Parallel-Powered Hybrid Cycle with Superheating “Partially” by Gas Turbine Exhaust

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Abstract

It is of great importance to acquire methods that has a sustainable solution for treatment and disposal of municipal solid waste (MSW). The volumes are constantly increasing and improper waste management, like open dumping and landfilling, causes environmental impacts such as groundwater contamination and greenhouse gas emissions. The rationalization of developing a sustainable solution implies in an improved way of utilizing waste resources as an energy source with highest possible efficiency. MSW incineration is by far the best available way to dispose the waste. One drawback of conventional MSW incineration plants is that when the energy recovery occurs in the steam power cycle configuration, the reachable efficiency is limited due to steam parameters. The corrosive problem limits the temperature of the superheated steam from the boiler which lowers the efficiency of the system. A suitable and relatively cheap option for improving the efficiency of the steam power cycle is the implementation of a hybrid dual-fuel cycle.

This paper aims to assess the integration of an MSW incineration with a high quality fuel conversion device, in this case natural gas (NG) combustion cycle, in a hybrid cycle. The aforementioned hybrid dual-fuel configuration combines a gas turbine topping cycle (TC) and a steam turbine bottoming cycle (BC). The TC utilizes the high quality fuel NG, while the BC uses the lower quality fuel, MSW, and reaches a total power output of 50 MW. Using a high-quality fuel in cogeneration can prove to be beneficial for improving and enhancing the overall plant profitability and efficiency while eliminating the corrosion problems with conventional MSW firing. The need for few interconnections between the different subunits in a parallel-fueled system allows for a wider range of operation modes and leaves room for service modes of the subunit. The hybrid dual-fuel cycle will be assessed for optimal cycle configuration and evaluated to how it compares to the sum of two separate single-fuel plants with optimal cycle configurations. Investigation of such aspects is a very important issue in order to be able to fully promote an implementation of hybrid combined cycle. The work presented herein also concentrates on investigating scenarios that include a full-load and part-load analysis in both condensing and combined heat and power (CHP) mode of operation.

Through simulations and evaluation of obtained data, the results strengthens the fact that the electrical efficiency of hybrid configurations increases at least with 2% in condensing mode and 1,5% in CHP mode, comparing it to the sum of two separate single-fuel units of similar scale. The simulations show increased electrical efficiencies when running the BC in part-load and the TC in full load, with a higher NG to MSW ratio. The results also indicated that it is possible to extract more power output from the cycle by operating in CHP mode, due to more energy being utilized from the input fuel.
Keywords:

MSW, Hybrid Cycle, Electricity Production, Combined Heat and Power, Aspen Utilities Planner
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\[ \eta_{el} = \frac{P_{ST}}{Q_{MSW}} \]  
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Equation 2 28

\[ \eta_{el} = \frac{P_{ST} + P_{GT}}{Q_{NG}} \]  
Equation 3 30

\[ \eta_{thermal} = \frac{P_{ST} + \dot{Q}_{\text{cond}} + P_{GT}}{Q_{NG}} \]  
Equation 4 30

\[ \eta_{ref} = \phi_{NG}\eta_{NG,\text{ref}} + (1 - \phi_{NG})\eta_{BC,\text{ref}} \]  
Equation 5 31

\[ \phi_{NG} = \frac{m_{NG}LHV_{NG}}{m_{BC}LHV_{BC} + m_{NG}LHV_{NG}} \]  
Equation 6 32

\[ \eta_{el,HCC} = \frac{P_{TC} + P_{BC}}{\dot{Q}_{TC,Fuel} + \dot{Q}_{BC,Fuel}} \]  
Equation 7 32

\[ \eta_{thermal,HCC} = \frac{P_{TC} + P_{BC} + \dot{Q}_{\text{cond}}}{\dot{Q}_{TC,Fuel} + \dot{Q}_{BC,Fuel}} \]  
Equation 8 33
# Nomenclature

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
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<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>TC</td>
<td>Topping Cycle</td>
</tr>
<tr>
<td>BC</td>
<td>Bottoming Cycle</td>
</tr>
<tr>
<td>WtE</td>
<td>Waste-to-Energy</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>GT</td>
<td>Gas Turbine</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher Heating Value</td>
</tr>
<tr>
<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>OOM</td>
<td>Object Oriented Modeling</td>
</tr>
<tr>
<td>HSE</td>
<td>Health, Safety and Environment</td>
</tr>
<tr>
<td>DLE</td>
<td>Dry Low Emissions</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic User Interface</td>
</tr>
<tr>
<td>EOH</td>
<td>Equivalent Operating Hours</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
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<tr>
<td>FAC</td>
<td>Flow Assisted Corrosion</td>
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1. Introduction

1.1 Background and motivation

Mankind has developed and perfected technology throughout history. But the added welfare and higher living standards have also resulted in higher energy consumption. One big problem is the limitation of energy resources in many countries. The current technology is energy hungry and strongly depends on the import of fossil fuels. The excessive usage of finite energy sources like oil and coal lead to great environmental problems. At the same time there is a trend towards continued growth in the world energy demand, which certainly will not lessen the negative impact of the fossil fuels. Fuels that are cleaner and readily available like biomass have been used since early days of man. These were the primary source of energy before the industrialization of the world. (Petrov, 2003) With advancements in technology that is based around fossil fuel, like current transportation systems, and global economies whose growth is dependent on fossil energy source; biomass has taken a less prominent place in the energy scale. The heightened demand that is put on fossil fuels brings unpredictability and volatility of the fuel prices which in turn cause severe energy supply problems.

Advancements in sustainable energy systems are a great way of achieving a less fossil fuel dependent and sustainable energy supply. Alternate fuels and methods of energy supply that are easily compatible with existing systems are desirable. With the ever growing production of material waste in the households and the industries, the trend towards biomass and waste usage for energy and heat production has once again risen. This alternative provides a good waste management solution while retaining a lowered carbon dioxide (CO$_2$) and other greenhouse gas (GHG) emissions compared to the alternative usage of fossil fuels. Although it contributes to a small part in the world energy mix, it plays an important role in many developing regions; and is sometimes the only available source of energy.

Many power plants utilize municipal solid waste (MSW) as fuel. Although not perfect, this approach has considerable advantages over the principal coal and peat power plant technologies. By deploying this methodology the waste is being used as a useful energy source and simultaneously diminishes GHG emissions produced by open dumping and landfilling. Conventional MSW incineration provides an environmentally friendly method of disposal. MSW is also accepted as a common locally available renewable energy source that is produced in large quantities in residential or domestic sources. These amounts grow larger each year and represent one of the largest renewable energy sources worldwide. (U.S EPA, 2009)

In Europe, biomass is mostly utilized as a cogeneration solution. Because of the many different environmental laws in place in EU, more and more parties have shown interest in biomass energy utilization for energy production. (European Commission, 1997) This is because of the
lower emissions, which will offer a cleaner use of natural resources. Because of this a growing number of waste-to-energy (WtE) facilities are coming up.

Solid waste incineration in Sweden is a critical source of heat generation during the wintertime. This source of fuel is used for both heat and electricity generation which maximizes its sustainability. (Avfall Sverige -Swedish Waste Management, 2012)

Sweden is a leading country in employing clean and sustainable alternatives in its energy mix. Sweden’s bright energy policy underlines the sustainable value of waste incineration as a beneficial solution for waste management as well as a great net heat and energy production source. In 2009, 26.27 TWh of the total heat production in Sweden was from biofuel sources. MSW poses as the second largest thermal heat energy source in Sweden, with 8.89 TWh generated from this source during 2009. (iea - International Energy Agency, 2009)

There are many noteworthy advantages in using MSW as fuel in WtE facilities. As mentioned before by utilizing locally produced MSW in incineration facilities, the need for landfilling and open dumping is reduced drastically. This method has proven to be a favorable waste disposal alternative. Operating with MSW as fuel will result in decreased import of nondomestic environmentally hazardous fuels, which will lead to greater revenues.

One other significant benefit of MSW incineration is the rather low, or near zero, carbon emission. (U.S EPA, 2005) This means that the net production of CO₂ almost adds up to zero, when balancing the amount of carbon released with an equivalent amount of carbon that has been taken up (i.e. in the case of trees and wood). (Petrov, 2003)

Incineration facilities using MSW for production of power and heat must install specific components for disposing the incineration residue produced. The remaining ashes and slag from the combustion process must be taken care of, while other special filters must be installed to clean the flue gases from fly ash etc. But with proper application and in well-controlled environments the byproducts can be reduced to only about 15-20% of the MSW weight. (Persson, 2005)

By far the biggest disadvantage of using biomass as fuel is the amount of inbound moisture content. It is estimated that newly cut wood contains about 50 weight-% of moisture and untreated MSW gathered from residential or domestic waste can contain up to 70% moisture content. (University of Central Florida, 2001)

The moisture content in the fuel is important for the calorific value of the fuel (heating value). This shows how much energy can be produced per kilogram of the fuel when combusted. This number is expressed in either lower heating value (LHV) or higher heating value (HHV). Furthermore, this water content requires a pre-treatment which uses energy. This must be accounted for when considering WtE. Also, without proper research and lack of optimization for the incineration process, an incomplete combustion of the fuel can lead to even more severe
environmental impacts, like carbon monoxide (CO) poisoning, than using fossil fuels. (Greiner, 1997)

Another major limitation in WtE plants is the overall limited temperatures and pressures that can be achieved. Because of the chemical composition of the waste, large amounts of halogen and alkali salts are released during combustion. These compounds can gravely damage and incapacitate the components and pose as severe corrosion risks. This limits the achievable temperatures of the steam produced in the boiler to around 380-400°C with a pressure of about 40 bar. This relatively low temperature of the produced steam in boiler limits the steam quality and the overall plant efficiency. (Li, et al., 2013)

This is a setback that is not present with the corrosion free high quality fuel source such as coal or peat. A suitable and relatively cheap option for improving the total efficiency of the conventional WtE plant is by a simple addition of a gas turbine (GT) to the existing plant. This can be done by applying minor modifications and adding only a few components to the cycle. The main principle of a hybrid dual-fuel cycle is that lower quality steam generated from the MSW in the bottoming cycle (BC), is heated further using a heat recovery system with the outgoing higher quality steam from the topping cycle (TC). Because the TC has the capability of reaching much higher temperatures, outgoing total steam from the heat recovery system will be superheated and have temperatures of about 500-550°C. (Udomsri, et al., 2011) (Petrov, 2003)

The main driving motivation for this project is hence implementing a GT cycle which utilizes high quality, corrosion free fuel like natural gas (NG) as a topping cycle. This system layout has its own generator and the flue gas outlet will then be coupled together with an existing MSW utilized BC in order to maximize the cycles efficiency. The hot steam from the MSW boiler will be superheated by the GT cycle, and will gain an overall higher quality steam. A cogeneration of this kind is beneficial for improving and enhancing the overall plant profitability and efficiency by eliminating the corrosion problems with conventional MSW incineration. The need for few interconnections between the different subunits in a parallel-fueled system allows a wider range of operation modes and leaves room for service modes of the subunit. This makes this solution particularly attractive with the rising fossil fuel prices.

1.2 Research procedure background

For this project, the work builds upon existing information and previous work done in this field by (Petrov, 2003) and (Udomsri, et al., 2011). Therefore the main, essential, primal approach and the basic concept of the hybrid cycles use similar methods to (Udomsri 2011, p 360) and (Petrov, 2003 - Paper I, p. 35). Further information is gathered from relevant databases and previous work done on similar projects. The hypothetical power plants describe in this report, utilizing MSW and NG in the cycles are simulated using the Aspen Utilities Planner software. This software is discussed in detail in chapter 4.2.
Existing calculation models are utilized for optimizing and calculating the results of the simulations. These mathematical models are numbered throughout the report.

1.3 Objectives of the thesis

The main focus of this thesis is put on maximizing the efficiency of an MSW cycle for heat and power generation. This will be done by combining and utilizing a high quality conversion TC with an existing MSW cycle. The mentioned systems are modeled and simulations are done using the Aspen Utilities Planner simulation software for power plant component analysis. The MSW utilized BC in the WtE plant design is aimed towards the highest possible efficiency while retaining authenticity in accordance to real life plants (a good balance between cost and performance). The basic design of this cycle consists of a boiler where MSW is fed in, steam turbine with four extractions coupled with a generator which will utilize the steam outlet from the boiler to generate power, a condenser is placed right after the steam turbine and various pumps, closed water heat exchangers and feedwater tanks are present in the system in order to ensure maximum efficiency.

In the hybrid cycle dual-fuel generation, the TC GT cycle has a simple design utilizing only one single shaft turbine and a small combustion chamber. Flue gases from the TC are sent to a heat recovery steam generator (HRSG) which will help superheat the lower quality steam generated in the boiler in the BC. The GT will also utilize a generator and the power output of this generator will be added up together with the power generated by the steam turbine. As part of the simulations, the system will be optimized for two different operation modes. Power only operating mode, or cold-condensing mode, where only electricity production is of interest. Another mode, where the system will utilize both heat and power in a combined heat and power (CHP) operation will be investigated as well. Here the excess heat extracted by the condenser can be utilized for district heating. The operation efficiency will be analyzed for these two different operation modes. Another objective is simulation of full-load operation suiting for wintertime and cold climates and a scenario where the system is running in part-load simulating summertime.

Finally, a component-by-component analysis of the operation modes is carried out where the parameters are described. This also includes identification of commercially available industrial grade components.

Putting the main objectives for the thesis project into focus, the following questions are investigated:
i. Designing and optimizing separate single-fuel MSW-fired steam cycle and a single-fuel NG-fired GT cycle.

ii. Designing a cogeneration facility with MSW incineration and GT hybrid combined cycle, with a total electricity production of 50 MW. MSW is fed into MSW boiler while NG is fed to the GT to achieve higher efficiency.

iii. Conducting a full analysis and optimization of the total efficiency of the hybrid cycle. The system is based on a total 50 MW power output. Use best available techniques for all components.

iv. Estimating the performance of the hybrid cycle according to the parameters given. These parameters are based on the different scenarios described above. The investigated scenarios include a full-load and part-load analysis of the condensing and CHP mode of operation.

v. Component by component analysis of commercially available components based on the results obtained from the simulations and optimizations.

1.4 Outline of the report

The current thesis is divided into several chapters. The main procedure for the methodology is presented in Chapter 4 and the main research findings and the analysis of that are presented in Chapter 5 Chapter 7.

Chapter 1 - The introduction part of the paper where the main motivation behind the research is found. Also the key research questions are presented.

Chapter 2 - The background of the research question, looking over the energy situation and the technology.

Chapter 3 - Literature study of previous work done on the subject.

Chapter 4 - The methodology of the work is described. This includes the choice of simulation software, the calculation models and the system designs.

Chapter 5 - The results of the research is presented here

Chapter 6 - Identification of commercially available components

Chapter 7 - The results are discussed and analyzed, conclusions on the subject are presented

Chapter 8 - Suggestions on expanding the work in the future
2. **Background**

As already established, a remarkably efficient and environmentally friendly way of waste management is incineration of MSW in a MSW-fired steam cycle. These types of facilities are often locally based and utilize household, and to some extent industrial, waste from nearby domains. Due to low energetic quality of the fuel, often times the efficiency of the plant is rather low. This report will go over the possibility of maximizing the total efficiency of such facility by implementing another cycle, which utilizes a high quality fuel. A so called cogeneration facility will be able to increase the efficiency through combining the heat and power from both cycles.

The use and utilization of MSW as well as NG is discussed more in detail below.

**2.1 Brief overview of world energy status**

The world energy status refers to the total combined energy use of the people in the world. This includes primary energy sources like fossil fuels, nuclear power and renewable energy. The main driving force for the harnessing energy and utilizing different energy sources is for human comfort. This can be about the most basic needs like heat, cooking food or lighting, but also takes into account the energy utilization for facilities and other application. The overview of the energy use, for the sake of this project, will help to put the use of renewable and green energy resources into perspective. Figure 1 below gives a representation of the total world energy use, outlining the share of each energy source.
By comparing the total share of the world’s energy use, it is clear that the world energy production is dominated by non-renewable sources of fossil fuels, which have serious environmental impacts. The largest consumers of oil, coal and natural gas are developing countries, where the growth in population is rapidly increasing. For the year 2012, the total world energy use is counted to be roughly about 145 PWh, where almost 87% is from primary fossil fuels. (BP- British Petroleum, 2013) Research done shows a global growth in energy demand, and the trend is assumed to persevere towards usage of fossil fuels. (iea - International Energy Agency, 2012) This trend can clearly be seen in Figure 2 where the rates of energy use are plotted out from the 70’s all the way to 2011. Apart from the fact that fossil fuels are a finite energy source, they also tend to stand for harmful byproducts and impact the atmosphere and important groundwater reservoirs. Other sources of energy are constantly being researched and improved. Energy from renewable and sustainable resources is considered to be an important
factor for us and the future generations. Different utilization alternatives are being explored and implemented to benefit residential and public sectors. But regardless, renewable energy resources like hydropower, solar energy, biomass and MSW still stand for a fraction of the world’s total energy mix posing for a total 4.7% of the global power generation. (BP- British Petroleum, 2013)

A major drawback in world energy is the underutilization of the available energy sources. The share of renewable and green energy can be made larger by further research and investigation. Locally produced fuels which can offer cleaner energy and lower emission are important sources in driving the sustainable society and the economy. Using MSW for this purpose is therefore highly desirable. Many countries do not cease the opportunity and instead rely on landfilling or open dumping of MSW. It is important to note that the global energy use indicates the combined use of energy in all different sectors; this means that industry and transportation sectors are also accounted for in this figure. Even though biofuels like MSW and wood have shown to be viable options for partially replacing fossil fuels, it will take long before they can be utilized efficiently in energy hungry sectors like transportation. According to the European Environment Agency (EEA), the transport sector is accountable for 32% of the total energy use in EU, while services and agriculture together pose for less than 15%. (European Environment Agency, 2009) Considering that the existing technology and the power plants present are mostly running on old technology and lower efficiency, a technological advancement and replacing the existing plants would boost the overall efficiency possible. According to an impact assessment done by the European Commission, more than half of the existing coal and peat power plants are on rates less than 40% efficiency, while newer technology developed would allow for increase of this efficiency by 10-15%. (European Comission, 2011)
Further investigation implies that facilities running oil boilers have for the most part an efficiency of between 35-40%. Comparing that to the gas-fired plants, with an average efficiency of up to around 60%, it is all the more reasons to move away from the current generation of oil and coal firing. This means that a possible advancement in the cogeneration hybrid facilities running on MSW would be highly beneficial. Such facilities could potentially cover the entire need of power and even heat for the household and industry sectors. (European Comission, 2011)

2.2 Municipal solid waste as a fuel

Industrialized societies share a great concern regarding the disposal of massive amounts of MSW and the problems that comes along with it, such as environmental and sanitary concerns. The growing rate of MSW is a direct consequence from the increased movement towards urban areas. In industrial regions the production rate of MSW is approximately 500 kg, or more, per person per year. (Petrov & Hunyadi, 2002) There are different ways to manage the waste. The most common alternatives are landfilling, recycling or incineration. Most commonly used and the cheapest alternative is landfilling. This poses a high impact on the environment due to its release of carbon dioxide and contamination of the groundwater and build-up of GHGs. A more environmentally friendly way of waste management is using MSW as fuel in incineration process. Power production by utilizing MSW as a fuel will provide a range of benefits, not only will it increase the share of renewable resource used, it will also mitigate the severe issues regarding waste volumes and GHG emissions. As a result from the incineration process the created waste heat can be reused in power plants. (Udomsri, et al., 2011) One of the limitations of using MSW as fuel is that it cannot be stored for a long time due to the immediate start of decaying. It is therefore essential to begin the incineration process for sanitary purposes. The mixture of MSW is very heterogeneous and is dependent on a combination of residential or domestic waste. The large number of constituents and average values for wastes from urban centers can be seen in Figure 3. (Petrov, 2003 - Paper I) Another factor that plays a significant role is how much of it that originates from industrial, commercial or tourist activity. (Udomsri, et al., 2011)
Although the plastic only contributes with a small mass percentage it plays a significant role in raising the energy value of the fuel. As the mass percentage of plastic increases, the quality of the fuel consequently improves. This poses some obstacles such as occurrence of aggressive compounds in the flue gases after combustion of MSW, which hinders the possibility to increase the steam parameters in a conventional MSW-fired steam cycle. Even though MSW is widely accepted as a renewable source, and has a large mass percentage that originates from biological materials, it is not a CO$_2$-free fuel source. Extensive investigations mean that the net release of CO$_2$ is highly diminished by using MSW as a fuel. (Petrov, 2003)

In order to become a more sustainable city, management of MSW is an essential service that needs to be provided for. In many low- and middle-income countries, MSW stands for a large share of the countries budget and is one of the largest employers. (Hoornweg & Bhada-Tata, 2012) With this in mind, the largest disposal share in Europe is still from landfilling. In Figure 4 an overview of how the waste treatment has developed in Europe can be seen.

![Figure 4 Waste treatment in EU-27 between 2004 and 2010. Source: Eurostat (Eurostat, 2010)](image-url)
2.3 MSW Incineration with energy recovery (WtE)

Looking at the integrated waste management across Europe, depicted in Figure 5 above, it is apparent that only a small percentage of the total MSW (around 23%) is thermally treated and it is with this amount that the WtE technology is operational. The waste used for this purpose is mostly the organic and residual waste. Although more and more countries are moving away from landfilling, thermal treatment is starting to gain larger momentum. (Manders, 2013)

It is shown that management of solid waste through incineration and energy extraction is one of the most efficient and cleanest ways. As mentioned before, this method of disposal will limit the amount of waste in the landfills and eliminates the development of the GHG such as methane, CH₄, and other environmentally harmful byproducts. Also in well-constructed and well-optimized power plants, the produced ashes and sludge will only be a small fraction of the space otherwise required. Managing the produced sludge is also much simpler and can be done by for example combining them into concrete blocks and use it for construction.

Although for the most part many advantages are associated with incineration, there are some limitations. The facilities and the apparatus, like the boilers and steam turbines, all have rather high investment costs. Apart from the initial cost, there are large costs associated with the maintenance. (Moustakas & Loizidou, 2010) This requires knowledge and precise development to be fully functional. High maintenance costs are mostly due to the previously described corrosive nature of the flue gases from the MSW, which would harm the boiler.

As a reason, WtE is mostly adapted for more developed regions in the world and is a widespread waste management method in Europe and Japan. Employing and adapting this technology is not solely due to economic benefits, but limited space for landfilling could also be a possible reason. (CEWEP, 2012) This is the only method of waste management that most efficiently reduces the overall volume and weight of the solid waste by about 80%. (Weston, 1992)
One other discouraging factor for successfully utilizing MSW for WtE is the many different criteria that must be fulfilled. Calculating the overall achievable LHV for MSW by looking at typical compositions, it can be deduced that about 8-16 MJ/kg is to be expected. (Jenkins, 1993) Table 1 shows a more descriptive representation of the composition of typical solid waste and the LHV. This can be compared to brown coal with an LHV of 9 MJ/kg. While this is a typical value for MSW, it does not mean that all incoming waste to the facility will have the same LHV. One of the main reasons for this is the many different components which add up and result in the heat content. A typical MSW collection consists of different parts with different moisture content and calorific values. Table 2 represents the typical composition of MSW. To fully keep the plant operative and at a respectable efficiency, the LHV of the incoming fuel must be kept above 6 MJ/kg (The International bank for Reconstruction and Development / THE WORLD BANK, 1999). Also the incoming fuel rate is important. This aspect involves a high functioning waste disposal and recycling mentality from the population, as well as an evolved and controlled waste management system. This system must ensure that sufficient amount of waste can be brought to the facility at a steady rate.

Table 1 Heat content values for different types of fuels and biomass for US and European standards. The net calorific value for MSW is based on LHV found in this table. (Jenkins, 1993) (Jenkins, et al., 1998) (Energy research Centre of the Netherlands (ECN), 2012)
Table 2 Typical composition and moisture content of MSW components. Moisture content is dependent on the location of the solid waste. LHV is based on the different compounds in the waste. (Energy research Centre of the Netherlands (ECN), 2012)

<table>
<thead>
<tr>
<th>Common composition</th>
<th>Moisture content [%]</th>
<th>Lower Heating Value (LHV) [MJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food wastes</td>
<td>50 - 80</td>
<td>15.1</td>
</tr>
<tr>
<td>Papers</td>
<td>4 - 10</td>
<td>17.7</td>
</tr>
<tr>
<td>Plastics</td>
<td>1 - 4</td>
<td>33.5</td>
</tr>
<tr>
<td>Yard wastes</td>
<td>30 - 80</td>
<td>17.0</td>
</tr>
<tr>
<td>Glass</td>
<td>1 - 4</td>
<td>0.0</td>
</tr>
<tr>
<td>Wood</td>
<td>30 - 60</td>
<td>20.0</td>
</tr>
<tr>
<td>Textile</td>
<td>2.5</td>
<td>32.5</td>
</tr>
<tr>
<td>Rubber &amp; leather</td>
<td>5 - 8</td>
<td>23.5</td>
</tr>
</tbody>
</table>

As previously mentioned, the fresh solid waste contains high amounts of moisture which is unwanted in the combustion process. This makes it necessary for the incoming MSW to be pretreated and the wet content to be reduced. Except from that, the waste can be taken care of in the combustor without any more refinement. In some cases, special treatment is needed for the waste though. This includes if the waste contains highly toxic garbage.

Assuming that all of the criteria for the fuel are met, the MSW must be combusted in a suitable incinerator. There are many different techniques available for incineration of waste like rotary kiln incinerator, fixed grate, moving grate-firing (mass-burning) or fluidized beds. The last two methods mentioned are the most common and preferable for WtE application. The incinerators must be able to take care of large amounts of incoming material, without being selective. The content of the MSW will be different with every batch and the combustor must still be operational. A moving grate has the advantage of constantly pushing the waste down through the incinerator to achieve a complete combustion. Air is pumped into the incinerator throughout the grate, to ensure excess of oxygen gas and creating turbulent conditions; this will result in a better self-sustaining combustion. In this kind of incinerator, the ash and sludge is collected at the end of the device in a pile where it can be taken care of. One of the major benefits of using the moving grate incinerator is its capability to do “mass burning”. This indicates that the waste does not have to be pretreated or specially sorted which is a reason why this method is popular. Another suitable alternative is incineration in fluidized bed combustion. This type of incinerator is most suited for homogenous and sorted MSW. Here the waste is put into the incinerator and a stream of air-jet is pushed through the bed where fuel particles are suspended in the air. This technology is more delicate and requires close monitoring and also pretreatment of the waste to remove noncombustible material.

Usually after the incineration process, different filtering equipment must be installed to clean the flue gases from hazardous pollutions like organic compounds, nitrogen oxide (NOx) and
sulphur oxide (SO\textsubscript{x}). This is one benefit of using the fluidized bed combustion; there the flue gas from the combustion of the MSW is cleaner. This can also be achieved by careful planning and design of the combustor.

An important part of the WtE is the energy recovery from the waste. The steam produced by the boiler is expanded in a steam turbine where energy can be extracted from the generator. An important factor is optimizing the facility for the use. Depending on the location, requisites and the end use the cycle can be operated to produce electricity, heat or both. Generating electricity requires low thermal efficiency and the selling price of the energy is higher. Meanwhile heat production for district heating requires higher thermal efficiency and the cost of generated heat is quite low.

It is important to remember that energy production from solid waste and landfill gas stand for roughly less than 4% of the total biomass sources in the world energy share (shown in Figure 6 below). (Bauen, et al., 2009) Although this is a very small percentage, it is growing due to many countries wanting to meet energy policy criteria on use of non-fossil fuel power generation. This leads to more and bigger scale MSW power generation facilities being erected all the time.

![Figure 6 Share of bioenergy in the world energy mix. (Bauen, et al., 2009)](image)

2.3.1 **MSW-fired steam cycle**

The basic principle in this thermodynamic cycle is that saturated water is heated in the boiler to saturated vapor. The heat transferred in the boiler is generated by MSW incineration and the saturated vapor continues and goes through an expansion in the steam turbine. The expansion creates a rotational force on the turbines and heat is transformed into work and electricity. In order to prevent any damage to the steam turbine, in terms of corrosion, the saturated vapor coming in should leave the steam turbine as at least a mixture of saturated vapor and saturated
liquid. The steam turbine can have one or several outlets which are connected to a condenser, feed water tank or heat exchanger. These steam extractions that are led into heaters is a practical approach of regeneration, thermal efficiency is improved and temperature difference in the boiler is essentially decreased. Nevertheless the last steam extraction is connected to the condenser, which could be used for providing hot water for district heating and at the same time change the state of wet vapor to saturated liquid so that the pumps can be able to start the cycle again.

As mentioned previously in WtE plants, the temperature and pressure are limited to around 380-400°C and 40 bar respectively. This is because the risk of corrosion in the MSW-fired boiler is increased, due to existence of halogen acidic compounds and alkali salts. These setbacks prevent conventional MSW-fired facilities to have a net electrical efficiency no higher than around 24%. (Petrov, 2003)

2.4 Natural gas as a fuel

Natural gas is the world’s third largest energy source after coal and oil. The primary compound in NG is methane (CH\textsubscript{4}) which is mixed with other alkanes and some carbon dioxide. (NaturalGas.org, 2004) Table 3 below shows the typical composition of untreated NG.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Percentage</th>
<th>Origin Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH\textsubscript{4}</td>
<td>70-90%</td>
</tr>
<tr>
<td>Ethane</td>
<td>C\textsubscript{2}H\textsubscript{6}</td>
<td>0-20%</td>
</tr>
<tr>
<td>Propane</td>
<td>C\textsubscript{3}H\textsubscript{8}</td>
<td>0-8%</td>
</tr>
<tr>
<td>Butane</td>
<td>C\textsubscript{4}H\textsubscript{10}</td>
<td>0-5%</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO\textsubscript{2}</td>
<td>0.2%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O\textsubscript{2}</td>
<td>0-0.2%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N\textsubscript{2}</td>
<td>0-5%</td>
</tr>
<tr>
<td>Hydrogen sulphide</td>
<td>H\textsubscript{2}S</td>
<td>0-5%</td>
</tr>
<tr>
<td>Rare gases</td>
<td>Ar, He, Ne, Xe</td>
<td>trace</td>
</tr>
</tbody>
</table>

There are big reservoirs found in the US, Russia and in the Middle East. Even though this source is considered a sustainable or “green” energy resource, it is a finite or nonrenewable resource. The benefit with using NG for power production is that it provides a cleaner solution to coal and oil. This is due to the lower CO\textsubscript{2} emission of NG when incinerated and is generally seen as the cleanest fossil fuel. (Vattenfall, 2013) Today NG is mostly used for cooking and heating in district use, as raw material in the chemical industry and as a clean fuel for generation of heat and electricity in the EU. (Vattenfall, 2013)

As one of the primary world energy resources, NG is also showing a trend towards increased use. From the previously discussed figure, Figure 1, it is apparent that NG stands for almost 24% of the total world energy use. One of the most widespread utilizations of NG is for generation of
electricity in cogeneration facilities, usually helping to make the total cycle more efficient. It is therefore well suited for cogeneration facilities with renewable sources such as solar or wind. This is preferred in contrast to coal or oil due to the lower emissions with up to 30% lower carbon dioxide (CO$_2$) production. (NaturalGas.org, 2004-2001) One other major driving point for using NG in combined cogeneration cycles is due to the relatively low cost. The high efficiency of the fuel is due to its high LHV value of about 47-49 MJ/kg according to Table 4 below. (GREET, 2001)

Table 4 LHV and HHV values for common fuels.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>983 20.267</td>
<td>47.164</td>
<td>1584 21.905</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>290 51.682</td>
<td>120.21</td>
<td>343 61.127</td>
</tr>
<tr>
<td>Steam (in refineries)</td>
<td>1458 20.163</td>
<td>45.898</td>
<td>1.584 21.905</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>129,670 18.352</td>
<td>42.686</td>
<td>138,350 19.580</td>
</tr>
<tr>
<td>Conventional gasoline</td>
<td>116,090 18.679</td>
<td>43.448</td>
<td>124,340 20.007</td>
</tr>
<tr>
<td>Reformulated or low-sulfur gasoline</td>
<td>113,802 18.211</td>
<td>42.358</td>
<td>121,848 19.533</td>
</tr>
<tr>
<td>CA reformulated gasoline</td>
<td>113,927 18.272</td>
<td>42.500</td>
<td>122,174 19.685</td>
</tr>
<tr>
<td>U.S. conventional diesel</td>
<td>128,450 18.397</td>
<td>42.791</td>
<td>137,389 19.676</td>
</tr>
<tr>
<td>Low-sulfur diesel</td>
<td>129,488 18.320</td>
<td>42.612</td>
<td>138,490 19.594</td>
</tr>
<tr>
<td>Petroleum naphtha</td>
<td>116,920 19.320</td>
<td>44.938</td>
<td>125,080 20.069</td>
</tr>
<tr>
<td>NG-based FT naphtha</td>
<td>111,520 19.081</td>
<td>44.383</td>
<td>119,740 20.448</td>
</tr>
<tr>
<td>Residual oil</td>
<td>140,353 16.986</td>
<td>39.466</td>
<td>150,110 18.147</td>
</tr>
<tr>
<td>Methanol</td>
<td>57,250 8.369</td>
<td>20.094</td>
<td>65,200 9.838</td>
</tr>
<tr>
<td>Ethanol</td>
<td>76,300 11.587</td>
<td>25.952</td>
<td>84,330 12.832</td>
</tr>
<tr>
<td>Butanol</td>
<td>99,837 14.775</td>
<td>34.366</td>
<td>108,458 16.051</td>
</tr>
<tr>
<td>Acetone</td>
<td>83,127 12.721</td>
<td>29.589</td>
<td>89,511 13.698</td>
</tr>
<tr>
<td>E-Diesel Additives</td>
<td>116,090 18.679</td>
<td>43.448</td>
<td>124,340 20.007</td>
</tr>
<tr>
<td>Liquefied petroleum gas (LPG)</td>
<td>84,950 20.038</td>
<td>46.607</td>
<td>91,410 21.561</td>
</tr>
<tr>
<td>Liquefied natural gas (LNG)</td>
<td>74,720 20.098</td>
<td>48.632</td>
<td>84,820 23.734</td>
</tr>
<tr>
<td>Dimethyl ether (DME)</td>
<td>68,930 12.417</td>
<td>28.882</td>
<td>75,510 13.620</td>
</tr>
<tr>
<td>Dimethyl carbonate (DMC)</td>
<td>72,200 10.081</td>
<td>23.407</td>
<td>70,107 11.036</td>
</tr>
</tbody>
</table>

2.4.1 NG-fired Gas turbine cycle

In the first stage work is consumed in order to pressurize air in the compressor. The delivered work will increase the temperature of the air and lead it to the next stage. In the combustion chamber the compressed air is mixed with pressurized natural gas. Production of thermal energy increases the temperature of the mixed fuel gas through combustion and is then expanded in the turbine. Rotation of the turbine shaft is caused by the expansion taking place. Some of the work is used by the compressor the rest is used for electricity production.
2.5 Heat Recovery Steam Generator (HRSG)

To achieve higher efficiencies a combination of steam and gas cycle can be used. HRSG works as the link between the steam cycle and the gas turbine in a combined cycle. Heat from the exhaust of the gas turbine is utilized in order to generate steam in the steam cycle. HRSG is constructed by three main heat exchangers for feed water heating, water vaporization and steam superheating. (COMPEDU - KTH energy, u.d.) As steam goes through the HRSG the quality increases. At the superheated state the value of heat is at its highest. The incoming steam to the HRSG system is preheated by the boiler. Each component is designed specifically for the intent of the end use and are all designed to maximize the efficiency of the steam outlet. The evaporator and the superheater raise the temperature of the low quality steam and produce superheated high quality steam which will yield in a higher efficiency. A typical single pressure HRSG flow diagram is depicted in Figure 8 below

HRSGs are widely adopted for combined cycle power plants and have proven to be an efficient way of “connecting” power cycles together. One of the best utilizations of HRSG is for superheating the lower quality steam from a BC through heat exchange by a high quality high temperature steam. This steam could come from a TC like NG fired GT cycle.

As mentioned, the construction of the HRSG is dependent on the end use and therefore the cost of this device varies. One deciding factor is the operating efficiency of the apparatus. This factor is decided by the pinch point temperature difference of the device. This is due to the real life factors of the heat exchangers, where the temperature difference between the two media on each side of the exchanger is never actually zero. For ideal heat exchanger, the possible size of the heat exchanger surface area is not limited, and hence an efficiency of 100% for the heat transfer is possible. In real heat exchangers, the larger the temperature difference between the two media is, the lower the efficiency of the heat exchanger will get. The pinch point temperature difference is calculated through the difference between the temperature of the exhaust exiting the evaporator and the temperature of water evaporation. (COMPEDU - KTH energy, u.d.) The usual pinch point temperature difference is between 5°C and 15°C and with lower pinch point temperature; the cost of the heat exchanger goes up because the efficiency is increased. Figure 7 below shows the difference between cost and pinch point temperature.
2.6 MSW incineration and Gas turbine hybrid dual-fuel cycle

Although already establishing that heat and power recovery from MSW incineration has tremendous benefits coming to waste management and power production from locally available fuels, the conventional MSW incineration leads to rather low overall efficiencies. As mentioned in previous parts, one of the largest factors for this is due to the low steam temperatures that are achieved in the boiler in such arrangement. It is calculated that by maintaining the limited temperature and pressure in a conventional single fuel MSW-fired cycle, the net electric efficiency is only about 22-24%. ([Udomsri, et al., 2011](#)) One of the most attractive and effective ways on improving the system performance is the application of a so called hybrid dual-fuel combined cycle. This method manages to raise the temperature of the steam while completely avoiding the corrosion problems associated with superheating MSW.

The basic idea of the method is coupling the non-aggressive exhaust gases from a TC which deploys a clean high quality GT based cycle together with the low quality steam generated from a boiler in a BC steam based cycle like MSW incinerator through an HRSG. The simple arrangement is an efficient way of increasing the energy conversion of MSW and is being more and more popular in developed countries which already have MSW incineration in place, like Sweden. The measured improvement from this arrangement is an overall net electrical efficiency of 51% from previous 22-24%. This is due to the increased temperature of the steam, up to 500-550°C from previous 400°C, into the steam turbine which in turn generates more energy. ([Udomsri, et al., 2011](#))

In Figure 9 below, the simple schematic of the hybrid dual-fuel combined cycle used in this project is illustrated.
This hybrid cycle is essentially using two basic power cycles and using the HRSG coupling them together. The steam turbine is provided with four extraction points in order to increase the overall system thermodynamic efficiency. NG is provided into a conventional combustion chamber and the exhaust is brought to the HRSG.
3. Literature study

For this thesis work, a brief literature study on the implementation of GT in existing MSW-cycles was conducted. The main purpose of this study was to get a deeper insight into different existing alternatives and what kind of affects a hybrid cycle would have. The results from this literature study are presented in this chapter.

3.1 Hybrid steam-cycle MSW-fired boiler and NG-fired gas turbine cycle

There are many advantages in particularly combining a low grade steam cycle with a gas turbine in a combined cycle process. Many previous works and research is done investigating the best suitable incineration and gas turbine combination. The hybrid dual-fuel cycle analyzed by M.A Korobitsyn at the Laboratory of Thermal Engineering of the University of Twente in Netherlands in 1998 is one of the first examples of the a system suggesting low quality steam from MSW boiler to be superheated externally by the means of an HRSG. (Korobitsyn, 1998) In this work, different cycles and their efficiencies were analyzed by the author. For three cases where a GT cycle is used as TC in conjunction with a MSW boiler, it was recognized that the temperature of the steam outlet from the MSW boiler is a limiting factor. Hence the use of HRSG before the steam turbine was looked at. Here it was found that the exhaust of the GT cycle could raise the temperature and superheat the steam from the MSW cycle, and resulted in a temperature increase to 520°C. Figure 10 shows the cases studied in the mentioned report. In the report, the authors suggested that using this system the overall conversion efficiency of the cycle increases by almost 5 percentages. (Korobitsyn, et al., 1999)
As one of the main benefits in using a combined power generation cycle is the low emissions and high cycle performance, another report investigating combined cycle for MSW incineration and GT was reviewed. Stefano Consonni (Consonni, 2000) describes the integration of NG-fired combined cycle with a steam cycle which deploys a grate combustor for incineration of MSW. Like before, an HRSG system is used to generate superheated steam. From there, the steam is lead to a steam turbine which serves both the hybrid cycle and the energy production. This system is described as having a relative low cost and low environmental impact while offering a much higher performance. The suggested flow diagram of the hybrid cycle is shown in Figure 11 below. One of the main reasons for the low cost of this system is the use of a single steam turbine. The results from the report show that an increase of the energy recovery efficiency up to 50% is possible at the same time as the cost of MSW disposal is reduced by 30-40%. (Consonni, 2000)
Finally the works of (Udomsri, et al., 2011) and (Petrov, 2003) are heavily used in the design and investigation of the systems used in this thesis work. In these two papers, both authors investigate parallel-powered cycles where a steam turbine and a generator is operated by the superheated steam generated in an HRSG coupling MSW boiler and NG-fired GT cycle. The systems investigated here all use steam entirely generated from an MSW incinerator, moving grate or fluidized bed, and the GT exhaust is heating up this stream of steam. The mathematical models used in the work of (Petrov, 2003) describe the scale effect of the hybrid power plant. This is important in defining a reference curve for the system. The capacity of the power plants used in both papers is 50 MWel.

In the results both authors express the increased efficiency of the hybrid cycle in contrast to the single fuel cycles. It is also discussed that the hybrid parallel cycle is a cost-competitive alternative for power generation purposes. According to Petrov, the hybrid cycle utilizing MSW and NG is a very attractive option because of the added improvement in energy conversion efficiency than the individual cycles alone. (Petrov, 2003)

Looking at all the studies done on the subject of hybrid dual-fuel cycle and using the exhaust of an NG-fired GT-cycle as a topping cycle, it is apparent that the overall efficiency is increased. It is beneficial for the waste management as well as the power generation. In the works by Petrov and Udomsri the greenhouse gas emissions in terms of CO2-emissions and the environmental impact of such system has also been assessed. The result show that out of the different hybrid cycle configurations and alternatives where MSW is utilized as BC, the parallel hybrid cycle with NG is resulting in the highest reduction of CO2 levels. This is due to MSW incineration being almost CO2 neutral as well as the lower emissions from the TC fuel, NG. (Udomsri, et al., 2011)
3.2 Existing examples of hybrid plants

There are a few good examples of power plants in operation which actually utilize the parallel-fired hybrid cycle in the facility. These plants are functional proof that the concept of using NG-fired GT as a topping cycle is a viable and efficient option. One of the earliest plants is located in Karlskoga, Sweden. This facility uses few different boilers for bottoming steam cycles, where an MSW incineration is one of the sources. This cycle is designed at a capacity of 25 MW_{el} and also has an HRSG coupled with a TC gas turbine cycle, but this is not in operation today. This leads to the actual operating efficiency of the plant to be at 11 MW_{el}. (Udomsri, 2011) (Petrov, 2003)

A fully operational parallel-fired plant is constructed in Horsens, Denmark. This facility has utilizes the low quality steam produced with MSW incineration and deploys exhaust gas from a GT cycle for superheating that steam in an HRSG and can reach temperatures of 425°C at 47 bar. The overall net electricity of this plant is about 35 MW_{el}, from which 13 MW_{el} is produced from the steam turbine. (Horsens Kraftvarmeværk, 2000) (Petrov & Hunyadi, 2002) (Udomsri, 2011)

Another hybrid dual-fuel combined cycle utilizing GT and MSW is located in Mainz, Germany. This power plant uses in the same fashion as the others described, GT as a TC for superheating and maximizing the efficiency of the steam cycle. In this plant, the superheated steam from the HRSG system has a temperature of 400°C at 40 bar and is generated using the exhaust of the GT cycle, which is measured at about 555°C. (Petrov, 2003) (Udomsri, 2011)
4. Methodology and calculation models

In order to sufficiently achieve results for the hybrid dual-fuel power cycle, a row of different models on the suggested systems are analyzed. For these models, simulation software is used and based on the values obtained from the program; calculations are carried out based on relevant models. The procedure of the work is described in detail in this chapter.

4.1 General Approach

As described previously, the main focus of this project is put on the modelling and simulation of the NG-MSW hybrid cycles. An arbitrary model of the single fuel steam cycle is to be designed and optimized. The system performance is then compared to a hybrid design. The hybrid cycle, using the NG-fired GT is to be designed on the same principles of the single fuel MSW-fired cycle and must incorporate the use of an HRSG. This includes different load factors considering condensing (power only) and the CHP operation mode. The overall output of the MSW cycle is first investigated within a separate simulation followed by modelling and simulating the hybrid cycle.

For the thesis, based on the literature study and the background on each different system the preferred cycles are designed. This process is done using simulation software called Aspen, which is described in more detail in the coming part. The thesis is divided into three distinct cycles, a single fuel MSW-fired steam cycle, one NG-fired gas turbine combined cycle and finally the hybrid cycle. All of the simulations are optimized and ran at a total output of 50 MW. In the software, a steady state condition is required. The electrical and thermal efficiency of each cycle is calculated based on the outputs from the software using calculation models. Finally the results obtained from the calculations are presented and discussed.

4.2 Simulation - the way to Aspen

One important aspect of the project is to design and evaluate the suggested systems using simulated models. In real life applications this is a very important factor to first simulate and test the achievable efficiency of a cycle, before investing in costly components. As seeing that energy is one of the largest costs in an industry, having energy and heat simulations is becoming more and more important and these rely on accurate modeling and optimization of utilities systems. Deploying a simulation on the designed system has a number of benefits for the manufacturers and also for actual finalized design of the cycle. Some of the benefits from a system optimization are improved fuel selection and accurate fuel flow rates, well sized and optimized components like boiler and turbines, reduced environmental impacts by employing monitoring etc. and finally reduced costs. A thermal power plant simulation will also give a detailed insight in understanding the processes and also looking at unpredictable situations like different load changes and flow alterations.
For this purpose, there are a broad range of heat and mass balance commercial software packages. There are many different advantages and disadvantages with the different mass balance software for heat and power plant simulation. There is other specialized software for simulation and calculation of process industry or specifically for gas turbines available, though these are not considered for this report. Here the importance is put on ease of use, availability and accessibility. The last requirement defines how well integrated the libraries of models are in the software. Some examples of commercially available simulation software are the Finnish developed Prosim, IPSEpro produced in Austria, Thermoflow made in Germany and Aspen Utilities Planner from the US Aspentech Incorporated. When choosing simulation software, many aspects are of utmost importance for the ease of use. A general well-built graphical user interface (GUI) increases the program's user friendliness. Another factor is the time that the program takes for performing simulation calculations. Although the systems designed in this project are not complicated, the added benefit of keeping simulation runtimes to a minimum is desirable. Finally as mentioned previously, the power plant component library help ease the design of the cycle. Deploying power plant simulation, there are different modeling techniques of which the easiest and most hands-on method is the so called Object Oriented Modeling (OOM). In this method the model is designed using structuring approached based on graphical representation of different components. This ties in closely to the available library of the software. (Assadi, 1997) Also here, the interconnections between the different components are to be represented on the flow design. OOM has the added advantage of the user seeing the components based on schematics and easily locate mistakes. All of the mentioned software do a good job of adopting OOM, but the degree of freedom given to the user is not equal. For the case of IPSEpro the power plant library is small in comparison with Aspen Utilities Planner or Prosim. Aspen Utilities Planner has the benefit of having specially developed library models adapted for utility consuming systems. Utility diagrams are easily obtained from the software and reconfigurations. (Häggståhl & Dahlquist, 2003) (Aspentech, 2013) Depending on the hardware the program is running on, the runtimes of the simulations are different. One major drawback of the Finnish Prosim is the long simulation times which can take up to 30 seconds for larger scale models. Aspen Utilities Planner and IPSEpro on the other hand handle the simulations on a much faster rate, which makes them well adapted for these applications. IPSEpro uses a model development kit which allows for users to build new and modify existing components in the library. Although this offers great flexibility, for the novice user this might be confusing and can be rather time consuming. Another drawback with this software, which is shared with Aspen Utilities Planner simulation software, is the lack of proper calculation log file which leads to difficulty when an error occurs in the simulation. One thing that the users must keep in mind is the fact that in Aspen Utilities Planner, the software might show that the cycle is at steady-state condition when in fact using false values. This is one of the limitations of this software package. The calculation algorithms are designed to drive the cycle to steady-state using mathematical models. This may lead to water outlets having temperatures of -60°C without
the software reacting. For this reason a basic understanding of the different components and regular checking of the output data is required.

Although there are advantages and disadvantages for all of the heat and power plant simulation software, the one software that is chosen for the sake of this project is Aspen Utilities Planner from Aspentech Incorporated. This package offers unprecedented speed and simulation flexibility while having a major comprehensive plant library. This simulation software is also one of the leading and well adopted software for industries which makes it an attractive choice.

Designing the power generation cycles in Aspen Utilities Planner is done in three different stages. Here the first step is to plan out the system and connect all the different apparatus, ensuring that the right connection between each component is achieved. From there the numbers of fixed and free parameters are to be balanced and reasonable values are put in. The fixed parameters are defined by the user before the simulation and the free parameters are changed based on the inputs by the software. This can be fixing the power output to a set value and getting the mass flow of a fuel. It is in this step that steady-state condition must be achieved. Lastly as mentioned, desirable parameters are changed in order to get needed output data. For this project the output is read manually, but there is an option to output the data to an Excel file for further analysis. Figure 12 below describes the simulation process in Aspen Utilities Planner.

![Figure 12 Stages of simulation process in Aspen Utilities Planner.](image-url)
4.3 MSW-fired steam-cycle

The layout of a steam power plant with MSW incineration is depicted in Figure 13 below. The MSW incineration plant is developed using Aspen Utilities Planner. The configuration of this system has been touched upon in a previous section (2.3.1), nevertheless this cycle mainly consists of an MSW-fired boiler, a steam turbine with four extractions connected to a condenser and several heat exchangers for regeneration purposes.

4.3.1 Definition of electrical and thermal efficiencies

It is possible to operate this cycle in two different modes, namely cold condensing mode and CHP mode. The cold condensing operation mode only focuses on electrical power production. Running the plant in CHP mode adds heat production, for this alternative both heat and electricity can be sold. According to which operation mode the plant is running on, the plant efficiency calculation is affected. In the case of cold condensing the heat produced in the condenser is rejected and is considered as heat loss and will not take part in the efficiency calculation. The formula that defines cold condensing mode only considers the electrical output; hence Equation 1 can be used for electrical efficiency:

$$\eta_{el} = \frac{P_{ST}}{Q_{MSW}}$$  

Equation 1
where the electrical efficiency for the whole cycle has been expressed as $\eta_{el}$. The amount of fuel energy that has been converted into electrical power output from the steam turbine corresponds to $P_{ST}$, while $Q_{MSW}$ is the fuel or energy input in the cycle.

When defining the formula used for CHP operation mode, the added parameter of heat must be taken into account when calculating the overall plant efficiency. Hence Equation 2 is used for CHP operation mode calculating the plants efficiency:

$$\eta_{thermal} = \frac{P_{ST} + \dot{Q}_{cond}}{\dot{Q}_{MSW}}$$

where the added parameter $Q_{cond}$ expresses the rejected heat from the condenser, when condensing the last steam extraction.

4.3.2 Cold condensing operation mode

In order to maximize the MSW incineration plant’s efficiency, running cold condensing operation mode, some parameter adjustments had to be made. Changes in parameters were done while the power output of the steam turbine was fixed to 50 MW. The first step was to set the pressure of the condenser to an appropriate value of 0.056 bar, depicting real plant operation of cold condensing. While observing the plants efficiency efforts were put on finding the best combination of pressures in the turbine extractions. Thereafter, the mass flows of the first and second extractions were gradually changed in order to improve the plant efficiency furthermore. When changing the temperature of the saturated water coming out of the condenser, taking into account the pressure to keep the water into a saturated state, a change in the overall efficiency could be seen.

4.3.3 Combined heat and power operation mode

The output of the power plant still need to meet the required value of 50 MW and is therefore set as a fixed value. An increased pressure in the condenser is needed due to an elevated interest of heat production. Increased pressure to 1.6 bar provides that steam condensation is performed at high enough temperatures to deliver the required quality to customers for district heating purposes. While observing the plants overall efficiency pressure of the steam extractions were set to fixed values and a gradual change of first and second steam mass flows were performed. A variation of condenser pressure and mass flow from extraction one was put under scrutiny to reach the optimal efficiency.
4.4 NG-fired Gas turbine combined cycle

The schematics of GT combined cycle is depicted in Figure 14 below. Using Aspen Utilities Planner, this configuration was developed. In a previous section (2.4.1) the set-up of this system has been touched upon. This cycle mainly consists of a GT, a steam turbine attached to a condenser and several heat exchangers for regeneration purposes and HRSG that connect the two cycles and.

![Diagram of a NG-fired Gas turbine combined cycle](image)

**Figure 14 Layout of a NG-fired Gas turbine combined cycle**

4.4.1 Definition of electrical and thermal efficiencies

As the case with the MSW incineration plant this facility can operate in cold condensing mode and CHP mode. Depending on which operation mode that is in use affects how the plant efficiency is calculated. Operation in cold condensing, rejected heat in the condenser is not accounted for, hence the electrical efficiency is defined as Equation 3
where the electrical efficiency is calculated by adding the power that is produced by the GT, $P_{GT}$, while $Q_{NG}$ is the energy input in the cycle. $\eta_{el}$ and $P_{ST}$ has been defined in a previous section.

In order to calculate the overall thermal efficiency of the combined cycle running CHP mode the heat rejected in the condenser is taken into consideration as well as the power output of the steam and GT. Equation 4 has been used for calculating the overall thermal efficiency of the combined cycle.

$$\eta_{thermal} = \frac{P_{ST} + \dot{Q}_{cond} + P_{GT}}{Q_{NG}}$$

where the added parameter $Q_{cond}$ expresses the rejected heat from the condenser, when condensing the last steam extraction.

4.4.2 Cold condensing operation mode

Optimization of the efficiency while operating in cold condensing mode the mass flow of the first steam extraction of the combined plant was investigated. During the optimization stage a close look was taken upon the high pressure heat exchanger in order to observe the UA-value and that the pinch point temperature difference was between 5 to 15°C. For this to be possible the outgoing hot water from the high pressure heat exchanger had to be set as a fixed value. While trying to optimize the overall plant efficiency the total power output of 50 MW$_{el}$ could not be reached with the steam and gas turbine having a fixed power output of 25 MW. To amend to this obstacle, the power generated from the GT cycle was kept at a fixed value whereas power output of the steam turbine had to be set as a free value. Depicting real plant operation of cold condensing the pressure of the condenser was fixed to an appropriate value of 0,056 bar. With this configuration the optimal efficiency was conducted by finding an optimized value for the mass flow of the first extraction and taking a closer look at the pressure of the first and second steam extractions.

4.4.3 Combined heat and power operation mode

Adapting to the specified operational mode, the pressure was increased to a fixed value of 1,6 bar to amend with the added interest of heat production. Close attention was paid so that the requirements of the pinch point temperature difference and the UA-factor were met. Changes in power output of both the condenser and steam turbine were observed when the pressure and mass flow at the first extraction optimized. Same procedure was taken for finding the right parameters for the second extraction. In order to be sure that the provided heat quality was sufficient the ingoing temperature to the condenser was regularly checked.
4.5 Hybrid dual-fuel cycle

Development of the hybrid dual-fuel cycle was done using Aspen Utilities Planner as per standard. From Figure 15 the arrangement of the facility can be observed. Further detail of this system has been introduced in an earlier section (2.6). The hybrid cycle is operated at parallel-power mode, meaning that the exhaust gas from GT cycle is used in parallel with the BC for preheating the steam to the steam turbine. The mentioned system is mainly consisting of MSW incineration and gas turbine hybrid combined cycles.

![Figure 15 Layout of a hybrid dual-fuel cycle.](image)

In order to more easily compare the overall efficiency of a hybrid plant, reference curve based on single-fuel cycles are first obtained. This is done by essentially taking the average efficiency of the two separate cycles and plotting out the net efficiency of the hybrid cycle against this reference line. One way of obtaining the reference line is by using Equation 5 which is based on the net electrical efficiency of the GT cycle and the efficiency of the steam cycle. For this report, the scale effect coming from the overall losses and efficiencies based on the output scale is not considered. That is the reference line is based on values irrespective of the scale leading to a straight line.

\[ \eta_{\text{ref}} = \phi_{NG} \eta_{NG,\text{ref}} + (1 - \phi_{NG}) \eta_{BC,\text{ref}} \]

Equation 5
In Figure 16 below, the reference line for the average efficiency of two independent single-fuel cycles are depicted. This is based on a total power output of 50 MW.

![Reference curve representing the electrical efficiency range of two separate single-fuel power units. Without taking the scale effects into consideration.](image)

In order to calculate $\phi_{NG}$ later for comparison between the actual electrical efficiency of the hybrid dual-fuel cycle, Equation 6 below is used. This equation takes into account the power of the input fuel which is based on the mass flow and the LHV of each fuel.

$$
\phi_{NG} = \frac{m_{NG}LHV_{NG}}{m_{BC}LHV_{BC} + m_{NG}LHV_{NG}}
$$

Equation 6

4.5.1 Definition of electrical and thermal efficiencies

Depending on the wanted output hybrid cycles can operate in cold condensing mode and CHP mode.

When calculating the overall electrical efficiency of a hybrid cycle, there are two point of power production, namely from the NG-fired TC and the MSW-fired BC. The definition can be extended to incorporate the energy input of the TC and the BC. The definition of the electrical efficiency for the hybrid dual-fuel cycle is expressed as defined by Equation 7:

$$
\eta_{elHCC} = \frac{P_{TC} + P_{BC}}{Q_{TCFuel} + Q_{BCFuel}}
$$

Equation 7
where the overall electrical efficiency is calculated by adding the power that is produced by the TC expressed as, $P_{TC}$, with the power produced by the BC expressed as, $P_{BC}$. The sum of the total energy input from the TC and the BC are expressed as $Q_{TCFuel}$ and $Q_{BCFuel}$.

In order to calculate the overall thermal efficiency of the hybrid dual-fuel cycle operating in CHP mode the heat rejected in the condenser is accounted for as well as the power output from the TC and BC. Calculation of the overall thermal efficiency was done with Equation 8.

$$\eta_{thermalHCC} = \frac{P_{TC} + P_{BC} + \dot{Q}_{cond}}{Q_{TCFuel} + Q_{BCFuel}}$$

Equation 8

where $Q_{TCFuel}$ and $Q_{BCFuel}$ are the separate fuel energy inputs of the respective cycles. $\dot{Q}_{cond}$ expresses the rejected heat from the condenser, when condensing the last steam extraction.

4.5.2 Cold condensing operation mode

In cold condensing mode of operation, only the net electrical output of the cycle is taken into account. In order to maximize the efficiency of the designed hybrid dual-fuel cycle operating in condensing mode, each of the four extraction points from the steam turbine were closely analyzed and the pinch point considered. The main parameters adjusted were the pressure of the first, second and third extraction points as well as the mass flow of the extraction one and two. Depicting real plant operation of cold condensing the pressure of the condenser, or the fourth extraction point, was fixed to an appropriate value of 0,056 bar. While changing and adjusting the values for the extraction points, a close eye was kept in order to not get any wrong or unreasonable values for the different parameters. Also the simulated temperatures were looked at; this was done for the two high and low pressure closed heat exchangers, HP1 and LP1, and also in the HRSG. Changing the pressures affected the incoming fuel mass flow of the BC, while the input of NG remained constant. This was all done while controlling that the pinch point temperature difference was in range and the free UA-value of the heat exchanger were appropriate. The power production of the TC and the BC was fixed at 25 MW respectively.

4.5.3 Combined heat and power operation mode

The essential change of the increased condenser pressure, extraction 4, were performed and set to a fixed value of 1,6 bar to amend with the added interest of heat production. Optimizing the efficiency during CHP was done in the same fashion as the cold condensing mode. As the highest efficiency was sought some parameters posing as restriction factors were observed. Making sure those parameters such as the temperature of the ingoing steam to the condenser provided efficient heat quality. The biggest difference in optimizing and reaching steady-state here was the temperature differences set in the HP1 and LP1 closed heat exchangers. Close
attention was also paid at the pinch point temperature difference of the low-pressure heat exchanger, changing the temperature of the hot steam ensuring the requirements were met.

4.6 Analysis of part-load and full-load operation for Condensing and CHP
When studying hybrid combined cycles an interesting feature is their part-load performance. This depicts the real life situations in a hybrid cycle facility, where the rates of the fuels can be changed depending on the demand levels. Investigation for this part allows a greater insight into the application for times of winter and summer. The overall electrical efficiency of the cycle is dependent on the amount of energy coming from each cycle, when decreasing the input fuel from the NG for example the overall net electrical efficiency would be altered.

Hybrid dual-fuel cycle configuration provides flexibility in fuel ratios, which allows for flexible performance when running in part-load. The fact that there is an HRSG available that creates a thermal integration between the TC and the BC, with two separate fuel inputs makes it possible to adjust the fuel ratio. This helps obtaining a better fuel utilization depending on fuel availability, prices, required output and preferred operation points. In order to set the hybrid dual-fuel cycle into part-load operation one or both of the fuel inputs are decreased. This means for the case of the cycle investigated in this thesis, the fuel mass flows would be decreased from their baseline amounts.

For simulating the part-load scenarios in this report, the mass flow values for the baseline cases are first obtained. From there, two different cases are simulated, one for the fuel input and one for the power output. For the first mentioned case two scenarios are investigated:

- Changing the MSW-input to 75% and 50% of the base, while keeping NG input unchanged.
- Keeping the MSW-input unchanged while changing the mass flow of the GT fuel to 75% and 50% of base.

Likewise changing the power output to the same ratios and noting the change occurring in the mass flow inputs. This allows for comparison between the two cases and gives the best case scenario of the efficiency against total combined power output.
5. Results

The results obtained from the simulations and the gathered data are presented in this chapter. The most representative values for the optimizations of the cycles are also shown. In order to achieve satisfactory results for the final hybrid parallel-fired cycle, the two systems were first separately optimized and the changes in the efficiencies where noted. This includes optimizing and simulating the MSW-fired steam cycle and the designed NG-fired combined GT cycle in condensing and CHP modes for full-load operation.

5.1 Single fuel cycle design and optimization

The hybrid cycle chosen for the sake of this project consists of two main cycles, the MSW-fired steam cycle and the NG-fired GT cycle. In this part, these two systems are optimized and analyzed separately in order to easier get an understanding for the final hybrid cycle. Also setting the results from this part of the report in conjunction with the results obtained from the hybrid cycle, the overall change in the different operation modes can be seen. In order to find the best suited optimizations, many cases were tried out and different combinations were tested. Between each simulation, the overall electrical and/or CHP efficiency were calculated. The overall cycle efficiency is depending on the pinch point of the heat exchangers also, therefore the pressures in the extraction points for the steam turbine were adjusted accordingly to assure best efficiency. The trials were carried out until the extraction pressure changes no longer could hold steady state by the system. From there the combination which yielded in the highest achievable efficiency for each mode was chosen.

5.1.1 MSW-fired single fuel cycle

For this steam cycle, steam is only produced in the MSW-fired boiler; the steam turbine and the generator are hence only operating with the MSW input. First the cycle is set to operate in full condensing mode. In order to extract the most electrical energy output from the steam produced in the boiler, therefore the goal is to get the steam to cool down the to the lower pressure as much as possible (0,056 bar as previously mentioned). In condensing mode, the four extractions from the steam turbine are varied in accordance to the extraction mass flows for extraction 1 and extraction 2. This is done within the boundaries where steady state is achievable, and also the best pinch point is sought after. In Table 5 below, some of the accepted extraction pressures and mass flow rates are presented. From the total power output and the simulated fuel mass flow, an overall electrical efficiency is calculated for each case according to the previously presented Equation 1. The combination yielding in the highest net electrical efficiency has been marked out on the table.
Table 5 Variations together with the achievable electrical efficiencies for single fuel MSW-fired steam cycle in condensing mode.

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<td>21,786</td>
<td>25,50%</td>
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</table>

As described, for each combination the pinch point and also the UA-value (overall heat transfer coefficient) of the HP1 and LP1 heat exchangers were controlled. Lower extraction flow rates from the steam turbine, together with higher pressure in the first extraction yields in the best pinch point and also the best electrical efficiency as seen above.

In the same fashion, the case for the steam cycle was optimized in CHP mode. In this mode, the system will also have a measurable thermal output that is sent to use in district heating. The increase of the extraction pressure for the condenser is, as mentioned in previous parts, so that higher enthalpy can be used for heat production. From regulations for district heating, the temperature of the water should lie between 80-120°C. (Svensk Fjärrvärme, 2012) The pressures for the first and second extractions are higher, because a part is used for the heat exchanger in CHP mode. The effect of the increased pressure from the extractions can be seen in Table 6. Because the efficiency is calculated from the total energy output, that is both the electrical and the heat, the quantity transferred by the condensing steam (duty) is also taken into account for calculating the system efficiency. Increasing the first extraction point pressure above 20 is not possible without altering other parameters of the cycle.
5.1.2 NG-fired GT cycle

For the optimization of the NG-fired GT cycle, the same process as earlier was adopted. Here the designed GT cycle is used together with the steam turbine using an HRSG. This design is mainly used in order to get optimized values for mass flow of NG as fuel input in the system. The output of the GT cycle generator is set to be 25 MW which reflects the full-load scenario in the hybrid cycle. From there the pressure for the four extractions from a steam turbine coupled to the HRSG is changed. This is done to achieve the highest combination of net electrical output possible from the two generators in the condensing mode. Table 7 below outlines the most relevant combinations of the simulation.

As it can be seen above, the best electrical efficiency in the condensing operation mode for the combined GT cycle is gained with the lowest mass flow of 1.6 kg/s from steam turbine extraction 1 and 2 while the pressure for the first extraction is at 7 bar. One important change here is the fact that the pinch point for HP1 and LP1 become larger with the increase in mass flows, but a decrease in the pressures for the second and third extraction means better pinch point for the heat exchangers. But this comes with the cost of the overall electrical efficiency; therefore a balance must be contained between the pinch point and the efficiency when coming to the optimization.
Below in Table 8, the GT combined cycle is optimized for CHP operation mode. Here, like before, the extraction pressure for the fourth steam turbine pass out is raised to 1.6. From the table it is apparent that in this operation mode, the output for the steam turbine is lower than for the condensing mode. The scenario with the highest CHP efficiency is when the duty from the condenser is at almost 24 MW; in this case the efficiency of the cycle is just over 80%. Although as it can clearly be seen, the change in efficiency is very small. Moreover changing the pressure for the second and third extractions affects the efficiency very little and are changed for keeping the pinch point at an acceptable range.

Table 8 Optimization of GT combined cycle

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5.2 Hybrid cycle design and optimization

The hybrid cycle is utilizing the hot exhaust from the GT cycle for getting a higher temperature for the steam that goes to the steam turbine. This will result in better efficiency for the cycle. In this part, the results for the simulations done are presented and the efficiencies for the two different operation modes are shown. For the case of the hybrid cycle, apart from the condensing and CHP modes, a full-load and part-load input of the fuel has also been analyzed. The purpose of this is to more easily simulate real life operation scenarios and also investigating the possibility of operation based on season and geographic location, where the need for heating might not be large.

For the first step for optimization of the dual fuel hybrid cycle, the total electrical efficiency of the designed hybrid cycle was set towards the aforementioned reference line for the average output of two independent cycles. This result shows the actual benefit of the hybrid cycle, this essentially means that parallel power hybrid cycle with superheating partially from GT exhaust yields in an overall higher efficiency than any of the cycles alone. Figure 17 below shows the measured electrical output for the hybrid cycle set against the ratio of NG input. The data used for the reference is based on the single cycles and using Equation 5 has been calculated for different values. The result shows that the hybrid cycle surpasses the reference case by about 1 to 1.5 percentages. It isn’t hard to believe that the result will be even more significant if considering the scale effect for the reference. (Petrov, 2003)
5.2.1 Hybrid cycle at full-load (design-load)

After establishing a final design for the hybrid cycle using references from the previous two independent cycles, the system was optimized. The optimization process of the system is similar to the previous systems mentioned. Here consideration is taken towards mass flow of both fuels for each system. The power outputs of both systems are fixed to 25 MW. The first case for the hybrid cycle is operation in condensing mode. The goal is, as with the reference comparison, to achieve a higher electrical efficiency with the hybrid cycle than with the independent systems. Table 9 shows results for the condensing mode.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>8,40</td>
<td>3,60</td>
<td>2,30</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>1,49024</td>
<td>5,49920</td>
<td>40,76%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>8,40</td>
<td>4,00</td>
<td>2,30</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>1,49013</td>
<td>5,50360</td>
<td>40,75%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>8,40</td>
<td>3,60</td>
<td>3,00</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>1,49024</td>
<td>5,52236</td>
<td>40,69%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>8,40</td>
<td>3,60</td>
<td>3,00</td>
<td>0,056</td>
<td>2,0</td>
<td>2,0</td>
<td>1,49024</td>
<td>5,52996</td>
<td>40,67%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>6,00</td>
<td>3,60</td>
<td>3,00</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>1,49022</td>
<td>5,52823</td>
<td>40,68%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>4,00</td>
<td>3,00</td>
<td>2,30</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>1,49022</td>
<td>5,51436</td>
<td>40,72%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>3,50</td>
<td>3,00</td>
<td>2,30</td>
<td>0,056</td>
<td>1,8</td>
<td>1,8</td>
<td>Steady state failure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The operation was started by keeping the values for the pressure of the extractions near the values observed when optimizing single fuel cycles. Like before the pinch points for the heat exchangers were checked to ensure acceptable values were gotten. A decrease in pressure for extraction 1 resulted in better electrical efficiency but this increases the pinch point of the heat exchanger which is not acceptable as the efficiency gain is not more than 0,15%. The best electrical efficiency for the cycle in condensing mode, also regarding feasible UA-value and pinch point temperature values, was 40,76%.

Again for CHP mode, the pressure for the last extraction is increased to 1,6 bar. Here the lower mass flow of 1,2 kg/s was chosen for the simulations. This value is regarding the simulation of the single fuel steam cycle. The extractions must also have higher pressure generally than the condensing mode. The mass flow of the MSW is therefore increased to meet with the higher pressure needed. Here the temperatures are generally higher, therefore the fixed temperatures for the hot water out for LP1 was raised in order to keep the pinch point in good range. This fact is helped thanks to the higher extraction pressures. The final CHP efficiency of the systems falls just under 87%. The optimization scenarios are found in Table 10. In Table 11 the pinch point and UA value for the two heat exchangers, HP1 and LP1, are presented for the best optimized combinations. Although the UA values are showing to be rather low but they are feasible and the pinch points falls in good range.

### Table 10 CHP for the hybrid cycle

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>16</td>
<td>9</td>
<td>4,6</td>
<td>1,6</td>
<td>1,2</td>
<td>1,2</td>
<td>1,49022</td>
<td>7,73754</td>
<td>73,95891</td>
<td>86,80%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>16</td>
<td>10</td>
<td>4,0</td>
<td>1,6</td>
<td>1,2</td>
<td>1,2</td>
<td>1,49022</td>
<td>7,74617</td>
<td>73,98503</td>
<td>86,77%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>17</td>
<td>10</td>
<td>4,0</td>
<td>1,6</td>
<td>1,2</td>
<td>1,2</td>
<td>1,49022</td>
<td>7,74453</td>
<td>73,96475</td>
<td>86,77%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>17</td>
<td>11</td>
<td>5,0</td>
<td>1,6</td>
<td>1,2</td>
<td>1,2</td>
<td>1,49022</td>
<td>7,77078</td>
<td>74,37623</td>
<td><strong>86,91%</strong></td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>18</td>
<td>10</td>
<td>4,0</td>
<td>1,6</td>
<td>1,2</td>
<td>1,2</td>
<td>steady state failure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2.2  Analysis and estimation of part-load in condensing and CHP mode

The optimization of the hybrid cycles described only the full-load operation, which does not give a full view over real operation. The existence of two different fuel inputs means that the ratio could easily be varied to match the power or heat demand. For this purpose, the best optimized scenarios for the full-load were chosen and simulated further. Here, the outputs of the generators are free while the fuel inputs are fixed at ratios of 75% of full-load and 50% of full-load. This is done for both MSW and NG. The case where the power output was fixed can be seen in Table 13. There it is apparent that the change is proportional to the fuel input alteration in the condensing mode. Finally the electrical efficiency and CHP efficiency for the cycle is calculated. As part of the objective of the paper, a set of simulations with the altered power output would also be done. After running the simulations the ratio between fuel input and power output showed to be proportional which rendered the case unnecessary. This is shown for the first case though. The result is presented in Table 12 and Table 14 where the mass flow of the fuel inputs are respectively changed to 70% and 50% of their full-load counter parts. The total power output represents the sum of the two powers from the generators.
Table 13 Part-load power output for condensing mode. The power output ratio yields in same result as the fuel input ratio alteration

<table>
<thead>
<tr>
<th>% GT</th>
<th>Steam cycle</th>
<th>m_NG [kg/s]</th>
<th>m_MSW [kg/s]</th>
<th>P_NG [MW]</th>
<th>P_MSW [MW]</th>
<th>P_comb [MW]</th>
<th>( \eta_{el} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>75</td>
<td>1,490224033</td>
<td>4,148177471</td>
<td>25</td>
<td>18,75</td>
<td>43,75</td>
<td>87,5%</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>1,490224033</td>
<td>2,788695179</td>
<td>25</td>
<td>12,5</td>
<td>37,5</td>
<td>75,0%</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>1,146537678</td>
<td>5,499211509</td>
<td>18,75</td>
<td>25</td>
<td>43,75</td>
<td>87,5%</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0,802851324</td>
<td>5,499211509</td>
<td>12,5</td>
<td>25</td>
<td>Steady state fail</td>
<td></td>
</tr>
</tbody>
</table>

Table 14 Operation of the hybrid cycle in part-load during CHP mode

<table>
<thead>
<tr>
<th>% NG</th>
<th>% MSW</th>
<th>m_NG [kg/s]</th>
<th>m_MSW [kg/s]</th>
<th>P_NG [MW]</th>
<th>P_MSW [MW]</th>
<th>Q_cond [MW]</th>
<th>( \eta_{CHP} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>75</td>
<td>1,4902</td>
<td>5,8281</td>
<td>25,00</td>
<td>18,70</td>
<td>55,862</td>
<td>79,25%</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>1,4902</td>
<td>3,8854</td>
<td>25,00</td>
<td>12,35</td>
<td>37,446</td>
<td>69,17%</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>1,1177</td>
<td>7,7708</td>
<td>Steady State Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0,7451</td>
<td>7,7708</td>
<td>Steady State Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The system is not able to run at steady state condition once the fuel input to the GT cycles gets too low.

Though the combined power output of the system is changed according to the fuel input, the total combined power output can be set towards the efficiency of the system. This will put the ratio of the fuels and the net efficiency behavior in perspective. Figure 19 and Figure 18 show the behavior of part-load efficiencies for the hybrid cycle at different power output arrangements.
6. Commercially available equipment

In this chapter commercially available counterparts to the larger components found the designed cycles are identified and reference examples are given. Prices of the components were not available at the time of research, and contact with the companies did not result in any success.

6.1 Siemens Gas Turbine SGT-800:

SGT-800 is a gas turbine that is made by Siemens, shown in Figure 20. This specific turbine has an ISO power generation of 50.5 MW, which makes it suitable for combined heat and power generation based on the design parameters. It has a reliable robust design, high efficiency and low emissions and its high exhaust energy content makes it especially suitable for three different fields of applications: Simple cycle power generation, combined cycle power generation, and CHP. (Siemens, 2013)

Some of the benefits of this type of turbine are:

- At 40-60 MW, the emissions performance is best at high load ranges
- High efficiency where fuel can be saved and CO$_2$ emissions to atmosphere could be reduced
- Ability to switch the fuel type from gas to oil and oil to gas (dual operation)
- Health, Safety and Environment (HSE) are followed in the design of this turbine to satisfy the international standards and regulations
- Big emphasize and focus on the investment cost, efficiency, emission and long life-cycle, which make this type of turbine economical (Siemens.com, 2013)

The SGT-800 machine is as a single-shaft with 15 compressor stages and can operate on both gas and liquid fuel. To minimize NO$_x$ and CO emissions, this turbine is compact built as one module and equipped with low emission combustion system known as Dry Low Emission (DLE). This DLE system enables high stability and the possibility to handle different loads. (Siemens, 2013)

The turbine has excellent capability to achieve high efficiency and steam production which allows such a turbine to be used in cogeneration and combined cycle installations. Its outstanding operational availability and reliability as well as the high electrical efficiency that can be attained in addition to the high exhaust energy with wide range of gas fuel compositions make it exceptional. The life cycle cost is competitive due to the low maintenance cost and excellent heat rate as well as the high equivalent operating hours (EOH). (Siemens, 2013) Table 15 Technical data for SGT-800 shows the technical data for the GT, and it is apparent that the electrical efficiency and the exhaust gas temperatures rather compatible with the design.
6.2 Steam Turbine SST-300

This steam turbine is also made by Siemens and has a power output of up to 50 MW. Table 16 is a combined technical data for the steam turbine mentioned. Its design satisfies most of the industrial needs as in power plants, cogeneration and district heating plants as well as combined cycle applications. The single-casing steam turbine drives a 1500 to 1800 rpm generator. (Siemens.com, 2013)

The design concept includes a single casing turbine that has double internal extractions and proven modular and thermo flexible design.

The turbine casing is a single-body symmetrical casing which helps to provide short start-up times and load flexibility. The blading design in the rotor characterizes the SST-300 with the ability of high efficiency range and fast changes of load. The gearbox has a high reliability and performance proofed by world-class gear manufacturers. Moreover, the exhaust part can be upward, downward or axial oriented according to the planned installations arrangement.
The benefits of the SST-300:

- Design that is exceptional as it is very compact allowing more free space
- Delivery time for this machine is very short
- Easy and fast access to the mechanical components which results in low maintenance costs
- For simple operations, remote controls can be applied
- High reliability, availability and efficiency
- Operational flexibility, fast load changes

Table 16 Technical data for SST-300

<table>
<thead>
<tr>
<th>Power output</th>
<th>up to 50 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet steam pressure</td>
<td>up to 120 bar</td>
</tr>
<tr>
<td>Inlet steam temperature</td>
<td>up to 520°C</td>
</tr>
<tr>
<td>Controlled Extraction</td>
<td>up to 45 bar</td>
</tr>
<tr>
<td>- Pressure</td>
<td>up to 45 bar</td>
</tr>
<tr>
<td>- Temperature</td>
<td>up to 400°C</td>
</tr>
<tr>
<td>Exhaust Pressure</td>
<td>up to 16 bar</td>
</tr>
<tr>
<td>- Back pressure</td>
<td>up to 16 bar</td>
</tr>
<tr>
<td>- Condensing</td>
<td>up to 0.3 bar</td>
</tr>
</tbody>
</table>

6.2.1 Reference Example/project:

This steam turbine SST-300 is installed in a combined heat and power generating plant in northeast Germany, “Malchin factory”, to produce renewable energy from waste products. In this project, the waste product is mainly lemon peels that are shipped to Germany from USA, South America and South Africa. These lemon peels are processed and reduced to be able to get at the end basic pulp and fibres that can be used as fuel to generate electricity and steam. (Hecker, 2006)

The 452°C steam at 62 bar from the boiler, a Detroit Stoker, is fed into the SST-300 steam turbine that drives a generator with a voltage of 10.5 kV. With the help of a transformer, this output is raised to 20 kV that is then fed to the distribution networks. The power plant can even supply 10 kg/s of processed steam. (Hecker, 2006)

This power plant is highly reliable and has an operating availability of around 93%, which give it a great environmental performance by providing clean energy and contributing to the reduction of atmospheric CO₂ emissions.
6.3 HRSG:

6.3.1 NEM Vertical-HRSG

HRSG generates steam to produce electricity by using the hot exhaust gas of the gas turbine. By means of HRSG in the combined cycle processes, the power plant’s efficiency can be boosted by up to 50-60%. A vertical HRSG from “NEM” would be suitable for the type of operation discussed. NEM Energy is a pioneer engineering company that support solutions for power generation and industry. (NEM, 2013)

The type of HRSG recommended has a bundle of horizontal heat exchanger tubes and the exhaust gas follows a vertical path. Depending on the temperature of the exhaust gas, this HRSG can either be internally insulated where a so called “cold” casing concept can be applied in case of high exhaust temperatures or it can be externally insulated in case of low exhaust gas temperatures. (NEM, 2013)

The benefits of this HRSG are:

- Free expansion of headers and tubes
- On-site construction
- Repair and maintenance are easy to be performed

6.3.2 Alstom HRSGs

Alstom provides worldwide solutions for power production where 25% of the world’s capacity depends on Alstom technology and services with more than 100 years of experience and in more than 70 countries. Alstom has provided more than 300 vertical HRSG for plants with gas turbines range between 40 and 150 MW. This type of HRSG has an optimised monitoring system that could optimise the plant operation and reduce the lifetime consumption. The firing system increases the operational flexibility and achieves a reliable peaking power. The environmental impact is low due to the utilization of selective catalytic reduction (SCR) and CO catalysts that help to reduce the emissions of NOx, CO and volatile organic compounds (VOC). On top of this, the noise reduction is highly enhanced by using acoustic enclosure, stack and valve silencers. (Alstom, 2012)

The design features of this HRSG involve small diameter headers, faster start-up times by reducing thermal stresses and minimised flow assisted corrosion (FAC) through the use of low alloy and the limited flow velocities of the piping design. The inlet duct is compact allowing a reduced pressure drop and improved flow distribution. Drum and superheater outlet are designed with high strength materials. (Alstom, 2012)
Different HRSGs with different capacities made by Alstom are already installed in many projects that are functioning today. Some of these projects are “Fujairah 2” in UAE that include a cogeneration plant for desalination. In France, the “Cycofos” project provides an innovative power solution with 420 MW gas-fired combined cycle power plants and 60 MW steam power plant. Other projects that can be looked at are the “Keppel” project in Singapore and the “Astoria” in USA. (Alstom, 2012)

6.3.3 Reference Example

In the Öresundsverket project in Malmö, Sweden, such vertical HRSG from NEM was installed in 2009. Öresundsverket includes an old power plant that has been refurbished for commercial operations that delivers 440 MW electricity and 250 MW heating. The plant is a combined cycle power plant that has e.on as an end user and uses distillate oil as main fuel. The performance of this HRSG occurs at steam flow of 31 kg/s, a steam temperature of 540°C and steam pressure of 89 bars. This HRSG is also equipped with SCR unit to help reduce NOx gases. (NEM, 2013)

Öresundsverket supplies the electrical system in the Nordic region with 3 TWh of electricity and 1 TWh of heat per year to Malmö’s district heating network. This kind of power plant helps to reduce the carbon dioxide emissions by roughly one million tons per year. (e.on, 2012)

6.4 Fluidized bed incinerator

The fluidized bed incinerator from Eisenmann is an example of a potential combustion unit that can be used in our application. It is mainly used for solid wastes as biomass to achieve the thermal treatment intended. In addition, this can be sold either as an individual component or as a complete system where downstream waste heat recovery and flue gas purification can be added to the system. Basically, it has three main components: windbox, sand bed/fluidized bed and freeboard, see Figure 21. (Eisenmann, 2014)

The windbox is the lowest part where the high pressurized whirled airflow is directed to the system. The connection between the fluidized bed and the windbox is done through a nozzle floor. The sand bed is the main part of the unit and is located above the nozzle floor. The direction of the airflow allows the fluidization of the sand bed to achieve a good mixing between the input and the sand. The last part above the fluidized bed is the freeboard where the complete oxidization of the produced flue gases is taking place. (Eisenmann, 2014)

In order to achieve a better start-up of the system and to reach the operating temperatures quickly in the fluidized bed, a starting burner is installed in the windbox. The waste is fed and combusted into the bed up on reaching the temperature needed, where heat is transferred to the sand bed achieving a constant temperature throughout the whole fluidized bed. (Eisenmann, 2014)
The advantages of such a system are:

- Solutions can be tailored to specific applications
- Unlimited types of waste feed materials
- Energy generated is highly effective where heat and mass is at optimal state
- Homogeneous combustion
- No moving parts in the combustion zone
- Perfect for low-calorific value input material (auto thermal combustion)
- Additives such as limestone can be added in the fluidized bed to reduce and purify the flue gas

Figure 21 Eisenmann Fluidized Bed Incineration
6.5 Incineration: Moved bed Type Cd - V

Another type of incineration process recommended is the moving grate of the type Cd-V made by Michaelis in Germany and satisfies ISO standards. This type of incineration is especially used for non-homogenous and low calorific waste. It consists of the following components: waste feeder, incineration without grate, automatic ash discharger, and incineration air duct system and incineration chamber. Two residence times of waste combustion are taken into account to ensure the complete combustion, between 30 and 60 minutes and less than two seconds accordingly. In the main combustion chamber, primary air and secondary air are supplied to insure the direct combustion, where the temperature of the gases should be between 800°C and 1200°C for at least two seconds in order to achieve the accomplishment of the flue gases burn out and breakdown of organic toxins in the post combustion chamber. (Michaelis GmbH & Co. KG, 2010)

The kind of waste suitable could be solid, liquid and solid with up to 40% moisture content. The amount of waste should not exceed 1.39 kg/s and the calorific value of waste should not exceed 45 MJ/kg. In addition, the density of waste should be not more than 1250 kg/m3. (Michaelis GmbH & Co. KG, 2010)

The waste is fed and moved over steps continuously. A complete burnout is achieved in the combustion chamber, which provides a product of sterile ashes. In the post combustion chamber, the elimination of odours is attained. The ash discharging is done automatically which provide a safe technology. This incineration has a rigid construction and automatic function control that allow the easy operation. In addition, it is resistant against wear, has high heat storage and the heat emission of the furnace is low. (Michaelis GmbH & Co. KG, 2010)

Seeing that the designed system, hybrid cycle and single-fuel steam cycle, requires a waste input capacity which is much larger than the one that this type can handle, it would be more beneficial to use a fluidized bed incinerator.
7. Discussion and Conclusions

As already established and discussed, the growing amount of the MSW produced each year is sharply becoming a problem. As more and more countries realize the benefit of MSW incineration as a high efficiency waste management method, the technology for WtE facilities is developed further. This method contributes significantly to the sustainable society as locally produced fuel is utilized for power generation. The CO$_2$ reduction of MSW and the already shown high power generation value speaks for itself for using it in power plants for production of heat and electricity. MSW incineration leads to a decrease of the overall GHG emissions due to minimizing or totally eliminating the CH$_4$ gas production. A usual point made against this fact is the argument that the methane produced in landfills can be utilized. But the reality of the situation is that still more than 50% if this gas escapes to the atmosphere which can be harmful and poses additional hazards for the environment. This is not taking the actual place-occupying problem with landfilling into account.

In this paper, the investigated subject was to maximize the overall plant efficiency of an existing MSW incinerated steam cycle. By adding on and coupling a GT cycle as a TC, the steam output from the MSW incinerator gained much needed additional thermal energy which then could be extracted in the steam turbine. The main purpose is to show that the integration of a TC adds measurable gains in the overall efficiency of the conventional single fuel steam cycle.

Here in this part of the paper, the results presented in the previous sections are discussed and analyzed further.

7.1 Single-fuel cycles vs Hybrid dual-fuel cycle

Utilization of a hybrid dual-fuel cycle has proven to be an efficient solution for increasing the power generated in a power plant. The concept behind the system is rather simple, with use of two simple unmodified conventional cycles. The steam cycle deploying MSW-fired boiler can be an existing power plant and the TC is standard gas turbine with a common combustion engine. There are many industrial alternatives for these systems, as discussed earlier, which makes this solution highly adapted for retrofitting. The only part is the need of an HRSG and the system can be coupled together. Without any major differences in cycle arrangements in the set up itself, this concept manages to enhance the fuel energy conversion efficiency for both the TC and the BC.

When comparing the power output from this arrangement to running two separate single-fuel cycles, the combined cycle manages to output more total power due of the “boost” of the BC thanks to the TC. For the NG-fired cycle it is combined together with the HRSG and using excess NG as supplementary firing, the power output is only altered with the rate of fuel input. While the power output of the MSW-fired steam cycle is highly dependent on both the rate at which MSW is fired in the boiler and also the mass flow of the hot exhaust gases from the GT.
cycle. The former mentioned limitation is present in the single fueled steam cycle which in combination with the actual properties of the fuel can pose inconsistency and large variations in the power output. Therefore the results shown for the single fuel steam cycle only shows the output and the efficiency at optimal steady state scenario.

One of the major benefits of using and running a hybrid dual-fuel cycle is the reduction of total components used for the power production. This is seeing that operation a single GT combined cycle already utilizes an HRSG and a steam turbine. Applying an MSW-fired steam cycle as BC is able to make great use of the heat rejected from the TC, even though the hybrid configuration utilizes a less technically advanced thermal heat transfer between the two cycles.

From the simulation results presented above, it is clearly depicted that the hybrid dual-fuel cycle provides a significant efficiency improvement over two separate single-fuel cycles. One aspect that must be taken into account is the change in the fuel flows. For the cases simulated, the mass flow of the MSW-fired steam cycle is greatly reduced in order to achieve the mentioned 50 MW output. For more cases, where the fuel ratios are adjusted more, this increase in efficiency is clearer. But this aspect was not simulated within the scope of this paper, where optimization of a condensing and CHP cycle was focused on instead. For this case, either simulating the single fuel cycles with the input fuel mass flows or simulating the power generated with the same ratio of fuels for the hybrid cycle gives a better insight. This is seen from the results where the electrical efficiency of the single fuel steam cycle in CHP mode falls at roughly at 17% while the electrical efficiency of the combined cycle is between 34% and 35%. This is of course due to the much larger amount of fuel input needed for the single fuel steam cycle.

Utilization of a parallel powered hybrid configuration enables an easy way of boosting the efficiency whether we are talking about repowering an MSW-fired steam cycle by partial superheat with GT exhaust or completely developing a new hybrid cycle. This is due to the fact that the optimal steam pressure is quite low for an MSW-fired boiler with a HRSG that is set for a single-pressure level. Even though parallel configuration is still coupled with a simple one leveled pressure HRSG, it provides a better steam flow expansion capacity generated from the MSW and the HRSG. The thermal energy is well controlled in the GT exhaust and delivers higher efficiencies. In order to reach a superheated state of the steam with the help of GT exhaust, the pressure level in the boiler is increased. Depending on the size of the GT a large amount of thermal energy will be carried with the GT exhaust. This is directly affecting the superheat temperature and steam pressure in the BC, which results in an increased efficiency advantage. The noted improvement in electrical efficiency comes at the expense of energy conversion of a high quality fuel.

One deciding factor for application and utilization of such system is the cost of operation. This cost takes into account the prices of the fuels as well. While MSW incineration is a good alternative for waste management, the supplement at steady rate and the capacity of the waste system should be further optimized to ensure continuous operation. Also the availability of NG
at economically feasible prices is important for the power plant. For this manner the part-load operation simulations are valuable, but more cases should be tested for getting a better insight.

Although not considered for calculations in this report, another major benefit of the hybrid cycle is the lowered overall CO₂ and other GHG emissions. This is mainly due to the CO₂ near neutrality of MSW as fuel. The main sources of carbon dioxide emissions from MSW come from plastic and other waste of fossil fuel origin found in MSW. By careful waste management and addition of NG for power production the overall CO₂ levels can be reduced by 5-10%. (Udomsri, 2011) Operating a hybrid cycle essentially allows for achieving increased power efficiencies without the corrosion problems.

### 7.2 Cold condensing/CHP mode

When searching for an indication that explains the thermodynamic gains for a power cycle, what is usually presented is the electrical efficiency. Nevertheless, another interesting perspective is the total efficiency which incorporates the possible heat output. For this paper, two distinct operation modes have been investigated. The cold condensing operation, where electrical power is optimized to be highest and CHP mode, where both heat and electrical power output are generated in combination. The investigations show that the overall utilization of the contained energy in the input fuel favors the CHP operation mode over the cold condensing mode. What this means is that the conversion becomes more efficient and more power is gained from utilizing both heat and electricity. The improved utilization of the fuel comes from the added heat output in the form of hot water, which can be used for district heating or industrial processes. (Petrov, 2003) By making adjustments on the condenser at the end of the steam cycle and coupling it to district heat production, you avoid wasting heat to the environment. It is the cooling water of the condenser that delivers the thermal energy through heat transport. This way the energy contained in the fuel is better utilized, although it is of great importance that the heat output is of value.

Preparing and optimizing the configuration for condensing mode finding optimal parameters for the four extractions, improves the overall efficiency. (Weston, 2000) As observed from the optimization, the mass flows at the extractions affect the efficiency more than a change of pressure does. Lowering the mass flows delivers increased efficiencies, while higher extraction pressure decreases the efficiency. A better heat exchange obviously results in a higher efficiency; these could be observed by the values of pinch point temperature difference and UA-value.

In the simulations performed on the hybrid configuration in CHP mode, there was no need for change in the thermal connection of the two cycles in the HRSG. The main parameter that was changed for operating in CHP and cold condensing mode, was the pressure of the fourth extraction to the condenser, 1,6 bar for CHP mode and 0,056 bar for condensing mode. From the results, it was deduced that the overall efficiency for CHP mode is higher than in condensing mode. A reason for this is possibly the higher utilization of the two power sources. However, the
electrical efficiency in condensing mode is naturally higher compared to CHP mode. This is of course because the condensing operation mode is designed to extract larger power by the generator. Higher extraction flows and pressures were seen to increase the overall efficiency. The results also indicated that in CHP mode, the higher the overall CHP efficiency gets the lower the electrical efficiency got.

Here it can be noted that the operation mode of the cycle, however easy to change, should be determined and optimized beforehand depending on the end use. The deciding factor could be the geographic location, climate or cost of energy. Another dictating factor is the general distance of the plant to the user sight. For the case of a power plant generating a larger amount of heat than power, there will be a certain cost with the transportation of the heat. For example for rural-areas where there is a large distance between households the cost for piping for transportation and also the heat losses from the system will be enormous. For a case like this, perhaps optimization of the system for operation on condensing mode would be more beneficial. Another possible argument for condensing operation mode, or optimization for generation of more power than heat would be the end-use and the selling cost of the energy. Electricity has more end-uses and does cost more to buy than heat from say district heating. Although not the optimal way of heating, electricity can be utilized for room heating, lighting and operation of other electrical devices while heat cannot be used for other utilizations other than heating.

7.3 Part-load performance

Hybrid dual-fuel cycle configuration provides flexibility in fuel ratios, which allows for flexible performance when running in part-load. The efficiency characteristics are highly dependent on the fact that the NG-fired TC is running at full power and the power output of the BC is decreased. The simulations show increased efficiencies when running the BC in part-load and the TC in full load, with a higher NG to MSW ratio. As the power output decreases the part-load efficiency increases to the point where the efficiency of the BC is too low or the exhaust from the TC cannot be fully utilized any further.

7.4 Application

The described scope of the steam cycle optimization is not complete without also describing possible implementations for the designed system. Here this system is assumed to be utilized as a CHP facility providing heat and part of electricity for end-use in households. Assuming best case scenario in a well temperate city, the designed hybrid dual-fuel cycle in CHP mode with an efficiency of 87% could theoretically provide enough heat and power for a city with a population of 62000 inhabitants. This is based on the assumption that the average energy consumption per person is 2 kW. (U.S Energy Information Administiration - eia.gov, 2012) Also taking into consideration the amount of MSW needed for the plant to operate without any hiccups, a total of 4100 tonnes of MSW/year is needed, leaving the amount of waste needed to be produced per person each year to 66 kg/pers, year. Based on previous research done each person produces
more than 500 kg of waste on average each year (Petrov, 2003), which further drives the argument that the power plant would be a feasible option for this fictitious city. Here a well operating waste management system is needed though.

The broad application and economic feasibility of such a hybrid configuration has been addressed in a number of publications as described in the literature study. These types of configurations are of great interest, providing a low cost way of waste management at high efficiencies, and their existence are growing. In order to further increase the share of MSW that is used in incineration processes, this concept needs to become more recognized. As noted from the results operating hybrid configurations in condensing mode is not the optimal way of making use of this concept. Depending on a number of factors such as fuel availability, prices, high total efficiency, required output and preferred operation points the cycle should run in CHP mode. Internationally there are some installations of these CHP configurations in operation.
8. Future work

During the past decade the cooling demand around the world has increased. This is also true for cooler climates like Sweden and this trend is expected to continue in the coming decade. With a higher demand for cooling, new and alternate solutions are emerging. One of the great features of a cogeneration system is its expansion prospect. Operating the facility in CHP mode deliver increased efficiency, but has some negative aspects. During summer period there is little need for heating which will consequently lead to lower capacity and relatively lower efficiency for the system. A possible solution for maximizing the efficiency of a CHP system would be to utilize waste heat for cooling production. By utilizing additional components the rejected heat from the condenser could be advantageous in other ways, such as trigeneration. With trigeneration an added absorption chiller could provide chilled water and hot water for air conditioning or alternatively to heat. Conventional compression chillers from refrigeration and air-conditioning systems pose for very large electricity consumption. (Udomsri, 2011) Adding a thermally driven absorption chiller could be a possible alternative for making the best of the waste heat during warmer periods. Investigation of the techno-economic aspects of this type of addition to the hybrid cycle could be of great benefit. This is a desirable addition due to the rising comfort cooling demand, which will bring a higher electricity use. A solution of this kind will provide a “year-around” mixture of electricity and thermal comfort. This type of investigation could lead to a more environmentally friendly solution, and possibly a better utilization of the excess heat.

As the efficiency increases with integration of a TC into a hybrid combined cycle arrangement, this suggests that a thorough economic assessment should be carried out to evaluate how it compares to the sum of two separate single-fuel plants. Investigation of such aspects is a very important issue in order to be able to fully promote an implementation of hybrid combined cycles. Approaching this kind of analysis is extremely influenced by the conditions of the investigated area, their energy policy, taxes for emission, availability of various fuels and components.

The global interest of hybrid configurations is growing and there is a necessity for a systematic assessment of thermodynamic performance utilizing various hybrid configurations. Investigate the possibility with different fuel combinations such as natural gas and coal- or biomass-fired BC with varying fuel ratio and how the electrical efficiency will respond to such changes.
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