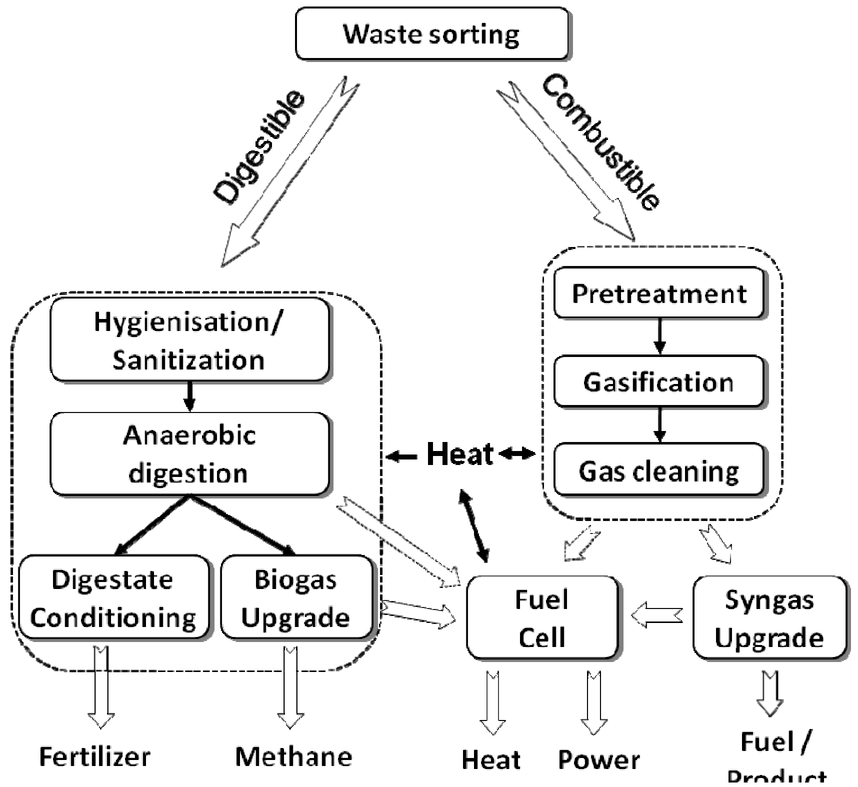

Energy balance calculation of selected refinery concepts for Energy from Waste facilities

Master of Science Thesis

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Göteborg, Sweden 2012

MASTER'S THESIS

Energy balance calculation of selected refinery concepts for Energy from Waste facilities

Master's Thesis within the Sustainable Energy Systems programme

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ABSTRACT

Three different EfW (Energy from Waste) scenarios are constructed consisting of combinations of incineration, gasification, anaerobic digestion, and fuel cell technology. Each scenario represents different EfW concepts but uses the same basic structure and operational condition. All scenarios consist of two waste treatment processes; thermal and biological treatment. The first scenario is an adaption of the Borås waste treatment facility reference case where fluidized bed CHP cycle is used to incinerate combustible waste and anaerobic digestion is used for biological waste. The second scenario is foreseeable future concept where gasification and incineration take place. The third is scenario is the futuristic scenario where waste is gasified and used in fuel cell for electricity conversion. The three scenarios have the same biological process where waste turns into biogas and upgrade for high methane concentration.

In order to investigate the energy production, an energy and mass balance calculation for each scenario was made using information collected from actual waste treatment facility and literature data. The balance model was created and evaluated using performance data collected from actual plant, literature data, and estimations. The biological process is based on the Sobacken biogas plant and Läckeby water biogas upgrade plant.

The energy from waste reference case with 100 000 ton combustible wastes and 30 000 ton biological waste produce 18.4 GWh of 97.5% methane biogas, 62.7 GWh_e and 220 GWh_{heat} annually. Using the same structure and operation condition, Scenario 1 produced 26 GWh of 97.5% methane biogas, 62.7 GWh_e and 214.12GWh_{heat}.

The second scenario with gasification using gas turbine and steam cycle produce 26 GWh of 97.5% methane biogas, 70.1 GWh_e and 181.61 GWh_{heat}. The third scenario with gasification and fuel cell technology produced 26 GWh of 97.5% methane biogas, 81.7 GWh_e and 93.4 GWh_{heat}.

The integration of gasification in second and third scenario has affected the heat and electricity production of the power plant.

Considering the heat and power generation on the sustainable perspective, the third scenario is the best option for Energy from waste.

Keywords: EfW, Anaerobic digestion, gasification, incineration

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Acknowledgements

I would like to thank all the colleagues at Chalmers and who offered their assistance, comments, and support during the master thesis work. I could not have done this without their support. I also like to thank all the staff at SP for their generosity and support during my time at SP office.

Lastly, I like to thank Roger Nordman and Ingmar Schüßler for your time and patience supervising me with this thesis work.

Pratavee Amornvareesaman

April, 2012

Preface

This diploma thesis was composed in a collaboration between the Technical Research Institute of Sweden (SP) and Chalmers University of Technology. The diploma thesis is part of the SP part of the research project “Review of state of the art of integration of processes of optimizing resource recovery from municipal solid waste” assigned by the International Energy Agency.

The thesis work was conduct at Technical Research Institute of Sweden, Energy and Environment department office in Borås between February 2011 and April of 2012. The research work is performed by Pratavee Amornvareesaman as a researcher under the supervision of Roger Nordman and Ingmar Schüßler.

Abbreviations, Symbols and Constants

Abbreviations

IEA	International Energy Agency
SP	Technical Research Institute of Sweden
EfW	Energy from Waste
MSW	Municipal Solid Waste
GTCC	Gas turbine combines cycle
RDF	Refuse derived fuels
ER	Equivalent ratio

Symbols

Symbols	*Meaning*	*Unit*
m	Mass	ton/year
m_w	Mass of waste	ton/year
m_{wa}	Mass of water	ton/year
m_{bio}	Mass of biogas	ton/year
$m_{mixture}$	Mass of mixture	ton/year
m_{air}	Mass of air	ton/year
m_{solid}	Mass of solid content	ton/year
TS	Total solid content	%
MO	Moisture content	%
LHV	Lower heating value	MJ/kg
Cp	Specific heating capacity	kJ/kg*K
U	Overall heating transfer coefficient	W/m^2*K
A	Area	m^2
T	Temperature	°C
T_w	Temperature of waste	°C
T_{wa}	Temperature of water	°C
Q	Heat transfer	kWh
Q_{loss}	Heat loss	kWh
Q_{bio}	Potential energy of biogas	kWh
P_{el}	Electric power generation	kWh
P_{el_loss}	Electric power consumption	kWh

eff_bio	Biogas coefficient	Nm3/ton waste
ρ	Density	kg/Nm3

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1 Introduction

1.1 Background

The International Energy Agency (IEA) is an intergovernmental organization founded in the 1970's and acts as energy policy advisor to member countries. Under the IEA, an implementing agreement called "IEA bioenergy" has been setup, focusing in bioenergy research, development and deployment. During year 2010-2012 IEA bioenergy has set up 12 different tasks and one of them is the task 36, "Integrating Energy Recovery into Solid Waste Management". The task aims to examine issues concerning energy recovery system for solid waste, and within the task; there are five subtopics in which SP (Technical Research Institute of Sweden) is responsible for subtopic 2, "Integration of processes for optimizing resource recovery".

In a preliminary study, SP has come up with different possible technology combinations concerning energy recovery systems, including current and foreseeable technologies. SP has also come up with three different scenarios involving both incineration and biological processes. The three scenarios represent state of art concept, foreseeable future and futuristic scenario.

1.2 Aim and Scope of work

The aim of the thesis work is to study the three different EfW concepts by performing energy and mass balance calculations in defined models, as well as collecting and evaluation of necessary process data. The results of the energy and mass balance model will be used to compare and contrast the uses of energy, efficiency and the energy production of different EfW concepts. Another target of this study is to evaluate the uses of waste heat for heat requiring processes and heat production.

1.3 Method and Theory

The main work of this thesis work is to study the EfW technologies and construct an energy and mass balance model for each EfW concept.

From the preliminary study of SP, three EfW scenarios have been developed with different perspective of the energy recovery system. The scenarios, using different technologies, are created with simple waste and energy flow paths in Microsoft excel models. Since the initial information and work outline has been collected and compiled by SP, this work proceed in more depth level.

1.3.1 Data collection and evaluation

A key part of the thesis work is to collect and evaluate information on different EfW technologies and compile the existing information on the EfW system. In order to collect information and understand the different EfW technologies a literature review has been performed, focusing on understanding the different technologies as part of the system and as a complete EfW system. In the he literature review different sources such as journals, research papers, engineering reports, and interviews were used.

Since EfW technologies share the same basic principle as other energy conversion technologies, some partially related literature sources are included in the study but most of the literature review is still focused on the use of waste as feedstock.

As operational waste treatment facilities exist within the Borås municipal area, a reference case based on those facilities was created in order to compare results. The data collection of the Borås waste treatment facilities were performed via email and phone contact with the plant operator.

1.3.2 Scenarios

The three scenarios developed by SP's preliminary study contain a basic structure of the EfW system with different energy and mass flow paths using different waste treatment technologies. The structures of the scenarios are sufficient to give a basic understanding of the EfW concepts and shall represent state of the art, foreseeable future, and futuristic technology. To be able to continue with the investigation of the scenarios as well as the energy and mass model simulation, more detailed structures are needed. Therefore, in depth developments were made to the scenarios. The changes are made with the intention of making the system realistic, operational, and efficient.

1.3.2.1 State of the art scenario

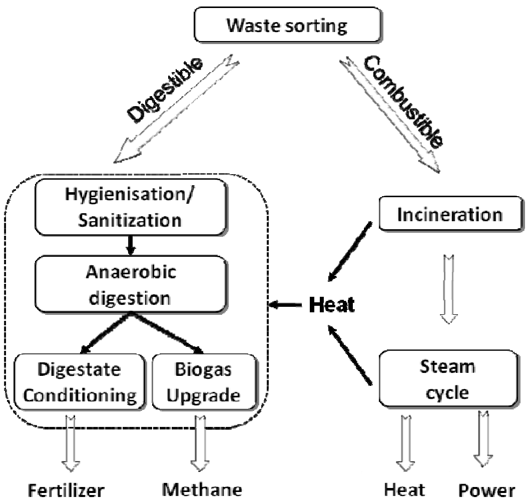


Figure 1.1 Scenario 1basic diagram

The first scenario is the state of the art scenario; representing the most current and implied EfW combination. The scenario can be separated into two waste flows, combustible and biodegradable. The combustible waste is incinerated in a combustion chamber such as fluidized bed and grate furnace to supply heat for a steam cycle for power and heat generation. For the second flow, the biodegradable waste is fed into a continuous anaerobic digestion process with hygienisation and upgrading process. As a result, high concentration methane biogas and bio-fertilizer is produced, and in order to maximize the methane production, waste heat from the incineration and steam cycle is used in the biological process to increase the biogas production.

1.3.2.2 Foreseeable future scenario

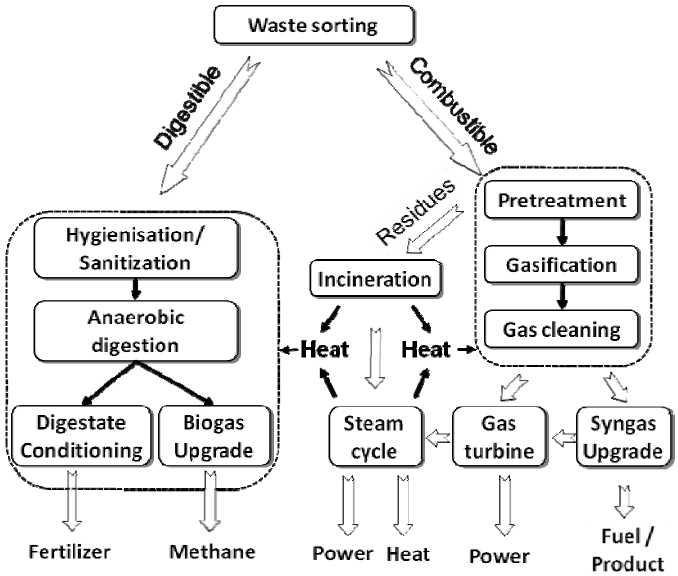


Figure 1.2 Scenario 2basic diagram

The second scenario is the Foreseeable future scenario representing a possible EfW system using technologies that are probable to be commercialized within a foreseeable future. For the combustible waste stream, the waste is gasified in a gasification chamber to produce syngas. The syngas is then burned in a gas turbine to provide power and heat for a secondary waste heat boiler with steam cycle (GTCC). Additional to the gas turbine, there is the possibility to use syngas in a fuel conversion process to produce fuels. The gasification process not only produces syngas but also char and other residues. Char and other residues are incinerated in a separate combustion chamber. The heat from that process is transferred to the same steam cycle used by the gas turbine to produce power and heat for district heating. The second waste flow is the biodegradable waste, and it remains unchanged from the first scenario as the technology is considered to be mature. Heat from the incineration process and the steam cycle is used in the biological process to maximize the biogas production.

1.3.2.3 Futuristic scenario

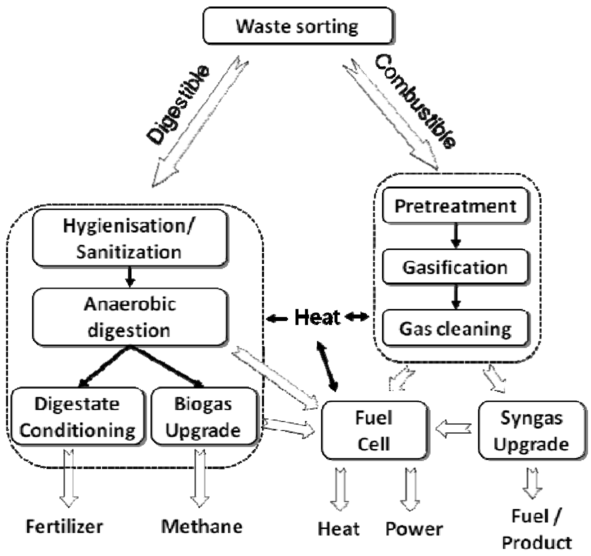


Figure 1.3 Scenario 3basic diagram

The third scenario is the futuristic scenario. In this scenario, promising technologies are combined to create a highly efficient and flexible waste refinery. The combustible fuel is gasified in the gasification chamber to produce syngas for a fuel cell or for synthetic fuel conversion, with the assumption that there is no char residue from the gasification. The syngas and the biogas from the digestion path are also used in the fuel cell, or converted to synthetic fuel. Waste heat from the gasification and fuel cell process is used in the biological process.

1.3.2.4 Reference case

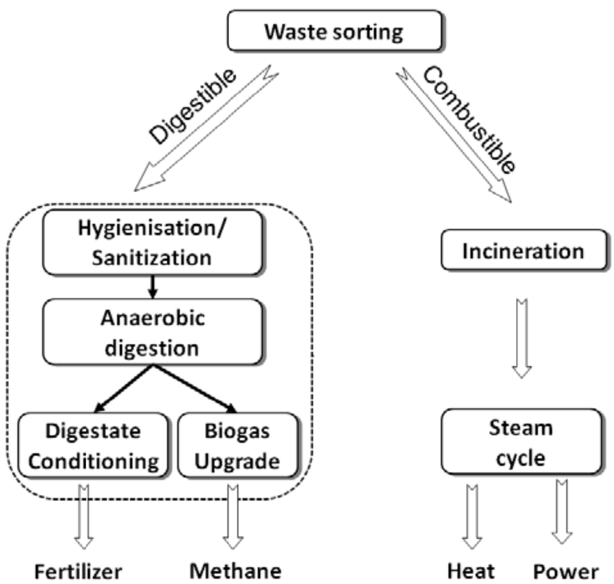


Figure 1.4 Reference case basic diagram

The mass- and energy calculation of all scenarios were carried out using the input data and boundary conditions from the reference case. The reference case represents the actual EfW system of the Borås municipal area. For this case, a fluidized bed is used for incineration and a conventional steam cycle for power and heat production. As for the biological process, thermophile anaerobic digestion is used with pretreatment and biogas upgrading process. The product of the biological process is methane gas and the byproduct is bio-fertilizer. Some of the produced biogas is burned to heat the process

1.3.3 Energy and mass balance

The most important part of the thesis work is the energy and mass balance model. The aim of the balance model is to calculate the energy production and mass flows based on the different scenarios.

Since the reference case and the scenarios share the same biological process, the heat and mass balance employed in the calculations are the same for all scenarios.

1.3.3.1 Heat balances

Conservation of energy is considered in the equation.

$$E_{in} - E_{out} = \Delta E_{system} \quad (1)$$

The heat transferred between two system parts is calculated using equation (3)

$$Q = mC_P\Delta T, \text{ [kW]} \quad (3)$$

1.3.3.2 Mass balances

The conservation of mass principle state that “mass cannot be created or destroyed” (Cengel, 2004). A subtraction of mass of an object entering and exiting a system must equal to a mass within a system.

$$m_{in} - m_{out} = \Delta m_{system}, \text{ [kg]} \quad (4)$$

1.3.3.3 Coefficients of yield and material data

In order to calculate the energy and mass balance, different coefficients such as gas yield coefficient and ash content are obtained through different literature sources as well as appropriated estimations. Due to the fact that each literature source have different experimental conditions, the output coefficient will be different therefore acceptable parameters will be derived from an average or mean value of identified coefficients.

1.3.3.4 Mass balance

The mass balance calculation started with waste input into the system. First the input and output from the process is identified then the mass conversion coefficient is used. The amount of mass input must equal the mass output since no accumulation is anticipated. For example, the ash filtering is calculated with ash output coefficient. According to a literature source, bottom ash output from the furnace accounts to 30% of the total ash content in the fuel. Then that figure is used by multiply with the waste input and the bottom output is obtained. With the waste input and bottom ash output, the rest of the mass output can be calculated.

In some case the mass output is calculated using energy balance calculation. From the energy balance calculation, the amount of energy produced from the input is known and by reversing the calculation, the amount of energy produced would consume certain mass of fuel.

For the biological process, the main mass balance calculation is the mixing of waste and water. The mass of waste and water is added together to form the mixture.

$$m_w + m_{wa} = m_{mixture}, \text{[kg]} \qquad (5)$$

But in order to calculate the mass of waste mixture, the mass of the dilute water required in the buffer and digester tank must be known. To calculate this, specified solid content is needed; TS_1 and TS_2. TS_1 is the solid content of the waste or waste mixture and TS_2 is specified solid content of the waste mixture from the process.

$$[(m_w*\%TS_1)/(\%TS_2)]-m_w = m_{wa}, \text{[kg]} \qquad (6)$$

Another important equation for the biological process is the mass of biogas produced from the anaerobic digestion process which biogas coefficient (eff_bio) is used.

$$eff\_bio*m_w = m_{bio}, \text{[kg, Nm}^3\text{]} \ (7)$$

With the density known, the volumetric production of biogas can be calculated.

As for the incineration process, an equation similar to the biological process is used to determine the amount of material entering and exit the system. Like equation (5), the mass of air-fuel mixture is calculated by adding mass of fuel and air required for complete combustion.

$$m_w + m_{air} = m_{mixture}, \text{[kg]} \qquad (8)$$

For the incineration process, the equation uses are varies depending on the technologies used for the combustion process. In the reference case and scenario 1, the waste fuel is assumed to be completely combusted, therefore only flue gas and ashes remains in the system. To determine the different ash output, the fuel input is multiplied with the ash content and ash output coefficient.

$$m_w * \text{ash content} = m_{ash}, \text{[kg]} \qquad (9)$$

$$m_{ash} * eff\_fly\_ash = {}_{mash\_fly}, \text{[kg]} \qquad (10)$$

In scenario 2, a gasification and fuel pretreatment process is added to the system. The fuel pretreatment process is a drying process to lower the moisture content in the fuel. The mass of water at specified moisture content is calculated with:

$$\%moisture * [(m_{ash} + m_{solid}) / (1 - \%moisture)] = m_{wa}, \text{[kg]} \quad (11)$$

As for the gasification process, the amount of fuel converted to syngas and air needed for gasification process is calculated using different coefficient.

$$m_w * \text{coefficient} = m, \text{[kg, Nm}^3\text{]} \qquad (12)$$

For scenario 3 where gasification and electrochemical reaction take place, the product from the process is determined using equation (12).

1.3.3.5 Energy balance

According to the conservation of energy, the energy input and energy output must equal. The energy balance is calculated in the same fashion as the mass balance calculations.

The calculation starts with identifying the energy input and output. There may be two or more energy inputs for the some process, and it is the same for energy output. The energy input may be calculated from the energy content in the fuel in form of kilojoules per kilogram fuel with a known value for mass input and moisture content. Then energy balance is created by adding and subtracting the amount of energy consumed by the processes.

For example, in the combustion or gasifying process, the total amount of energy input is calculated by multiplying the mass input with the lower heating value of the fuel. Then the energy output is calculated based on the combustion efficiency or product gas yield and LHV of the product gas.

An important step in calculating the energy and mass balance is to identify the output from the process whether the output is inform of heat, product gas, or waste residue.

In order to analyze the energy aspect of each scenario, the energy balance has been calculated. First the energy input into the system is calculated. The total waste content is multiply with the LHV to get the total energy input.

$$m_w * LHV = Q, [MJ] \quad (13)$$

The second equation is the calculation of specific heat (Cp) of mixed mass flows since different fluids have different specific heat. The calculated specific heat is the sum of Cp of solid and liquid component.

$$(Cp_1 * \%TS) + (Cp_2 * \%MO) = Cp_{1\_2}, [kJ/kg*k] \quad (14)$$

Another factor that influences the energy balance is the temperature of the fluid which is calculated using an equation derived from equation (3).

The most important energy balance inputs for the biological process are the electrical and heat consumption of the system. For the electrical consumption, the energy balance is calculated using electrical consumption coefficient based on actual values from the operating plant. As for the heat consumption, the calculation is separated into two sections; anaerobic digestion and biogas upgrading. The heat consumption of the biogas upgrading plant is calculated using average heat consumption coefficient from plant specification.

As for the heat consumption of the anaerobic digestion process, it is the sum of heat loss and heat demand to increase the temperature of waste mixture, equation (3).

As the methane content in the biogas changes, the energy content also changes therefore, the LHV of the biogas is calculated based on the methane concentration.

$$LHV * \rho * \%CH_4 / 3600 = \text{Energy content}, [kWh/Nm^3] \quad (15)$$

For the incineration process the heat balances must be considered individually since each scenario uses different energy conversion technology. For Scenario 1 and 2 where combustion of solid fuel is the main technology, heat is calculated using:

$$Q = m*h, [MJ] \quad (16)$$

As the product of combustion is heat, the energy is converted to mechanical power through the steam turbine.

2 Literature review

2.1 Waste

The definition of Waste defined by the European commission (European comission, 1975)is “Waste is any object or substance which is included in a category of waste and which the ‘holder’ disposes of or intends to or is obliged to dispose of”. And by that definition, waste can categorize into four types; household waste, industrial waste, construction and demolition waste, and hazardous waste. Household waste and industrial waste is the main feedstock for the EfW facility. In many cases, waste feedstock are referred to as municipal solid waste (MSW) since the waste collected contain both household and industrial waste.

The municipal solid waste consists of food waste, plastic, paper, glass, metals, garden waste, and other materials. The waste composition in each waste stream may differ depending on many parameters such as geographical area, culture etc. The typical source of MSW can be classified as developed and developing country. The waste from developed countries can be represents with European and North American waste since the two regions are alike in many ways. The waste from 22 European countries has the average waste content of 32.5% food and organic waste, 7.5% plastic,25.2% paper, 4.7% metal, 6.2% glass, and 24% others (The international bank for reconstruction and development, 1999). As for North America municipal solid waste contains 11.4% food waste, 11.1% plastic, 35% paper, 7.5% metal, 5.5% glass, and 28.3% other (Environmental protection agency, 2001). North America and European countries are considered to have many similarities in economic, and culture, therefore the waste content is not much different except for the food waste which European countries contain much more variety due different ethics group. One example of the differences is Spain where 40-45% of the total MSW is organic waste(T. Forster-Carneiro, 2008).

In other regions, e.g. the developing countries such as Asian countries have much greater difference. In China, the municipal waste contains 46.9% food and organic waste, 4.9% plastic, 3.1% paper, 0.7% metal, 2.2% glass, 42.3% others (development, Decision makers' guide to municipal solid waste incineration, 1999). The food and organic waste is much higher than the average one in European countries (such as Spain) and there is also less plastic and paper in the waste. The assumption was made that developing country tends to have lower efficiency in food storage, consumption and habits, resulting in higher food waste. The developing countries will have higher food waste fraction than the developed countries. The similarity among the Asian countries waste content can be seen in Thailand where the waste contains 50% food waste, 10 % paper, 14 % plastic, 5%glass, 3%metal, and 18% other (P.H.L. Nguyen, 2007).

Another type of waste that has large influence on the energy recovery system is industrial waste. Industrial wastes are wastes collected from the industrial sector. The waste content in industrial waste can be anything from food waste from slaughter house or food manufacturers to high energy content woodchip from furniture factories. The waste content in industrial waste tends to be more homogenous and easier to handle than MSW.

In order to treat municipal waste properly, waste is sorted into combustible and biodegradable waste. The combustible wastes are wastes that contain high amount of carbon or combustible material with moisture content such as paper and plastic which is suitable for the combustion process. And the biodegradable wastes are organic wastes that can be easily degraded such as food waste.

The biological waste can be characterized in many different ways but there are two important parameters that are used to describe the biodegradable waste; total solid content and volatile solid content. The total solid content (TS) is the total amount of solid content in the fuel. The total solid content is normally described in percentage between solid content and moisture content. The biological waste normally contain lower amounts of solid content and higher moisture content compared to the combustible waste, making it less suitable for the incineration process. The total solid content in the biological waste may vary depending on the source area but it can be estimated to be around 20-30%. The second parameter, the volatile solid content is the amount of the biodegradable material with the solid fraction of the waste. Examples of biological waste used for anaerobic digestion are waste from Lisbon area having total solid content of 26% and volatile solid of 78% (C. Neiva Correia, 2010).Another example is the biological waste entering the Borås Sobacken biogas plant, having 30% total solid content and 70% volatile solid content (Martinsson, 2011).

2.2 Pretreatment

There are many pretreatment methods available and each method is suitable for different type of material. The main pretreated methods are sorting, sizing, drying, and mixing.

2.2.1 Sorting

Sorting is a process of separating and grouping waste by manual and mechanical method. And since MSW contains different variety of material, sorting is needed to separate materials for specific processes such as recycling, anaerobic digestion, and incineration.

The manual sorting method is waste separation using human inspection. This is normally done by an inspector manually picking waste from a moving conveyer (Roman, 1990). In some cases such as incineration plants, cranes are used to remove large objects such as TV sets, car tires, and other unordinary sized objects. The advantage of manual sorting is that large objects can be separated before entering the treatment process and specific type of wastes can be separated. But the disadvantage is that the waste can only be separated at low speed, the method is costly and an experienced inspector is needed.

The second sorting method is the automatic sorting. The automatic sorting method involves an automatic machine for separating material and different materials require different types of machines (Roman, 1990). One of the materials that are separated from the waste is metal, ferrous and non-ferrous. The sorting of non-ferrous and ferrous material could be done by using a mechanical method, an eddy current sorting (Cogelme, 2011). The machine uses eddy current to separated ferrous and non-ferrous material from the feedstock. First the waste will flow through the conveyer and at the turning end, the magnetic rotor will create an eddy current and it will repel the non-ferrous of the conveyer and the ferrous will go down as usual. Another method is magnetic separator, which uses magnetic force to attract ferrous material to other conveyer. There are many methods to separate metal from the feedstock but this depends on the cost, size, and purpose. Metals are separated due to many reasons but the main reason is for recycling and metals are non-combustible objects.

Another material that is commonly separated is plastic. There are two reasons for separating plastic, recycling and energy recovery. An example of a plastic sorting method is a machine used in a biological process or biogas plant called a screw conveyer (Eriksson, 2009). The screw conveyer will crush the feedstock, and then water is added to dilute the waste and squeezes the slurry fluid out to separate the organic and inorganic material such as plastic. In the case of waste incineration plants, separation of plastic is currently of less priority since plastic contains high energy content and is suitable for incineration. However, in the context of recycling material, plastics should be separated.

Another sorting method that needs to be considered is decentralized sorting, where sorting is done at site, following pre-sorting by the residential occupant in their homes. In some areas such as Borås, a city west of Sweden, waste is sorted in the homes by using black and white bags (K. Rousta, 2011). The black plastic bag contains organic waste for anaerobic digestion process and the white bags are for combustible waste. The bags are then separated at the site by optical methods.

2.2.2 Sizing

Another important pretreatment process is the sizing or the waste size reduction using mechanical methods. There are many different ways to size the feedstock but the common methods are grinding and crushing. The chosen method depends on the waste treatment technology since different waste treatment technologies requires different waste size.

In the incineration process, waste feedstocks are sized to fit the specific requirement of the furnace. Sizing would also make the feedstock more homogenized and create a more stable combustion. The degree of sizing depends mainly on the requirement of the process. A Grate furnace, a furnace design to handle large object, require less attention for waste sizing but as for the fluidized bed furnace, sizing is very important since the furnace limits the feedstock to a maximum size of 50 mm in diameter(European commission, 2006). With the size limitation, waste feedstock needs to be sized before entering the combustion chamber or the furnace. The common sizing method is grinding and shredding which turns large feedstock into smaller piece but there is a limit to how small the waste can be so sometimes multi-stage machines are used.

Another process that requires waste sizing is the biological waste pretreatment. Due to the microscopic process of the anaerobic digestion, the waste feedstock should be as small as possible for highest efficiency (L.M. Palmowski, 2000). The common method used is crushing since biological wastes are mostly soft and degradable material. An example of the machine used is the screw conveyor, where rotating screw blade pushes the feedstock against the wall from one end to the other (Martinsson, 2011). The sizing of biological wastes would create a higher total surface area allowing greater reaction between the waste and the micro-organism.

2.2.3 Drying

Drying is another important pretreatment for the incineration process which uses direct or indirect heating to dry the waste feedstock. Direct heating is a convection heat transfer between the supplying hot air and the feedstock. Indirect method is the conduction heat transfer between the feedstock and the contacting surface. The drying will decrease the moisture content in the feedstock. Waste feedstock is dried for two main reasons, corrosion and efficiency. In the waste incineration plant there is a possibility that chlorine-water mixture could cause corrosion inside the boiler which requires the plant to shut down for maintenance. The second reason for drying is the combustion efficiency of the fuel since heat is lost due to evaporating of the moisture content in the feedstock. For the gasification process, higher moisture content will result in lower LHV of the syngas (Klein, 2002).

2.2.4 Hygienisation

Hygienisation is a process of eliminating unwanted micro-organisms in the biodegradable feedstock using high temperature. After the sorting and sizing process the feedstock is transferred to a storage tank and it will be heated to a temperature of70°C or higher for a period of time. The purpose of hygienisation is to make sure that the bio-fertilizer, a by-product of the biogas, will be disease-free and to increase to the methane output from the fermentation process (Åsa Davidsson, 2006).

2.3 Waste conversion

2.3.1 Anaerobic digestion

Anaerobic digestion is a process which micro-organisms convert organic material into gases in absence of oxygen. The micro-organisms breakdown the organic matter and in return give-off methane and other gas components, so called “biogas”. The organic material is converted to biogas through a three stage process; hydrolysis, acidogenesis and acetogenesis, and methanogenesis.

The first stage is the conversion of Cellulous hydrolysis to glucose. The complex polymeric substrate is broken down into monomer compound. In this stage the carbohydrate, protein, and lipids are broken down by the enzymes produced by the dominating bacteria. The simple chemical reaction can be represented by three equations:

Carbohydrates + water →Monosaccharide’s

Proteins + water → Amino Acids

Lipids + water → Fatty Acids

The second stage involves two bacteria, acidogenic bacteria and acetogenic bacteria. The acidogenic bacteria convert the hydrolysis product to volatile acid and in the process it produces a byproduct, ammonia, hydrogen, carbon dioxide and other compounds. The second bacteria, the acetogenic convert the volatile acid to acetic acid.

The third stage is the methanogenesis. In this stage acetic acid is converted to methane and carbon dioxide but in the process hydrogen is consumed. Not only acetic acid is used, other substrates can also be used in the conversion process.

During the third stage, anaerobic digestion process, there are two main types of microorganisms that are used to produce the biogas; mesophilic and thermophilic. The difference between the two is that mesophilic bacteria grows at a moderate temperature around 30-38°C and thermophilic grows at higher temperatures, around 44-57°C.Another difference is the gas yield, the thermophilicbacteria gain more gas output than mesophilic but it will requireadditional heat during the process (Young-Chae Song*, 2004). A study on anaerobic digestion using thermophilic digester at 42°C for 426 days using food waste as feedstock showed that the biogas yield is 642 Nm3/ton VS with 62% methane content and 405kWh of potential recoverable energy for each ton of waste input (Charles J. Banks M. C., 2011).

By comparing the two types of digesters, the thermophilic digester has shown a better performance than mesophilic digester (Charles J. Banks, 2008). The thermophilic digester has a volatile solid destruction of 70% and 0.67 Nm3 methane/kg VS and mesophilic digester have the volatile solid destruction value of 67% and 0.63Nm3 methane /kg VS.

The efficiency of the anaerobic digestion is determined by many factors such as methane gas yield, volatile solid destruction, and energy consumption. In methane production, the most influential factor is the type of feedstock since different materials give different methane output since moisture content and volatile solid content are different. For feedstock such as liquid manure, the methane output is very low (14-18 Nm3/ton fresh weights) comparing to a slaughterhouse waste (45 Nm3/ton fresh weights) and sorted households waste (130 Nm3/ton fresh weights)(Nordberg, 2007).Even though the manure have low methane yield, it could be increase with co-digestion. According to Maritza Macias-Corral a, 2008, co-digestion of municipal waste and manure could greatly increase the methane yield from 37 Nm3/ton dry wastes to 172 Nm3/ton dry wastes.

Another minor influence of the anaerobic digester is the stirring of waste fluid inside the digester. In an experiment by Peter G. Stroot (2001),a mesophilic digester with continuous mixing has shown unstable performance at high loading rate while minimal mixing showed good performance at all loading. Another result of the experiment showed that reduced digester mixing improved digester performance.

Another research by Maria Berglund (Maria Berglund, 2006) has shown that the overall energy consumption of a large scale biogas plant corresponds to 20-40% of the energy content in the biogas produced. The research also showed that the energy output will become negative when the transportation of feedstock exceed 200km for manure and 700 km for slaughterhouse waste where plant operation already consume 40-80% of the total energy input. The investigation also showed that high water content and low biogas yield waste will give low energy output.

2.3.2 Incineration

Incineration is a process which fuel is converted to other form of energy. The conversion process is called “combustion”. The basic principle is that fuel-air mixture is ignited causing continuous reaction and giving off heat in the process. The combustion process can be classified as liquid fuel and solid fuel combustion. There are two process steps for liquid combustion and three steps for the solid fuel combustion. The liquid fuel combustion involves evaporating and oxidation between fuel and oxygen. As for solid fuel combustion, the processes are evaporating, devolatilisation, and char combustion. If oxygen is present during the devolatilisation, the volatile gas will oxidize and form flames surrounding the fuel. The basic principle is the same for all type of fuel but the method which fuels are injected into the chamber is different. The methods which fuel are injected and combusted determine the type of furnace such as grate and fluidized bed (Thunman, 2010).

Grate or moving grate is the most common type of furnace. For this technology, fuel is supplied from the side of the furnace and air from the bottom. The waste feedstock burns as it moves slowly down the incline slope and leave the furnace as ash. The advantage of this type of furnace is that large amounts of waste can be incinerated in short period of time and it requires less pretreatment compared to other types of furnaces.

There are five main types of grate furnaces; rocking grate, reciprocating grate, travelling grate, rolling grate, and cooled grate(Rasmussen, 2004). But for waste incineration the most common type is reciprocating and rolling grate. They comprise more than 90% of the total incineration plants in Europe. The reciprocating grates are widely used for untreated municipal solid waste and treated municipal solid waste while rolling grate is widely used for only treated municipal waste (European commission, 2006).

In order to rate the performance of a Grate furnace, efficiency of the plant is often used as the rating parameter. There are many types of efficiency but the important ones are combustion efficiency, thermal efficiency, electrical efficiency and overall efficiency. Most grate furnaces are used with steam cycle to utilized the heat of combustion to produce electricity, therefore electrical efficiency is often used to rate the performance of the system. The electrical efficiency of the waste incineration plants can vary from plant to plant depending on the plant design. A research by Smedberg (2009), has investigated different power plants such as SYSAV in Malmö and Värmekällan in Skövde. The first plant, SYSAV; an 85 MW waste incineration plant has an electrical efficiency of 19.8% with steam temperature of 400°C and steam admission pressure of 40 bar. The second plant is22 MW Värmekällan waste incineration plant in Skövde with electrical efficiency of 13.7%,steam temperature of 215°C and steam admission pressure of 16 bar.

Another type of furnace is the fluidized bed (FB). For this technology the structure of the furnace is similar to the grate furnace but the furnace is filled with sand to increase the heat transfer and mixing efficiency. In fluidized bed, the fuel is injected either at the side or at the bottom of the furnace and air is inject at the bottom of the furnace blowing upward. Fluidized beds are classified as bubbling fluidized bed and circulating fluidized bed. The difference between bubbling fluidized bed and circulating fluidized bed is the air velocity and the furnace design. In a Bubbling fluidized bed, sand inside the chamber act as a fuel-air mixture and heat transfer medium. As the combusted gas rise upward, it carries particles with it causing a bubbling image like. The advantage of a fluidized bed is the complete mixture of air-fuel due to the movement of the sand.

Circulating fluidized bed is a fluidized bed furnace same as the bubbling fluidized bed but the air injected to the chamber have much greater velocity, causing the sand to blow upward and flow with the flue gas. The sand carried with flue gas is then filtered and reused in the combustion chamber(Thunman, 2010).

A comparison of five operational fluidized bed incineration units has been made (Granatstein, 2000). The electrical efficiency of these plants varies from 14 % to 23 %. In many aspects the fluidized bed is considered to be more suitable for pretreated waste compared to other types of furnaces. The first incineration plant is Robbins resource recovery facility in Illinois, the plant is 50MWe with steam temperature of 443°C, 62 bar and electrical efficiency of 23%. The second plant is Toshima Incineration plant in Japan. The plant is 7.8 MWe with steam temperature of 300C, 31.4bar and electrical efficiency of 14.4%. The third plant is TIRMadrid in Madrid, Spain. The plant is 29MWe with steam temperature of 420°C, 46bar and electrical efficiency of 19.4%. The forth plant is DERL Energy from waste facility in Dundee, Scotland. The plant is 10.5 MWe with steam temperature of 400°C, 40 bar and electrical efficiency of 20.9%. The last plant is Valene waste recovery facility in Mantes La Jolie, France. The plant is 7.4 MWe with steam temperature of 390°C, 39 bar and electrical efficiency of 17.7%.

Even though fluidized bed yield better efficiency with waste as feedstock, there are many disadvantages. One of the disadvantages is that there is a possibility that solid fuel will melt and sticks to the wall of the furnace causing disruption in the flow pattern(D.L. Granatstein, 2000).

Both grates and fluidized bed furnaces are fuel conversion technologies and they are usually connected to a steam cycle for power and heat production.

2.3.3 Gasification

Gasification is a method for converting feedstock to gases by drying and devolatilisation of the waste feedstock using high temperature medium such as oxygen and steam. The temperature of the gasified agent supplying to the chamber can varies from 500-900°C. The results of the gasification process are char residue and product gas, called syngas, which contains different types of compound gaseous such as carbon dioxide, carbon monoxide, hydrogen and etc. (Thunman, 2010).

The basic principle of gasification is the drying and devolatilisation of the fuel. As the drying process is complete, the solid begins to decompose and releases volatile gas. During this stage the solid fuel will react with the supplying medium and release a product gas. The basic chemical reactions of gasification are:

1. $C + O2 \rightarrow CO2$
2. $C + CO2 \rightarrow 2CO$
3. $C + H2O \rightarrow CO + H2$
4. $C + 2H2 \rightarrow CH4$
5. $CO + H2O \rightarrow CO2 + H2$
6. $CO + 3H2 \rightarrow CH4 + H2O$

The major difference between gasification and incineration is that there is no flame ignition during the entire process. The advantages of gasification over the incineration are the possibility of separation of toxic gases and converting syngas to other forms such as synthetic fuel. After the Gasification process there is a possibility of separating toxic components such as sulfur from the product gas.

Another closely related process to gasification is pyrolysis. Pyrolysis is basically the same thermal process as gasification however there is absence of oxygen during the process (Thunman, 2010). Concerning the performance of gasification and pyrolysis, the material destruction of gasification is better than pyrolysis. In the same experiment, char gasification is tested to be more sensitive to reactor temperature than pyrolysis however pyrolysis can start at 400°C but gasification start at 700°C (I. Ahmed, 2009)

In an experiment by Paolo et al, pyrolysis process of municipal waste with a gas turbine and steam cycle is performed. The pyrolysis process takes place in a rotary kiln at 500°C with waste input of 19.2 MJ/kg HHV. The research showed that the lower heating value of the product gas accounted for 28-30% of the energy content in the fuel and the product gas contains 10.9% hydrogen, 7% carbon monoxide, 16.6% methane and 65.5% carbon dioxide. The energy content in the syngas was22 MJ/kg syngas and the gas yield from the pyrolysis process was approximately 0.2915 kg/kg MSW (Paolo Baggio a, 2008).

In some cases the presence of dolomite in the combustion chamber will decrease char and oil residue from the process. A study by (Maoyun He, 2010) has shown that a fixed bed pyrolysis at 750-900°C with dolomite will result in higher product yield and lower oil and char production. The study also showed that higher temperature will increase H2 and CO content in the syngas. But there are few other types of catalyst materials that are used and one of them is Olivine. The used of catalysis will result in a 300% increase in H_2 concentration in syngas (Umberto Arena a, 2010).

There are many different methods and plant designs in which gasification and pyrolysis can be done. In one design, two-stage gasification is used as well as five different fuel mixtures; methane, RDF, MSW, waste oil, and land fill gas. The result of the experiment showed that MSW gives the best H2/CO ratio. There is one issue that needs to be taken into consideration if the process involve synthetic fuel conversion, the H2/CO ratio should be higher than 1.7 (Paolo De Filippis, 2004).

The syngas yield from gasification can be influenced by the air-fuel ratio or equivalent ratio (ER) and the temperature of the gasification process. The steam gasification of RDF by (Ajay K. Dalai, 2009)has shown that the optimal temperature for gasification is 725°C. The waste with higher carbon and hydrogen content tends to produce more H2 and CO in syngas.

A gasification simulation using three different MSW mixtures at 400-800°C with ER value of 0.2-0.6 has showed that plastic should be gasified with temperatures higher than 500°C (Gang Xiao, 2009). There is another gasification experiment using fluidized bed gasification at 500-700°C with ER of 0.2-0.5 and this result in syngas energy content of 4 000 to 12 000 kJ/nm^3 (XIAO Gang1, 2007).

2.4 Energy conversion

After the incineration or gasification process, heat, power or syngas is generated. Therefore more energy conversion steps must take place.

2.4.1 Steam cycle

The steam cycle or Rankine cycle is the most common method to convert useful heat to power. The heat from the combustion process is transferred to the steam cycle through the boiler which turns water into superheated steam. The steam rotates the turbine and the generator producing power. The steam from the turbine outlet is then cooled and condensed in a condenser which is connected to a cooling tower or heat sink. If the steam is used for some purpose it is called useful heat but if not it is waste heat. In order to increase total efficiency, waste heats are used for process heat or for district heating for residential areas (Khartchenko, 1997).

2.4.2 Organic Rankine Cycle

The organic rankine cycle or ORC is a rankine cycle that uses an organic fluid as its medium. The difference between the normal rankine cycle and the organic rankine cycle is the working fluid and the operating temperature range that is much lower in the ORC. The ORC can operate with low temperature and different medium such as propane, R134a, etc. An ORC is normally applied as a secondary rankine cycle to harvest as much heat as possible (Agustín M. Delgado-Torres, 2010).

2.4.3 Gas turbine

A gas turbine is another type of energy conversion technology which combines the combustion process and energy conversion process in one component. Gas turbines consist of three stages; compressor, combustor and turbine. In the first stage, the inlet air is compressed and mixed with the fuel. At the second stage the air-fuel mixture is combusted inside the combustion chamber to produce hot flue gas. And then in the third stage, the expanding flue gas rotates the turbine and the generator. There are many advantages of the gas turbine which we can classify into three topics; fuel, energy, and pollution. The first advantage of the gas turbine is the ability to use both gases and liquid fuel which make it more economical. To be able to use many different type of fuel will allow the power plant to adjust the type of fuel according to the fuel price. Another advantage is the GHG emissions which gas turbine tends to produce less nitrogen oxide compared to typical incineration (Khartchenko, 1997).

2.4.4 Biogas upgrading

Biogas upgrading is a process of increasing methane concentration in biogas by separating unwanted gas compounds and moisture content. The main purpose of the biogas upgrading is to upgrade the biogas to a specific standard. The upgraded biogas can be used for different purposes such as substitution for cooking gas or natural gas, and fuel for transportation. The methods for upgrading biogas are water scrubber, pressure swing absorption (PSA), adsorption, chemical absorption, membranes, and cryogenic separation. These technologies are already in use and considered to be matured technology. There is also on-going research on biogas upgrading technology such as ecological lung, where enzymes are used as catalysis to fasten the carbon dioxide dissolution which imitates our lung (Anneli Petersson, 2009).

In raw biogas there are many components which are not useful and toxic to the user and environment. These components are water, hydrogen sulfur, carbon dioxide, ammonia, particle, and other minor gas compounds (Rylander, 2010).

In order to separate the gas compounds, a series of cleaning processes are required since different substances require different methods. In this report three upgrading processes from three different companies are presented to illustrate the different combinations.

The first company is Cirmac or Läckeby group; a private company originates from Sweden. They developed a cleaning process called CUpure which consisted of adsorption, condensing, PSA, and chemical absorption process.

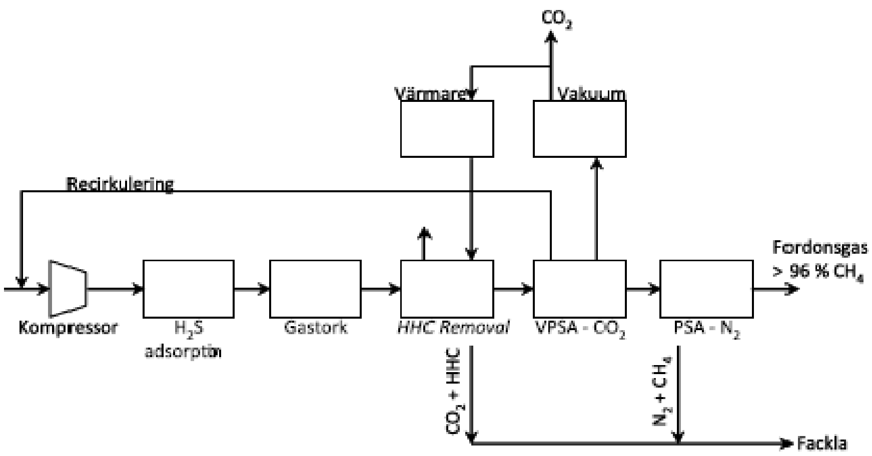


Figure 2.1CUpure/LPCooab biogas upgrading process diagram

The second company is Guild Associates, Inc. /Molecular Gate. Molecular gate uses a similar process to the Läckeby group process but instead of using chemical absorption process to remove CO_2, they use membrane technology and adsorption process called Air Liquid Advanced Technologies. After the CO_2 is removed, a cryogenic separation is used to separate the nitrogen.

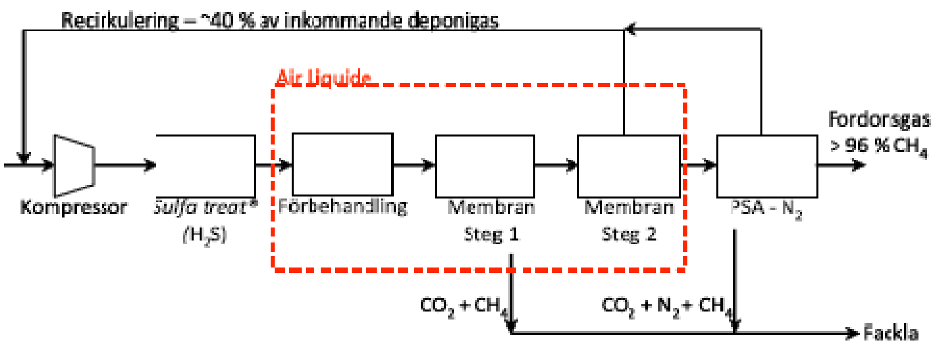


Figure 2.2Molecular Gate biogas upgrading process diagram

The third company is Acrion, and their technology is called Terracastus technologies. Terracastus' main component is CO_2 wash, which separate carbon dioxide from the biogas. The CO_2 wash uses a distillation process to purify the biogas and dispose of carbon dioxide. The carbon dioxide is then treated with membrane and cryogenic separation or nitrogen (Rylander, 2010).

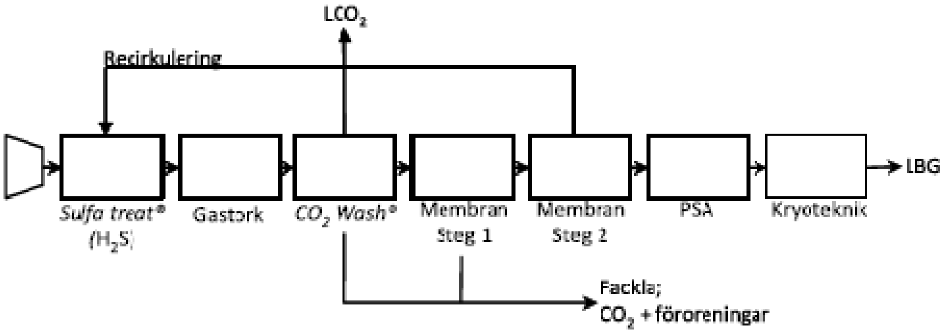


Figure 2.3Terracatus technologies

2.4.5 Syngas reforming

Syngas reforming is another form of energy conversion. The processes convert the syngas to other forms of fuel such as methane and synthetic fuel. The conversion processes are methanation, Fischer-Tropsch-Synthesis, Methanol/DME conversion.

Methanation is a conversion process which converts H2 and CO into Methane and water using catalysts such as Ni-La2O3-Ru.The conversion process can operate at low temperature as low as 230°C. In some research Rh (Rhodium) is added to enhance the reaction (Muhamad B.I. Choudhury a, 2006). The methanation reaction can be represented as (G. C. Bond, 1985):

$$CO + 3H_2 \rightarrow CH_4 + H_2$$

Fischer-Tropsch-Synthesis is another form of synthetic fuel conversion. The Fischer-Tropsch process converts hydrogen and carbon monoxide into synthetic fuel and this require high temperatures around 800°C. During this process a water shift reaction could occur.

1. $(2n+1)H_2 + nCO \rightarrow CnH_{2n+2} + nH_2O$
2. $H_2O + CO \rightarrow CO_2 + H_2$

Another possible conversion technology is the methanol/DME conversion. This technology converts CO and H_2 into methanol and possibly DME. The key reaction of this process is:

1. $CO + 2H_2 \rightarrow CH_3OH$
2. $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

The three conversion technologies have been proven to be practical and they are commercialized, but the feedstocks are coal and biomass. There is not much research on these technologies using waste as feedstock since the main input is carbon monoxide and hydrogen.

2.4.6 Fuel cell

A fuel cell is an electrochemical device that converts fuel into electricity through a chemical reaction. Fuel cells exist in many different forms and sizes but all of them operate by the same basic principle of an electrochemical cell between anode, electrolyte, and cathode. There are many types of fuel cells and each type is classified though the material and fuel it uses.

From the waste perspective, Solid oxide fuel cell (SOFC) is the most appropriate and suitable for waste feedstock. SOFC is a fuel cell that uses solid oxide material as electrolyte and it operates on two basic principles, the electrochemical reaction between the fuel and air and the transfer of electron and oxygen ion between cathode and anode. SOFC has the ability to use many different kinds of fuel such as methane, gasoline, propane, and syngas but there is a disadvantage to this ability, SOFC needs to operate at high temperatures around 500-1000°C. As SOFC is a promising technology for electricity and heat production it still remains on experimental stage and there is no commercial plant yet. Based on the literature review there is a concern on material degradation since syngas contains many toxic components such as hydrogen sulfide (H2S). But in one experiment a single cell SOFC operated at 850°C with and without H2S in syngas showed no major degradation. The fuel cell showed 10-12% degradation after570 operating hours(Jason P. Trembly, 2006).

In order to consider SOFC as energy recovery system, the efficiency of the fuel cell needs to be taken into account. As a promising technology, efficiency of the cell is very important to the decision maker whether to build the plant or not. A SOFC system developed in co-operation between three companies; Alstom, Prototech, and Forschungszentrum Julich claim that their system has an electric conversion efficiency of 50 %. In another research, a high temperature SOFC and intermediate temperature SOFC produced an efficiency of 57.6% and 62.3% but in a two stage combined cycle intermediate SOFC can goes up to 65.5% (A. Musa, 2008).

3 Energy and mass balance modeling

According to the preliminary study of the subtopic 2 of the task 36, received from IEA bioenergy, SP has developed three scenarios of EfW concepts which represent the state of the art concept, foreseeable future, and futuristic scenario. The three scenarios were modeled based on the literature data as well as energy and mass balances. With the difference structures and technological combinations in the three scenarios, different ranges of energy output is obtained.

3.1 Reference case (Borås)

The reference case is the basic EfW system base on the actual information from the EfW facility in Borås. In the preliminary study, a basic EfW system was constructed, having both incineration and a biological process. For the reference case, all of the waste heat from the incineration process is used for district heating and the heat required by the anaerobic digestion process is supplied by burning some of the produced biogas.

The difference between the reference case and scenario one is the amount of waste input and the heat generation for the biological process. The waste input for the reference case is 100 000 ton where scenario one is 102 700 ton. In the anaerobic digestion process and biogas upgrading process, a gas furnace is used for heat supply. The produced biogas from the process is used to heat the process, thus decreasing the final biogas production.

3.2 Scenario 1, State of the art

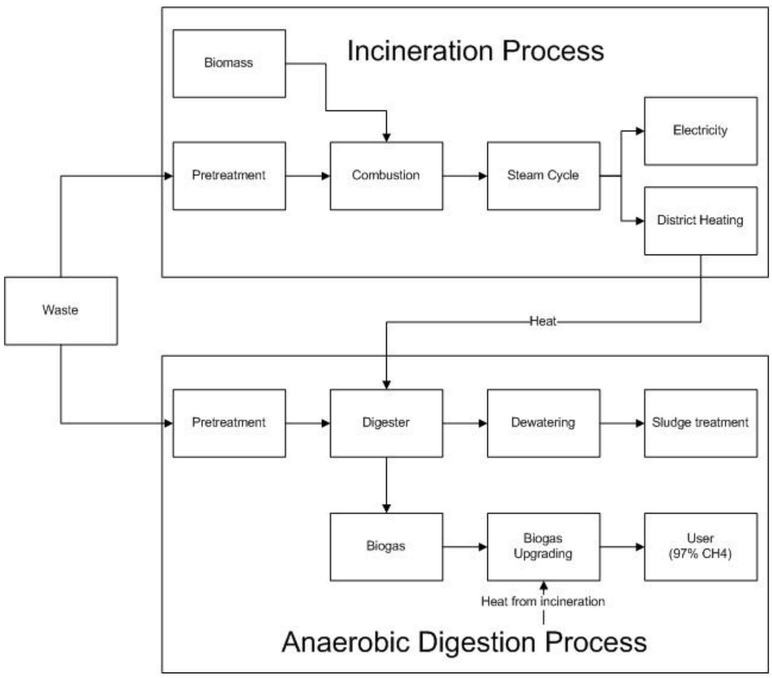


Figure 3.1 Scenario 1extended flow path diagram

Scenario 1 is the state of the art EfW concept based on the reference case. The scenario wasmodifiedto maximize both biogas and power output,but the main energy and mass flow pathsremained the same as for the reference case.Changes were made to both the incineration and biological process by expanding major processes and adding important processes such as pretreatment, biomass input and sludge treatment. Since the aim of this thesis work is to study the energy from waste recovery system, biomass is excluded in the reference case but not in scenario 1 to show the possibility of using biomass as fuel. Even though the biomass flow is shown in the diagram, it is excluded in the calculations.

3.2.1 Scenario modifications

Each section of the EfW system is modified by expanding the processes based on practical EfW systems. The modifications were made to waste pretreatment, combustion chamber, steam cycle, digestion, sludge treatment, and the biogas upgrade unit.

For the feedstock pretreatment, there are two pretreatment systems; one for combustible waste and another one for biological waste. The combustible wastes are pretreated by sorting and size reduction. The pretreatment is assumed to have no differential effect on the energy and mass balance between the three scenarios. Even though the pretreatment is excluded from the calculations, the sorting process is shown in the structural diagram. The second modification is to the combustion chamber and flue gas treatment. In the preliminary study, the incineration process is described as an energy converter having waste as input and heat as output. The modification is made to the incineration process by adding air input, flue gas output, bottom ash output and other important components. For the first scenario, fluidized bed is used for the combustion process as being current state of the art technology. The biomass feedstock flow is also shown in the flow chart since many incineration plants are co-combustion plants but the biomass feedstock is excluded from the calculations. After the combustion chamber, flue gas is cleaned in a flue gas treatment process. From the flue gas treatment, fly ash and filter ash is extracted.

The last section of the incineration process is the steam cycle. The steam cycle is connected to the combustion chamber and it is assumed that heat will be transferred to the boiler feed water turning it into steam. For this scenario, the steam cycle will consist of two turbines; one generator and a condenser are added to the steam cycle. The steam cycle consists of two turbines for modeling purpose. The output from the steam turbine is power and low pressure steam. The second part of the scenario is the biological process. The modifications are made to three sections; pretreatment, anaerobic digestion, and biogas upgrading. The first section is the waste pretreatment where waste is hygienized and diluted with water to reach a specific moisture content. All of the waste entering the biological process is assumed to be well mixed, sorted, and reduced to proper size. In the anaerobic digestion process, a thermophilic digester is used. Mixed waste from the hygienisation tank is fed into the digester and heat is supplied to maintain the temperature of 53°C for 20 days. The output from the digester tank is biogas and waste residue which is pumped into a digestate storage tank. The remaining volatile solid in the waste continues to degrade and produce biogas but it is assumed that all of the biogas is produced in the digester. The digestate storage tank is also connected to the heat recovery system to use the excess heat to for heating up diluting water. After the digestate storage tank, the sludge is pumped into the dewatering system where water is extracted from the waste and output solid residue is used as bio-fertilizer. The extracted water is then treated in a sequence batch reactor (SBR).The water from the SBR circulates in the water supply system and leachates are dumped in the reservoir.

In the upgrading process, the Hydrogen sulfide content (H_2S) is removed with PSA and the carbon dioxide CO_2 is separated with a chemical absorption process called COOAB. The purification of biogas is done in several process steps and the main input and output are heat input, CO_2 output, and biogas output. The process is simplified since the upgrading process used in this scenario is one of the many possible methods to upgrade biogas.

3.2.2 Model creation

An energy and mass balance model was created. The calculation can be separated into an incineration and biological part in which the results from both parts are used to evaluate the final energy production. The energy and mass balance calculation can start with either incineration or biological process since they are two separated processes. An Energy and mass balance model was set up in Microsoft Excel and all relevant data was fed into this model. The models are attached in Appendices, and a screenshot is shown in Figure 3.2 below.

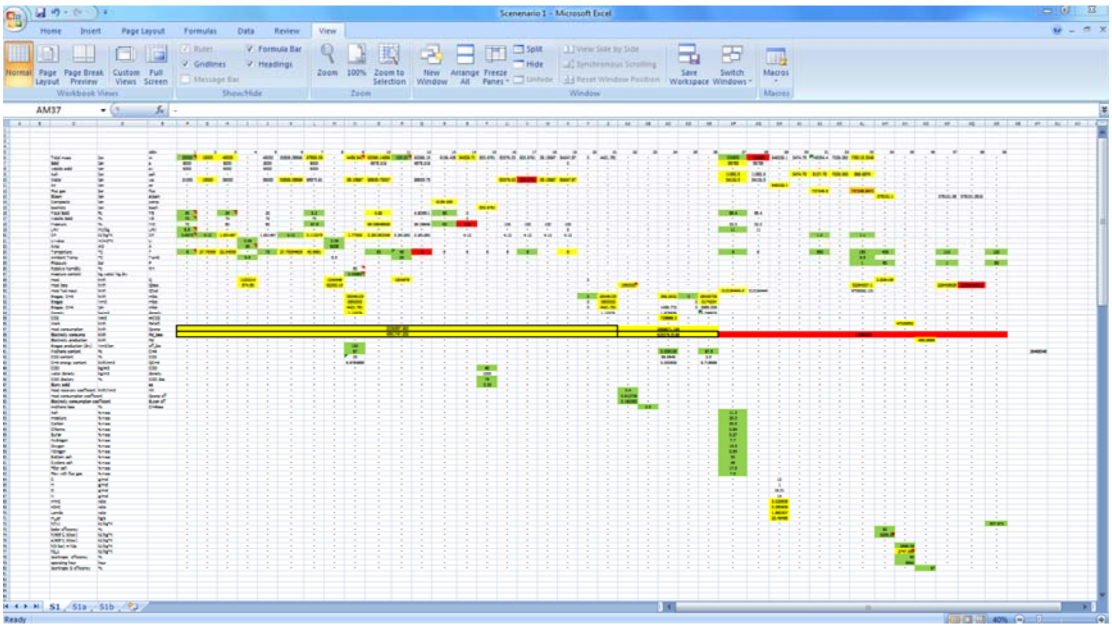
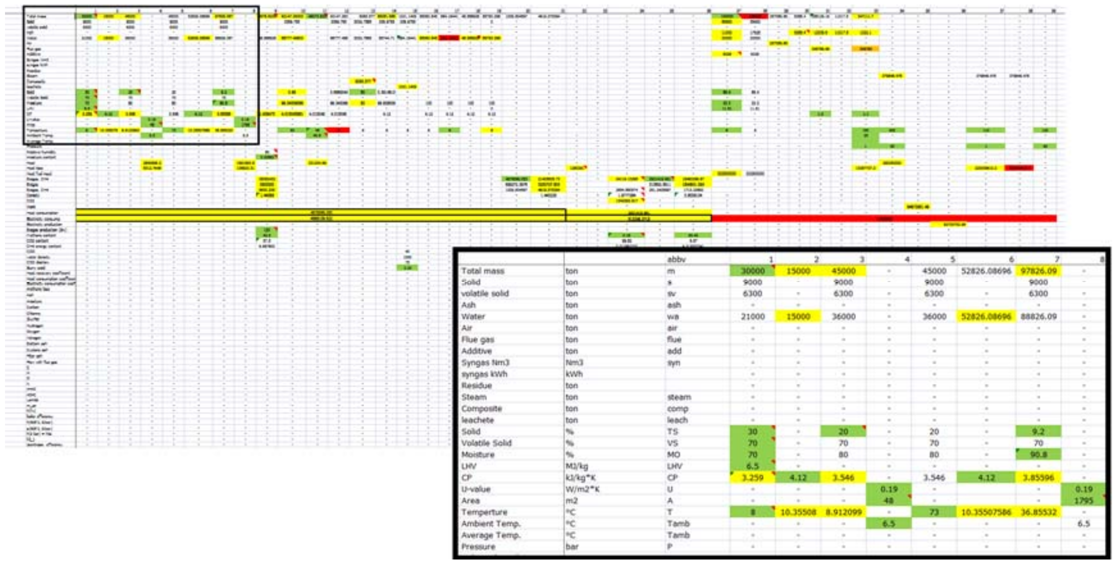


Figure 3.2Energy and Mass balance model

3.2.2.1 Biological process



		abbv	1	2	3	4	5	6	7	8
Total mass	ton	m	30000	15000	45000	-	45000	52826.08696	97826.09	-
Solid	ton	s	9000	-	9000	-	9000		9000	-
volatile solid	ton	sv	6300	-	6300	-	6300	-	6300	-
Ash	ton	ash	-	-	-	-	-	-	-	-
Water	ton	wa	21000	15000	36000	-	36000	52826.08696	88826.09	-
Air	ton	air	-	-	-	-	-	-	-	-
Flue gas	ton	flue	-	-	-	-	-	-	-	-
Additive	ton	add	-	-	-	-	-	-	-	-
Syngas Nm3	Nm3	syn	-	-	-	-	-	-	-	-
syngas kWh	kWh		-	-	-	-	-	-	-	-
Residue	ton		-	-	-	-	-	-	-	-
Steam	ton	steam	-	-	-	-	-	-	-	-
Composite	ton	comp	-	-	-	-	-	-	-	-
leachete	ton	leach	-	-	-	-	-	-	-	-
Solid	%	TS	30	-	20	-	20	-	9.2	-
Volatile Solid	%	VS	70	-	70	-	70	-	70	-
Moisture	%	MO	70	-	80	-	80	-	90.8	-
LHV	MJ/kg	LHV	6.5	-	-	-	-	-	-	-
CP	kJ/kg*K	CP	3.259	4.12	3.546	-	3.546	4.12	3.85596	-
U-value	W/m2*K	U	-	-	-	0.19	-		-	0.19
Area	m2	A	-	-	-	48	-		-	1795
Temperture	°C	T	8	10.35508	8.912099	-	73	10.35507586	36.85532	-
Ambient Temp.	°C	Tamb	-	-	-	6.5	-	-	-	6.5
Average Temp.	°C	Tamb	-	-	-	-	-	-	-	-
Pressure	bar	P	-	-	-	-	-	-	-	-

Figure 3.3Scenario 1, Biological process

The first calculation is the feed water demand. Feed water is supplied to dilute the waste for pumping efficiency. The initial condition of the waste as well as total solid content of the waste mixture is an input to the model. The input values are entered in the green colored cells and the results are shown in the yellow colored cells. Based on the input value and mass balance, the amount of water required and the specific heat (Cp) of the waste-water mixture is calculated. Another value that is calculated is the temperature of the waste mixture. The temperature is calculated using an energy balance. The initial condition of waste is shown in Figure 3.3. The biological waste input is based on Sobacken biogas plant and the temperature is based on the average Borås municipal area temperature but the total solid content and volatile solid as well as other values are based on the literature review. The temperature of the feed water is calculated from the mixture of fresh and recirculated water.

The next calculation is the hygienisation of the waste substrate, where heating is supplied to increase the temperature to 73°C. The amount of energy required and the heat loss is calculated based on the heat transfer balanceusing specific heat, temperature, mass and U-value. The heat required is calculated from Q=m*Cp*ΔT and the heat loss from the hygienisation tank is calculated from the overall heat transfer coefficient and total tank surface area Q=U*A*ΔT. The surface area is calculated from the hygienisation tank specification.

	3	4	5	6	7	8	9	10
Total mass	45000	-	45000	52826.08696	97826.09	-	5678.824	92147.26303
Solid	9000	-	9000	-	9000	-	-	3369.765
volatile solid	6300	-	6300	-	6300	-	-	-
Ash	-	-	-	-	-	-	-	-
Water	36000	-	36000	52826.08696	88826.09	-	48.58893	88777.49803
Air	-	-	-	-	-	-	-	-
Flue gas	-	-	-	-	-	-	-	-
Additive	-	-	-	-	-	-	-	-
Syngas Nm3	-	-	-	-	-	-	-	-
syngas kWh	-	-	-	-	-	-	-	-
Residue	-	-	-	-	-	-	-	-
Steam	-	-	-	-	-	-	-	-
Composite	-	-	-	-	-	-	-	-
leachete	-	-	-	-	-	-	-	-
Solid	20	-	20	-	9.2	-	-	3.66
Volatile Solid	70	-	70	-	70	-	-	-
Moisture	80	-	80	-	90.8	-	-	96.34306556
LHV	-	-	-	-	-	-	-	-
CP	3.546	-	3.546	4.12	3.85596	-	1.439475	4.015045981
U-value	-	0.19	-		-	0.19	-	-
Area	-	48	-		-	1795	-	-
Temperture	8.912099	-	73	10.35507586	36.85532	-	-	53
Ambient Temp.	-	6.5	-	-	-	6.5	-	-
Average Temp.	-	-	-	-	-	-	-	-
Pressure	-	-	-	-	-	-	-	-
Relative humidity	-	-	-	-	-	-	80	-
moisture content	-	-	-	-	-	-	0.00863	-
Heat	-	2840696	-	-	-	1691664	-	-
Heat loss	-	5312.765	-	-	-	138923.3	-	-
Heat fuel input	-	-	-	-	-	-	-	-
Biogas, CH4	-	-	-	-	-	-	26082432	-
Biogas	-	-	-	-	-	-	3900000	-
Biogas, CH4	-	-	-	-	-	-	5630.235	-
Density	-	-	-	-	-	-	1.44365	-
CO2	-	-	-	-	-	-	-	-
Work	-	-	-	-	-	-	-	-
Heat consumption								
Electricity consump								
Electricity production	-	-	-	-	-	-	-	-
Biogas production (dry)	-	-	-	-	-	-	130	-
Methane content	-	-	-	-	-	-	42.5	-
CO2 content	-	-	-	-	-	-	57.5	-
CH4 energy content	-	-	-	-	-	-	6.687803	-

Figure 3.4Scenario 1, Biological process

The next calculation is the waste digestion process. The output from the digester is biogas and sludge. The biogas production is calculated using anaverage gas yield coefficient and fresh waste input. The average gas yield coefficient varies for differnet types of wastes. From the interview with Sobacken plant operator, the gas yield is between 100-150 Nm^3 per ton fresh waste. The value used for this scenario is 130 m^3 per ton fresh waste based on the assumtion that household waste is the major type of waste. The heat requirement and the heat loss is also calculated since the temperature in the digester is kept constant at 53°C at all time. For this scenario, the gas yield is approximately 3 900 000Nm^3per year with about 67 % methane weighting 5 679 ton with gas density of 1.44 kg per Nm^3. The waste sludge is calculated by subtracting the waste input with the gas output.

The heat recovery from the digestate storage and sequence batch reactor is done via heat exchanger with a4.5 K minimum temperature difference. The heat transfer in the heat exchanger is0.23GWh.The waste residue and water is separated inside the sequence batch reactor. The amount of leachete from the SBR is calculated using a slurry solid coefficient. The coefficient used to calculate the leachete was obtained from the literature review.

	14	15
Total mass	86081.7	1021.14
Solid	336.977	336.977
volatile solid	-	-
Ash	-	-
Water	85744.7	684.164
Air	-	-
Flue gas	-	-
Additive	-	-
Syngas Nm3	-	-
syngas kWh	-	-
Residue	-	-
Steam	-	-
Composite	-	-
leachete	-	1021.14

CH4 energy content	-
COD	40
water density	1000
COD destory	75
Slurry solid	0.33
Heat recovery coefficient	-

Figure 3.5 Scenario 1, Biological process SBR

The energy and mass balance of the biogas upgrading process is calculated using coefficients obtained from the company plant specification. Läckeby water is the company responsible for constructing and developing the biogas upgrading technologies called CUpure or LPCooab. The important calculation is the CO_2 separation efficiency and heat consumption. In order to calculate the CO_2 extraction, the specific methane content is required. The raw biogas contains approximately 67 % methane and the upgrading process will increase the concentration to 97 %. The upgrading process separated carbon dioxide and methane. Therefore the CO_2 output is calculated using a mass balance. Another important parameter needed is the power and heat consumption of the plant which can be obtained using different literature data. The energy consumption coefficient is derived from energy consumption and energy production of an actual plant as well as contractor brochures.

Heat recovery coefficient	kWh/nm3	0.4	-
Heat consumption coefficient	kWh_heat/nm3	0.91274	-
Electricity consumption coefficient	kWh_e/nm3	0.16035	-
methane loss	%	-	0.5

Figure3.6Scenario 1, Biogas upgrading coefficients

3.2.2.2 Incineration process

		27	28	29	30	31	32	33	34	35	36	37	38	39
Total mass	ton	100000	106328	257089.6	5288.4	358129.2	11017.5	347111.7	-	-	-	-	-	-
Solid	ton	55400	55400	-	-	-	-	-	-	-	-	-	-	-
volatile solid	ton	-	-	-	-	-	-	-	-	-	-	-	-	-
Ash	ton	11300	17628	-	5288.4	12339.6	11017.5	1322.1	-	-	-	-	-	-
Water	ton	33300	33300	-	-	-	-	-	-	-	-	-	-	-
Air	ton	-	-	257089.6	-	-	-	-	-	-	-	-	-	-
Flue gas	ton	-	-	-	-	345789.6	-	345790	-	-	-	-	-	-
Additive	ton	6328	6328	-	-	-	-	-	-	-	-	-	-	-
Syngas Nm3	Nm3	-	-	-	-	-	-	-	-	-	-	-	-	-
syngas kWh	kWh	-	-	-	-	-	-	-	-	-	-	-	-	-
Residue	ton	-	-	-	-	-	-	-	-	-	-	-	-	-
Steam	ton	-	-	-	-	-	-	-	379848.478	-	-	379848.478	379848.478	-
Composite	ton	-	-	-	-	-	-	-	-	-	-	-	-	-
leachete	ton	-	-	-	-	-	-	-	-	-	-	-	-	-
Solid	%	55.4	55.4	-	-	-	-	-	-	-	-	-	-	-
Volatile Solid	%	-	-	-	-	-	-	-	-	-	-	-	-	-
Moisture	%	33.3	33.3	-	-	-	-	-	-	-	-	-	-	-
LHV	MJ/kg	11.61	11.61	-	-	-	-	-	-	-	-	-	-	-
CP	kJ/kg*K	-	-	-	-	1.2	-	1.1	-	-	-	-	-	-
U-value	W/m2*K	-	-	-	-	-	-	-	-	-	-	-	-	-
Area	m2	-	-	-	-	-	-	-	-	-	-	-	-	-
Temperture	°C	8	8	-	-	-	-	150	405	-	-	110	-	120
Ambient Temp.	°C	-	-	-	-	-	-	25	-	-	-	-	-	-
Average Temp.	°C													
Pressure	bar	-	-	-	-	-	-	1	50	-	-	1	-	60
Relative humidity	%	-	-	-	-	-	-	-	-	-	-	-	-	-
moisture content	kg water/ kg dry gas	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat	kWh	-	-	-	-	-	-	-	290250000	-	-	-	-	-
Heat loss	kWh	-	-	-	-	-	-	13257737.2	-	-	-	220009610.2	211773342.9	-
Heat fuel input	kWh	322500000	322500000	-	-	-	-	-	-	-	-	-	-	-
Biogas, CH4	kWh	-	-	-	-	-	-	-	-	-	-	-	-	-
Biogas	Nm3		-	-	-	-	-	-	-	-	-	-	-	-
Biogas, CH4	ton		-	-	-	-	-	-	-	-	-	-	-	-
Density	kg/m3	-		-	-	-	-	-	-	-	-	-	-	-
CO2	Nm3	-	-	-	-	-	-	-	-	-	-	-	-	-
Work	kWh	-	-	-	-	-	-	-	-	64673951.5	-	-	-	-
Heat consumption	kWh	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricty consump	kWh								11600000					

Figure 3.7 Scenario 1, Incineration process

The incineration process is the second part of the balance model. The first step in energy and mass balance calculation is the energy content in the fuel. The waste is assumed to have a lower heating value of 11.61 MJ/kg and with given mass input, the energy content in the fuel is approximately 325 GWh per year. The combustion air requirement is calculated based on the assumption of stoichiometric or completes combustion. The amount of air needed to complete the combustion depends on four elements in the fuel; carbon, hydrogen, oxygen, and nitrogen. It is important that the four elements are specified so the air supply can be calculated. The flue gas mass flow rate is multiplied with the specific heat and the temperature difference. The amount of heat transferred to the steam is calculated with the boiler efficiency which in this case is set to be 90 %.

methane loss	-
Ash	11.3
moisture	33.3
Carbon	30.5
Chlorine	0.84
Sulfer	0.27
Hydrogen	7.7
Oxygen	15.5
Nitrogen	0.64
Bottom ash	30
Cyclone ash	45
Filter ash	17.5
Flow with flue gas	7.5
C	-

Figure 3.8 Waste properties

The amount of ash from the combustion is calculated based on the data obtained from research on the Borås waste incineration plant which is approximately 11.3 % of the waste mass. This may seem low comparing to other source (Källander, 2005). The ashes can be categorized into three main types; bottom ash, filter ash, and fly ash. The bottom ash accounted for 30 % and cyclone ash plus filter ash is 62.5 % and filter ash is 7.5 %.

To simulate the power and heat production, temperature, pressure, turbine efficiency, isentropic efficiency and enthalpy of the steam is used. The turbine work is calculated using $Q=m*(h_2-h_1)$ where h1 is the enthalpy before the turbine, and h2 is after the turbine. The enthalpy of the steam can be found using steam data tables based on temperature and pressure of the steam as well as turbine isentropic efficiency. Once the enthalpies of the steam at different positions are known, the energy or work can be calculated. From that, electricity production can be calculated by multiplying the work with generator efficiency.

h(fw)	kJ/kg*K	-	-	-	-	-	507.972
boiler efficiency	%	90	-	-	-	-	-
h(405°C, 40bar)	kJ/kg*K	3206.05	-	-	-	-	-
s(405°c, 40bar)	kJ/kg*K	-	-	-	-	-	-
h(2 bar) = h2s	kJ/kg*K	-	2525	-	-	-	-
h2_1	kJ/kg*K	-	2593.105	-	-	-	-
Isentropic efficiency	%	-	90	-	-	-	-
operating hour	hour	-	8592	-	-		
Generator efficiency	%	-	-	97		-	-

Figure 3.9 Scenario 1, steam cycle

.

3.3 Scenario 2, Foreseeable future

The second scenario is the foreseeable scenario where the biological process is based on the reference case and the incineration process is gasification as the main processing unit. The incineration process is equipped with a gasifier, combustion chamber, and a gas turbine. In this scenario, non-biological wastes are gasified and the product is syngas and char residue. The syngas is then combusted in the gas turbine to produce heat and power. The char residue is incinerated in the combustion chamber. The flue gas from the incineration and gas turbine is then used in a waste heat boiler steam cycle to produce power and heat for district heating as well as for the biological process.

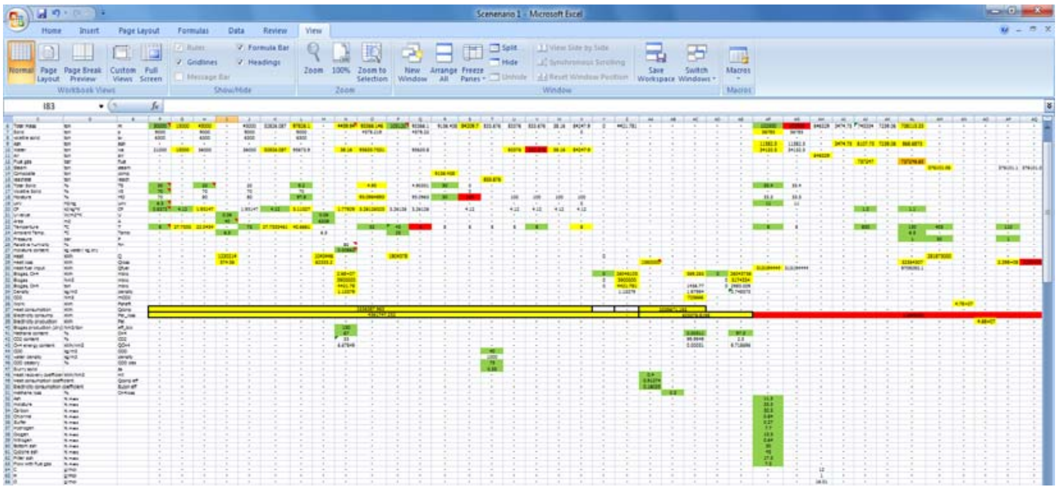


Figure 3.10Scenario 2, Energy and Mass balance model

3.3.1 Scenario modification

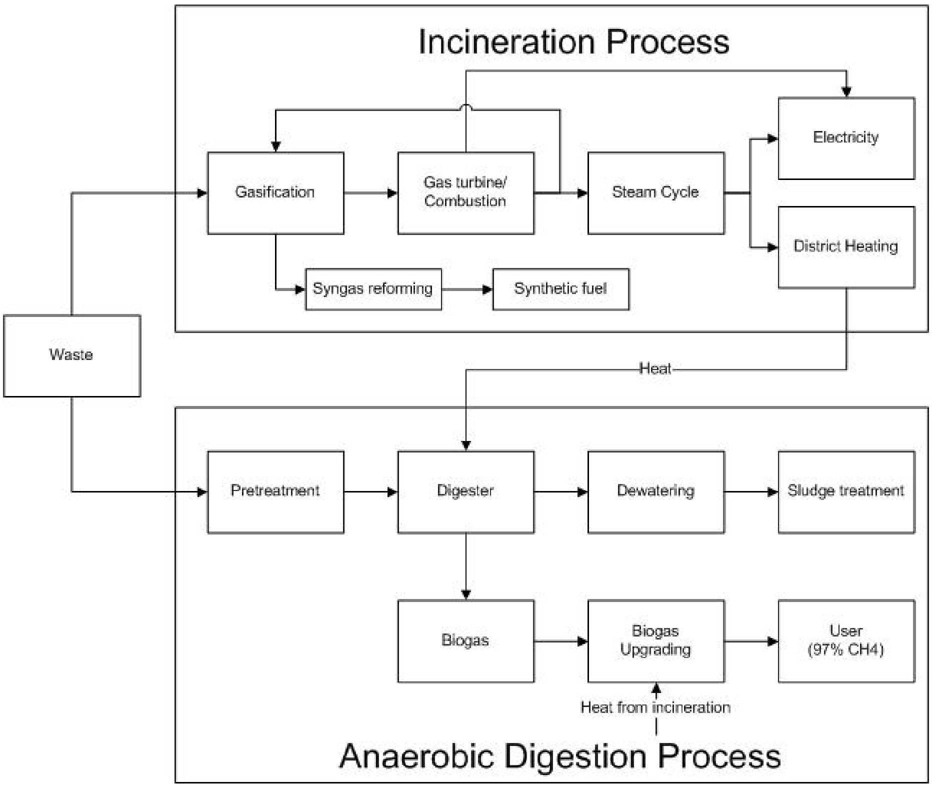


Figure 3.11 Scenario 2 extend flow diagram

In this scenario, different sections of the incineration process are modified. The structure modification starts with the pretreatment section, where the combustible waste feedstock is sorted and dried. To dry the feedstock, hot air is supplied indirectly to the drying chamber. The drying process is an important process for waste pretreatment because moisture content in the feedstock could cause the formation of toxic compounds and lower the thermal efficiency of the gasifier.

The second modification is the gasification process. In the gasification process, waste is gasified with hot air at 850°C. The gasification agent is heated with the heat from char combustion via a heat exchanger. As a result of the gasification, syngas and char residue are produced. The char residue is combusted in the combustion chamber to provide heat for other processes.

As syngas contains many different elements and compounds, gas treatment is required to clean the syngas. Gas cleaning technology is not specified in this scenario and it is excluded from the calculation. It is however assumed that a water scrubber is used and the water entering the gas treatment exit as waste water. The syngas from the gas treatment process is then used in the gas turbine. There is also a possibility to use the syngas in synthetic fuel reforming but in this scenario, synthetic fuel conversion from waste is still in experimental stage and therefore no syngas is converted. The gas turbine cycle generates heat and power.

3.3.2 Model creation

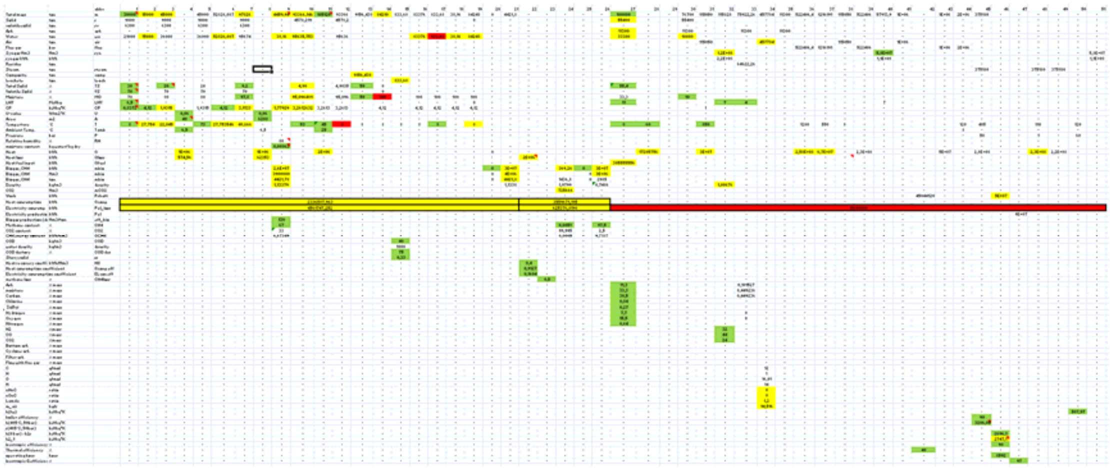


Figure 3.12 Scenario 2

The energy and mass balance model of this scenario is created in a similar method as the first scenario. In this balance model, the biological part is identical as in the first scenario.

3.3.2.1 Incineration process

The initial condition of the waste is assumed to be the same as the first scenario. The first process is drying of waste feedstock. The incoming waste contains 33.3 % moisture which is not suitable for the gasification process. Therefore hot air is supplied to evaporate the moisture. The moisture of the waste going to the gasifier is specified at 10 %. To calculate the heat needed to dry the waste, reversed calculation is used. By subtracting the water content before and after the drying process, the amount of water needed to evaporate is known. Using heat transfer theory $Q=m*Cp*\Delta T$, and heat of vaporization, the amount of heat needed is calculated.

		27	28	29	30	31	32	33	34
Total mass	ton	100000	-	-	74111.1	185277.7778	56700	202688.89	584555
Solid	ton	55400	-	-	55400	-	-	-	-
volatile solid	ton	-	-	-	-	-	-	-	-
Ash	ton	11300	-	-	11300	-	-	-	-
Water	ton	33300	-	-	7411.11	-	-	-	-
Air	ton	-	-	-	-	185277.7778	-	-	584555
Flue gas	ton	-	-	-	-	-	-	-	-
Additive	ton	-	-	-	-	-	-	-	-
Syngas Nm3	Nm3	-	-	-	-	-	54000000	-	-
syngas kWh	kWh	-	-	-	-	-	1.11E+08	-	-
Residue	ton	-	-	-	-	-	-	202688.89	-
Steam	ton	-	-	-	-	-	-	-	-
Composite	ton	-	-	-	-	-	-	-	-
leachete	ton	-	-	-	-	-	-	-	-
Solid	%	55.4	-	-	-	-	-	-	-
Volatile Solid	%	-	-	-	-	-	-	-	-
Moisture	%	33.3	-	-	10	-	-	-	-
LHV	MJ/kg	11.61	-	-	-	-	7.425	4	-
CP	kJ/kg*K	1	-	-	-	1.17	-	-	-
U-value	W/m2*K	-	-	-	-	-	-	-	-
Area	m2	-	-	-	-	-	-	-	-
Temperture	°C	8	60	-	-	850	-	-	-
Ambient Temp.	°C	-	-	-	-	-	-	-	-
Average Temp.	°C	-	-	-	-	-	-	-	-
Pressure	bar	-	-	-	-	-	-	-	-
Relative humidity	%	-	-	-	-	-	-	-	-
moisture content	kg water/ kg dry gas	-	-	-	-	-	-	-	-
Heat	kWh	-	17546913.6		-	50701263.89	-	-	-
Heat loss	kWh	-	-	-	-	-	-	-	-
Heat fuel input	kWh	322500000	-	-	-	-	-	-	-
Biogas_CH4	kWh	-	-	-	-	-	-	-	-

Figure 3.13Scenario 2, Incineration process

The syngas yield from the gasification process is calculated using a gas yield coefficient at 0.54 Nm^3/kg waste giving $54*10^6$ Nm^3 of syngas with lower heating value of 7.425 MJ/Nm^3 (Gang Xiao, 2009).

All the syngas is used in the gas turbine. The gas turbine is assumed to have an electrical efficiency of 35 % based on the chosen gas turbine specification. According to the gas turbine specification, the efficiency of ABB GT26 is 38.3 % with natural gas, therefore the efficiency of the turbine with syngas should be lower (Khartchenko, 1997).By using gas turbine efficiency, LHV and syngas output, the gas turbine produces approximately 38.9 GWh of work. By subtracting the work and the energy content in the syngas the waste heat is about 72.4 GWh of which part of the heat is used for the drying process.

		37	38	39	40	41	42	43	44	45
Total mass	ton	1190700	185277.78	775943.644	56700	1134000	-	1190700	1966643.6	261208.923
Solid	ton	-	-	-	-	-	-	-	-	-
volatile solid	ton	-	-	-	-	-	-	-	-	-
Ash	ton	-	-	-	-	-	-	-	-	-
Water	ton	-	-	-	-	-	-	-	-	-
Air	ton	-	185277.78	-	-	1134000	-	-	-	-
Flue gas	ton	1190700	-	775943.644	-	-	-	1190700	1966643.6	-
Additive	ton	-	-	-	-	-	-	-	-	-
Syngas Nm3	Nm3	-	-	-	54000000	-	-	-	-	-
syngas kWh	kWh	-	-	-	111375000	-	-	-	-	-
Residue	ton	-	-	-	-	-	-	-	-	-
Steam	ton	-	-	-	-	-	-	-	-	261208.923
Composite	ton	-	-	-	-	-	-	-	-	-
leachete	ton	-	-	-	-	-	-	-	-	-
Solid	%	-	-	-	-	-	-	-	-	-
Volatile Solid	%	-	-	-	-	-	-	-	-	-
Moisture	%	-	-	-	-	-	-	-	-	-
LHV	MJ/kg	-	-	-	7.425	-	-	-	-	-
CP	kJ/kg*K	-	-	1.1	-	-	-	-	-	-
U-value	W/m2*K	-	-	-	-	-	-	-	-	-
Area	m2	-	-	-	-	-	-	-	-	-
Temperture	°C	550	8	986.155335	-	-	-	501.77101	120	405
Ambient Temp.	°C	-	-	-	-	-	-	-	8	-
Average Temp.	°C	-	-	692.885925	-	-	-	692.88593	-	-
Pressure	bar	-	-	-	-	-	-	-	-	50
Relative humidity	%	-	-	-	-		-	-	-	-
moisture content	kg water/ kg dry gas	-	-	-	-	-	-	-	-	-
Heat	kWh	65154375	-	151987625	-	-	-	47607461	-	199595086
Heat loss	kWh	-	-	-	-	-	-	-	-	-
Heat fuel input	kWh	267843264	-	-	-	-	-	-	-	-
Biogas, CH4	kWh	-	-	-	-	-	-	-	-	-
Biogas	Nm3	-	-	-	-	-	-	-	-	-
Biogas, CH4	ton	-	-	-	-	-	-	-	-	-
Density	kg/m3	-	-	-	-	-	-	-	-	-
CO2	Nm3	-	-	-	-	-	-	-	-	-
Work	kWh	-	-	-	-	-	38981250	-	-	-

Figure 3.14 Scenario 2 gasification

The heat produced by the char combustion is calculated using mass of residue and lower heating value of 4 MJ/kg. As for the temperature of the flue gas, it is assume to be approximately 1 200°C based on using adiabatic flame temperature of wood at 1 980°C.

3.4 Scenario 3, Futuristic scenario

The third scenario is the most complex, where experimental EfW technology with high efficiency is assumed to be operational. The processing steps are gasification and electrochemical oxidation (fuel cell). The combustible waste feedstocks are gasified with hot air at so high efficiency that there will be no residue. The product syngas is then heated and supplied to the fuel cell. There is also a possibility of converting syngas to synthetic fuel.

3.4.1 Scenario modification

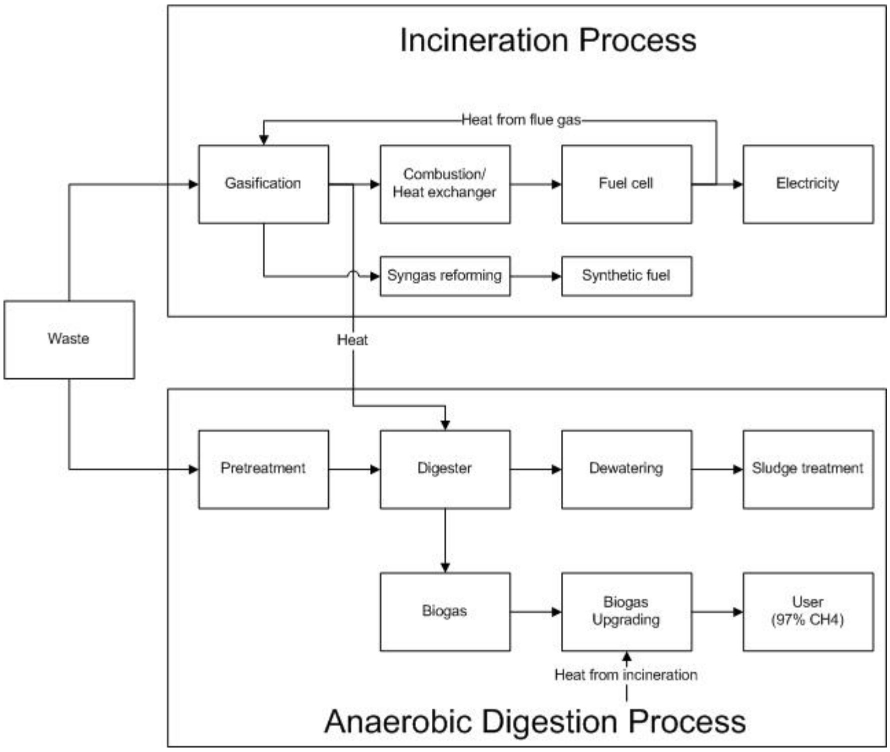


Figure 3.15 Scenario 3

The modifications made to the third scenario are the detailed structures of the EfW system and the energy and mass flows. The waste which enters the incineration process is pretreated with drying. The heat needed to dry the feedstock is obtained from the hot syngas before the gas treatment process. The heat is extracted from the hot syngas in order to utilize the possible useful heat.

After the pretreatment process, the feedstock enters the gasification process and is gasified with waste heat from the fuel cell with the assumption that there is no char residue and the product of the gasification is ash and syngas.

The syngas can be used for three purposes; synthetic fuel conversion, fuel cell, and syngas combustion. In order to operate efficiently, the temperature inside the fuel cell needs to be higher than 800°C. Therefore a fraction of the syngas produced from the gasification process is combusted in a gas furnace to heat the syngas. Both biogas from the biogas reactor and syngas are then used in the fuel cell to generate electricity. The excess syngas from the fuel cell then enters the heat exchanger to extract heat for heating up the gasification agent since not all syngas will oxidize with the air inside the fuel cell. After exchanging the heat with the gasification agent, the syngas is supplied to the gas furnace for heating up syngas.

Within the third scenario, there are three main heat exchangers; after the gasifier, the combustor and the fuel cell. The first heat exchanger is used for waste pretreatment. The second heat exchanger is for heating up the raw syngas before the fuel cell and the last one is for heating the gasification agent. The reason that setting up the first heat exchanger is because the product gas is set to be cleaned in gas treatment process where it will be cooled down to 50°C.

3.4.2 Model creation

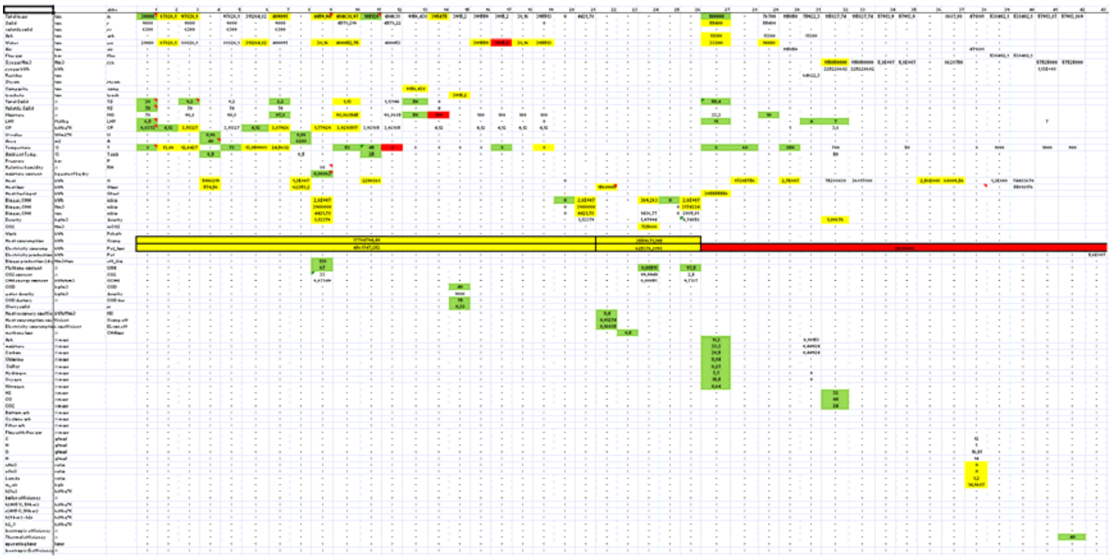


Figure 3.16 Scenario 3, Balance model

3.4.2.1 Incineration process

The balance model of the third scenario starts with the waste pretreatment and ends with combustion of excess syngas. As the waste entered the pretreatment process, the feedstock is heated with hot air at 60°C. The heat required to dry the waste feedstock is calculated by multiplying the reduced water content with water specific heat and temperature difference. The energy required to vaporize the water content is determined using heat of vaporization multiplying with water content.

		27	28	29	30	31	32	33
Total mass	ton	100000	-	74111.11	129694.44	11300	192505.5556	219368.8889
Solid	ton	55400	-	55400	-		-	-
volatile solid	ton	-	-	-	-	-	-	-
Ash	ton	11300	-	11300	-	11300	0	0
Water	ton	33300	-	7411.111	-	-	-	-
Air	ton	-	-	-	129694.44	-	-	-
Flue gas	ton	-	-	-	-	-	-	-
Additive	ton	-	-	-	-	-	-	-
Syngas Nm3	Nm3	-	-	-	-	-	148222222.2	148222222.2
syngas kWh	kWh	-	-	-	-	-	397042708.3	397042708.3
Residue	ton	-	-	-	-	0	-	-
Steam	ton	-	-	-	-	-	-	-
Composite	ton	-	-	-	-	-	-	-
leachete	ton	-	-	-	-	-	-	-
Solid	%	55.4	-	-	-	-	-	-
Volatile Solid	%	-	-	-	-	-	-	-
Moisture	%	33.3	-	10	-	-	-	-
LHV	MJ/kg	11.61	-	-	-	4	7.425	-
CP	kJ/kg*K	-	-	-	1.17	-	3.6	-
U-value	W/m2*K	-	-	-	-	-	-	-
Area	m2	-	-	-	-	-	-	-
Temperture	°C	8	60	-	850	-	700	-
Ambient Temp.	°C	-	-	-	8	-	50	-
Average Temp.	°C	-	-	-	-	-	-	-
Pressure	bar	-	-	-	-	-	-	-
Relative humidity	%	-	-	-	-	-	-	-
moisture content	kg water/ kg dry gas	-	-	-	-	-	-	-
Heat	kWh	-	17546913.58	-	35490885	-	125128611.1	107581697.5
Heat loss	kWh	-	-	-	-	-	-	99345430.28
Heat fuel input	kWh	322500000	-	-	-	-	-	-
Biogas, CH4	kWh	-	-	-	-	-	-	-
Biogas	Nm3	-	-	-	-	-	-	-
Biogas, CH4	ton	-	-	-	-	-	-	-
Density	kg/m3	-	-	-	-	-	1.48	-
CO2	Nm3	-	-	-	-	-	-	-

Figure 3.17 Scenario 3, Incineration process

The second calculation is the gasification process, where gasification agent and waste is fed into the gasification chamber. The air to fuel ratio for this scenario is approximately 1.75 since complete gasification require more oxygen compared to the second scenario. The syngas yield is also assumed to be higher to due to the fact that the process is complete gasification and the lower heating value of the syngas will be at 7.425 MJ/kg.

		40	41	42	43
Total mass	ton	783653.46	117362.36	99758.00222	-
Solid	ton	-	-	-	-
volatile solid	ton	-	-	-	-
Ash	ton	-	-	-	-
Water	ton	-	-	-	-
Air	ton	-	-	-	-
Flue gas	ton	783653.46	-	-	-
Additive	ton	-	-	-	-
Syngas Nm3	Nm3	-	79298889	67404055.56	-
syngas kWh	kWh	-	242059858	-	-
Residue	ton	-	-	-	-
Steam	ton	-	-	-	-
Composite	ton	-	-	-	-
leachete	ton	-	-	-	-
Solid	%	-	-	-	-
Volatile Solid	%	-	-	-	-
Moisture	%	-	-	-	-
LHV	MJ/kg	-	7.425	-	-
CP	kJ/kg*K	-	-	-	-
U-value	W/m2*K	-	-	-	-
Area	m2	-	-	-	-
Temperture	°C	-	1000	900	-
Ambient Temp.	°C	-	-	-	-
Average Temp.	°C	-	-	-	-
Pressure	bar	-	-	-	-
Relative humidity	%	-	-	-	-
moisture content	kg water/ kg dry gas	-	-	-	-
Heat	kWh	263031181	-	84794301.89	-
Heat loss	kWh	111494238	-	-	-
Heat fuel input	kWh	-	-	-	-

Figure 3.18Scenario 3 combustion

The gas combustion is based on stoichiometric combustion where air and fuel are the main components. The syngas and excess syngas used in the combustion is assumed to have the same hydrogen and carbon monoxide content in order to simplify the calculation. Another assumption is the temperature of the flue gas from the combustion which is about 1 000°C. The assumption on flue gas temperature is made instead of calculation because uncertainty in excess syngas properties. After the combustion, flue gas is used to heat up the clean syngas for fuel cell.

The last calculation in this scenario is the electricity generation from the fuel cell. The electrical efficiency is estimate to be 50 % with 15 % excess syngas.

4 Results

The result overview is separated into three sections, incineration, biological, and summary. The first part is the incineration process. Three scenarios and five set of inputs have been used. The reference section represents the actual case in Borås where incineration and biological process is separated. Section 1a and 1b is the state of the art where 1a is the case where extra waste is fed to produce sufficient heat for the biological process. As for 1b, the same amount of waste as the reference case is used. The scenario two and three are the foreseeable future and the futuristic scenario.

Scenario 1 is separated into 1a and 1b because there is a limitation claimed by the plant operator. From the interview with the operator of Ryaverket incineration plant, they said that there is no available waste heat since it is all used up. Therefore more waste has to be incinerated to produce the heat for the biological process.

Scenario		Reference	1a	1b	2	3
Process		Incineration				
Waste input	ton/yr	100000	102700	100000	100000	100000
Ash	% mass	11.3	11.3	11.3	11.3	11.3
moisture	% mass	33.3	33.3	33.3	33.3	33.3
Carbon	% mass	30.5	30.5	30.5	30.5	30.5
Chlorine	% mass	0.84	0.84	0.84	0.84	0.84
Sulfer	% mass	0.27	0.27	0.27	0.27	0.27
Hydrogen	% mass	7.7	7.7	7.7	7.7	7.7
Oxygen	% mass	15.5	15.5	15.5	15.5	15.5
Nitrogen	% mass	0.64	0.64	0.64	0.64	0.64
LHV	MJ/kg	11.61	11.61	11.61	11.61	11.61
boiler efficiency	%	90	90	90	90	90
Heat input	GWh	322.5	331.2075	322.5	322.5	322.5
Syngas	GWh	-	-	-	111.375	305.708
Useful heat	GWh,heat	-	-	-	-	99.3
Heat output(furnace)	GWh,heat	290.25	298.0868	290.25	202.69	-
Gas turbine/Gas furnace	GWh,heat	-	-	-	65.1	35.4
Air input	ton/yr	257090	264031	257090	769832	781533
Bottom ash	ton/yr	5288	5431	5288	11300	11300
Fly ash + filter ash	ton/yr	11017	11315	11017		
Steam temperature	°C	405	405	405	405	-
Steam pressure	bar	40	40	40	40	-
Electrical production	GWh,EL	62.7	66.4	62.7	70.1	81.7
Heat production	GWh,heat	220	225	220	187.5	99.3
Electrical consumption	GWh,EL	11.6	11.9	11.6	17.4	11.6
power to heat ratio (EL/Q)	-	0.285	0.295111	0.285	0.373867	0.822759

Figure 4.1 Result overview: Combustible waste

For the reference case, the heat and the electricity production is approximately 220 GWh and 62.7 GWh. The heat input is the same for every scenario but the heat production gradually decrease from 1a to 3 since the fluidized bed is substituted with gasification and heat requiring drying processes etc.. The electricity production is about 15 % larger in scenario 2 compared to scenario1, and in scenario the electricity generation is about 30 % larger compared to scenario1.

Scenario		Reference	1a	1b	2	3
Process				Biological		
Waste input	ton/yr	30000	30000	30000	30000	30000
	kWh	54.1667	54.1667	54.1667	54.1667	54.1667
Total solid (TS)	%	30	30	30	30	30
Volatile solid (VS)	%	70	70	70	70	70
Total solid (TS) buffer	%	9.2	9.2	9.2	9.2	9.2
Total solid (TS) digester	%	3.6	3.6	3.6	3.6	3.6
LHV	MJ/kg	6.5	6.5	6.5	6.5	6.5
methane yield	Nm3/ton waste	130	130	130	130	130
Biogas yield	Nm3	3900000	3900000	3900000	3900000	3900000
	GWh	26.046105	26.04611	26.04611	26.04611	26.04611
methane content	%	67	67	67	67	67
Residue (fertilizer)	ton/yr	9156.438	9156.438	9156.438	9156.438	9156.438
Residue (leachete)	ton/yr	833.67611	833.6761	833.6761	833.6761	833.6761
Heat consumption	GWh	4.68	4.68	4.68	4.68	4.68
Sanitation temp	°C	73	73	73	73	73
Digester temperature	°C	53	53	53	53	53
Electrical consumption	GWh	4.56	4.56	4.56	4.56	4.56
Final gas output	GWh	21.4	26.04	26.04	26.04	26.04
Process				Biogas upgrade		
Raw Gas input	Nm3	3200727	3900000	3900000	3900000	3900000
CO2 output	Nm3	1342393	1635670	1635670	1635670	1635670
Heat consumption	GWh	2.92	3.55	3.55	3.55	3.55
Electrical consumption	GWh	0.5132	0.6253	0.6253	0.6253	0.6253
Temperature	°C	105	105	105	105	105
Gas output	GWh	18.4	26.045	26.045	26.045	26.045
	Nm3	1544641	2264330	2264330	2264330	2264330

Figure 4.2Result overview: Biodegradable waste

The biological process is arranged in the same order as the incineration process. The raw biogas production from anaerobic digestion is the same for every case except for the reference case where raw biogas is used in internal gas furnace for heat production at 23.7 GWh and 26.04 GWh. Since the waste input is the same, the electricity,heat consumption as well as biogas yieldis the same.

The difference between the reference case and the other scenariosis much greater since the raw biogas is upgraded for other purpose. The upgraded biogas is 18.4 GWh for the reference case and 26 GWh for the others. The heat and electricity consumption is also different because the gas input is different.

Scenario		Reference	1a	1b	2	3
Process				Summary		
Heat production	GWh,heat	220	216.77	211.77	179.27	91.07
Electricity production	GWh,EL	62.7	66.4	62.7	70.1	81.7
Biogas production	GWh	18.4	26.045	26.045	26.045	26.045
	Nm3	1544641	2264330	2264330	2264330	2264330

Figure 4.3Result overview: Overall

It can be seen that the biogas production remain constant at 18.4 GWh for the reference case and at 26GWh for the other cases. The heat production for the reference is the highest at 220GWh and lowest for scenario 3 at 93 GWh. The scenario three have the highest electricity production at 81.7GWh and lowest at 62.7GWh for the reference case.

4.1 Reference data and limitation

For scenarios and balance model creation, general assumptions and series of reference data is used. Starting with waste input, the biological waste comprises mostly of household waste and account for 30 000 ton. The total solid content of the waste is approximately 30 % and volatile solid is 70 % with lower heating value of 6.5 MJ/kg. For an anaerobic digestion process, waste mixture is diluted to 20%TS before hygienisation and 9.2 % TS before digestion. The temperature inside the hygienisation tank is set constant at 73°C and 53°C inside the digester tank. Other reference data used are the gas yield coefficient, temperature, specific coefficient, efficiency, and LHV.

As for Incineration process, the waste characteristic is based on a study on Borås Ryaverket incineration plant. All scenarios and the reference case use the same waste characteristic in order to be able to compare the energy input and heat production. The reference data used for the steam cycle is based on the Ryaverket, the superheated steam is set at 405°C at 40 bar. The power to heat ratio of the incineration process is 0.2 where more heat is produced.

The electrical consumption of the incineration process and biological process is roughly 11.8 GWh and 4.5 GWh, respectively. But for the electrical consumption for biogas upgrading process, an average coefficient of 0.16 kWh/Nm3is used.

The values and assumption present above is an ideal condition. The reason for using an ideal condition is to minimize the number of influence factor and highlight the most important part since the main purpose of this thesis work is the compare the overall energy production from different technologies. But there are issues concerning the irreversibility and losses in the system. For different technology, the irreversibility is also different such as heat loss and efficiency. If all of the irreversibilities were to be included in the scenario modeling, it would be too complicated and it would require much greater time and attention to use the balance model. Another reason that many of the irreversible was excluded is that many of the technologies is in experimental stage. If the technologies were proceed to the next stage, there is a possibility that irreversibilities might increase exponentially making the modeling more unreliable than excluding it from the calculation process.

In creating energy and mass balance there are many limitations to the model creation. One of the limitations is the operating temperature of the process and equipment. By analyzing the potential energy production, there is much heat loss from the stack. The lowest temperature of the flue gas exiting the stack is set to around 150°C but if this temperature can be lowered, there is more energy that can be harvested. Another limitation is the size of a heat exchanger. Between some processes there is the possibility to utilize the waste heat by exchanging the heat through heat exchanger. The limitation is the size because high heat transfer rate would require large heat exchange and in some case it is unpractical to do so.

4.2 Statement sensitivity of result

The result of each scenario and reference is present in the result overview. In order to have a better understanding, a sensitivity analysis was made. For each scenario, an adjustment is made to test the sensitivity of the energy and mass balance model.

The first sensitivity analysis is how changes in biological and combustible waste ratio would affect the energy and mass production on the three scenarios. For scenario one, the waste input ratio between biological and combustible waste was increased and decreased by 5 percentage point. The current waste ratio between biological and combustible waste is approximately 23 % with total waste content of 130 000 ton. With the current waste input ratio, the energy production for biogas, heat, and electricity are 8 %, 71 %, and 21 %, respectively.

By Increasing the share of biological waste by 5 percentage points, the biological waste would increase by 6 400 ton to a total biological waste of 36 400 ton and combustible waste of 93 600 ton. With the increase in the biological waste, the biogas production also increases. Comparing the original result and 5% increase scenario, the biogas production will increase by approximately 3 percentage point and heat production decreases by 2 percentage points. As for the electricity production, it will slightly decreased but not in a significant amount. The decrease in electricity production ratio is a result of electrical conversion efficiency.

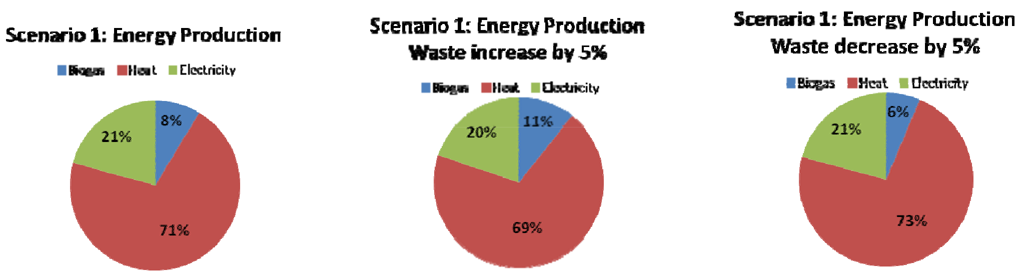


Figure 4.4Scenario 1increase in biological-combustible waste ratio with same total waste

By decreasing the waste by 5 percentage points from the original input ratio, the biological waste input decrease to 23 400 ton. As the biological waste fraction decrease, the share of combustible waste increase. This causes the heat production to increase by 2 percentage points but the electricity production increase in small amount. From the sensitivity result, the heat production tends to be more sensitive to decrease in input than an increase combustible waste input. On the other hand, the biogas production reacted in the opposite direction to the heat production. As for the electricity production it is the least sensitive to changes.

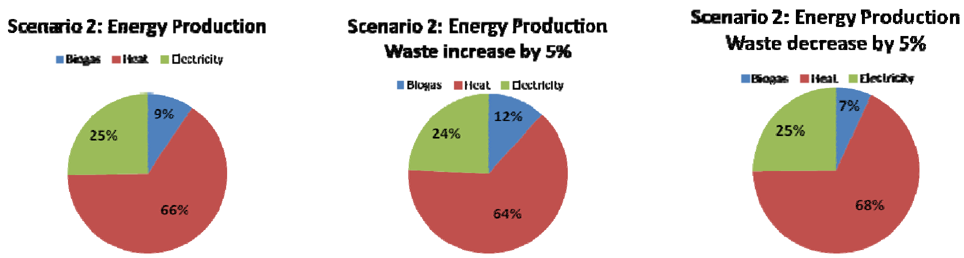


Figure 4.5 Scenario 2increase in biological-combustible waste ratio with same total waste

The same sensitivity analysis is performed on the scenario 2. The first graph on the left is the original energy production with biogas, electricity, and heat production of 9 %, 25 %, and 66 %, respectively. By comparing the energy production of scenario 1 and 2, it is clear that both biogas and electricity production share of scenario 2 is higher than 1. When the biological waste share increase by 5 percentage point, the biogas increased by 3 percentage points and heat production decrease by 2 percentage points. As for the electrical production, it slightly decreased by 1 percentage point but in small amount and the result is presented in the center graph.

The graph on the right is the energy production when biological waste share decreased by 5 percentage point. The biogas production decreased by 2 percentage points and heat increased by 2 percentage points. As for the electrical production it remains about the same. For the scenario 2, the energy production reacted to the changes equally for increased and decrease except for the decreased in biogas when biological waste decreased.

By comparing the changes in percentage point between scenario one and two, there is a small different in how the system react to the changes in waste ratio. This is the result of scenario schematic where both use similar technology.

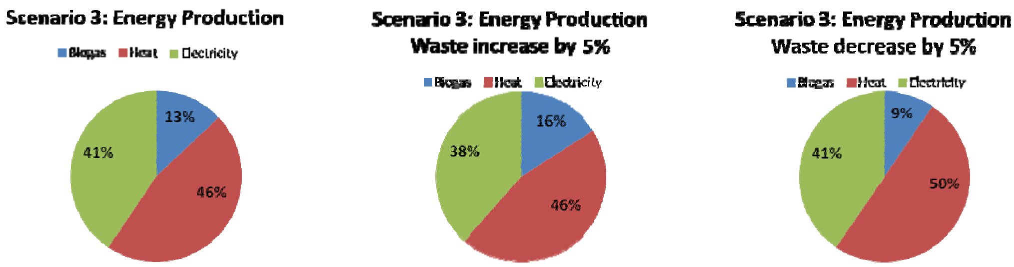


Figure 4.6 Scenario 3increase in biological-combustible waste ratio with same total waste

The last sensitivity test for the first changing parameter is presented in the figure above. The original energy production is 41 % electricity, 13 % biogas, and 46 % heat. In this scenario, the heat and electricity production is almost equal. The increase in biological waste share causes a decrease in electrical production by 3 percentage point. But the biogas production increase by 3 percentage points. The heat production remains the same. As the biological waste share decreases, the heat production increase by 4 percentage points but electricity remains the same. The biogas decrease by 4 percentage points and with the result, it can be conclude that biogas production is the most sensitive to changes.

By comparing the three scenarios, it is obvious that an increase or decrease in waste ratio would result in direct changes in the energy production. The degree on how much the change would be is solely depend on the scenario concepts and design. Another issue is the increase in the energy production share. The change in percentage points of the energy production tends to be lower than the changes in waste ratio.

Another change is made to test the sensitivity result and it is the biogas yield. By changing the component or type of biodegradable waste, the biogas yield would also change. First, the biogas yield increase by 20Nm^3/ton waste causing the biogas to changes by 2 percentage points. And both heat and electricity decrease by 1 percentage point. But when the biogas yield decreased by 20 Nm3/ton the biogas also decrease by 1 percentage point. By comparing the biogas production for each gas yield, it is clear that the energy production changes in a linear direction. In the actual situation, the waste entering the biogas plant tends to varies on day to day basis. In one of the biogas plant research, the biogas yield tends to varies between 100-150 Nm^3/ton fresh wastes. For a single biogas plant, the changes in biogas yield would have a great influence on the energy production of the plant but if the biogas co-operate the with an incineration plant this would not be a major problem.

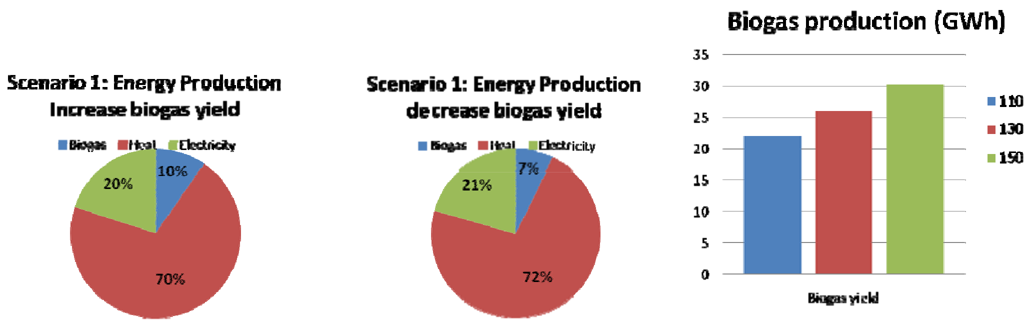


Figure 4.7 Scenario 1 Increase biogas yield

The third sensitivity test is the gas turbine efficiency. Gas turbine efficiency is increased and decreased by 5 percentage point to 40 % and 30 %. The test were made using scenario 2 as reference. The amount of waste input ratio is unchanged as well as other parameters. After the changes are applied to the balance model it can be seen that biogas production didn't change at all. But the electricity increase by 1 percentage point and heat production decrease by 1. On the contrary the decrease in efficiency cause a greater effect, the electricity decrease by 2 percentage points and heat increase by 2 percentage points. For the second scenario, the gas turbine efficiency is very important as much as the steam cycle efficiency since gasification is the main conversion technology. Another important aspect is the financial aspect, where a unit increase in efficiency of a high efficiency gas turbine is much higher than a low efficiency one.

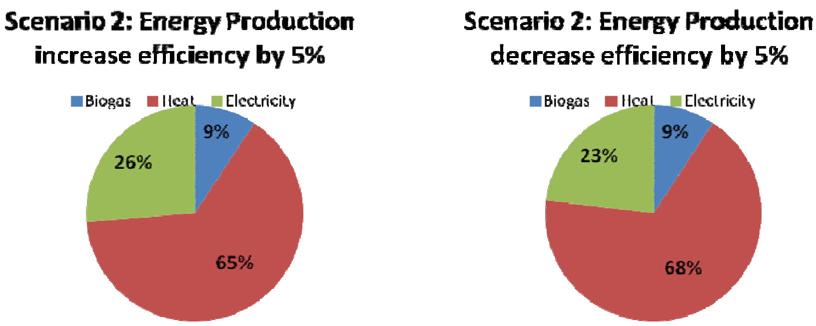


Figure 4.8 Scenario 2 gas turbine efficiency

The forth changes is the efficiency of the biogas upgrading plant. It is assumed that the heat consumption of the upgrading process improves by 20 % and 40 %. The heat consumption reduced by approximately 0.7 GWh. The heat production would increase as the heat consumption decrease but the changes in percentage are small since the overall energy production is much greater than the changes. The heat consumption becomes more important as the biogas production increase due to the fact that high heat consumption would result in high production cost.

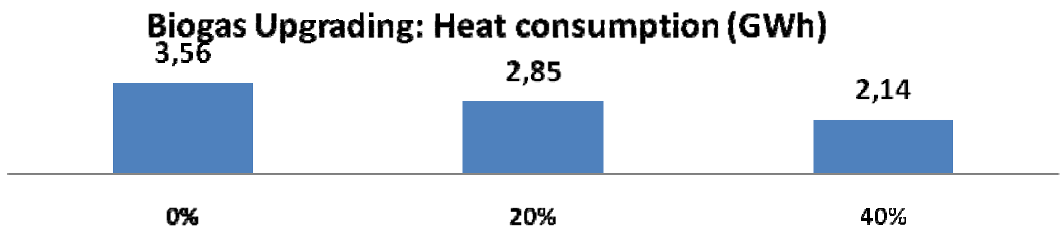


Figure 4.9Biogas upgrading

The last sensitivity tested is the product gas yield. For the scenario 2, the product gas is used to produce heat and power therefore an increase in gas yield would increase the electricity but heat production would decrease since there are fewer residues for combustion. As the overall energy production increase, the biogas production share would decrease since the biogas yield remain the same while syngas yield increase. By comparing the result from the increased and decreased gas yield, the electricity production is the most sensitive to changes.

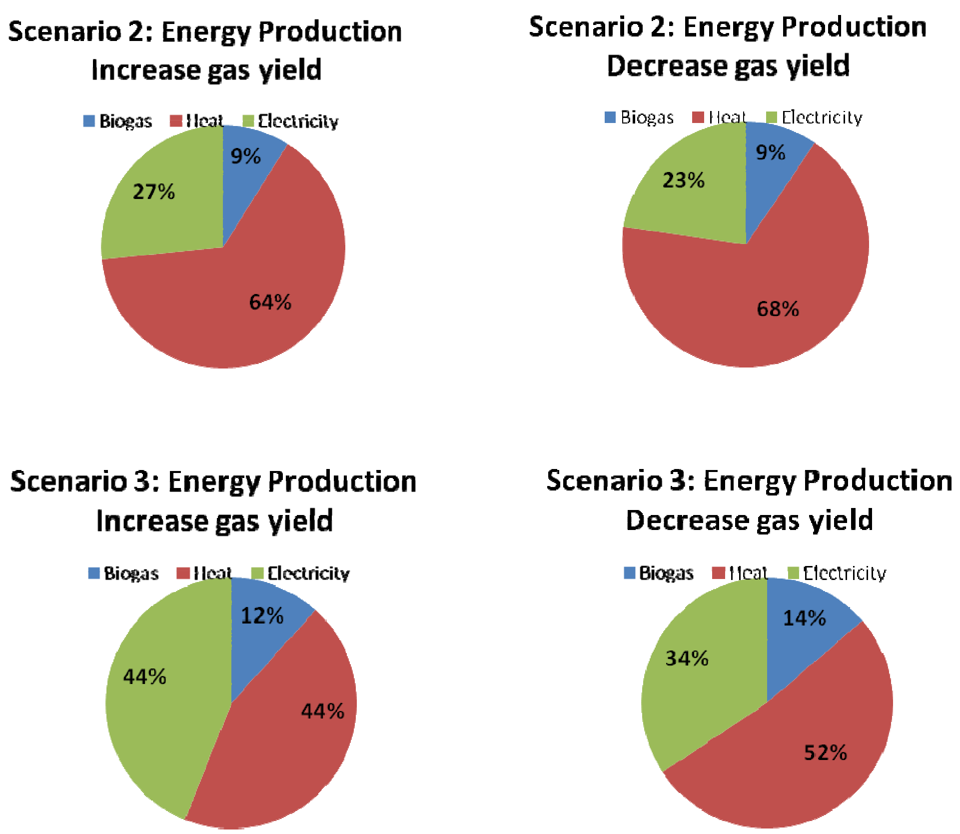


Figure 4.10Scenario 2&3 Increase gas yield

The same gas yield sensitivity test is applied to the scenario 3. The result is different from the expected result. The energy production changes slightly from the figure when gas yield increase but when gas yield decrease, the electricity and heat greatly decrease and increase. The reason for this behavior is the separation of product gas after gas treatment. Half of the product gas is used in a gas furnace to provide heat for the system therefore changes in gas production would cause changes in small range. A low gas yield waste may cause a high decrease in energy production and affect the whole system.

5 Conclusions and outlook

From the literature review, scenario modification as well as model creation, energy and mass balance calculations for many different possible EfW concept has been simulated.

From the heat production perspective, the first scenario or the state of the art technology is the most suitable system. For this concept the highest heat production is obtained as well as considerable amounts of biogas.

If considering the most potential technology, scenario three would be the best choice. From a sustainable perspective heat production can be substituted with cleaner technology compared to electricity production, since there are more suitable technologies to produce heat for district heating

The combination of the fuel cell and gasification has the most potential to be the state of the art in the future. Even though fuel cell and gasification produce half the heat of the current system, the electricity production is higher than the rest. In the future this scenario may produce a better result due to better understanding and development in fuel cell technology and gasification process.

The best EfW concept is the cogeneration of gasification, steam cycle and gas turbine. By gasification process and gas turbine cycle, large amount of electricity is produced. If the boundary is assumed to be overall Europe, this is the best choice since highest amount of electricity can be produced with some heat production. For most countries in Europe, district heating is not very popular. Therefore heat is not the first priority for energy production. This scenario also allows a possibility for plant upgrading such as synthetic fuel conversion.

For today onward the technology that likely to change the most is the fuel cell technology since it has the ability to use different kind of fuel and it has high electrical efficiency. Even though gasification is new for EfW, it has been proven to be practical for coal and biomass but for fuel cell there is no commercialize facility and most of the research is done in experiment scale.

The issues whether to continue research on gasification or fuel cell can be answered by analyzing the energy production. For gasification, the energy production depends on the chemical reaction between the operating condition, fuel and gasification agent. For gasification agent and operating condition, it is possible to maintain a constant standard but for fuel it is almost impossible to control the waste content for household waste. For fuel cell, syngas separation is possible and there is a possibility to develop a fuel cell with different material.

5.1.1 Influence

In EfW systems, different parameters influence the result differently. The most influential parameter is the waste input since it has the direct effect on the result. The combustible and biodegradable waste affects the result differently. Increasing biodegradable waste would result in higher biogas yield but this would also increase the electrical and heat consumption. And when combustible waste increases, the electrical and heat production would also increase.

Another influencing parameter is the efficiency of the energy converting component. The higher the efficiency is the more energy could be produced. But the efficiency does not always have great influence on the result since the technology is already mature and there is less chance that the efficiency would increase in foreseeable future.

For the biological process, the biogas yield coefficient has a large effect on the result since it involves the multiplication of two large values. Another reason is the possibility to increase the value. The gas yield coefficient for both anaerobic digestion and gasification process could increase by different methods such as pretreatment. The last reason is that the calculation using the coefficient is made at the beginning of the model.

5.1.2 Different waste input

Since municipal solid waste contains many different types of material, the amount of energy content in the waste is different. For waste incineration, materials such as paper and plastic have the highest energy content and food has the lowest due to high moisture content. It is almost impossible to sort the waste to specific type and sorting would require large amount of energy. The reason that paper and plastic have the highest energy content is because of carbon content.

5.2 Outlook

5.2.1 Improvement

For every energy and mass balance model, there is a space for improvement. The area which needs the most improvement is the specified electrical and heat consumption of the EfW system such as electrical consumption of each technology. In this report, electrical consumption of the reference case and scenario one is based on actual plant but for scenario two and three, different component are used. To be more precise in energy balance calculation, energy consumption of each component should be identified.

Another improvement is the specified syngas yield. Formulating precise gas yield equations for specific waste contents would allow better comparison and contrast since most literature reviews present their result based on different condition and assumption. Improvement could also be made in choice of technology such as gas treatment, and incineration process. Because the balance model is made aiming for general case, many input value are average numbers.

User interface is another area that needs improvement since energy and the mass balance model involve a lot of data therefore an improved user interface would allow easier understanding.

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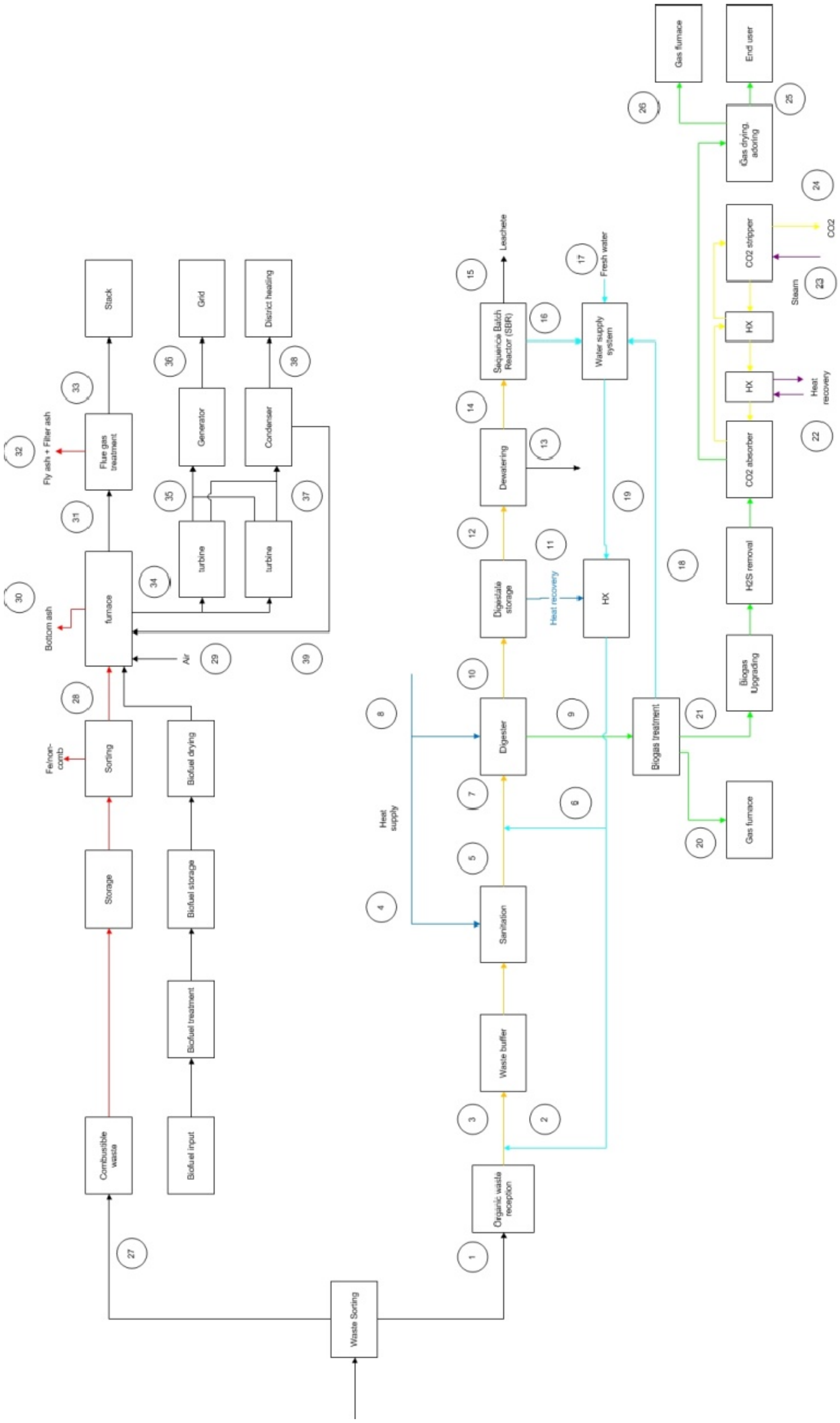
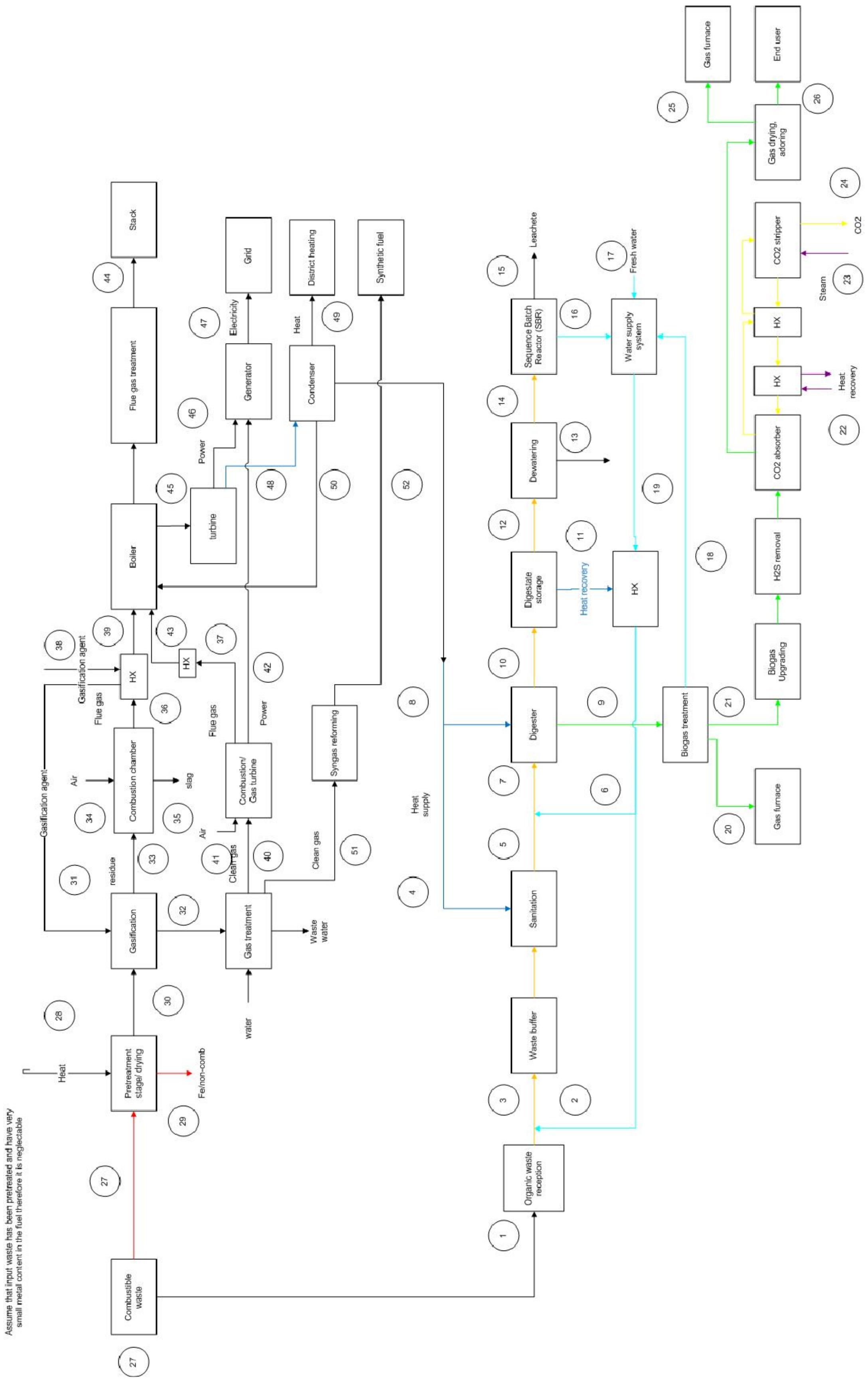
Appendix

1. Scenario 1 Flow chart



2. Scenario 2 Flow chart



3. Scenario 3 Flow chart