heat boiler is decided to produce superheated steam at 30 bar for electricity generation systems. Thus, to be comparable, in all scenarios, dryers are assumed to operate by superheated steam at 30 bar. Since this study aims to compare different cases by a theoretical energy and mass balance approach, technical capabilities for high pressure superheated drying is not investigated. In addition, partial drying may cause the sludge become sticky but, similarly, sticky phase problems are also ignored in this study.

Evaporated water is emitted. Except this, mass is conserved; organic volatilization is neglected. Heat is required to increase the initial wet sludge temperature up to dryer operation temperature and evaporation of water at 100°C. Schwarz (1982), considers the sludge to be dried as tripartite; volatile matter, non-volatile matter and water. For heating up solid and/or liquid to increase the temperature of matter, required heat is calculated by formula below Schwarz (1982):

$$\boldsymbol{E_d = \left(m_{vm} \times c_{vm} + m_{nvm} \times c_{nvm} + m_{w,d} \times c_w\right) \times (T_2 - T_1) + m_{w,e} \times \left(h_{v,T2} - h_{w,T2}\right) + E_{hl,d}} \quad \textbf{(21)}$$

Where,

E_d: Thermal energy required for drying (kJ/h),

$E_{hl,d}$: Heat losses of dryer (10 % of thermal energy) (Schwarz, 1982),

m_{vm}: Mass flow of volatile matter of sludge (kg/h),

m_{nvm}: Mass flow of non-volatile matter of sludge (kg/h),

$m_{w,d}$: Mass flow of water content of sludge feed into dryer (kg/h),

$m_{w,e}$: Mass flow of water to be evaporated (kg/h),

c_{vm}: Specific heat of volatile matter (kJ/kg°C) (Schwarz, 1982),

c_{nvm}: Specific heat of non-volatile matter (kJ/kg°C) (Schwarz, 1982),

c_w: Specific heat of water (kJ/kg°C) (Schwarz, 1982),

T_2: Dryer operation temperature (100°C) (Schwarz, 1982),

T_1: Feed temperature (assumed to be state temperature, 25°C),

$h_{v,T2}$: enthalpy of vapor at 100°C (2676 kJ/kg) (Sandler, 2006),

$h_{v,T2}$: enthalpy of water at 100°C (419 kJ/kg) (Sandler, 2006),

It is assumed that the evaporated water is removed from the system. Also partial dry product is cooled until being fed into furnace. In result of those assumptions, energy is consumed to evaporate water and increase the temperature of sludge. Since sludge is cooled and the vapor is removed from the system, input energy is considered also loss in general energy balance. Input energy is superheated steam. Superheated steam energy is transferred to sludge in dryer and output is saturated water at 100 °C. This water is recycled to additional boiler (scenario 3 and 4) or pumped to the waste heat boiler (scenario 5 and 6). So that, in all scenarios, condensers and dryers discharge saturated water at 100°C. By the energy difference of superheated steam and output water, amount of required steam is calculated for dryer. Energy equation is given below:

$$\boldsymbol{E_{ss} = E_{cw} + E_{cool} + E_{hl,d}} \qquad \textbf{(22)}$$

Where,

E_{ss}: Input energy by superheated steam either from additional boiler ($E_{ss,ad}$) or from waste heat boiler ($E_{ss,b}$) (MJ/h),

E_{cw}: Output energy by condensed water either in additional boiler ($E_{cw,ad}$) or in waste heat boiler ($E_{cw,b}$) (MJ/h),

E_{cool}: Energy lost due to cooling of sludge and evaporated water discharge (MJ/h)

3.3.6. Additional Boiler for Dryer

Scenarios 3 and 4 include an additional boiler to produce steam which is used as drying energy source. A basic energy calculation is done for this unit. Combustion reaction of natural gas or heats of flue gas are not evaluated. Since the drying requirement is found by Goal Seek and correspondingly the required steam amount is known as explained in previous section, natural gas amount is obtained by knowing LHV of natural gas and heat loss in additional dryer. Heat loss value is considered to be same with the waste heat boiler efficiency.

3.3.7. Electric Consumption Estimations

Electricity demands of scenarios are important regarding the energy balance and C footprint. Through the experiences from the fluidized bed sludge combustion furnace EPC, manufacturer company INEVA Çevre Teknolojileri San. Tic. A.Ş., electric consumption data are related to many parameters. Nevertheless, it may be reasonable to take active electric consumption for around 2.5, 3.75 and 5 ton/h sludge incineration plants as 125, 187.5 and 250 kWh/h respectively. Also, for electric generation system having up to around 1.5 MW capacity, actual electricity consumption can be taken as 75 kWh/h due to the cooling tower of condenser and other auxiliary equipment of turbine systems. Fonda and Lynch (2009), has stated that 15 to 20 % of total energy demand of dryers are electric energy demands. Thus, the electricity consumptions of drying units in this study is decided to be the 15 % of total energy demand. This corresponds to 20 % of thermal energy.

3.3.8. Carbon Footprint

Direct CO_2 emissions are calculated by mass balance. As mentioned previously, sludge related emissions are reported as biogenic emissions, which are not included into C footprint calculations. This is because, carbon content of sewage sludge is reported as non-fossil (IPCC, 2006b). Biogenic emissions due to sewage sludge is mentioned in many academic studies. Liu et al. (2013), construes the statement of IPCC (2006b) as;

microbial degradation of biosolids and combustion of biomass are carbon neutral processes. Houllion (2005), applies life cycle assessment methodology onto some wastewater urban sludge management scenarios in their study and subtracts the biogenic CO_2 emission amount from total GHG emissions estimated. Lim et al. (2012), emphasizes the effect of wastewater treatment sector onto global warming as wastewater treatment plants are significant sources of huge amounts of CO_2, CH_4 and N_2O emissions. However, direct CO_2 emissions due to biological treatment or anaerobic digestion is accepted as biogenic and have zero effect on global warming. Cao and Pawlowski (2013), assumes combustion of organic matter of sewage sludge, biogas and bio-oil emits biogenic GHG. Hong et al. (2013), also excludes sludge incineration caused CO_2 emissions from the GHG inventory, prepared in their study for co-combustion of sludge and coal in a power plant. Niu (2013), with a different perspective, calculates all biogenic emissions and add them into total emissions by indicating the statement 'biogenic'. Nor is this all, they consider CH_4 is also biogenic as long as it is emitted due to sludge degradation. Houillon and Jolliet (2009), substitutes the biogenic emissions from wet oxidation, incineration and pyrolysis processes in their life cycle assessment while presenting the GHG balance. In this study, biogenic CO_2 is calculated but not included into overall C footprint.

Fossil based direct emissions are due to natural gas combustion. Indirect emissions due to electricity consumption are also considered. Net fossil based CO_2 emissions of scenarios are calculated by adding direct and indirect fossil based emissions and subtracting the substituted CO_2 by electric generation. Sludge related CO_2 emissions are assumed to be biogenic. N_2O or CH_4 formations are neglected in the combustion reaction given in previous sections.

For indirect GHG emissions, electric consumption is the only component. In the report of Ülgen (2012), National emission data related to electricity generation is calculated as 0.5459 kg CO_2/kWh generated for 2008 – 2010 period of Turkey. This data is used in the report to calculate the possible savings if nuclear energy plants are operated in Turkey. Besides, Aslanoğlu and Köksal (2012), gives an estimation in their study as; in 2020 it is expected that 377 TWH electricity is going to be produced in Turkey and the related CO_2 emissions will be 194 million ton. From this, 0.515 kg CO_2/kWh data is achieved. In this study, emission factor is decided to be 0.53 kg CO_2/kWh for Turkey, average of the two data given above. This data is used as an emission factor of the consumed electricity and saving factor of the generated electricity in scenarios.

3.3.9. Initial Cost Estimations

Roughly, initial cost information are taken from INEVA Çevre Teknolojileri San. Tic. A.Ş., Turkish fluidized bed manufacturer, EPC and turnkey sludge incineration and energy recovery plant construction company. As the combustion furnace capacities decrease (due to drying, especially for sludges E and F), fluidized bed combustion furnace costs are decreased. As drying capacity increase, initial cost of dryer also increases but this creates no dramatic increase. Electric generation system costs, on the other hand, do not change dramatically when generation capacities change. This is because, steam turbine prices are not decreasing in the same ratio when generation capacity decreases. Which means cost of turbine with low electricity generation capacity would have similar price with a turbine having higher capacity.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Sludge Properties for Evaluation

Calculated LHV values are given and compared with the values given in TUBİTAK report in Table 22. Calculations are done by Dulong equation given as Equation 7 in section 3.3.2. Combustion Process. Calculated values are 14-23% higher than the values reported.

Table 22 – Sludge A, B, C, D, E and F Ultimate Analysis and Heating Value to be Evaluated in Scenarios

Parameters	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
C (% by weight MAF)	49.8	49.2	51.9	51.6	50.7	46.9
H (% by weight MAF)	8.9	8.3	8.8	8.3	8.5	7.6
N (% by weight MAF)	8.7	8.4	7.1	5.9	6.5	5.9
O (% by weight MAF)	31.0	32.9	30.8	32.6	32.3	37.7
S (% by weight MAF)	1.6	1.2	1.4	1.6	2.0	1.9
*LHV** (MJ/kg MAF)*	*23.9*	*22.5*	*24.3*	*23.3*	*23.4*	*20.2*
Ash (% by weight of dry matter)	19.2	19.9	29.6	29.3	45.5	41.8
*LHV** (MJ/kg dry matter)*	*19.3*	*18.0*	*17.1*	*16.5*	*12.7*	*11.8*
LHV (MJ/kg dry matter)*	*16*	*15.8*	*14.0*	*14.0*	*10.4*	*10.2*
Difference in %	120	114	123	118	123	116

* Average is calculated from the original report

** Calculated in this study

Dulong equation is not a sludge specific but a common equation for solid fuels. This is thought to be the main reason for the difference between the measured heating values stated in TÜBİTAK report and calculated values in this study. This difference deemed not significant for the scope of this study as comparisons will be made on heating values calculated with Dulong equation for all sludges Table 22 shows that even MAF calorific value is high. high ash content may result in decrease in LHV of dry matter.

4.2. Goal Seek Results

After selection of 6 different sludges and before final mass and energy balances. sludge combustibility is tested at initial condition without gas supply or drying. Difference between the required and input energy are calculated. Then two main Goal Seek method is applied. Results are given in Table 23. In result. without natural gas supply or drying. selected dewatered sludges (5 ton/h) cannot be combusted at 850 °C. With respect to the characteristics of sludge. 181–397 kg/h natural gas is required. Besides. if no natural gas is supplied. then dry matter content should be 31.2–44.4 % according to sludge.

Table 23 – Goal Seek results for combustion of 6 sludges in Scenarios

Sludge	**Initial Energy Gap*** **$E_{req} – E_{in}$** **(MJ/h)**	**Natural Gas Amount for Combustion (kg/h) by Goal Seek ($E_{req} – E_{in} = 0$) for Scenarios 1 and 2**	**Water Removal Amount (kg/h) by Goal Seek ($E_{req} – E_{in} = 0$) for Scenarios 3. 4. 5 and 6**
A	4 380	181	997
B	5 284	218	1 203
C	5 888	243	1 340
D	6 830	264	1 452
E	8 921	369	2 031
F	9 608	397	2 187

* Combustion of sludges with 25 % DM and without natural gas supply

4.3. Mass Balance

Sludge dry matter amounts are same for each scenario and each sludge. Prior to the scenarios. sludges are accepted to be dewatered and amount is 5 ton/day. As sludge calorific value decreases (given in previous section. from Sludge A to F) natural gas demand or drying requirements increase. Scenarios 1 and 2 consume natural gas in furnace. scenarios 3 and 4 consume natural gas in additional boiler and scenarios 5 and 6 have no fossil fuel consumption. Due to the input mass increase by natural gas feed into furnace. scenarios 1 and 2 have high air demand. flue gas amount and superheated steam production. Thus. fossil fuel is used but produced steam amount is increased with respect to other scenarios. Combusted sludge amounts and dry matter contents after Goal Seek are given in Table 24 below.

Table 24 – Combusted Sludge Amounts and Dry Matter Contents

Sludge	Scenarios 1 and 2		Scenarios 3. 4. 5 and 6*	
	Dry Matter Content (%)	Amount (kg/h)	Dry Matter Content (kg/h)	Amount (kg/h)
A	25	5 000	31.2	4 003
B	25	5 000	32.9	3 797
C	25	5 000	34.2	3 660
D	25	5 000	35.2	3 548
E	25	5 000	42.1	2 969
F	25	5 000	44.4	2 813

*For scenarios 3. 4. 5 and 6. as drying is applied. dry matter contents and total sludge amounts are variable in furnace.

As sludge is dried. some amount of water is removed from the system. so. flue gas and steam amounts are decreased. In addition. natural gas utilization in additional boiler also creates some amount of flue gas in scenarios 3 and 4. Natural gas required for combustion is higher than the natural gas required for drying. Natural gas demands of additional boiler in scenario 3 and 4 are in the range of 83-145 kg/h where natural gas demands in wet sludge incineration (scenarios 1 and 2) are between 181-397 kg/h.

given in Appendix B. Thus. if sludge is partially dried by an additional fuel to achieve auto thermal point. there is still a requirement for natural gas in scenarios 3 and 4. which is around 37-44 % of natural gas used in Scenario 1 and 2 by mass. Besides. the produced superheated steam by waste heat boiler in scenario 3 and 4 are only 42-72 % of the steam produced in Scenarios 1 and 2 by mass with respect to the sludges. In scenario 5 and 6 there is no natural gas consumption and steam generation rate is same with scenario 3 and 4.

SO_2 in the flue gas is also evaluated in order to observe the emissions and make discussion about flue gas treatment requirements. SO_2 amounts in flue gas for Sludge A. B. C. D and F are calculated by the combustion reaction given in Equation 2 and amounts are; 32 kg/h, 25 kg/h, 25 kg/h, 29 kg/h, 28 kg/h and 28 kg/h respectively. SO_2 emissions are directly related to the S content of sludge and emitted amounts do not change according to the scenario applied. Therefore. a scenario based evaluation cannot be done for SO_2 emissions. Instead. total flue gas amounts emitted to the atmosphere are given below in Table 25. It is observed that natural gas usage increases and drying decreases the flue gas amounts.

Table 25 – Flue Gas Emissions by 6 Scenarios for 6 Sludges

Scenario No.	Flue Gas Emissions (kg/h)					
	Sludge A	**Sludge B**	**Sludge C**	**Sludge D**	**Sludge E**	**Sludge F**
Scenario 1	19 903	20 177	20 197	20 396	20 717	20 974
Scenario 2	19 903	20 177	20 197	20 396	20 717	20 974
Scenario 3	15 879	15 209	14 596	14 284	11 950	11 490
Scenario 4	15 879	15 209	14 596	14 284	11 950	11 490
Scenario 5	14 377	13 510	12 767	12 347	9 462	8 851
Scenario 6	14 377	13 510	12 767	12 347	9 462	8 851

4.4. Energy Balance

Energy balances. considering the energy inputs and output from scenario boundaries. are given in the figures below. Similar with the result in mass balance. for furnace. input natural gas increases the energy recovery and electricity generation potential. Removing some amount of water also removes the demand on natural gas in furnace but also decreases the output energy. Exhausted flue gas. removed ash. heat losses. discharged water. inefficiencies and loss due to electricity consumption are all considered as losses. Input energy comes from natural gas. sludge and electricity consumed. Output energies are defined to be losses and electricity generation. Scenarios 1 and 2 show differences from other scenarios as the LHV of sludge decreases.

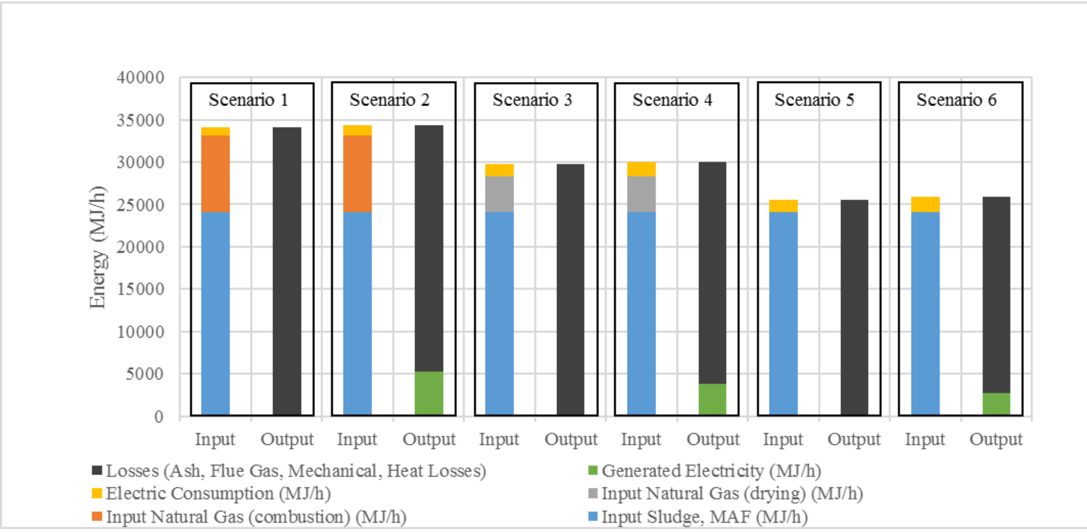

Figure 12 – Energy Balance Graph of Sludge A

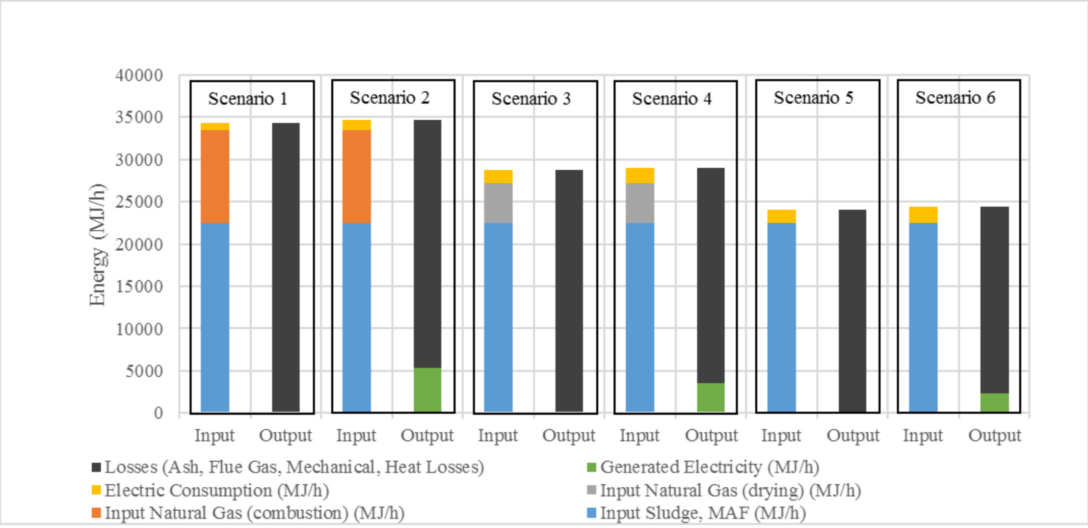

Figure 13 – Energy Balance Graph of Sludge B

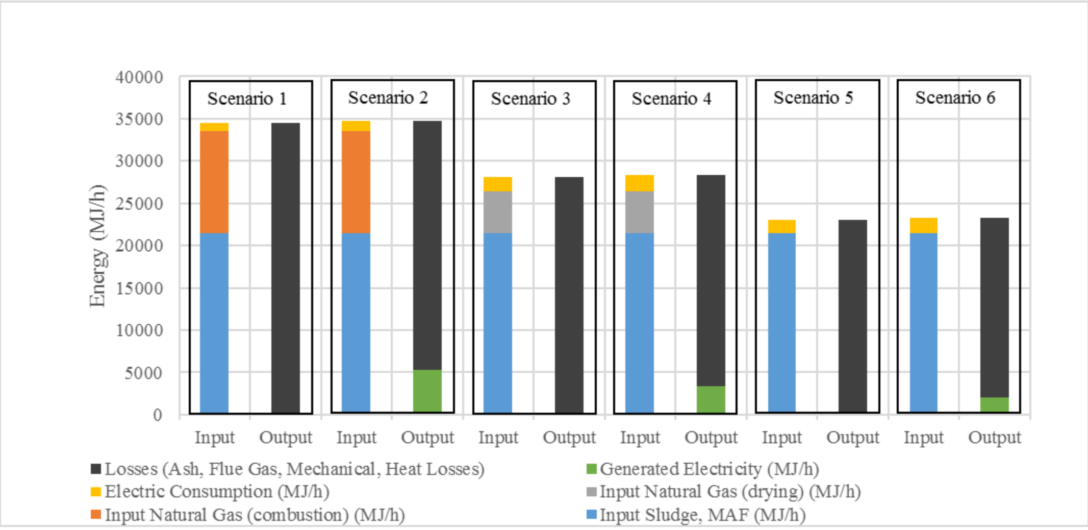

Figure 14 – Energy Balance Graph of Sludge C

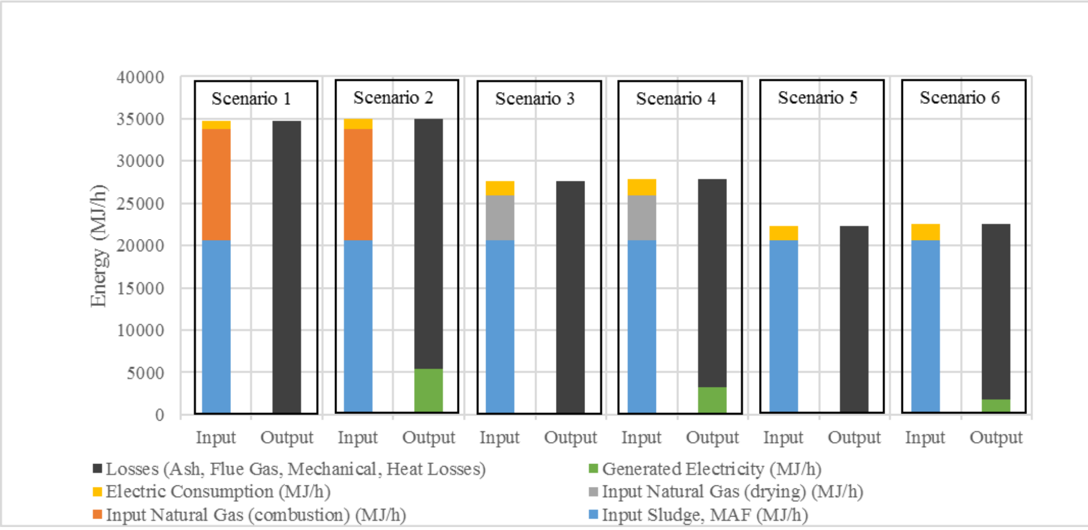

Figure 15 – Energy Balance Graph of Sludge D

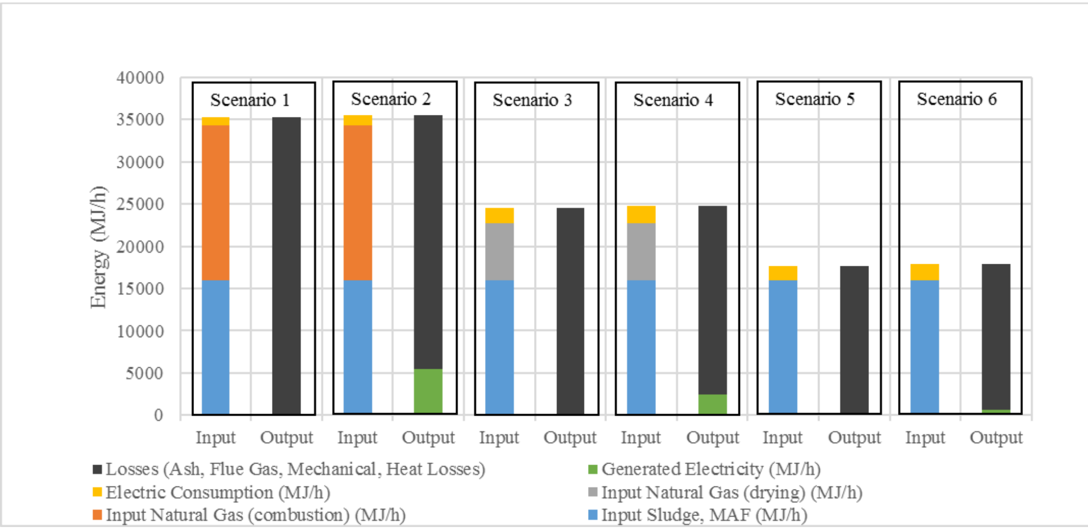

Figure 16 – Energy Balance Graph of Sludge E

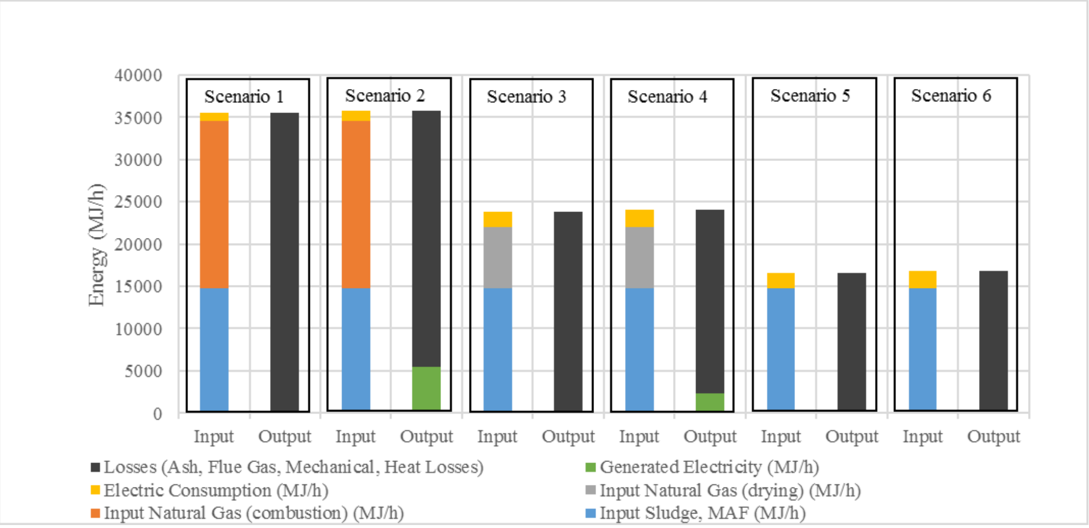

Figure 17 – Energy Balance Graph of Sludge F

Table 26 – Fossil Fuel Consumptions by 6 Scenarios for 6 Sludges

Scenario No	**Fossil Fuel Consumptions (MJ/h)**					
	Sludge A	**Sludge B**	**Sludge C**	**Sludge D**	**Sludge E**	**Sludge F**
Scenario 1	9 060	10 929	12 179	13 195	18 450	19 871
Scenario 2	9 060	10 929	12 179	13 195	18 450	19 871
Scenario 3	4 142	4 683	5 041	5 338	6 858	7 271
Scenario 4	4 142	4 683	5 041	5 338	6 858	7 271
Scenario 5	-	-	-	-	-	-
Scenario 6	-	-	-	-	-	-

Table 27 – Electricity Consumptions by 6 Scenarios for 6 Sludges

Scenario No	**Electricity Consumptions (MJ/h)**					
	Sludge A	**Sludge B**	**Sludge C**	**Sludge D**	**Sludge E**	**Sludge F**
Scenario 1	900	900	900	900	900	900
Scenario 2	1 170	1 170	1 170	1 170	1 170	1 170
Scenario 3	1 462	1 565	1 633	1 689	1 753	1 832
Scenario 4	1 732	1 835	1 903	1 959	2 023	2 102
Scenario 5	1 462	1 565	1 633	1 689	1 753	1 832
Scenario 6	1 732	1 835	1 903	1 959	2 023	2 102

Table 28 – Electricity Generation by 6 Scenarios for 6 Sludges

Scenario No	Electricity Generation (MJ/h)					
	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
Scenario 1	-	-	-	-	-	-
Scenario 2	5 253	5 316	5 325	5 368	5 462	5 524
Scenario 3	-	-	-	-	-	-
Scenario 4	3 793	3 555	3 362	3 242	2 489	2 322
Scenario 5	-	-	-	-	-	-
Scenario 6	2 708	2 327	2 041	1 843	692	416

For scenarios 1 and 2. natural gas energy shares increase while LHV of sludge gets lower. also. total input energy increases. Natural gas consumption in scenarios 3 and 4 are also increase by lowering LHV and increasing drying demand. Yet. this do not result in increase in overall input energy like in previous two scenarios. For scenarios 5 and 6. on the other hand. decrease in input energy is expected by decreasing LHV since only energy source is sludge.

Scenarios 2. 4 and 6 are furtherly compared regarding the electricity generation. Regarding the energy generation from sludge. scenario 2 is found to be the most favorable scenario. However, in this scenario there is a natural gas share in the produced electricity. Scenario 4 also consumes fossil fuel. not in the furnace but in additional boiler. Natural gas has no direct effect on electricity generated but fossil is consumed in the system boundaries. Nevertheless, scenario 4 is second favorable scenario when only electricity generation is the selection criteria. Scenario 6 on the other hand is advantageous as there is no fossil fuel demand, however, as LHV decreases. more steam is consumed for dryer and electricity generation is calculated to be too low. For all sludges. scenario 6 has low energy generation potential. In practice turbines with low capacity may not be feasible. Comparison of three scenarios (2. 4 and 6) based on electricity generation related to LHV of sludges is given by the graph in Figure 18 below.

A further assessment is done in order to understand the share of natural gas in generated electricity of scenario 2. Furnace input energy is coming from natural gas and MAF part of sludge. When LHV and amounts are considered. input natural gas energy corresponds to 27.3%, 32.7%, 36.3%, 39.1%, 53.7% and 57.4% and, input MAF energy corresponds to 72.7%, 67.3%, 63.7%, 60.9%, 46.3% and 42.6% of total input energy for sludges A, B, C, D, E and F respectively. In order to find the electric energy produced by MAF sludge and natural gas separately. these percentages are multiplied by the generated electricity values in scenario 2. By this approach, for sludges A, B, C, D, E and F. MAF related electricity generation values are found to be 3818, 3579, 3394, 3272, 2529 and 2351 MJ/h respectively. These values are still higher than the electricity generated in other scenarios. However, generated electricity is a function of amount. quality and temperature difference of steam. where. steam data is directly related to the temperature and amount of flue gas. Therefore, input energy share of MAF sludge does not directly give the share of sludge in generated electricity. Thus, only for a brief assessment these values are given above but not included in overall evaluation.

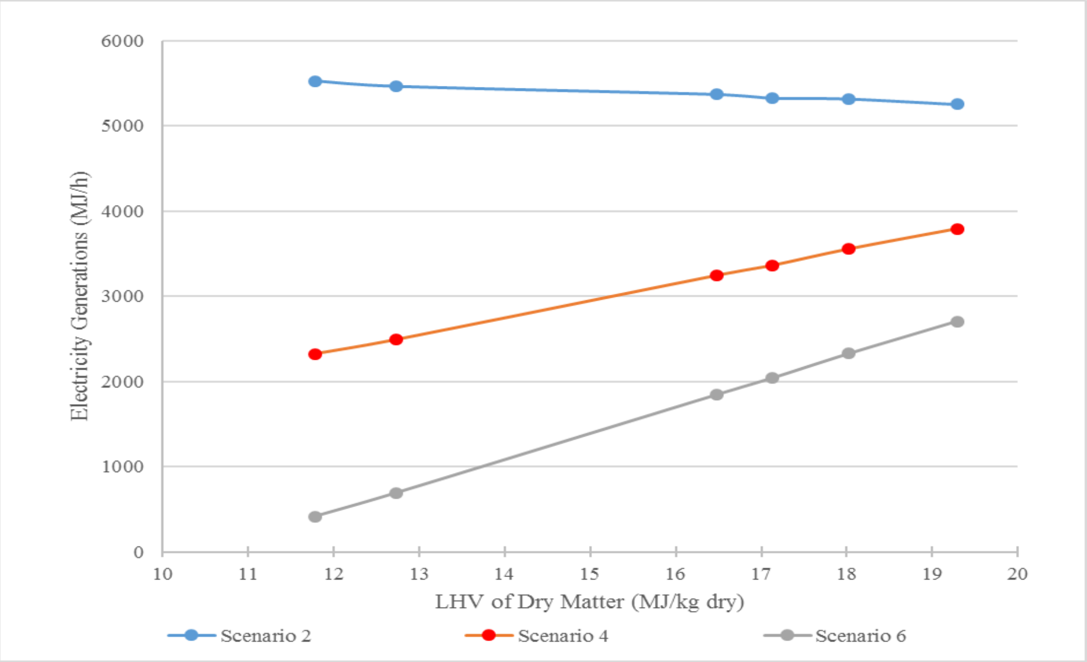

Figure 18 – LHV and Electricity Generation Relationship for Scenarios 2, 4 and 6

As it is observed from Figure 18. Electricity generation amount is directly related with the selected scenario. Scenario 2 has more stable electric generation profile even if the

LHV of sludge changes. That’s because, required energy for combustion at 850°C is satisfied by natural gas. As LHV decreases. share of natural gas increases in energy balance. Correspondingly, electricity generation also increases.

For scenarios 4 and 6 sludge is partially dried until combustion at 850°C can be achieved without additional fuel in furnace. Unnecessary water is removed from system. This also decreases the mass input. correspondingly mass of flue gas. Moreover, there is no natural gas supply into the furnace in these scenarios. Thus, it is reasonable that scenario 2 has higher potential for electricity generation. Opposite to scenario 2, in scenarios 4 and 6, decreasing LHV results in less energy generation. As LHV decreases. more water evaporation is required in dryer. Due to further mass decrease, electricity generation decreases. Net electricity of scenarios 2, 4 and 6 are given in Table 29.

Table 29 – LHV and Net Electricity Relationship for Scenarios 2. 4 and 6

Scenario	Electricity (MJ/h)	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
2	Consumption	1 170	1 170	1 170	1 170	1 170	1 170
	Generation	5 253	5 316	5 325	5 368	5 462	5 524
	Net	4 083	4 146	4 155	4 198	4 292	4 354
4	Consumption	1 732	1 835	1 903	1 959	2 023	2 102
	Generation	3 793	3 555	3 362	3 242	2 489	2 322
	Net	2 061	1 720	1 460	1 283	466	221
6	Consumption	1 732	1 835	1 903	1 959	2 023	2 102
	Generation	2 708	2 327	2 041	1 843	692	416
	Net	976	492	139	-116	-1 331	-1 685

As it is observed from Table 29, scenario 6 has a negative energy balance regarding the electricity. For sludges D, E and F (anaerobically digested), consumed electricity is higher than the generated electricity. The reason for decreasing electricity generation is explained above. Also electricity consumption demand increases due to the increased requirement in drying level when LHV of sludge decreases. In scenario 6, excess steam is used for electricity generation and it is not enough to generate more electricity than the consumptions. Scenario 4 has higher electric generation rates since steam is not used for drying but only for energy generation in turbine. As aforementioned, when drying requirements increase, consumed electricity also increases. Scenario 2 has a stable net electricity profile, since the electricity generation and consumption rates are stable in scenario 2, regardless of the LHV of sludge because there is no drying unit.

Relationship of electricity generation and LHV of sludge is given above but it is important to remark that there are many parameters effecting both of these such as; C, H, N, O, S, Ash percentages, dewatered dry matter content. operation temperature. input gas. sludge and air temperatures, etc.

4.5. C Footprint

Scenarios have different CO_2 emission profiles. As aforementioned in sections 2.5.2 and 3.3.8. sludge related direct emissions are accepted as biogenic and biogenic CO_2 emissions do not have adverse effect on global warming. These emissions are calculated but not included into overall C footprint. Therefore, biogenic emissions are given in Figure 19, not together with the C footprint. These emissions are directly related to the C content of sludge. As sludge is stabilized by anaerobic digestion. carbon content decreases. Since carbon content is lowest in sludge F, it has the lowest biogenic CO_2 emissions rather than other sludges selected in this study. Decreasing C content of sludge also decreases the LHV. Yet, a direct relationship between LHV and biogenic emissions cannot be established because LHV is affected not only by C but also by H, N, S, O and ash in sludge.

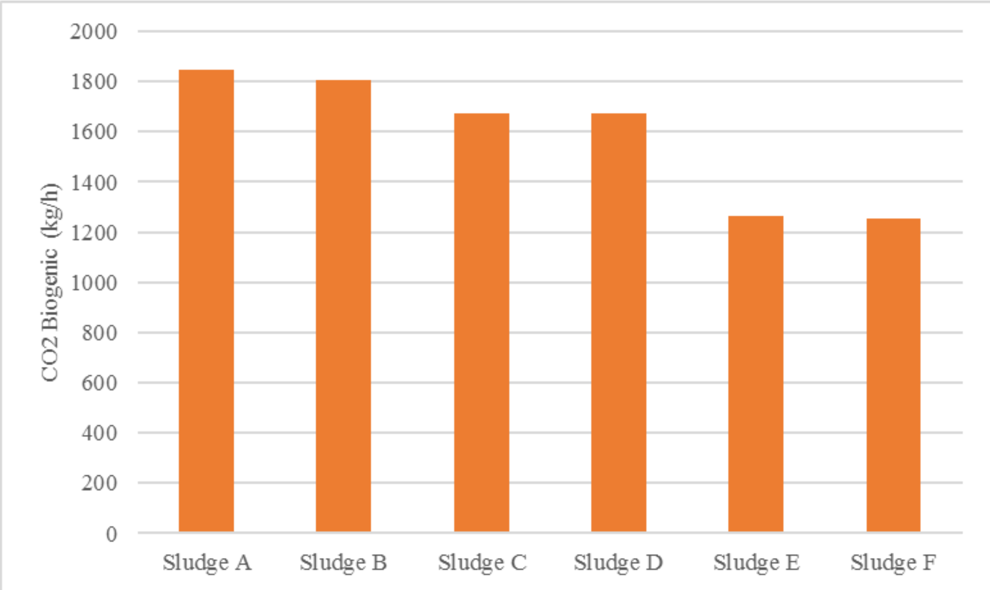

Figure 19 – Biogenic Emissions from Sludges

C footprint is done by using the data in mass balance and energy balance. Result are illustrated by graphs below. As expected, only electric generation scenarios have potential to save CO2. Yet, decrease in LHV of sludge, increases the natural gas demand and/or drying requirements. This results in increasing fossil CO2 emissions due to natural gas in scenarios 1 and 2. Also, in scenarios 3 and 4. natural gas related CO2 is increase since drying requirements are increased. Furthermore. CO2 substitutions of scenario 4 is decreased since more water is removed from the system when LHV of sludge decreases, which leads decrease in mass and energy output from furnace. In scenario 5 neither fossil is used nor electricity is generated. When the LHV changes, drying requirements change and only electric and steam consumption of scenario 5 changes. Therefore, scenario 5 has more stable result. In Scenario 6 since the steam which is not used in dryer is used for electric generation. As LHV decreases, scenario 6 electric generation related CO2 substitutions decrease. Comparison is done by considering fossil emissions and substitutions by electric generation. Any other reference scenario is not applied (landfill. land application) Therefore C footprint results are only valid for evaluation of 6 scenarios. Net CO2 emissions are also given in Table 30.

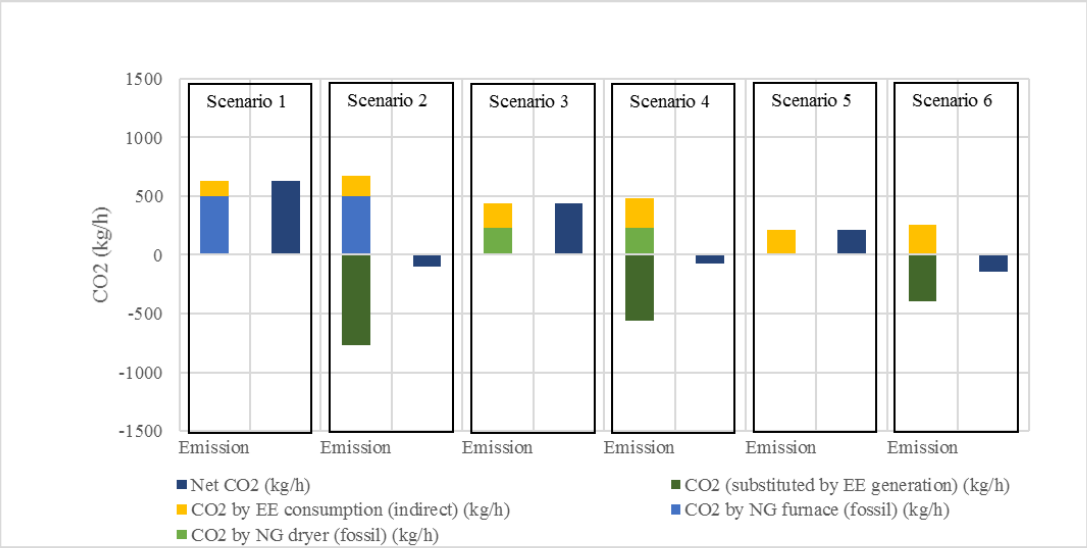

Figure 20 – Carbon Footprint Chart of Sludge A

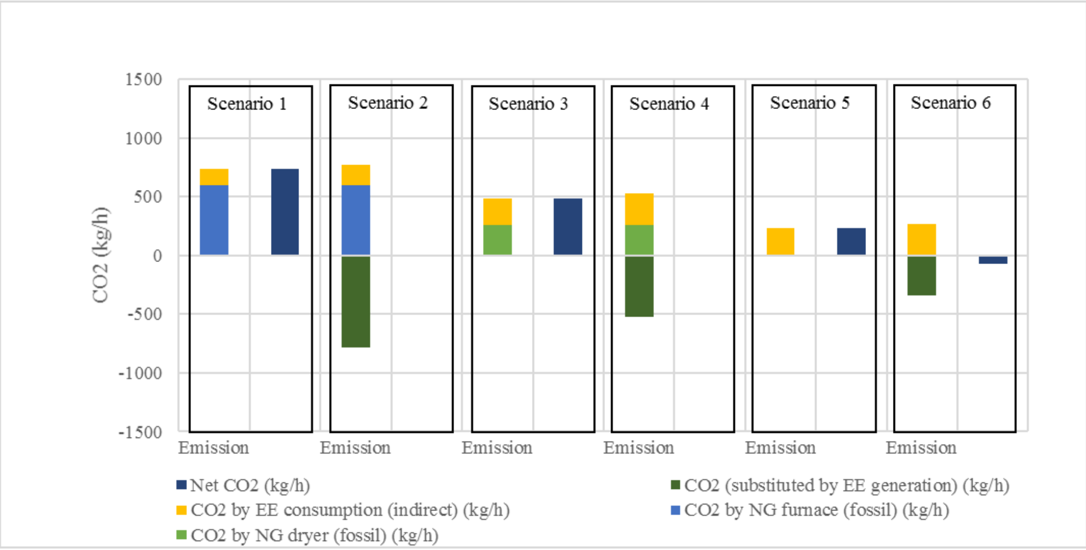

Figure 21 – Carbon Footprint Chart of Sludge B

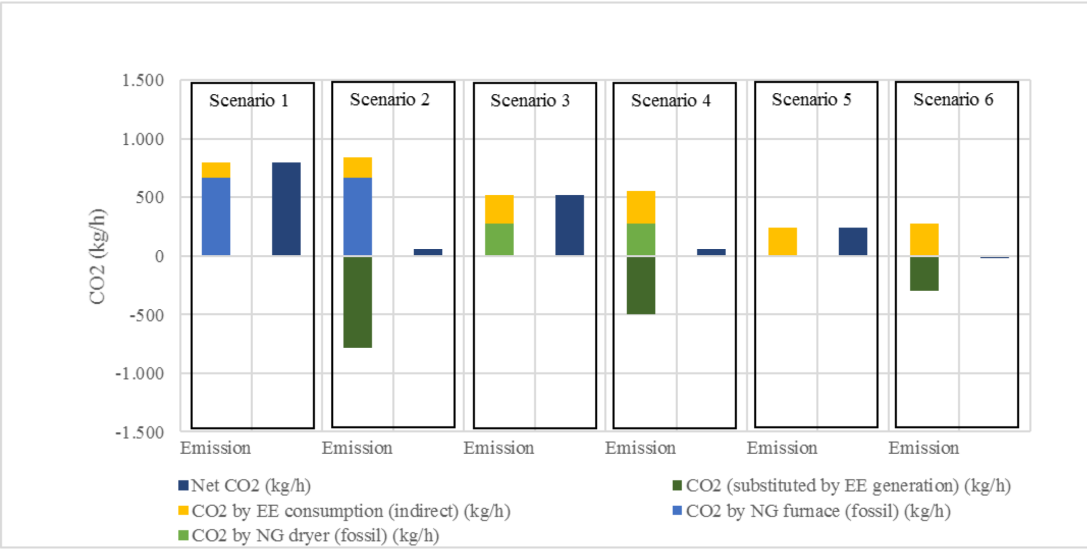

Figure 22 – Carbon Footprint Chart of Sludge C

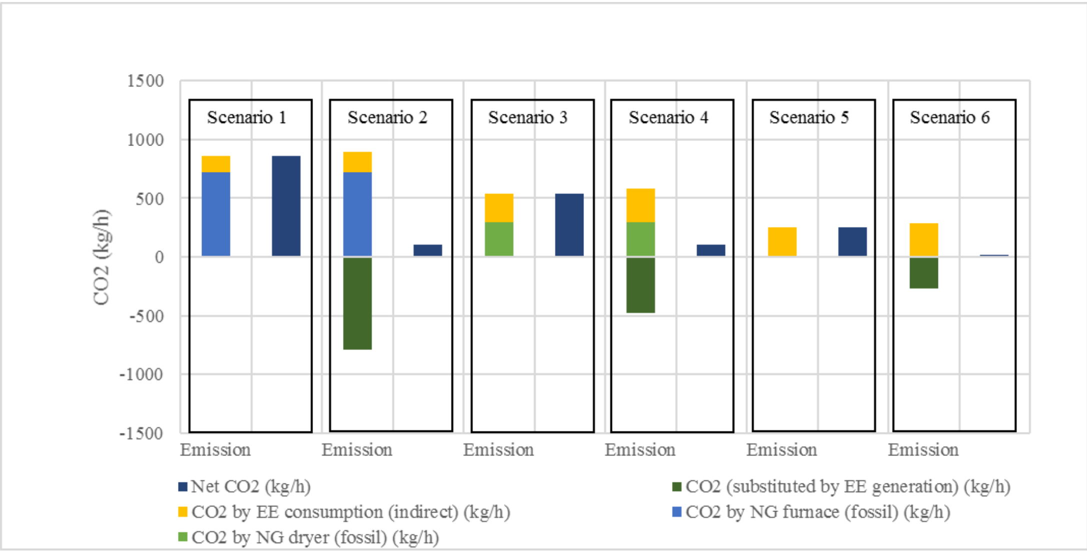

Figure 23 – Carbon Footprint Chart of Sludge D

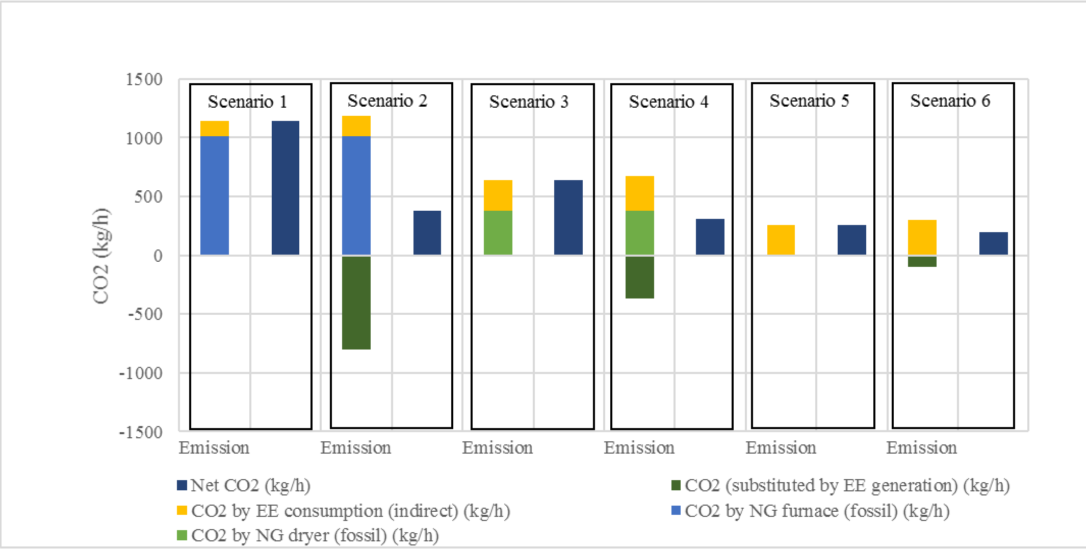

Figure 24 – Carbon Footprint Chart of Sludge E

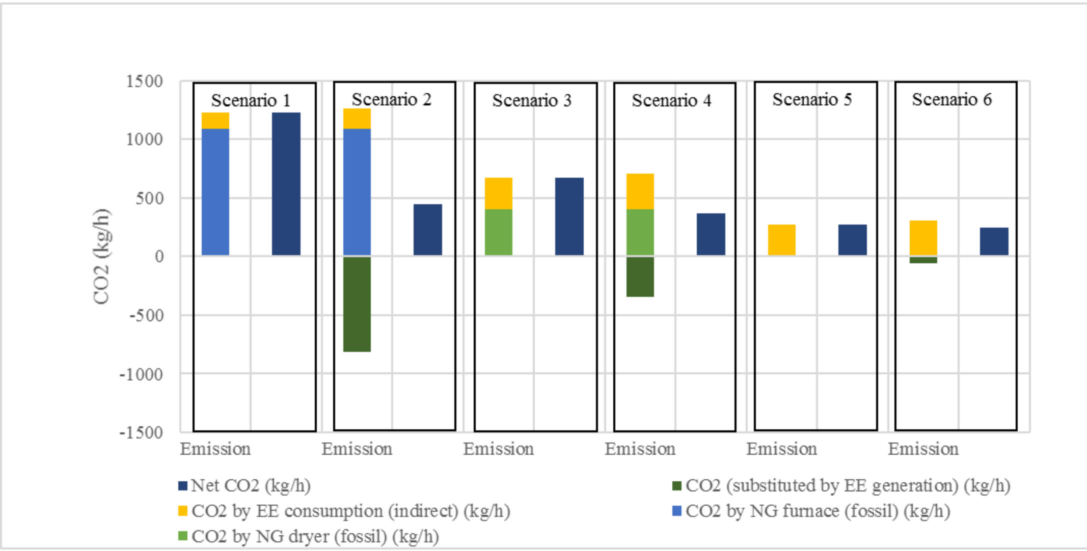

Figure 25 – Carbon Footprint Chart of Sludge F

Table 30 – Net CO_2 Emissions

Scenario No.	Net CO2 Emissions (kg/h)					
	Sludge A	**Sludge B**	**Sludge C**	**Sludge D**	**Sludge E**	**Sludge F**
Scenario 1	630	733	802	858	1.146	1.224
Scenario 2	-103	-10	57	106	381	450
Scenario 3	443	488	518	542	635	669
Scenario 4	-76	4	62	104	308	367
Scenario 5	215	231	241	249	258	270
Scenario 6	-144	-73	-20	17	196	248

Since CO2 savings can be done by electric generation according to scope of this study. scenarios 2, 4 and 6 are furtherly comparted, just like in energy balance. But in C footprint. different from energy balance, definite statements cannot be done without referring the conditions. CO2 is saved when Sludge A is incinerated in scenarios 2, 4 and 6. When sludge B is incinerated, scenarios 2 and 6 save CO_2 and only scenario 6 saves CO_2 when Sludge C is the case. No CO_2 is saved in neither of the scenarios when Sludges D, E and F are combusted. Sludges having high LHV has opportunity to achieve negative net CO2 emissions as long as electricity is generated, regardless of the scenario. In order to estimate the ideal LHV for each scenario, graph of relationship between C footprint and LHV of sludges are given in Figure 26 below.

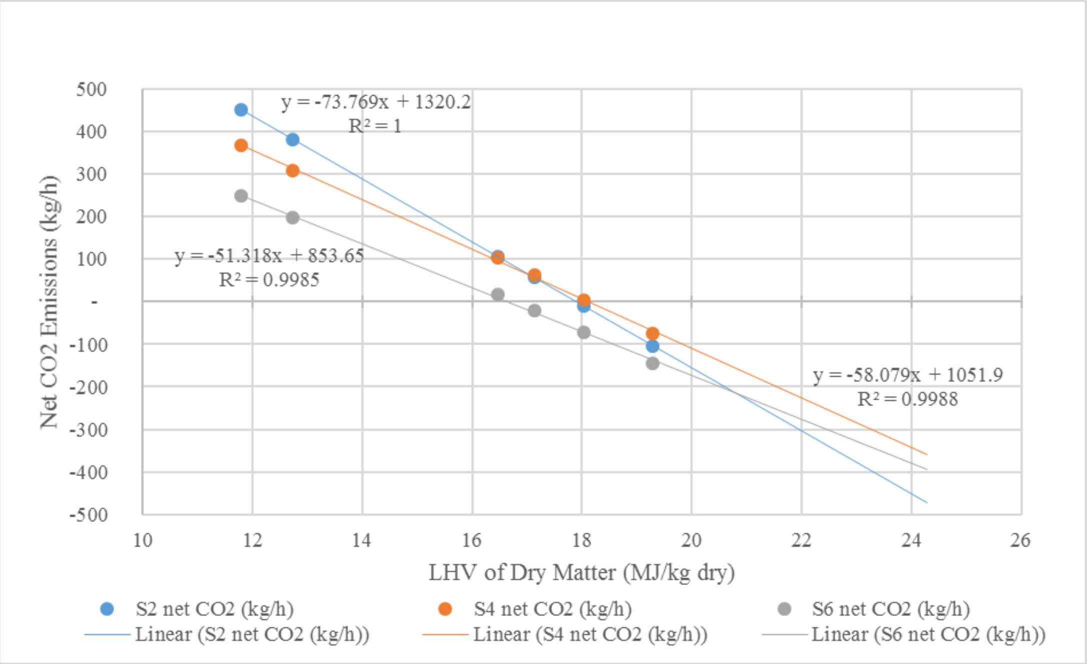

Figure 26 – Relationship between LHV of sludge and C footprint with respect to the Scenarios 2. 4 and 6

According to the graph above. three scenarios have different trend line angles. This means according to LHV of dry sludge, scenarios may be more advantageous than other. By using the equations given in the graph above, C neutral points for each scenario is found. CO_2 emissions are 0 for scenario 2, where LHV of sludge is 17.9 MJ/h. For sludges with higher LHV than this. scenario 2 saves CO_2. This critical LHV values are 18.11 and 16.63 MJ/h for scenarios 4 and 6 respectively. Scenario 6 requires the lowest LHV among other two scenarios to become C neutral. In addition, trend lines have cross points with each other too. For sludges having less LHV than 17.1 MJ/h. scenario 2 emits the most CO_2. When LHV of sludge increases from 17.1 MJ/h to higher levels, scenario 2 is more advantageous than scenario 4. Nevertheless. scenario 6 is the most advantageous one for all of the sludges evaluated (A-F). When the trend lines of graph are extended, for sludges having LHV higher than 20.78 MJ/h, maximum CO2 is saved by scenario 2.

4.6. Initial Cost Estimations

According to the results of mass and energy balances, initial investment cost estimations are done by INEVA by considering the capacities of dryer, furnace and turbines. From company, costs are taken for each sludge and scenario and given in Table 31. In result, dryer and turbine systems increase the cost but it is observed that drying decreases the cost of furnace.

Table 31 – Initial Cost Estimations

Scenario No	Initial Cost Estimations (€)					
	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
Scenario 1	3 500 000 €	3 500 000 €	3 500 000 €	3 500 000 €	3 500 000 €	3 500 000 €
Scenario 2	5 000 000 €	5 000 000 €	5 000 000 €	5 000 000 €	5 000 000 €	5 000 000 €
Scenario 3	4 300 000 €	4 300 000 €	4 300 000 €	4 400 000 €	2 850 000 €	2 850 000 €
Scenario 4	5 500 000 €	5 500 000 €	5 500 000 €	5 600 000 €	3 850 000 €	3 850 000 €
Scenario 5	4 200 000 €	4 200 000 €	4 200 000 €	4 300 000 €	2 750 000 €	2 750 000 €
Scenario 6	5 400 000 €	5 400 000 €	5 400 000 €	5 500 000 €	3 550 000 €	3 550 000 €

4.7. Overall Evaluation

Based on different criteria. some scenarios are resulted to be more beneficial. A basic comparison is done with respect to the energy balance (fossil fuel consumption. electric consumption. electric generation) and C footprint. Moreover, initial cost estimations are also considered in this section.

Scenario 1 consumes the lowest electricity due to having no dryer or electric generation equipment. Furthermore, for same reason this scenario has the lowest initial costs for sludge A, B, C and D. Scenario 2 has the greatest electricity generation potential and net electricity generation among other scenarios. Even though the LHV of sludge changes, scenario 2 has a more stable electricity generation profile than other scenarios. Scenario 3 and 4 have no advantageous over other scenarios for the defined criteria. This is mainly due to; dryer energy is satisfied by natural gas, not by the energy from combustion. Scenarios 5 and 6 have zero fossil fuel consumption and lowest flue gas emission. Scenario 5 also has lowest initial costs for sludge E and F because sludge amounts are decreased almost half and furnace costs are also decreased dramatically.

Scenario 6 has the lowest CO_2 emissions, thus, it is the most favorable scenario by means of C footprint. Best scenarios regarding those criteria are given in Table 32. Also, data per unit mass of dry matter input from scenario boundaries (25 % of 5000 kg/h: 1250 kg/h) in Table 33.

Table 32 – Best scenarios regarding different criteria

Criteria	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
Minimum Flue Gas Emission	S5 & S6	S5 & S6	S5 & S6	S5 & S6	S5 & S6	S5 & S6
Minimum Fossil Fuel Consumption	S5 & S6	S5 & S6	S5 & S6	S5 & S6	S5 & S6	S5 & S6
Minimum Electricity Consumption	S1	S1	S1	S1	S1	S1
Maximum Electricity Generation	S2	S2	S2	S2	S2	S2
Maximum Net Electricity Generation	S2	S2	S2	S2	S2	S2
Minimum Net CO2 Emission	S6	S6	S6	S6	S6	S6
Minimum Initial Cost	S1	S1	S1	S1	S5	S5

Table 33 – Data per unit mass of dry matter

Criteria	Sludge A	Sludge B	Sludge C	Sludge D	Sludge E	Sludge F
Minimum Flue Gas Emission (kg / kg DM)	11.5	10.8	10.2	9.9	7.6	7.1
Minimum Fossil Fuel Consumption (MJ / kg DM)	0	0	0	0	0	0
Minimum Electricity Consumption (MJ / kg DM)	0.7	0.7	0.7	0.7	0.7	0.7
Maximum Electricity Generation (MJ / kg DM)	4.2	4.3	4.3	4.3	4.4	4.4
Maximum Electricity Generation (MJ / kg DM)	3.3	3.3	3.3	3.4	3.4	3.5
Minimum Net CO2 Emission (kg / kg DM)	- 0.11	- 0.06	- 0.02	0.01	0.16	0.20
Minimum Initial Cost (€ / kg DM/h)	2800	2800	2800	2800	2200	2200

CHAPTER 5

CONCLUSION

In this study, different sludge mono-incineration applications are aimed to be evaluated based on their energy balances and C footprints for sludges having different characteristics. 6 different sludges have been selected for evaluation. All sludges assumed to be dewatered up to 25 % dry matter content before the boundaries of scenarios. By initial calculations. sludges had no enough energy for combustion at desired temperature. For that reason, in some scenarios natural gas is fed into furnace to increase the input energy and in others, partial drying is applied to remove desired amount of water and achieve an autogenous combustion at desired combustion temperature. 6 scenarios are developed by combinations of different approaches as; wet sludge combustion with natural gas. partial drying by additional fuel, partial drying by combustion energy and electricity generation. Desired combustion temperature is selected as 850 C and excess air ratio as 1.4.

By 6 scenarios and 6 sludges. 36 combustion cases are calculated and results are evaluated. Mass balance and energy balance calculations are done through the methodology developed in this study. Then, C footprint of each scenario are obtained for each sludge. Results are evaluated and best scenarios are stated with respect to the criteria; fossil fuel combustion, electric consumption. electric generation, net CO_2 emissions, flue gas amounts and initial cost estimations.

Results of the evaluations show that scenarios including partially drying with natural gas consumption have no advantage among other scenarios based on the mentioned criteria. Minimum fossil consumption and minimum flue gas emissions are achieved in scenarios 5 and 6, including partial drying by recovered combustion energy. For other scenarios as LHV decreases (especially sludge is anaerobically digested). natural gas requirements in plant increases. Minimum electricity consumption. on the other hand, is calculated for Scenario 1, dewatered sludge combustion with natural gas without energy generation since there is no dryer or turbine systems, which also consume electricity, applied.

Maximum electric generation is achieved by Scenario 2, dewatered sludge and natural gas combustion with energy generation. As LHV decreases, electric generation potentials of scenario 4 and 6 decreases too because the lower LHV result in higher drying and lower mass and energy output from furnace. However, electric generation capacity of scenario 2 increases by decreasing LHV because the energy gap is fulfilled by more natural gas. This makes an increase in output mass and energy when LHV is decreased. Furthermore, even though LHV of sludge changes, electricity generation is more stable in scenario 2 than other scenarios.

Lowest CO_2 emissions are obtained in Scenario 6, yet, for sludges having very high LHV (over 20.78 MJ/h) Scenario 2 saves more CO_2. Regarding the initial costs, for Sludges A, B, C and D, scenario 1 has the lowest initial cost due to not having dryer and turbine system. However, for sludges having low LHV (sludges E and F), initial costs are minimum in scenario 5 because drying requirements are high and correspondingly sludge amount is decreased in dryer prior to combustion, which creates a significant decrease in initial cost with respect to other sludges.

To sum up. scenarios 1, 2, 5 and 6 have advantages with respect to different criteria. LHV of sludge also affects the selection of best scenario for some criteria. Using natural gas for partial drying (scenarios 3 and 4), on the other hand, have no advantage with respect to neither of the criteria. These results should be used as initial estimations and for plant size investments and decisions, detailed engineering and financial analyses should be done. This study can be used by; engineers for assessing the scenarios with respect to the technical aspects, academicians for evaluating and discussing the results of scenarios, investors for decision making prior to feasibility studies and sludge experts for understanding and improving the transition in sludge management methods.

CHAPTER 6

FUTURE STUDIES AND RECOMMENDATIONS

- In this study, 6 mono-incineration scenarios are evaluated for 6 different sludge types. Numbers of combustion scenarios can be increased by considering combustion air pre heating with and/or without heat recovery from flue gas. Also, evaluations can be done for various sludge types.
- In this study, trace formations of NO_x emissions are neglected. Relationship between temperature and NO_x formation can be evaluated in future studies.
- Calculation tool can be improved to develop a software that would aid in decision making. By a software, it would be more practical for decision makers to use the calculation tool and analyze the results. Besides, regarding data gathering and result analysis, developing a software would be advantageous.
- Calculation tool can be enhanced to cover Analytical Hierarchy Process (AHP), SWOT, etc. AHP method is a multi-criteria decision making method, used when different criteria are used to select an alternative scenario among the others to achieve a defined goal. Also, SWOT is a strategic comparison tool with respect to strengths, weaknesses, opportunities and threats (Adar, 2016). This study focuses on evaluating the results of calculation tool. By adding SWOT approach; economic, environmental, social, legal and technical evaluation is going be done. Besides, by AHP method, best scenarios can be selected by multi-criteria evaluation, rather than criterion based evaluation.
- In this study, best scenarios are selected for each evaluation criteria. Rather than this, an aggregation approach can be used, such as AHP method, that

would take all criteria into consideration in decision making. AHP method starts with defining a goal, criteria and alternatives. In this study, goal can be defined as selection of best scenario for selected country. Then criteria are selected and to achieve the defined goal, all criteria and alternatives (scenarios) are weighted. At the end, scenario having the highest weight represents the best scenario to achieve the defined goal according to the given criteria (Adar, 2016). Criteria can be numbered as below:

Criteria 1: Minimum flue gas emissions

Criteria 2: Minimum fossil fuel consumption

Criteria 3: Minimum electricity consumption

Criteria 4: Maximum electricity generation

Criteria 5: Maximum net electricity generation

Criteria 6: Minimum CO_2 emission

Criteria 7: Minimum initial cost

All criteria can be compared to each other. The relative importance value of criteria 'i' compared to other criteria 'j' can be defined as '$x_{i,j}$'. Relative importance values represent the importance of each criterion over the others. 'x' values can be set between 1 and 9, where (Adar. 2016);

1 is used to define: criterion 'i' has equal importance with criterion 'j'

3 is used to define: criterion 'i' is slightly more important than criterion 'j'

5 is used to define: criterion 'i' is highly more important than criterion 'j'

7 is used to define: criterion 'i' is deemed superior to criterion 'j'

9 is used to define: evidence showing the superiority of criterion 'i' to 'j' is very substantial.

2. 4. 5. 6. 8 are used to define: values between two consecutive judgements to be used when specialization is needed. For example, for a selected country. if

minimum fossil fuel consumption (criterion 2) is highly more important than minimum net CO_2 emissions (criterion 6), then '$x_{2,6}$' equals to 5, '$x_{j,i}$' on the other hand equals to 1 / '$x_{i.j}$', therefore for the same case '$x_{6,2}$' is 1/5. Matrix for all relative importance values are given below:

$$X = \begin{pmatrix} j\backslash i & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 1 & x_{1,1} & x_{2,1} & x_{3,1} & x_{4,1} & x_{5,1} & x_{6,1} & x_{7,1} \\ 2 & x_{1,2} & x_{2,2} & x_{3,2} & x_{4,2} & x_{5,2} & x_{6,2} & x_{7,2} \\ 3 & x_{1,3} & x_{2,3} & x_{3,3} & x_{4,3} & x_{5,3} & x_{6,3} & x_{7,3} \\ 4 & x_{1,4} & x_{2,4} & x_{3,4} & x_{4,4} & x_{5,4} & x_{6,4} & x_{7,4} \\ 5 & x_{1,5} & x_{2,5} & x_{3,5} & x_{4,5} & x_{5,5} & x_{6,5} & x_{7,5} \\ 6 & x_{1,6} & x_{2,6} & x_{3,6} & x_{4,6} & x_{5,6} & x_{6,6} & x_{7,6} \\ 7 & x_{1,7} & x_{2,7} & x_{3,7} & x_{4,7} & x_{5,7} & x_{6,7} & x_{7,7} \end{pmatrix} \quad (23)$$

Then, distribution of importance can be found as;

$$N = \begin{pmatrix} j\backslash i & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 1 & n_{1,1} & n_{2,1} & n_{3,1} & n_{4,1} & n_{5,1} & n_{6,1} & n_{7,1} \\ 2 & n_{1,2} & n_{2,2} & n_{3,2} & n_{4,2} & n_{5,2} & n_{6,2} & n_{7,2} \\ 3 & n_{1,3} & n_{2,3} & n_{3,3} & n_{4,3} & n_{5,3} & n_{6,3} & n_{7,3} \\ 4 & n_{1,4} & n_{2,4} & n_{3,4} & n_{4,4} & n_{5,4} & n_{6,4} & n_{7,4} \\ 5 & n_{1,5} & n_{2,5} & n_{3,5} & n_{4,5} & n_{5,5} & n_{6,5} & n_{7,5} \\ 6 & n_{1,6} & n_{2,6} & n_{3,6} & n_{4,6} & n_{5,6} & n_{6,6} & n_{7,6} \\ 7 & n_{1,7} & n_{2,7} & n_{3,7} & n_{4,7} & n_{5,7} & n_{6,7} & n_{7,7} \end{pmatrix} \quad (24)$$

$$n_{i,j} = \frac{x_{i,j}}{\sum_{i=1}^{7} x_{i,j}} \quad (25)$$

Weight values can be found as below;

$$W_i = \frac{\sum_{j=1}^{7} N_{i,j}}{7} \quad (26)$$

Formulas are given for 7 criteria. By same approach. calculation tool results can be used to obtain weight values for scenarios too. By this way, a decision making tool can be developed and applied for different countries. At this point, best scenarios for different countries are going to be different. For example, countries having regulations regarding clean energy like Germany, would have higher weight value for minimum net CO_2 emissions criterion. This would affect the weight of scenario, which has lowest emission value. Furthermore, countries having their own natural gas reserves would have low weight value for minimum fossil fuel consumption criterion. Turkey, would probably have high weight value for maximum net electricity generation criterion due to the foreign dependency of Turkey in energy. All those weight values will affect the results, thus, the best scenarios for each country would vary. The highest value in AHP evaluation would define the best scenario for each country.

- In this study, initial cost estimations are given by the information achieved from INEVA Çevre Teknolojileri San. Tic. A.Ş. Scope of financial evaluation can be extended and operation and maintenance costs can also be included into evaluation. To do that, operation and maintenance costs data can be gathered by observations from full scale combustion plants and adjusted into calculation tool developed in this study.

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APPENDIX A

SAMPLE CALCULATION FOR SCENARIO 4 SLUDGE A

To show a sample calculation of all equipment, scenario 4 is selected since it has the largest amount of equipment (additional boiler, dryer and electric generation system). Combustion temperature is accepted to be 850 C, excess air ratio is 1,4 of theoretical air requirement and bottom ash is 80 % of total. Initial temperature of air and sludge prior to furnace are 25 C.

Average C, H, N, O, S and Ash percentages (by weight) of Sludge A are; 40,3, 7,2, 7,0, 25,0, 1,3 and 19,2 respectively. Total amounts for 25 % dry sludge with 5.000 kg/h are calculated:

H = (7,2/100) x 0,25 x 5.000 kg/h = 90 kg/h

N = (7/100) x 0,25 x 5.000 kg/h = 88 kg/h

O = (25/100) x 0,25 x 5.000 kg/h = 313 kg/h

S = (1,3/100) x 0,25 x 5.000 kg/h = 16 kg/h

MAF Total = 1.010 kg/h

Ash = (19,2/100) x 0,25 x 5.000 kg/h = 240 kg/h

Water = 0,75 x 5.000 kg/h = 3.750 kg/h

Total = 5.000 kg/h

Chemical composition of MAF part is calculated by using the molar weight of elements as below:

C = 503 / 12 kg/kmol = 42 kmol/h

H = 90 / 1 kg/kmol = 90 kmol/h

N = 88 / 14 = 6 kmol/h

O = 313 / 16 = 20 kmol/h

S = 16 / 32 = 0,5 kmol/h

$$C_{42}H_{90}O_{20}N_6S_{0,5} + 208H_2O + (1,4)\left(42 + \frac{90}{4} - \frac{20}{2} + 0,5\right)(O_2 + 3,76N_2)$$

$$\rightarrow\ (42)CO_2 + \left(208 + \frac{90}{2}\right)H_2O + (1,4 - 1)O_2$$

$$+\ 3,76\left(42 + \frac{90}{4} - \frac{20}{2} + 0,5\right)N_2 + 0,5SO_2$$

Input of furnace is calculated as below;

Sludge Input = 5.000 kg/h

O_2 Input = (1,4 x (42 + 90/4 - 20/2 + 0,5) kmol) x 32 kg/kmol = 2.474 kg/h

N_2 Input = (3,76 x 1,4 x (42 + 90/4 - 20/2 + 0,5) kmol) x 28 kg/kmol = 8.140 kg/h

Total Input = 15.614 kg/h

Output mass from furnace is calculated as:

CO_2 = 42 kmol/h x 44 kg/kmol = 1.845 kg/h

H_2O (formation) = 45 kmol/h x 18 kg/kmol = 812 kg/h

H_2O = 208 kmol/h x 18 kg/kmol = 3.750 kg/h

N_2 = 294 kmol/h x 28 kg/kmol = 8.227 kg/h

O_2 = 22 kmol/h x 32 kg/kmol = 707 kg/h

SO_2 = 0,5 kmol/h x 64 kg/kmol = 32 kg/h

Fly Ash = 240 kg/h x (1-0,8) = 48 kg/h

Bottom Ash = 240 kg/h x (0,8) = 192 kg/h

Total Output = 15.614 kg/h

Mass balance is concluded. Then, required energy and input energy is calculated. For input energy, LHV of sludge should be known. Moisture and ash free ultimate analysis are calculated as below:

C =(40,3/((100-19,20))x100)=49,8 (% by MAF weight)

H =(7,2/((100-19,20))x100)=8,9 (% by MAF weight)

N =(7,0/((100-19,20))x100)=8,7 (% by MAF weight)

O =(25,0/((100-19,20))x100)=31 (% by MAF weight)

S =(1,3/((100-19,20))x100)=1,6 (% by MAF weight)

HHV of MAF Sludge = (78,31×49,8 + 359,32 × (8,9-(31)/8) + 22,12×1,6 + 11,87×31+ 5,78×8,7) = 6173,3 kcal/kg-MAF

LHV of MAF = 6173,3 - 52,397 × 8,9 = 5705,5 kcal/kg-MAF (23,9 MJ/kg-MAF)

LHV of Dry Matter= 5705,5 ×((100-19,20))/100 = 4610,3 kcal/kg-dry (19,3 MJ/kg-dry)

Input energy is calculated as below:

Input Energy (E_{in}) = 23,9 MJ/kg x 1.010 kg/h = 24.112 MJ/h

For required energy, since combustion temperature is 850 C, sensible and latent heat of flue gas at 850 C should be calculated. Unit sensible enthalpies of gases are found by interpolation from the thermodynamic property tables. These values are multiplied by molar amounts. Latent heat of H2O is taken as 44 MJ/kmol. Ash sensible energy is calculated by specific heat value (0,25 kcal/kg C = 0,001046 MJ/kgC). Heat loss is assumed to be 10 % of total energy.

Flue gas and bottom ash energies

CO_2 = 42 kmol/h x 40,18 MJ/kmol = 1.685 MJ/h

H_2O (formation) = 45 kmol/h x 31,16 MJ/kmol = 1.405 MJ/h

H_2O = 208 kmol/h x 31,16 MJ/kmol = 6.492 MJ/h

Latent Heat of H_2O = 208 kmol/h x 44 MJ/kmol = 9.159 MJ/h

N_2 = 294 kmol/h x 25,53 MJ/kmol = 7.502 MJ/h

O_2 = 22 kmol/h x 27,03 MJ/kmol = 597 MJ/h

SO_2 = 0,5 kmol/h x 41,19 MJ/kmol = 21 MJ/h

Fly Ash = 48 kg/h x 0,001046 MJ/kgC x (850 C – 25 C) = 41 MJ/h

Bottom Ash = 192 kg/h x 0,001046 MJ/kgC x (850 C – 25 C) = 166 MJ/h

Total energy of required for flue gas and bottom ash to be at 850 C = 27.068 MJ/h

Energy Required (E_{req}) = 27.068 / (1-0,05) = 28.492 MJ/h

E_{req} – E_{in} = 28.492 – 27.068 = 4.380 MJ/h. This value is the gap between required and input energy.

By Goal Seek, this Gap is set to be zero by changing the value dry matter content. Then, Dry matter content is obtained to be 31,2 %. Then, 997 kg/h water should be evaporated in drying and new amount of sludge is 4.003 kg/h rather than 5.000 kg/h. Water content is 2.753 kg/h rather than 3.750 kg/h. This corresponds to 153 kmol/h water in sludge. New combustion reaction is rewritten:

$$C_{42}H_{90}O_{20}N_6S_{0,5} + 153H_2O + (1,4)\left(42 + \frac{90}{4} - \frac{20}{2} + 0,5\right)(O_2 + 3,76N_2)$$

$$\rightarrow (42)CO_2 + \left(153 + \frac{90}{2}\right)H_2O + (1,4 - 1)O_2$$

$$+ 3,76\left(42 + \frac{90}{4} - \frac{20}{2} + 0,5\right)N_2 + 0,5SO_2$$

Furnace Inputs are:

Sludge Input = 4.003 kg/h

O_2 Input = (1,4 x (42 + 90/4 - 20/2 + 0,5) kmol) x 32 kg/kmol = 2.474 kg/h

N_2 Input = (3,76 x 1,4 x (42 + 90/4 - 20/2 + 0,5) kmol) x 28 kg/kmol = 8.140 kg/h

Total Furnace Inputs: 14.377

Output mass from furnace is calculated as:

CO_2 = 42 kmol/h x 44 kg/kmol = 1.845 kg/h

H_2O (formation) = 45 kmol/h x 18 kg/kmol = 812 kg/h

H_2O = 153 kmol/h x 18 kg/kmol = 2.753 kg/h

N_2 = 294 kmol/h x 28 kg/kmol = 8.227 kg/h

O_2 = 22 kmol/h x 32 kg/kmol = 707 kg/h

SO_2 = 0,5 kmol/h x 64 kg/kmol = 32 kg/h

Fly Ash = 240 kg/h x (1-0,8) = 48 kg/h

Bottom Ash = 240 kg/h x (0,8) = 192 kg/h

Total Output = 14.617 kg/h

Mass is conserved for furnace. Thus energy calculations are done secondly. Input energy is calculated as below:

Input Energy (E_{in}) = 23,9 MJ/kg x 1.010 kg/h = 24.112 MJ/h

Flue gas and bottom ash energies

CO_2 = 42 kmol/h x 40,18 MJ/kmol = 1.685 MJ/h

H_2O (formation) = 45 kmol/h x 31,16 MJ/kmol = 1.405 MJ/h

H_2O = 153kmol/h x 31,16 MJ/kmol = 4.766 MJ/h

Latent Heat of H_2O = 153 kmol/h x 44 MJ/kmol = 6.723 MJ/h

N_2 = 294 kmol/h x 25,53 MJ/kmol = 7.502 MJ/h

O_2 = 22 kmol/h x 27,03 MJ/kmol = 597 MJ/h

SO_2 = 0,5 kmol/h x 41,19 MJ/kmol = 21 MJ/h

Fly Ash = 48 kg/h x 0,001046 MJ/kgC x (850 C – 25 C) = 41 MJ/h

Bottom Ash = 192 kg/h x 0,001046 MJ/kgC x (850 C – 25 C) = 166 MJ/h

Total energy of required for flue gas and bottom ash to be at 850 C = 22.906 MJ/h

Energy Required (E_{req}) = 27.068 / (1-0,05) = 24.112MJ/h

E_{req} – E_{in} = 28.492 – 27.068 = 0 MJ/h.

Thus, energy is conserved. Mass and energy balance is done for waste heat boiler at this point. Flue gas is fed into boiler and bottom ash is removed from furnace. Boiler heat losses are assumed to be 5 % or total energy. Besides, input water is assumed to have enthalpy of 0,422 MJ/kg and superheated steam at 3,682 MJ/h (given in methodology).

Waste heat boiler input and output flue gas (temperature decrease from 850 °C to 180 °C):

Flue Gas Amount = 14.425 kg/h

Flue Gas Input Energy = 22.741 MJ/h

Flue Gas Output Energy (at 180 °C) = 8.280 MJ/h

Energy Transferred = (22.741 – 8.280) / (1-0,05) = 13.738 MJ/h

Energy required to produce superheated steam from feed water = 3,682 – 0,422 = 3,26 MJ/kg

Steam Amount =13.738 MJ/h / 3,26 MJ/kg = 4.214 kg/h superheated steam production.

Energy of output flue gas is accepted as loss since it is emitted. Bottom ash and fly ash are also removed from the system; therefore, their energies are considered as loss too.

As it is given in methodology, turbine input superheated steam enthalpy is 3,682 MJ/kg and output steam enthalpy is 2,735 MJ/kg. Therefore, work out from turbine is calculated as:

W_T= 2,735 – 3,682 = -947,6 MJ/kg

Generator efficiency is taken as 0,95. Electricity output is:

E_{elec}= (947,6 MJ/kg x 4.214 kg/h) x 0,95 = 3.793 MJ/h (1,05 MW)

Exhaust steam is condensed to 100 °C saturated water with 0,419 MJ/h. The energy gap is accepted as loss in condenser.

Energy and mass balances of furnace, waste heat boiler and turbine systems are completed. Now, dryer and additional boiler energy and mass balances are going to be calculated. Dryer input is 5.000 kg/h. Volatile matter of sludge is calculated as 72,24 % of dry matter (25 % initially) by weight, which corresponds to 903 kg/h. Non-volatile matter is 347 kg/h. In order to increase the sludge temperature up to 100 °C from 25 °C (75 °C or °K difference) and evaporate desired amount of water, required energy is calculated. Enthalpy of water at 100 °C is already given above as 419 kJ/kg. vapor at 100 °C has enthalpy of 2.676 kJ/kg. Thermal efficiency is 10 % for dryer.

Energy for drying = (((((903 kg/h x 1,34 kJ/kg°K) + (347 kg/h x 0,88 kJ/kg°K) + (3.750 kg/h x 419 kJ/kg°K)) x 75°K) + (997 kg/h x 2.676 – 419)) / 1000) / 0,9 = 3.935 MJ/h (1ç093 kW)

In additional boiler, same with waste heat boiler, to produce 1 kg of steam, 3,26 MJ/kg energy should be supplied. By considering the 50,05 MJ/kg natural gas LHV and 5 % heat loss in additional boiler, natural gas amount is found to be 83 kg/h.

Mass and energy balances are completed for all system. Finally, C footprint is calculated. Unit national emissions are given in methodology per kWh of electricity. Electric consumptions are also given as 187,5 kW (675 MJ/h) for 4 ton/h sludge combustion in furnace (this value is given for around 3,75 sludge combustion capacity). Besides, 20 % of thermal energy in dryer is assumed to be additional electric demand and for electricity generation equipment, 75 kW (270 MJ/h) consumption is estimated.

Fossil CO_2 due to natural gas for drying = (83 kg/h / 16 kmol CH_4/kg) x 1 kmol C/kmol CH_4 x 1 kmol CO_2/kmol C x 44 kg CO_2/kmol = 228 kg CO_2/h

Electric consumption related CO_2 = (187,5 + 75 + (1.093 x 0,2)) kW x 0,53 kg CO_2/kWh = 255 kg CO_2/h

CO_2 substituted by electric generation = 1.050 kW x 0,53 kg CO_2/kWh = 558 kg CO_2/h

Net CO_2 = 228 + 255 – 558 = – 76 kg CO_2/h saved when Sludge A is combusted in scenario 4.

APPENDIX B

MASS BALANCE TABLES

Table 34 – Mass Balance for Sludge A Combustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	903	903	903	903	903	903	903	903
m_{nvm}	-	-	-	-	347	347	347	347	347	347	347	347
$m_{w,c}$	-	-	-	-	3 750	2 753	3 750	2 753	3 750	2 753	3 750	2 753
$m_{w,e}$	-	-	-	-	-	997	-	997	-	997	-	997
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	1 206	-	1 206
m_{ss}	-	-	-	-	-	-	-	-	1 206	-	1 206	-
$m_{cw,ad}$	-	-	-	-	-	1 206	-	1 206	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 206	-	1 206	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**6 206**	**6 206**	**6 206**	**6 206**	**6 206**	**6 206**	**6 206**	**6 206**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	83	-	83	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	1 420	-	1 420	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	1 503	-	1 503	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	1 206	-	1 206	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 206	-	1 206	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**2 709**	**2 709**	**2 709**	**2 709**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	1010	-	1010	-	1 010	-	1 010	-	1 010	-	1 010	-
m_{ash}	240	-	240	-	240	-	240	-	240	-	240	-
$m_{w,c}$	3750	-	3750	-	2 753	-	2 753	-	2 753	-	2 753	-
$m_{ng,c}$	181	-	181	-	-	-	-	-	-	-	-	-
m_{air}	14962	-	14962	-	10 614	-	10 614	-	10 614	-	10 614	-
m_{fg}	-	19951	-	19951	-	14 425	-	14 425	-	14 425	-	14 425
m_{ba}	-	192	-	192	-	192	-	192	-	192	-	192
Total	**20143**	**20143**	**20143**	**20143**	**14 617**	**14 617**	**14 617**	**14 617**	**14 617**	**14 617**	**14 617**	**14 617**
	Waste Heat Boiler											
m_{fg}	19951	-	19951	-	14 425	-	14 425	-	14 425	-	14 425	-
$m_{fg,b}$	-	19951	-	19951	-	14 425	-	14 425	-	14 425	-	14 425
m_{fw}	5835	-	5835	-	4 214	-	4 214	-	4 214	-	4 214	-
m_{ss}	-	5835	-	5835	-	4 214	-	4 214	-	4 214	-	4 214
Total	**25787**	**25787**	**25787**	**25787**	**18 638**	**18 638**	**18 638**	**18 638**	**18 638**	**18 638**	**18 638**	**18 638**
	Turbine and Generator											
m_{ss}	-	-	5835	-	-	-	4 214	-	-	-	3 008	-
$m_{ss,out}$	-	-	-	5835	-	-	-	4 214	-	-	-	3 008
Total	**-**	**-**	**5835**	**5835**	**-**	**-**	**4 214**	**4 214**	**-**	**-**	**3 008**	**3 008**
	Condenser											
m_{ss}	5835	-	-	-	4 214	-	-	-	3 008	-	-	-
$m_{ss,out}$	-	-	5 835	-	-	-	4 214	-	-	-	3 008	-
m_{cw}	-	5835	-	5 835	-	4 214	-	4 214	-	3 008	-	3 008
Total	**5835**	**5835**	**5 835**	**5 835**	**4 214**	**4 214**	**4 214**	**4 214**	**3 008**	**3 008**	**3 008**	**3 008**
	Pump											
m_{cw}	5835	-	5 835	-	4 214	-	4 214	-	3 008	-	3 008	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	1 206	-	1 206	-
m_{fw}	-	5835	-	5 835	-	4 214	-	4 214	-	4 214	-	4 214
Total	**5835**	**5835**	**5 835**	**5 835**	**4 214**	**4 214**	**4 214**	**4 214**	**4 214**	**4 214**	**4 214**	**4 214**
	Flue Gas Treatment and Exhaust											
$m_{fg,b}$	19951	-	19 951	-	14 425	-	14 425	-	14 425	-	14 425	-
$m_{fg,ad}$	-	-	-	-	1 503	-	1 503	-	-	-	-	-
$m_{fg,ex}$	-	19903	-	19 903	-	15879	-	15879	-	14 377	-	14 377
m_{fa}	-	48	-	48	-	48	-	48	-	48	-	48
Total	**19951**	**19951**	**19 951**	**19 951**	**15 927**	**15 927**	**15 927**	**15 927**	**14 425**	**14 425**	**14 425**	**14 425**

Table 35 – Mass Balance for Sludge B Combustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	863	863	863	863	863	863	863	863
m_{nvm}	-	-	-	-	387	387	387	387	387	387	387	387
$m_{w,c}$	-	-	-	-	3 750	2 547	3 750	2 547	3 750	2 547	3 750	2 547
$m_{w,e}$	-	-	-	-	-	1 203	-	1 203	-	1 203	-	1 203
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	1 363	-	1 363
m_{ss}	-	-	-	-	-	-	-	-	1 363	-	1 363	-
$m_{cw,ad}$	-	-	-	-	-	1 363	-	1 363	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 363	-	1 363	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**6 363**	**6 363**	**6 363**	**6 363**	**6 363**	**6 363**	**6 363**	**6 363**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	94	-	94	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	1 606	-	1 606	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	1 699	-	1 699	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	1 363	-	1 363	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 363	-	1 363	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**3 063**	**3 063**	**3 063**	**3 063**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	1 002	-	1 002	-	1 002	-	1 002	-	1 002	-	1 002	-
m_{ash}	249	-	249	-	249	-	249	-	249	-	249	-
$m_{w,c}$	3 750	-	3 750	-	2 547	-	2 547	-	2 547	-	2 547	-
$m_{ng,c}$	218	-	218	-	-	-	-	-	-	-	-	-
m_{air}	15 207	-	15 207	-	9 961	-	9 961	-	9 961	-	9 961	-
m_{fg}	-	20 227	-	20 227	-	13 560	-	13 560	-	13 560	-	13 560
m_{ba}	-	199	-	199	-	199	-	199	-	199	-	199
Total	**20 426**	**20 426**	**20 426**	**20 426**	**13 758**	**13 758**	**13 758**	**13 758**	**13 758**	**13 758**	**13 758**	**13 758**
	Waste Heat Boiler											
m_{fg}	20 227	-	20 227	-	13 560	-	13 560	-	13 560	-	13 560	-
$m_{fg,b}$	-	20 227	-	20 227	-	13 560	-	13 560	-	13 560	-	13 560
m_{fw}	5 905	-	5 905	-	3 949	-	3 949	-	3 949	-	3 949	-
m_{ss}	-	5 905	-	5 905	-	3 949	-	3 949	-	3 949	-	3 949
Total	**26 131**	**26 131**	**26 131**	**26 131**	**17 508**	**17 508**	**17 508**	**17 508**	**17 508**	**17 508**	**17 508**	**17 508**
	Turbine and Generator											
m_{ss}	-	-	5 905	-	-	-	3 949	-	-	-	2 585	-
$m_{ss,out}$	-	-	-	5 905	-	-	-	3 949	-	-	-	2 585
Total	**-**	**-**	**5 905**	**5 905**	**-**	**-**	**3 949**	**3 949**	**-**	**-**	**2 585**	**2 585**
	Condenser											
m_{ss}	5 905	-	-	-	3 949	-	-	-	2 585	-	-	-
$m_{ss,out}$	-	-	5 905	-	-	-	3 949	-	-	-	2 585	-
m_{cw}	-	5 905	-	5 905	-	3 949	-	3 949	-	2 585	-	2 585
Total	**5 905**	**5 905**	**5 905**	**5 905**	**3 949**	**3 949**	**3 949**	**3 949**	**2 585**	**2 585**	**2 585**	**2 585**
	Pump											
m_{cw}	5 905	-	5 905	-	3 949	-	3 949	-	2 585	-	2 585	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	1 363	-	1 363	-
m_{fw}	-	5 905	-	5 905	-	3 949	-	3 949	-	3 949	-	3 949
Total	**5 905**	**5 905**	**5 905**	**5 905**	**3 949**	**3 949**	**3 949**	**3 949**	**3 949**	**3 949**	**3 949**	**3 949**
	Flue Gas Treatment and Exhaust											
$m_{fg,b}$	20 227	-	20 227	-	13 560	-	13 560	-	13 560	-	13 560	-
$m_{fg,ad}$	-	-	-	-	1 699	-	1 699	-	-	-	-	-
$m_{fg,ex}$	-	20 177	-	"	-	15209	-	15209	-	13 510	-	13 510
m_{fa}	-	50	-	50	-	50	-	50	-	50	-	50
Total	**20 227**	**20 227**	**20 227**	**50**	**15 259**	**15 259**	**15 259**	**15 259**	**13 560**	**13 560**	**13 560**	**13 560**

Table 36 – Mass Balance for Sludge C Combustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	729	729	729	729	729	729	729	729
m_{nvm}	-	-	-	-	521	521	521	521	521	521	521	521
$m_{w,c}$	-	-	-	-	3750	2410	3750	2410	3750	2410	3750	2410
$m_{w,e}$	-	-	-	-	-	1 340	-	1 340	-	1340	-	1340
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	1468	-	1468
m_{ss}	-	-	-	-	-	-	-	-	1468	-	1468	-
$m_{cw,ad}$	-	-	-	-	-	1 468	-	1468	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 468	-	1468	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**6 468**	**6 468**	**6468**	**6 468**	**6 468**	**6 468**	**6 468**	**6 468**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	101	-	101	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	1 728	-	1728	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	1 829	-	1 829	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	1 468	-	1 468	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 468	-	1468	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**3 297**	**3 297**	**3297**	**3 297**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	881	-	881	-	881	-	881	-	881	-	881	-
m_{ash}	369	-	369	-	369	-	369	-	369	-	369	-
$m_{w,c}$	3750	-	3 750	-	2 410	-	2410	-	2 410	-	2 410	-
$m_{ng,c}$	243	-	243	-	-	-	-	-	-	-	-	-
m_{air}	15323	-	15 323	-	9 477	-	9477	-	9 477	-	9 477	-
m_{fg}	-	20 271	-	20 271	-	12 841	-	12 841	-	12 841	-	12 841
m_{ba}	-	296	-	296	-	296	-	296	-	296	-	296
Total	**20566**	**20 566**	**20 566**	**20 566**	**13 137**	**13 137**	**13 137**	**13 137**	**13 137**	**13 137**	**13 137**	**13 137**
	Waste Heat Boiler											
m_{fg}	20271	-	20 271	-	12 841	-	12 841	-	12 841	-	12 841	-
$m_{fg,b}$	-	20 271	-	20 271	-	12 841	-	12 841	-	12 841	-	12 841
m_{fw}	5915	-	5 915	-	3 735	-	3 735	-	3 735	-	3 735	-
m_{ss}	-	5 915	-	5 915	-	3 735	-	3 735	-	3 735	-	3 735
Total	**26186**	**26 186**	**26 186**	**26 186**	**16 576**	**16 576**	**16 576**	**16 576**	**16 576**	**16 576**	**16 576**	**16 576**
	Turbine and Generator											
m_{ss}	-	-	5 915	-	-	-	3 735	-	-	-	2 268	-
$m_{ss,out}$	-	-	-	5 915	-	-	-	3 735	-	-	-	2 268
Total	**-**	**-**	**5 915**	**5 915**	**-**	**-**	**3 735**	**3 735**	**-**	**-**	**2 268**	**2 268**
	Condenser											
m_{ss}	5 915	-	-	-	3 735	-	-	-	2 268	-	-	-
$m_{ss,out}$	-	-	5 915	-	-	-	3 735	-	-	-	2 268	-
m_{cw}	-	5 915	-	5 915	-	3 735	-	3 735	-	2 268	-	2 268
Total	**5 915**	**5 915**	**5 915**	**5 915**	**3 735**	**3 735**	**3 735**	**3 735**	**2 268**	**2 268**	**2 268**	**2 268**
	Pump											
m_{cw}	5 915	-	5 915	-	3 735	-	3 735	-	2 268	-	2 268	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	1 468	-	1 468	-
m_{fw}	-	5 915	-	5 915	-	3 735	-	3 735	-	3 735	-	3 735
Total	**5 915**	**5 915**	**5 915**	**5 915**	**3 735**	**3 735**	**3 735**	**3 735**	**3 735**	**3 735**	**3 735**	**3 735**
	Flue Gas Treatment and Exhaust											
mfg,b	20 271	-	20 271	-	12 841	-	12 841	-	12 841	-	12 841	-
mfg,ad	-	-	-	-	1 829	-	1 829	-	-	-	-	-
mfg,ex	-	20 197	-	20 197	-	14596	-	14596	-	12 767	-	12 767
mfa	-	74	-	74	-	74	-	74	-	74	-	74
Total	**20 271**	**20 271**	**20 271**	**20 271**	**14 670**	**14 670**	**14 670**	**14 670**	**12 841**	**12 841**	**12 841**	**12 841**

Table 37 – Mass Balance for Sludge D Combustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	779	779	779	779	779	779	779	779
m_{nvm}	-	-	-	-	471	471	471	471	471	471	471	471
$m_{w,c}$	-	-	-	-	3 750	2 298	3 750	2 298	3 750	2 298	3 750	2 298
$m_{w,e}$	-	-	-	-	-	1 452	-	1 452	-	1 452	-	1 452
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	1 554	-	1 554
m_{ss}	-	-	-	-	-	-	-	-	1 554	-	1 554	-
$m_{cw,ad}$	-	-	-	-	-	1 554	-	1 554	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 554	-	1 554	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**6 554**	**6 554**	**6 554**	**6 554**	**6 554**	**6 554**	**6 554**	**6 554**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	107	-	107	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	1 830	-	1 830	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	1 937	-	1 937	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	1 554	-	1 554	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 554	-	1 554	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**3 491**	**3 491**	**3 491**	**3 491**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	883	-	883	-	883	-	883	-	883	-	883	-
m_{ash}	367	-	367	-	367	-	367	-	367	-	367	-
$m_{w,c}$	3 750	-	3 750	-	2 298	-	2 298	-	2 298	-	2 298	-
$m_{ng,c}$	264	-	264	-	-	-	-	-	-	-	-	-
m_{air}	15 500	-	15 500	-	9 166	-	9 166	-	9 166	-	9 166	-
m_{fg}	-	20 470	-	20 470	-	12 420	-	12 420	-	12 420	-	12 420
m_{ba}	-	293	-	293	-	293	-	293	-	293	-	293
Total	**20 763**	**20 763**	**20 763**	**20 763**	**12 713**	**12 713**	**12 713**	**12 713**	**12 713**	**12 713**	**12 713**	**12 713**
	Waste Heat Boiler											
m_{fg}	20 470	-	20 470	-	12 420	-	12 420	-	12 420	-	12 420	-
$m_{fg,b}$	-	20 470	-	20 470	-	12 420	-	12 420	-	12 420	-	12 420
m_{fw}	5 963	-	5 963	-	3 602	-	3 602	-	3 602	-	3 602	-
m_{ss}	-	5 963	-	5 963	-	3 602	-	3 602	-	3 602	-	3 602
Total	**26 433**	**26 433**	**26 433**	**26 433**	**16 022**	**16 022**	**16 022**	**16 022**	**16 022**	**16 022**	**16 022**	**16 022**
	Turbine and Generator											
m_{ss}	-	-	5 963	-	-	-	3 602	-	-	-	2 048	-
$m_{ss,out}$	-	-	-	5 963	-	-	-	3 602	-	-	-	2 048
Total	**-**	**-**	**5 963**	**5 963**	**-**	**-**	**3 602**	**3 602**	**-**	**-**	**2 048**	**2 048**
	Condenser											
m_{ss}	5 963	-	-	-	3 602	-	-	-	2 048	-	-	-
$m_{ss,out}$	-	-	5 963	-	-	-	3 602	-	-	-	2 048	-
m_{cw}	-	5 963	-	5 963	-	3 602	-	3 602	-	2 048	-	2 048
Total	**5 963**	**5 963**	**5 963**	**5 963**	**3 602**	**3 602**	**3 602**	**3 602**	**2 048**	**2 048**	**2 048**	**2 048**
	Pump											
m_{cw}	5 963	-	5 963	-	3 602	-	3 602	-	2 048	-	2 048	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	1 554	-	1 554	-
m_{fw}	-	5 963	-	5 963	-	3 602	-	3 602	-	3 602	-	3 602
Total	**5 963**	**5 963**	**5 963**	**5 963**	**3 602**	**3 602**	**3 602**	**3 602**	**3 602**	**3 602**	**3 602**	**3 602**
	Flue Gas Treatment and Exhaust											
$m_{fg,b}$	20 470	-	20 470	-	12 420	-	12 420	-	12 420	-	12 420	-
$m_{fg,ad}$	-	-	-	-	1 937	-	1 937	-	-	-	-	-
$m_{fg,ex}$	-	20 396	-	20 396	-	14284	-	14284	-	12 347	-	12 347
m_{fa}	-	73	-	73	-	73	-	73	-	73	-	73
Total	**20 470**	**20 470**	**20 470**	**20 470**	**14 357**	**14 357**	**14 357**	**14 357**	**12 420**	**12 420**	**12 420**	**12 420**

Table 38 – Mass Balance for Sludge E Combustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	598	598	598	598	598	598	598	598
m_{nvm}	-	-	-	-	652	652	652	652	652	652	652	652
$m_{w,c}$	-	-	-	-	3 750	1 719	3 750	1 719	3 750	1 719	3 750	1 719
$m_{w,e}$	-	-	-	-	-	2 031	-	2 031	-	2 031	-	2 031
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	1 996	-	1 996
m_{ss}	-	-	-	-	-	-	-	-	1 996	-	1 996	-
$m_{cw,ad}$	-	-	-	-	-	1 996	-	1 996	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 996	-	1 996	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**6 996**	**6 996**	**6 996**	**6 996**	**6 996**	**6 996**	**6 996**	**6 996**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	137	-	137	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	2 351	-	2 351	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	2 488	-	2 488	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	1 996	-	1 996	-	-	-	-
$m_{ss,ad}$	-	-	-	-	1 996	-	1 996	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**4 485**	**4 485**	**4 485**	**4 485**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	681	-	681	-	681	-	681	-	681	-	681	-
m_{ash}	569	-	569	-	569	-	569	-	569	-	569	-
$m_{w,c}$	3 750	-	3 750	-	1 719	-	1 719	-	1 719	-	1 719	-
$m_{ng,c}$	369	-	369	-	-	-	-	-	-	-	-	-
m_{air}	15 918	-	15 918	-	7 061	-	7 061	-	7 061	-	7 061	-
m_{fg}	-	20 831	-	20 831	-	9 575	-	9 575	-	9 575	-	9 575
m_{ba}	-	455	-	455	-	455	-	455	-	455	-	455
Total	**21 286**	**21 286**	**21 286**	**21 286**	**10 031**	**10 031**	**10 031**	**10 031**	**10 031**	**10 031**	**10 031**	**10 031**
	Waste Heat Boiler											
m_{fg}	20 831	-	20 831	-	9 575	-	9 575	-	9 575	-	9 575	-
$m_{fg,b}$	-	20 831	-	20 831	-	9 575	-	9 575	-	9 575	-	9 575
m_{fw}	6 067	-	6 067	-	2 765	-	2 765	-	2 765	-	2 765	-
m_{ss}	-	6 067	-	6 067	-	2 765	-	2 765	-	2 765	-	2 765
Total	**26 899**	**26 899**	**26 899**	**26 899**	**12 341**	**12 341**	**12 341**	**12 341**	**12 341**	**12 341**	**12 341**	**12 341**
	Turbine and Generator											
m_{ss}	-	-	6 067	-	-	-	2 765	-	-	-	769	-
$m_{ss,out}$	-	-	-	6 067	-	-	-	2 765	-	-	-	769
Total	**-**	**-**	**6 067**	**6 067**	**-**	**-**	**2 765**	**2 765**	**-**	**-**	**769**	**769**
	Condenser											
m_{ss}	6 067	-	-	-	2 765	-	-	-	769	-	-	-
$m_{ss,out}$	-	-	6 067	-	-	-	2 765	-	-	-	769	-
m_{cw}	-	6 067	-	6 067	-	2 765	-	2 765	-	769	-	769
Total	6 067	-	-	-	2 765	-	-	-	769	-	-	-
	Pump											
m_{cw}	6 067	-	6 067	-	2 765	-	2 765	-	769	-	769	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	1 996	-	1 996	-
m_{fw}	-	6 067	-	6 067	-	2 765	-	2 765	-	2 765	-	2 765
Total	**6 067**	**6 067**	**6 067**	**6 067**	**2 765**	**2 765**	**2 765**	**2 765**	**2 765**	**2 765**	**2 765**	**2 765**
	Flue Gas Treatment and Exhaust											
$m_{fg,b}$	20 831	-	20 831	-	9 575	-	9 575	-	9 575	-	9 575	-
$m_{fg,ad}$	-	-	-	-	2 488	-	2 488	-	-	-	-	-
$m_{fg,ex}$	-	20 717	-	20 717	-	11950	-	11950	-	9 462	-	9 462
m_{fa}	-	114	-	114	-	114	-	114	-	114	-	114
Total	**20 831**	**20 831**	**20 831**	**20 831**	**12 064**	**12 064**	**12 064**	**12 064**	**9 575**	**9 575**	**9 575**	**9 575**

Table 39 – Mass Balance for Sludge F Cmbustion by 6 Scenarios (kg/h)

Parameter	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
m_{vm}	-	-	-	-	620	620	620	620	620	620	620	620
m_{nvm}	-	-	-	-	630	630	630	630	630	630	630	630
$m_{w,c}$	-	-	-	-	3 750	1 563	3 750	1 563	3 750	1 563	3 750	1 563
$m_{w,e}$	-	-	-	-	-	2 187	-	2 187	-	2 187	-	2 187
$m_{cw,d}$	-	-	-	-	-	-	-	-	-	2 117	-	2 117
m_{ss}	-	-	-	-	-	-	-	-	2 117	-	2 117	-
$m_{cw,ad}$	-	-	-	-	-	2 117	-	2 117	-	-	-	-
$m_{ss,ad}$	-	-	-	-	2 117	-	2 117	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**7 117**	**7 117**	**7 117**	**7 117**	**7 117**	**7 117**	**7 117**	**7 117**
	Additional Boiler											
$m_{ng,ad}$	-	-	-	-	145	-	145	-	-	-	-	-
$m_{air,ad}$	-	-	-	-	2 493	-	2 493	-	-	-	-	-
$m_{fg,ad}$	-	-	-	-	-	2 638	-	2 638	-	-	-	-
$m_{cw,ad}$	-	-	-	-	-	2 117	-	2 117	-	-	-	-
$m_{ss,ad}$	-	-	-	-	2 117	-	2 117	-	-	-	-	-
Total	**-**	**-**	**-**	**-**	**4 755**	**4 755**	**4 755**	**4 755**	**-**	**-**	**-**	**-**
	Combustion Furnace											
m_{MAF}	728	-	728	-	728	-	728	-	728	-	728	-
m_{ash}	522	-	522	-	522	-	522	-	522	-	522	-
$m_{w,c}$	3 750	-	3 750	-	1 563	-	1 563	-	1 563	-	1 563	-
$m_{ng,c}$	397	-	397	-	-	-	-	-	-	-	-	-
m_{air}	16 099	-	16 099	-	6 561	-	6 561	-	6 561	-	6 561	-
m_{fg}	-	21 078	-	21 078	-	8 956	-	8 956	-	8 956	-	8 956
m_{ba}	-	418	-	418	-	418	-	418	-	418	-	418
Total	**21 496**	**21 496**	**21 496**	**21 496**	**9 374**	**9 374**	**9 374**	**9 374**	**9 374**	**9 374**	**9 374**	**9 374**
	Waste Heat Boiler											
m_{fg}	21 078	-	21 078	-	8 956	-	8 956	-	8 956	-	8 956	-
$m_{fg,b}$	-	21 078	-	21 078	-	8 956	-	8 956	-	8 956	-	8 956
m_{fw}	6 136	-	6 136	-	2 579	-	2 579	-	2 579	-	2 579	-
m_{ss}	-	6 136	-	6 136	-	2 579	-	2 579	-	2 579	-	2 579
Total	**27 214**	**27 214**	**27 214**	**27 214**	**11 535**	**11 535**	**11 535**	**11 535**	**11 535**	**11 535**	**11 535**	**11 535**
	Turbine and Generator											
m_{ss}	-	-	6 136	-	-	-	2 579	-	-	-	463	-
$m_{ss,out}$	-	-	-	6 136	-	-	-	2 579	-	-	-	463
Total	**-**	**-**	**6 136**	**6 136**	**-**	**-**	**2 579**	**2 579**	**-**	**-**	**463**	**463**
	Condenser											
m_{ss}	6 136	-	-	-	2 579	-	-	-	463	-	-	-
$m_{ss,out}$	-	-	6 136	-	-	-	2 579	-	-	-	463	-
m_{cw}	-	6 136	-	6 136	-	2 579	-	2 579	-	463	-	463
Total	**6 136**	**6 136**	**6 136**	**6 136**	**2 579**	**2 579**	**2 579**	**2 579**	**463**	**463**	**463**	**463**
	Pump											
m_{cw}	6 136	-	6 136	-	2 579	-	2 579	-	463	-	463	-
$m_{cw,d}$	-	-	-	-	-	-	-	-	2117	-	2117	-
m_{fw}	-	6 136	-	6 136	-	2 579	-	2 579	-	2579	-	2579
Total	**6 136**	**6 136**	**6 136**	**6 136**	**2 579**	**2 579**	**2 579**	**2 579**	**2579**	**2579**	**2579**	**2579**
	Flue Gas Treatment and Exhaust											
$m_{fg,b}$	21078	-	21078	-	8956	-	8956	-	8956	-	8956	-
$m_{fg,ad}$	-	-	-	-	2638	-	2638	-	-	-	-	-
$m_{fg,ex}$	-	20974	-	20974	-	11490	-	11490	-	8851	-	8851
m_{fa}	-	104	-	104	-	104	-	104	-	104	-	104
Total	**21078**	**21078**	**21078**	**21078**	**11594**	**11594**	**11594**	**11594**	**8956**	**8956**	**8956**	**8956**

APPENDIX C

ENERGY BALANCE TABLES

Table 40 – Energy Balance for Sludge A Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	4 440	-	4 440	-
$E_{ss,ad}$	-	-	-	-	4 440	-	4 440	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	505	-	505
$E_{cw,ad}$	-	-	-	-	-	505	-	505	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	393	-	393	-	393	-	393
E_{cool}	-	-	-	-	-	3 541	-	3 541	-	3 541	-	3 541
Total	**-**	**-**	**-**	**-**	**4 440**	**4 440**	**4 440**	**4 440**	**4 440**	**4 440**	**4 440**	**4 440**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	4 142	-	4 142	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	505	-	505	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	4 440	-	4 440	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	207	-	207	-	-	-	-
Total	**-**	**-**	**-**	**-**	**4 647**	**4 647**	**4 647**	**4 647**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	24 112	-	24 112	-	24 112	-	24 112	-	24 112	-	24 112	-
$E_{ng,c}$	9 060	-	9 060	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	31 347	-	31 347	-	22 741	-	22 741	-	22 741	-	22 741
E_{ba}	-	166	-	166	-	166	-	166	-	166	-	166
$E_{hl,c}$	-	1 659	-	1 659	-	1 206	-	1 206	-	1 206	-	1 206
Total	**33 171**	**33 171**	**33 171**	**33 171**	**24 112**	**24 112**	**24 112**	**24 112**	**24 112**	**24 112**	**24 112**	**24 112**
	Waste Heat Boiler											
$E_{fg,c}$	31 347	-	31 347	-	22 741	-	22 741	-	22 741	-	22 741	-
E_{fw}	2 463	-	2 463	-	1 779	-	1 779	-	1 779	-	1 779	-
$E_{fg,c}$	-	11 321	-	11 321	-	8 280	-	8 280	-	8 280	-	8 280
E_{ss}	-	21 487	-	21 487	-	15 516	-	15 516	-	15 516	-	15 516
$E_{hl,b}$	-	1 001	-	1 001	-	723	-	723	-	723	-	723
Total	**33 810**	**33 810**	**33 810**	**33 810**	**24 519**	**24 519**	**24 519**	**24 519**	**24 519**	**24 519**	**24 519**	**24 519**
	Turbine and Generator											
E_{ss}	-	-	21 487	-	-	-	15 516	-	-	-	11 076	-
$E_{ss,out}$	-	-	-	15 958	-	-	-	11 523	-	-	-	8 226
$E_{loss,g}$	-	-	-	276	-	-	-	200	-	-	-	143
E_{elec}	-	-	-	5 253	-	-	-	3 793	-	-	-	2 708
Total	**-**	**-**	**21 487**	**21 487**	**-**	**-**	**15 516**	**15 516**	**-**	**-**	**11 076**	**11 076**
	Condenser											
E_{ss}	21 487	-	-	-	15 516	-	-	-	11 076	-	-	-
$E_{ss,out}$	-	-	15 958	-	-	-	11 523	-	-	-	8 226	-
E_{cw}	-	2 445	-	2 445	-	1 766	-	1 766	-	1 261	-	1 261
$E_{hl,cw}$	-	19 042	-	13 513	-	13 751	-	9 758	-	9 816	-	6 965
Total	**21 487**	**21 487**	**15 958**	**15 958**	**15 516**	**15 516**	**11 523**	**11 523**	**11 076**	**11 076**	**8 226**	**8 226**
	Pump											
E_{cw}	2 445	-	2 445	-	1 766	-	1 766	-	1 261	-	1 261	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	505	-	505	-
W_p	18	-	18	-	13	-	13	-	13	-	13	-
E_{fw}	-	2 463	-	2 463	-	1 779	-	1 779	-	1 779	-	1 779
Total	**2 463**	**2 463**	**2 463**	**2 463**	**1 779**	**1 779**	**1 779**	**1 779**	**1 779**	**1 779**	**1 779**	**1 779**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11 321	-	11 321	-	8 280	-	8 280	-	8 280	-	8 280	-
$E_{fg,ad}$	-	-	-	-	207	-	207	-	-	-	-	-
$E_{fg,ex}$	-	11 321	-	11 321	-	8 487	-	8 487	-	8 280	-	8 280
	11 321	**11 321**	**11 321**	**11 321**	**8 487**	**8 487**	**8 487**	**8 487**	**8 280**	**8 280**	**8 280**	**8 280**

Table 41 – Energy Balnce for Sludge B Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	5 020	-	5 020	-
$E_{ss,ad}$	-	-	-	-	5 020	-	5 020	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	571	-	571
$E_{cw,ad}$	-	-	-	-	-	571	-	571	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	445	-	445	-	445	-	445
E_{cool}	-	-	-	-	-	4 004	-	4 004	-	4 004	-	4 004
Total	**-**	**-**	**-**	**-**	**5 020**	**5 020**	**5 020**	**5 020**	**5 020**	**5 020**	**5 020**	**5 020**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	4 683	-	4 683	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	571	-	571	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	5 020	-	5 020	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	234	-	234	-	-	-	-
Total	**-**	**-**	**-**	**-**	**5 255**	**5 255**	**5 255**	**5 255**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	22 529	-	22 529	-	22 529	-	22 529	-	22 529	-	22 529	-
$E_{ng,c}$	10 929	-	10 929	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	31 613	-	31 613	-	21 231	-	21 231	-	21 231	-	21 231
E_{ba}	-	172	-	172	-	172	-	172	-	172	-	172
$E_{hl,c}$	-	1 673	-	1 673	-	1 126	-	1 126	-	1 126	-	1 126
Total	**33 457**	**33 457**	**33 457**	**33 457**	**22 529**	**22 529**	**22 529**	**22 529**	**22 529**	**22 529**	**22 529**	**22 529**
	Waste Heat Boiler											
$E_{fg,c}$	31 613	-	31 613	-	21 231	-	21 231	-	21 231	-	21 231	-
E_{fw}	2 492	-	2 492	-	1 667	-	1 667	-	1 667	-	1 667	-
$E_{fg,c}$	-	11 349	-	11 349	-	7 680	-	7 680	-	7 680	-	7 680
E_{ss}	-	21 743	-	21 743	-	14 540	-	14 540	-	14 540	-	14 540
$E_{hl,b}$	-	1 013	-	1 013	-	678	-	678	-	678	-	678
Total	**34 105**	**34 105**	**34 105**	**34 105**	**22 897**	**22 897**	**22 897**	**22 897**	**22 897**	**22 897**	**22 897**	**22 897**
	Turbine and Generator											
E_{ss}	-	-	21 743	-	-	-	14 540	-	-	-	9 520	-
$E_{ss,out}$	-	-	-	16 148	-	-	-	10 798	-	-	-	7 070
$E_{loss,g}$	-	-	-	280	-	-	-	187	-	-	-	122
E_{elec}	-	-	-	5 316	-	-	-	3 555	-	-	-	2 327
Total	**-**	**-**	**21 743**	**21 743**	**-**	**-**	**14 540**	**14 540**	**-**	**-**	**9 520**	**9 519**
	Condenser											
E_{ss}	21 743	-	-	-	14 540	-	-	-	9 520	-	-	-
$E_{ss,out}$	-	-	16 148	-	-	-	10 798	-	-	-	7 070	-
E_{cw}	-	2 474	-	2 474	-	1 655	-	1 655	-	1 083	-	1 083
$E_{hl,cw}$	-	19 268	-	13 673	-	12 885	-	9 144	-	8 436	-	5 986
Total	**21 743**	**21 743**	**16 148**	**16 148**	**14 540**	**14 540**	**10 798**	**10 798**	**9 520**	**9 520**	**7 070**	**7 070**
	Pump											
E_{cw}	2 474	-	2 474	-	1 655	-	1 655	-	1 083	-	1 083	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	571	-	571	-
W_p	18	-	18	-	12	-	12	-	12	-	12	-
E_{fw}	-	2 492	-	2 492	-	1 667	-	1 667	-	1 667	-	1 667
Total	**2 492**	**2 492**	**2 492**	**2 492**	**1 667**	**1 667**	**1 667**	**1 667**	**1 667**	**1 667**	**1 667**	**1 667**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11 349	-	11 349	-	7 680	-	7 680	-	7 680	-	7 680	-
$E_{fg,ad}$	-	-	-	-	234	-	234	-	-	-	-	-
$E_{fg,ex}$	-	11 349	-	11 349	-	7 914	-	7 914	-	7 680	-	7 680
	11 349	**11 349**	**11 349**	**11 349**	**7 914**	**7 914**	**7 914**	**7 914**	**7 680**	**7 680**	**7 680**	**7 680**

Table 42 – Energy Balance for Sludge C Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	5 404	-	5 404	-
$E_{ss,ad}$	-	-	-	-	5 404	-	5 404	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	615	-	615
$E_{cw,ad}$	-	-	-	-	-	615	-	615	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	479	-	479	-	479	-	479
E_{cool}	-	-	-	-	-	4 310	-	4 310	-	4 310	-	4 310
Total	**-**	**-**	**-**	**-**	**5 404**	**5 404**	**5 404**	**5 404**	**5 404**	**5 404**	**5 404**	**5 404**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	5 041	-	5 041	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	615	-	615	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	5 404	-	5 404	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	252	-	252	-	-	-	-
Total	**-**	**-**	**-**	**-**	**5 656**	**5 656**	**5 656**	**5 656**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	21 414	-	21 414	-	21 414	-	21 414	-	21 414	-	21 414	-
$E_{ng,c}$	12 179	-	12 179	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	31 658	-	31 658	-	20 088	-	20 088	-	20 088	-	20 088
E_{ba}	-	255	-	255	-	255	-	255	-	255	-	255
$E_{hl,c}$	-	1 680	-	1 680	-	1 071	-	1 071	-	1 071	-	1 071
Total	**33 592**	**33 592**	**33 592**	**33 592**	**21 414**	**21 414**	**21 414**	**21 414**	**21 414**	**21 414**	**21 414**	**21 414**
	Waste Heat Boiler											
$E_{fg,c}$	31 658	-	31 658	-	20 088	-	20 088	-	20 088	-	20 088	-
E_{fw}	2 496	-	2 496	-	1 577	-	1 577	-	1 577	-	1 577	-
$E_{fg,c}$	-	11 359	-	11 359	-	7 270	-	7 270	-	7 270	-	7 270
E_{ss}	-	21 781	-	21 781	-	13 754	-	13 754	-	13 754	-	13 754
$E_{hl,b}$	-	1 015	-	1 015	-	641	-	641	-	641	-	641
Total	**34 154**	**34 154**	**34 154**	**34 154**	**21 664**	**21 664**	**21 664**	**21 664**	**21 664**	**21 664**	**21 664**	**21 664**
	Turbine and Generator											
E_{ss}	-	-	21 781	-	-	-	13 754	-	-	-	8 350	-
$E_{ss,out}$	-	-	-	16 176	-	-	-	10 215	-	-	-	6 201
$E_{loss,g}$	-	-	-	280	-	-	-	177	-	-	-	107
E_{elec}	-	-	-	5 325	-	-	-	3 362	-	-	-	2 041
Total	**-**	**-**	**21 781**	**21 781**	**-**	**-**	**13 754**	**13 754**	**-**	**-**	**8 350**	**8 350**
	Condenser											
E_{ss}	21 781	-	-	-	13 754	-	-	-	8 350	-	-	-
$E_{ss,out}$	-	-	16 176	-	-	-	10 215	-	-	-	6 201	-
E_{cw}	-	2 479	-	2 479	-	1 565	-	1 565	-	950	-	950
$E_{hl,cw}$	-	19 302	-	13 697	-	12 189	-	8 649	-	7 400	-	5 251
Total	**21 781**	**21 781**	**16 176**	**16 176**	**13 754**	**13 754**	**10 215**	**10 215**	**8 350**	**8 350**	**6 201**	**6 201**
	Pump											
E_{cw}	2 479	-	2 479	-	1 565	-	1 565	-	950	-	950	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	615	-	615	-
W_p	18	-	18	-	11	-	11	-	11	-	11	-
E_{fw}	-	2 496	-	2 496	-	1 577	-	1 577	-	1 577	-	1 577
Total	**2 496**	**2 496**	**2 496**	**2 496**	**1 577**	**1 577**	**1 577**	**1 577**	**1 577**	**1 577**	**1 577**	**1 577**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11 359	-	11 359	-	7 270	-	7 270	-	7 270	-	7 270	-
$E_{fg,ad}$	-	-	-	-	252	-	252	-	-	-	-	-
$E_{fg,ex}$	-	11 359	-	11 359	-	7 522	-	7 522	-	7 270	-	7 270
	11 359	**11 359**	**11 359**	**11 359**	**7 522**	**7 522**	**7 522**	**7 522**	**7 270**	**7 270**	**7 270**	**7 270**

Table 43 – Energy Balance for Sludge D Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	5 723	-	5 723	-
$E_{ss,ad}$	-	-	-	-	5 723	-	5 723	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	651	-	651
$E_{cw,ad}$	-	-	-	-	-	651	-	651	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	507	-	507	-	507	-	507
E_{cool}	-	-	-	-	-	4 564	-	4 564	-	4 564	-	4 564
Total	**-**	**-**	**-**	**-**	**5 723**	**5 723**	**5 723**	**5 723**	**5 723**	**5 723**	**5 723**	**5 723**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	5 338	-	5 338	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	651	-	651	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	5 723	-	5 723	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	267	-	267	-	-	-	-
Total	**-**	**-**	**-**	**-**	**5 990**	**5 990**	**5 990**	**5 990**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	20 590	-	20 590	-	20 590	-	20 590	-	20 590	-	20 590	-
$E_{ng,c}$	13 195	-	13 195	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	31 843	-	31 843	-	19 308	-	19 308	-	19 308	-	19 308
E_{ba}	-	253	-	253	-	253	-	253	-	253	-	253
$E_{hl,c}$	-	1 689	-	1 689	-	1 030	-	1 030	-	1 030	-	1 030
Total	**33 786**	**33 786**	**33 786**	**33 786**	**20 590**	**20 590**	**20 590**	**20 590**	**20 590**	**20 590**	**20 590**	**20 590**
	Waste Heat Boiler											
$E_{fg,c}$	31 843	-	31 843	-	19 308	-	19 308	-	19 308	-	19 308	-
E_{fw}	2 517	-	2 517	-	1 520	-	1 520	-	1 520	-	1 520	-
$E_{fg,c}$	-	11 378	-	11 378	-	6 947	-	6 947	-	6 947	-	6 947
E_{ss}	-	21 959	-	21 959	-	13 263	-	13 263	-	13 263	-	13 263
$E_{hl,b}$	-	1 023	-	1 023	-	618	-	618	-	618	-	618
Total	**34 360**	**34 360**	**34 360**	**34 360**	**20 828**	**20 828**	**20 828**	**20 828**	**20 828**	**20 828**	**20 828**	**20 828**
	Turbine and Generator											
E_{ss}	-	-	21 959	-	-	-	13 263	-	-	-	7 540	-
$E_{ss,out}$	-	-	-	16 308	-	-	-	9 850	-	-	-	5 600
$E_{loss,g}$	-	-	-	283	-	-	-	171	-	-	-	97
E_{elec}	-	-	-	5 368	-	-	-	3 242	-	-	-	1 843
Total	**-**	**-**	**21 959**	**21 959**	**-**	**-**	**13 263**	**13 263**	**-**	**-**	**7 540**	**7 540**
	Condenser											
E_{ss}	21 959	-	-	-	13 263	-	-	-	7 540	-	-	-
$E_{ss,out}$	-	-	16 308	-	-	-	9 850	-	-	-	5 600	-
E_{cw}	-	2 499	-	2 499	-	1 509	-	1 509	-	858	-	858
$E_{hl,cw}$	-	19 460	-	13 809	-	11 753	-	8 340	-	6 682	-	4 741
Total	**21 959**	**21 959**	**16 308**	**16 308**	**13 263**	**13 263**	**9 850**	**9 850**	**7 540**	**7 540**	**5 600**	**5 600**
	Pump											
E_{cw}	2 499	-	2 499	-	1 509	-	1 509	-	858	-	858	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	651	-	651	-
W_p	18	-	18	-	11	-	11	-	11	-	11	-
E_{fw}	-	2 517	-	2 517	-	1 520	-	1 520	-	1 520	-	1 520
Total	**2 517**	**2 517**	**2 517**	**2 517**	**1 520**	**1 520**	**1 520**	**1 520**	**1 520**	**1 520**	**1 520**	**1 520**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11 378	-	11 378	-	6 947	-	6 947	-	6 947	-	6 947	-
$E_{fg,ad}$	-	-	-	-	267	-	267	-	-	-	-	-
$E_{fg,ex}$	-	11 378	-	11 378	-	7 214	-	7 214	-	6 947	-	6 947
	11 378	**11 378**	**11 378**	**11 378**	**7 214**	**7 214**	**7 214**	**7 214**	**6 947**	**6 947**	**6 947**	**6 947**

Table 44 – Energy Balance for Sludge E Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	7 351	-	7 351	-
$E_{ss,ad}$	-	-	-	-	7 351	-	7 351	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	837	-	837
$E_{cw,ad}$	-	-	-	-	-	837	-	837	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	651	-	651	-	651	-	651
E_{cool}	-	-	-	-	-	5 863	-	5 863	-	5 863	-	5 863
Total	**-**	**-**	**-**	**-**	**7 351**	**7 351**	**7 351**	**7 351**	**7 351**	**7 351**	**7 351**	**7 351**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	6 858	-	6 858	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	837	-	837	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	7 351	-	7 351	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	343	-	343	-	-	-	-
Total	**-**	**-**	**-**	**-**	**7 694**	**7 694**	**7 694**	**7 694**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	15 910	-	15 910	-	15 910	-	15 910	-	15 910	-	15 910	-
$E_{ng,c}$	18 450	-	18 450	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	32 249	-	32 249	-	14 722	-	14 722	-	14 722	-	14 722
E_{ba}	-	393	-	393	-	393	-	393	-	393	-	393
$E_{hl,c}$	-	1 718	-	1 718	-	795	-	795	-	795	-	795
Total	**34 360**	**34 360**	**34 360**	**34 360**	**15 910**	**15 910**	**15 910**	**15 910**	**15 910**	**15 910**	**15 910**	**15 910**
	Waste Heat Boiler											
$E_{fg,c}$	32 249	-	32 249	-	14 722	-	14 722	-	14 722	-	14 722	-
E_{fw}	2 561	-	2 561	-	1 167	-	1 167	-	1 167	-	1 167	-
$E_{fg,c}$	-	11 427	-	11 427	-	5 232	-	5 232	-	5 232	-	5 232
E_{ss}	-	22 342	-	22 342	-	10 182	-	10 182	-	10 182	-	10 182
$E_{hl,b}$	-	1 041	-	1 041	-	474	-	474	-	474	-	474
Total	**34 810**	**34 810**	**34 810**	**34 810**	**15 889**	**15 889**	**15 889**	**15 889**	**15 889**	**15 889**	**15 889**	**15 889**
	Turbine and Generator											
E_{ss}	-	-	22 342	-	-	-	10 182	-	-	-	2 831	-
$E_{ss,out}$	-	-	-	16 593	-	-	-	7 562	-	-	-	2 102
$E_{loss,g}$	-	-	-	287	-	-	-	131	-	-	-	36
E_{elec}	-	-	-	5 462	-	-	-	2 489	-	-	-	692
Total	**-**	**-**	**22 342**	**22 342**	**-**	**-**	**10 182**	**10 182**	**-**	**-**	**2 831**	**2 831**
	Condenser											
E_{ss}	22 342	-	-	-	10 182	-	-	-	2 831	-	-	-
$E_{ss,out}$	-	-	16 593	-	-	-	7 562	-	-	-	2 102	-
E_{cw}	-	2 542	-	2 542	-	1 159	-	1 159	-	322	-	322
$E_{hl,cw}$	-	19 800	-	14 050	-	9 023	-	6 403	-	2 509	-	1 780
Total	**22 342**	**22 342**	**16 593**	**16 593**	**10 182**	**10 182**	**7 562**	**7 562**	**2 831**	**2 831**	**2 102**	**2 102**
	Pump											
E_{cw}	2 542	-	2 542	-	1 159	-	1 159	-	322	-	322	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	837	-	837	-
W_p	18	-	18	-	8	-	8	-	8	-	8	-
E_{fw}	-	2 561	-	2 561	-	1 167	-	1 167	-	1 167	-	1 167
Total	**2 561**	**2 561**	**2 561**	**2 561**	**1 167**	**1 167**	**1 167**	**1 167**	**1 167**	**1 167**	**1 167**	**1 167**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11 427	-	11 427	-	5 232	-	5 232	-	5 232	-	5 232	-
$E_{fg,ad}$	-	-	-	-	343	-	343	-	-	-	-	-
$E_{fg,ex}$	-	11 427	-	11 427	-	5 575	-	5 575	-	5 232	-	5 232
	11 427	**11 427**	**11 427**	**11 427**	**5 575**	**5 575**	**5 575**	**5 575**	**5 232**	**5 232**	**5 232**	**5 232**

Table 45 – Energy Balance for Sludge F Combustion by 6 Scenarios (MJ/h)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
	Dryer											
E_{ss}	-	-	-	-	-	-	-	-	7 795	-	7 795	-
$E_{ss,ad}$	-	-	-	-	7 795	-	7 795	-	-	-	-	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	-	887	-	887
$E_{cw,ad}$	-	-	-	-	-	887	-	887	-	-	-	-
$E_{hl,d}$	-	-	-	-	-	691	-	691	-	691	-	691
E_{cool}	-	-	-	-	-	6 217	-	6 217	-	6 217	-	6 217
Total	**-**	**-**	**-**	**-**	**7 795**	**7 795**	**7 795**	**7 795**	**7 795**	**7 795**	**7 795**	**7 795**
	Additional Boiler											
$E_{ng,ad}$	-	-	-	-	7 271	-	7 271	-	-	-	-	-
$E_{cw,ad}$	-	-	-	-	887	-	887	-	-	-	-	-
$E_{ss,ad}$	-	-	-	-	-	7 795	-	7 795	-	-	-	-
$E_{hl,ad}$	-	-	-	-	-		-	-	-	-	-	-
$E_{fg,ad}$	-	-	-	-	-	364	-	364	-	-	-	-
Total	**-**	**-**	**-**	**-**	**8 158**	**8 158**	**8 158**	**8 158**	**-**	**-**	**-**	**-**
	Combustion Furnace											
E_{MAF}	14 729	-	14 729	-	14 729	-	14 729	-	14 729	-	14 729	-
$E_{ng,c}$	19 871	-	19 871	-	-	-	-	-	-	-	-	-
$E_{fg,c}$	-	32 509	-	32 509	-	13 632	-	13 632	-	13 632	-	13 632
E_{ba}	-	361	-	361	-	361	-	361	-	361	-	361
$E_{hl,c}$	-	1 730	-	1 730	-	736	-	736	-	736	-	736
Total	**34 599**	**34 599**	**34 599**	**34 599**	**14 729**	**14 729**	**14 729**	**14 729**	**14 729**	**14 729**	**14 729**	**14 729**
	Waste Heat Boiler											
$E_{fg,c}$	32 509	-	32 509	-	13 632	-	13 632	-	13 632	-	13 632	-
E_{fw}	2 590	-	2 590	-	1 089	-	1 089	-	1 089	-	1 089	-
$E_{fg,c}$	-	11 451	-	11 451	-	4 779	-	4 779	-	4 779	-	4 779
E_{ss}	-	22 595	-	22 595	-	9 498	-	9 498	-	9 498	-	9 498
$E_{hl,b}$	-	1 053	-	1 053	-	443	-	443	-	443	-	443
Total	**35 099**	**35 099**	**35 099**	**35 099**	**14 720**	**14 720**	**14 720**	**14 720**	**14 720**	**14 720**	**14 720**	**14 720**
	Turbine and Generator											
E_{ss}	-	-	22 595	-	-	-	9 498	-	-	-	1 704	-
$E_{ss,out}$	-	-	-	16 780	-	-	-	7 054	-	-	-	1 265
$E_{loss,g}$	-	-	-	291	-	-	-	122	-	-	-	22
E_{elec}	-	-	-	5 524	-	-	-	2 322	-	-	-	416
Total	**-**	**-**	**22 595**	**22 595**	**-**	**-**	**9 498**	**9 498**	**-**	**-**	**1 704**	**1 704**
	Condenser											
E_{ss}	22 595	-	-	-	9 498	-	-	-	1 704	-	-	-
$E_{ss,out}$	-	-	16 780	-	-	-	7 054	-	-	-	1 265	-
E_{cw}	-	2 571	-	2 571	-	1 081	-	1 081	-	194	-	194
$E_{hl,cw}$	-	20 024	-	14 209	-	8 417	-	5 973	-	1 510	-	1 071
Total	**22 595**	**22 595**	**16 780**	**16 780**	**9 498**	**9 498**	**7 054**	**7 054**	**1 704**	**1 704**	**1 265**	**1 265**
	Pump											
E_{cw}	2 571	-	2 571	-	1 081	-	1 081	-	194	-	194	-
$E_{cw,d}$	-	-	-	-	-	-	-	-	887	-	887	-
W_p	19	-	19	-	8	-	8	-	8	-	8	-
E_{fw}	-	2 590	-	2 590	-	1 089	-	1 089	-	1 089	-	1 089
Total	**2 590**	**2 590**	**2 590**	**2 590**	**1 089**	**1 089**	**1 089**	**1 089**	**1 089**	**1 089**	**1 089**	**1 089**
	Flue Gas Treatment and Exhaust											
$E_{fg,b}$	11451	-	11451	-	4 779	-	4 779	-	4 779	-	4 779	-
$E_{fg,ad}$	-	-	-	-	364	-	364	-	-	-	-	-
$E_{fg,ex}$	-	11451	-	11451	-	5 143	-	5 143	-	4 779	-	4 779
	11451	**11451**	**11451**	**11451**	**5143**	**5 143**	**5 143**	**5 143**	**4 779**	**4 779**	**4 779**	**4 779**