MÄLARDALEN UNIVERSITY
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TECHNO-ECONOMIC EVALUATION FOR PYROLYSIS AND GASIFICATION PROCESS INTEGRATION WITH CHP PLANTS TO PRODUCE BIOFUELS

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ABSTRACT

Mälarenergi newest production unit, Unit 7 is located in Västerås, Sweden and has a maximum capacity of 150 MW. It produces heat and electricity for the city of Västerås and is operated by Mälarenergi AB.

The main purpose of this work is to determine whether pyrolysis gasification or pyrolysis electrolyser gasification process is the most economic and profitable for Mälarenergi CHP plants. This analysis carries out a techno-economical evaluation to assess the possibility of specific gasification process modifications in CHP plants to improve energy efficiency as well as additional production useful by-products such as renewable transport biofuels. The calculation is based on cost estimations regarding the different implementations in Mälarenergi CHP plants such as pyrolysis gasification or electrolyser. The simulation model developed in the simulation program Aspen Plus is based on energy and mass balances. The scenario analysis is based on different heat demand load curves, electricity prices and weather forecast. This work investigates different modifications that could be implemented to the CHP, one type of modification is to implement a combination of pyrolysis, gasification and electrolyser to the plant.

The results that have been collected from the Aspen plus simulations and data from Mälarenergi AB give a good picture of how a CHP plant with integrated solutions such as pyrolysis gasification or electrolysis gasification have a good potentiality. The results obtained during the simulation process are considered as reliable. Any errors may be due to outlier data points and model inadequacies.

Keywords: CHP, boiler, district heating, pyrolysis, electrolyser, Aspen Plus simulation

PREFACE

This study has been assigned to us as a final project to complete our bachelor's degree at Mälardalen University in Västerås, Sweden. The project is part of our last Energy Engineering Program, incorporated within course code ERA 206.

The work was performed over the time of 11 weeks, by two students who have been working side by side with equal research shares, that includes a literature study in order to gain knowledge about the gasification combination process. Mälarenergi AB provided for us the measuring data and our school supervisor Chaudhary C.A. Salman helped us with simulations in Aspen plus and Prof. Erik Dahlquist gave us important information, materials and knowledge in the field as well as our examinator Jan Skvaril.

This thesis was conducted as part of FUDIPO project funded by the European Commission. FUDIPO, or Future Directions of Production Planning and Optimized Energy – and Process Industries, focuses on developing and testing a platform for optimization and control techniques in industry processes. Mälarenergi AB is one of the partners and study case in the project.

We would like to sincerely thank everyone involved in this work. A special thanks to Elena Tomas-Aparició at Mälarenergi, our university supervisor Prof. Erik Dahlquist, Chaudhary A. Salman and our examinator Jan Skvaril, without whom this work would not have been possible.

Västerås, June 2020

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SUMMARY

Nowadays, the demand of nature based energy is continuously growing due to the increase of world population and the change and improvement in people's lifestyle. Consequently, the energy consumption around the world is also growing to satisfy the needs of different countries and societies. Unfortunately, the unlimited and continuously consumption of energy around the globe is modifying the nature of the earth and causing global warming and pollution that are threatening the wellbeing of humans and animals. Thus, to reduce the negative effects of global pollution we suggest the use of alternative system.

The Integration of pyrolysis gasification or pyrolysis electrolyser gasification could potentially decrease global pollution and offer a long term solution to limit its negative consequences.

Pyrolysis is a process that occurs when biomass decomposes because of the heat. The biomass reaches high temperature without oxygen during the pyrolysis which results in a chemical compound of the biomass decomposing into gases and charcoal. Electrolysis is the process when electricity goes through a substance and creates a chemical change within the substance. In Scandinavian countries to fulfil the high demand of heat, power and electricity there are many combined heat and power (CHP) plants available. CHP is an energy efficient technology that generates electricity and reuses the heat that is produced during the process to provide useful thermal energy like hot water or steam that can be used for cooling, heating, domestic hot water and industrial processes. The CHP plants operate by combustion of fuels or by burning waste.

The cause of expansion with renewable energy such as wind and solar power is another huge competition issue between CHP plants and renewable source energy plants. Additionally, the variation of heat demand throughout the year made CHP plants operate on part load with few operational hours. Low heat demand and few operation hours made it possible to decrease these overall process energy efficiency prospects and negatively harm the economic performance.

The purpose of this study is to determine whether pyrolysis gasification or pyrolysis electrolyser gasification process is the most economic and profitable option for Mälarenergi CHP plants. Moreover, the main goal of this research paper is to investigate and analyze a

techno-economical evaluation to assess the possibility of specific gasification process modifications in CHP plants to develop energy efficiency as well as the production of additional useful by-products such as renewable transport biofuels. The economic analysis and evaluation in this work is based on the cost estimations related to different implementations in Mälarenergi CHP plants such as pyrolysis gasification or pyrolysis electrolyser gasification.

The result from the simulations illustrates that with todays' technology pyrolysis gasification is the best option. However, in the future pyrolysis electrolyser is predicted to overtake due to the development of the technique. When it comes to the economic aspects, it is more profitable to invest in pyrolysis electrolyser combination as its profit relies on electricity prices. We predict that in future the electricity prices decrease thanks to the introduction and expansion of wind power and other renewable energy sources. Thus, in relation to the current scenario, the pyrolysis gasification seems to be the most advantageous. Yet, there is a good chance that pyrolysis electrolyser will advance rapidly depending on the price of electricity.

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NOMENCLATURE

Symbol	Description	Unit
T	Temperature	°C
η	Efficiency	%
H	Height	M
L	Length	mm
P	Pressure	Bar
W	Width	M
H_2	Hydrogen	-
C	Carbon	-
Cl	Chlorine	-
N	Nitrogen	-
O	Oxygen	-
S	Sulfur	-
H_2O	Water	-
CH_4	Methane	-

ABBREVIATIONS

Abbreviation	Description
BFB	Bubbling fluidized bed
CFB	Circulating fluidized bed
CHP	Combined heat and power
DH	District heating
G-VALVE	Gravity valve for overflow protection
HP	High pressure

Abbreviation	Description
IRENA	International Renewable Energy Agency
LP	Low pressure
ME	Mälarenergi
MEA	Monoethanolamide
NPV	Net present values
PB	Payback
RDF	Refuse Derived fuel

DEFINITIONS

Definition	Description
Boiler	A closed structure in which water is heated by burning a fuel, in this work always referring to large scale industrial boilers
Gasification	Is a thermochemical process that uses heat, pressure and steam to convert materials directly into a gas composed primarily of carbon monoxide and hydrogen
Pyrolysis	Is a thermal decomposition process of a biomass, which with high temperature of 200-800 °C and with absence of air and oxygen form syngas and liquids
Electrolyser	Electrolyser is a device which splits water into hydrogen and oxygen using electrical energy. Electrolysis is the process when electric current goes through a substance and creates a chemical change within the substance.

1   INTRODUCTION

As our lifestyle is continuously changing and progressing, our demand to energy based products is also increasing. A great deal of our necessities such as house hitting system, cars, hot water, cooking require an enormous consumption of energy. Unfortunately, the constant consumption of energy has been threating our world, and it has brought several issues such as migration, food insecurity, and disappearance of many animals. Moreover, it has caused pollution in many countries and brought illnesses related to low air quality. In an attempt to reduce global warming and pollution, pyrolysis gasification or electrolyser could be a solution. Throughout this research, we will investigate the possibility of the utilization of pyrolysis gasification or electrolyser to decrease global pollution. Furthermore, we will discuss the possibility of its implementation. The CHP plants that will be investigated on this work is in Västerås at Mälarenergi AB and focus will be on unit 7.

Pyrolysis is the process when biomass decomposes with help of heat. The biomass will reach high temperatures without oxygen during the pyrolysis which results to the chemical compounds of the biomass decompose into gases and charcoal. Electrolysis is the process when electricity goes through a substance and creates a chemical change within the substance. This can be seen during hydrogen production water or alkaline water will be exposed to electric current and this current will chemically change the water into hydrogen and oxygen.

1.1   Background

In order to accomplish the increasing heat and electricity demand in Scandinavian countries, it is fundamental to consider multiple (CHP) plants that could combine heat and power. Indeed, CHP is an energy efficient technology that has the ability to generate electricity while using the heat produced to provide other useful thermal energy such as hot water. The CHP plants operates through combustion of fuel or through waste burning. Most of the time, CHP is located at facilities where there is a need for both electricity and thermal energy. The cause of expansion with renewable energy such as wind and solar power is another huge competition issue between CHP plants and renewable source energy plants.

Additionally, the variation of heat demand throughout the year made CHP plants operate on part load with few operational hours. Low heat demand and few operation hours made it

possible to decrease these overall process energy efficiency prospects and negatively harm the economic performance.

1.2 **Pyrolysis**

According to the article written by Salman et al. (2018), it is stated that CHP plants integrated with thermochemical processes for production of biofuels can be operated for more hours with high energetic return and may also increase the profitability provided by the additional integrated processes such as gasification or pyrolysis. The article mentions that gasification or pyrolysis processes can treat biomass and waste into a variety of biofuels processes. However, these processes are carried out at a high temperature and require heat at various unit operations. Existing CHP plants can provide the required heat for these thermochemical processes during off-peak hours and increase its overall operating capacity throughout the year.

1.3 **Electrolysis**

In this report, we intend to use water or alkaline water-electrolysis through the use of electricity that is produced in the plant will be investigated. Electrolyser plants produce hydrogen to increase the energy output of the biofuels and the waste heat from the biofuel plants is supplied to the district heating grid. The district heating demand is mainly based on excess heat from CHP biofuel fired plants and heat pumps.

Electrolyser technology could potentially be more important in a local perspective or with higher hydrogen consumption for liquid or gaseous fuel production processes. Electrolysers therefore have a larger role in a high-renewable energy system for balancing electricity production and demands. With low electricity prices the installation of electrolysis is the best alternative for hydrogen production and during summertime solar power will be in surplus and give the same effect.

According to Power2Hydrogen (2016), electrolysers play a great role in the energy system with high wind percentage in the system (50% of the electricity demand or higher), electrolysers should operate with a high utilization rate when the hydrogen demand is limited

and utilization rate is lower (larger capacity) when the hydrogen demand is higher. In this way, the electrolysers will offer greater benefits to the energy system.

1.4   **Mälarenergi AB and CHP plants in Västerås**

Mälarenergi AB is a municipally owned energy company with main aims to completely be free from fossil fuels and is the operator of a combined heat and power (CHP) plant located in Västerås. Mälarenergi has provided Västerås with energy in terms of electricity and district heating for over 150 years. Nowadays, more than 150 000 people can light up their homes with electricity from Mälarenergi (Mälarenergi, 2020). Mälarenergi CHP plant consists of three units (boiler and turbine) different boilers and as fuel uses mainly recycle fuels as waste and biomass.

Unit 5 is fired with biofuel and has previously acted as the base load boiler. Unit 6 is the only one fuelled with municipal solid waste (MSW). It was commissioned in 2014 and has since then replaced the base load boiler at the power plant. Mälarenergi is building a new seventh CHP plant (Unit 7). Mälarenergi (2020), acknowledges that Unit 7 will produce energy for the electricity grid and for the district heating network. Unit 7 will be fuelled by recycled wood with design capacity of 150 MWh (thermal power) and will represent approximately 36 percent of heating production.

Mälarenergi have conducted and provided for us the load profile production of heat and power CHP plants in Mälarenergi as shown in figure 1, the plant will have the peaks in winter periods where the demand of heat will be higher. During summer periods the demand of heat will be lower due to the warm climate. This was the reason behind Mälarenergi need to investigate the possibility of biofuel production especially during the summer period where the production is low.
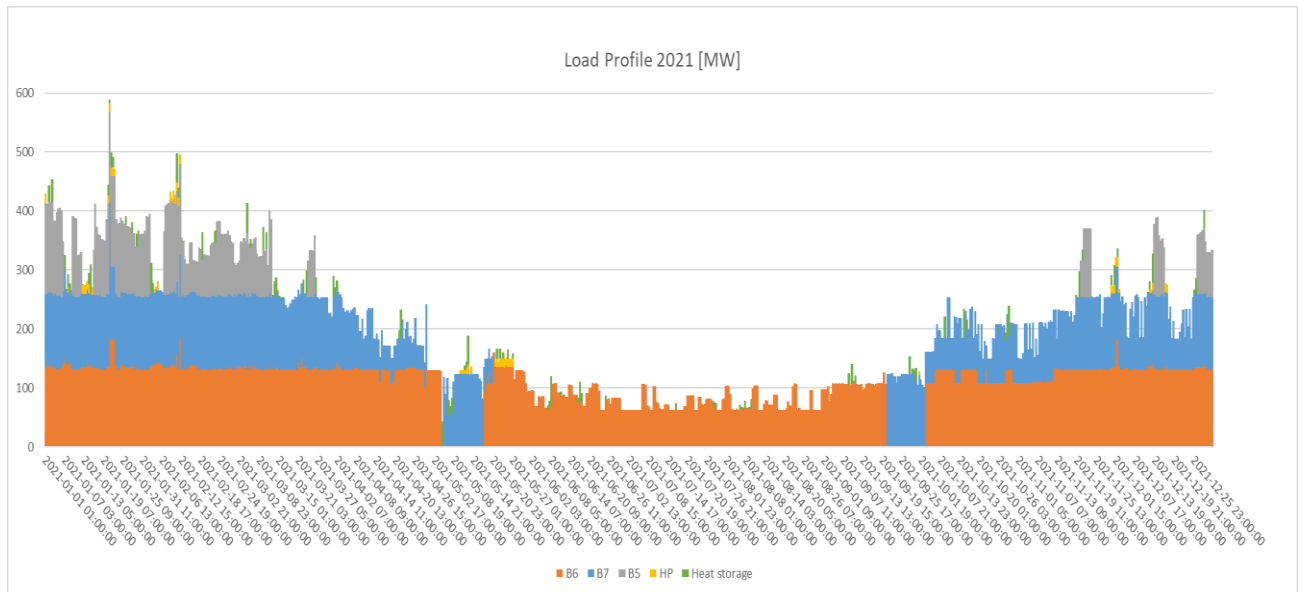
Figure 1 Load profile production of heat and power CHP plants in Mälarenergi AB
Source:(Mälarenergi, 2020)

1.5   **Purpose**

The main purpose of this work is to determine whether pyrolysis gasification or pyrolysis electrolyser gasification combination process is economical profitable with Mälarenergi CHP plants.

1.6   **Research questions**

RQ1: Which gasification combination process is the most economic and profitable with Mälarenergi CHP plants?

RQ2: How does the economic evaluation look regarding different scenarios with CHP plants?

1.7 **Delimitation**

The study focuses on the technical simulations connected to the implementation of CHP and economic analysis regarding the implementations. The applications that have been considered in this investigation have followed pyrolysis gasification and electrolyser.

2 **METHOD**

The main purpose of this project is to carry out a techno-economical evaluation to assess the possibility of specific gasification process modifications in CHP plants to improve energy efficiency as well as producing additional useful by-products such as renewable transport fuels.

Moreover, the study also gathers information from different scientific articles, books, reports, and literatures. The literature chosen for the purposes of this paper is related to pyrolysis gasification and electrolysis in CHP plants. This information will be used to describe the different process in the CHP work and are referenced in the report. The techno-economic analysis is connected to three key aspects: process integration design, mass and energy balance, and cost estimation.

The economic analysis uses the following methodologies to analyse the economic costs, income, and investment. The calculation is based on cost estimations regarding the different implementations in Mälarenergi CHP plants such as pyrolysis gasification or pyrolysis electrolyser.

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│  Materials, updated information      │
│  within the field, Aspen Plus        │
│  simulations, economic inputs        │
│  (E. Dahlquist and C.A. Salman, 2020)│
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Definition of research questions and deeply research regarding the implementations

Analysis of the simulation data

Economic researches

Literature study

Compile and illustrate the results

Economic evaluations

Discussions and conclusions

Compile and illustrate the results
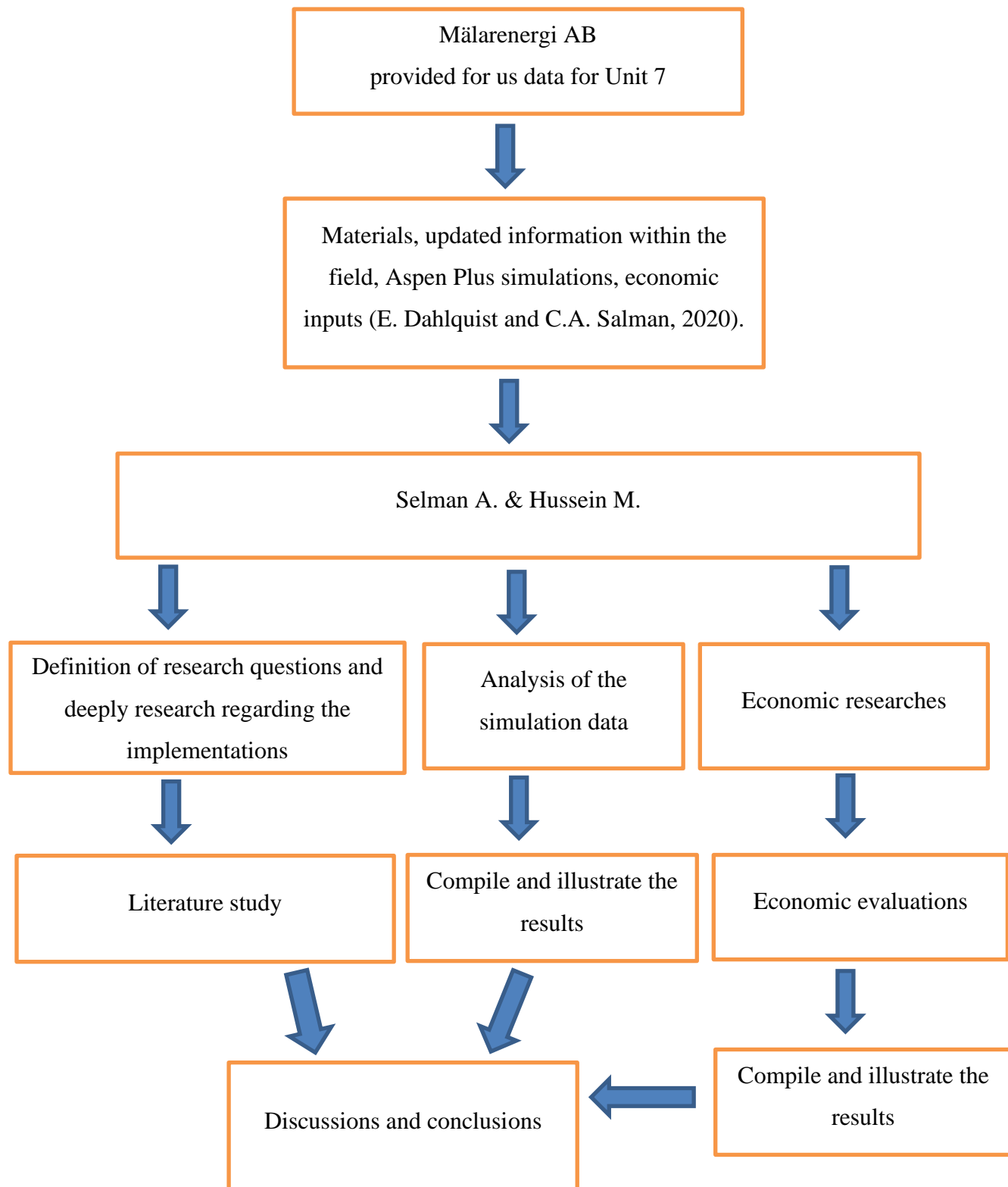
Figure 2 Methodology scheme of the work

Figure 2 briefly illustrates this study's methodology scheme. Mälarenergi AB participates in an energy project for optimization in industry processes founded by the European

commission, FUDIPO project. Mälarenergi provided us with data for unit 7 to investigate the possibility with implementing pyrolysis gasification and electrolyser to the Unit. Materials and updated information within the field, Aspen Plus simulations, input regarding the field on pyrolysis gasification and electrolyser and generally economic evaluation help and suggestion was provided for us by (E. Dahlquist and C.A. Salman, 2020).

Based on the above mentioned considerations and necessities, Selman A. and Hussein M. made literature review, analysis, definition of research questions, methodology, results, discussions, conclusions and mentioned some suggestions for further work in the future. Moreover, Selman A. and Hussein M. analyzed the gasification integration process, come to the solution which gasification integration process is the most economic and profitable with Mälarenergi CHP plants in accordance with the results obtained. Made economical evaluations for pyrolysis gasification and electrolyser. Other aspects have been considered. For example, different price scenarios and climate temperature have been examined in an attempt to understand their influence on the simulation.

2.1 Equations

Equation 1 Annuity factor formula

$$Annuity\ facor = \frac{r(1 + r)^n}{r(1 + r)^n - 1}$$

r = interest rate

n = years

Equation 2 Net balance formula

$$Net\ balance = Profits - (Annuity + costs)$$

2.2   **Aspen Plus Simulation**

Aspen Plus is a well-developed chemical industry's leading process simulation software. The purpose of this software is to build different process models and thereafter simulate it with the assistance of advanced calculations. The program is one of the most commonly commercial software used globally and specifically in CHP technology (home.aspentech.com, 2020). According to a report written by M. Salman (2017), to design and run a simulation with Aspen plus, five main steps must be elaborated and taken into considerations:

1. Adding properties, setup and calculation method: For example, which fluids is used, what important setup and the calculation method. Aspen plus offers many calculation methods suitable for different processes.

2. Adding components and modelling in the flowsheet: In the flowsheet sub system components are added and connected to achieve a working cycle.

3. Configuration of blocks and streams: Once a design is completed, the configuration of its components and flow properties needs a block and fluid specifications. What important and necessary data input is given into each block. For example, the isentropic efficiency both in turbine and pump, heat source or heat sink temperatures.

4. Run the simulation: Once all data, method, specifications are given, appropriate model is drawn, run a simulation then proceed to analysis.

5. Model analysis: For analysis, mostly depends on the design, what or which variables or parameters to be analysed (Mohamad Salman, 2017).

For this study, the simulation model that will be developed on Aspen plus simulation program will be based on energy and mass balance. The scenario analysis will also be based on different heat demand load curves, electricity process and outside temperature this data will be provided for us from Mälarenergi AB.

2.3   **Pyrolysis with modifications**

This research investigates different alterations that could be implemented to the CHP, one type of modification is to implement a combination of pyrolysis, gasification and electrolyser to the plant this will be further explained in section 4 current study.

Pyrolysis is the process when thermal decomposition of biomass occurs rapidly without oxygen, forming syngas or liquids. This process is rapid when temperatures get up to 400-500C and the release of chemical elements with low boiling points occurs. Also, un-reacted carbon char and ash becomes the end-product for this process, a good example of this process that could occur during daily life is burned toast (Brown Robert, 2019).

The gasification process is the process after pyrolysis that occurs during higher temperature such as 700-1000C. The un-reacted char from the pyrolysis is converted to syngas that can be used to generate electric power. During this process steam is added to the gasifier this results in carbon converts to syngas and the ash becomes the end-product (Brown Robert, 2019).

Water that is stored in a storage tank is filling up the electrolyser. Electricity from the CHP plant is supplied to the electrolyser, this allows for a chemical reaction to occur in the electrolyser which results to water is converted into hydrogen and oxygen. The hydrogen can then be used in the hydrotreating process in the CHP plant this is the process when oxygen in the bio-oil is removed with the help of hydrogen at a high pressure. With the help of electrolysis, the plant can generate hydrogen for this process instead of purchasing it this would be expensive.

According to the article written by Y. Kirosa (2016), reports that the pyrolysis process can also be combined with an electrolyser, which is an environmentally friendly way of creating hydrogen by using water electrolysis. The electrolysis process uses electricity as an energy source to produce hydrogen from the molecules. The water molecules divide up during the process where the oxygen is in the anode and the hydrogen are in the cathode. If the electricity used during this process is renewable, it would be a worthy application to implement for the CHP.

2.4 Process Integration

2.4.1 Case 1: Pyrolysis-gasification integrated with G-valve of boiler 7 of Mälarenergi CHP plant

Recycled wood is mostly used in municipal power plants, both for the CHP plants and for heat applications. In both cases, it is beneficial to complement existing CHP plants with a

gasifier to utilize existing infrastructure and to extend the business possibilities by producing CH_4 for sale as a high value energy product. In such process integration, the gasifier can either be upstream of the main combustion section or in the case of a CFB boiler, in the G-valve like shown in figure 3 case 1 where pyrolysis and gasification are integrated with G-valve. In the case where the gasifier is integrated upstream of the combustor, the synthesis gas is cleaned prior to entering the combustor. After the particle removal, a membrane filter system could be installed where H_2O would first be condensed out followed then by H_2 passing through a membrane. Furthermore, CO would be removed through extraction with an organic acid and CO_2 would be removed with monoethanolamide (MEA) with the residual gas comprising primarily CH_4. The separated CH_4 from the synthesis gas could be sold then as bio-methane.

Figure 3 Process scheme of pyrolysis integrated with G-valve of boiler 7 of Mälarenergi plant and gasification for hydrogen Source: (Supervisor C.A. Salman, 2020)

2.4.2 Case 2: Pyrolysis-Electrolyser integrated with G-valve of boiler 7 of CHP plant

In case 2 where pyrolysis and electrolyser are integrated with G-valve, the only difference from previous case 1 is that in case 2 to produce hydrogen water and power goes into the electrolyser and produces hydrogen. Pyrolysis integrated with G-valve and hydrogen will be separated in the bio-oil upgradation and then biodiesel will be produced like presented in figure 4.
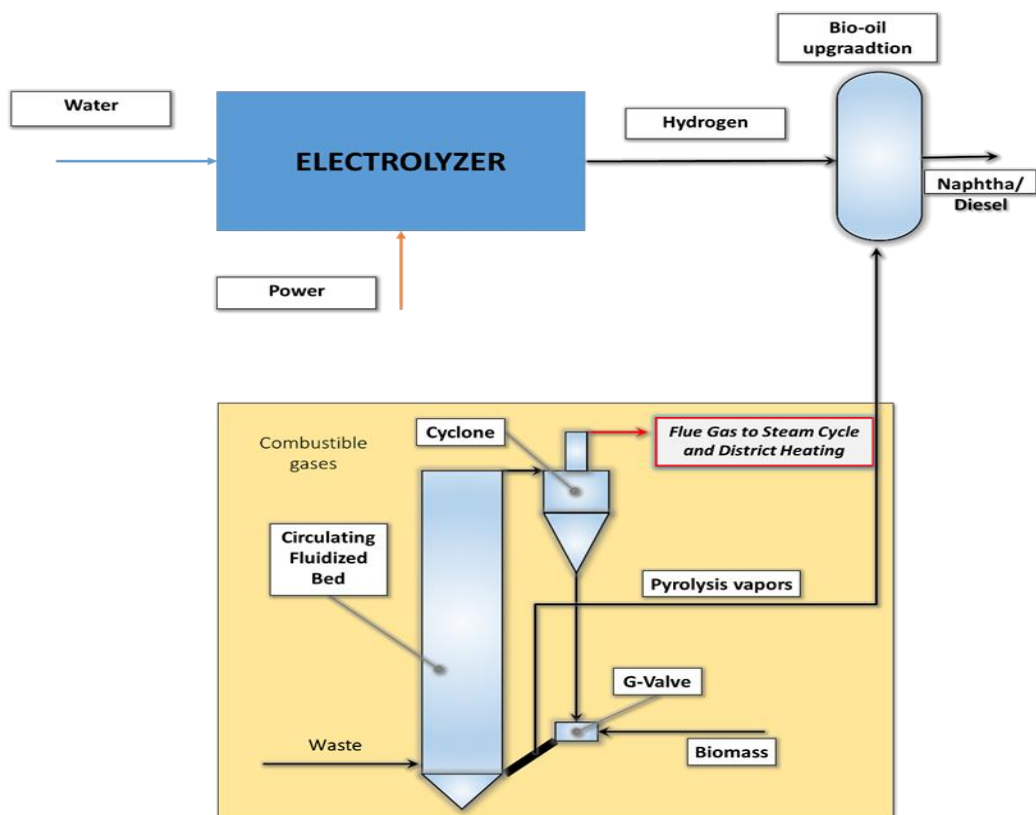
Figure 4 Process scheme of pyrolysis integrated with G-valve of boiler 7 of Mälarenergi plant and Electrolyser for hydrogen Source: (Supervisor C.A. Salman, 2020)

2.5   **Modelling and simulations**

CHP plant modelling

The parameters for the modelling are introduced in this section that has been used by C.A. Salman to produce the result from the simulation program Aspen plus, thereafter the result will be analysed in this research.

A boiler in Mälarenergi plant (Unit 7) has been used as a reference for process integration. The parameters used in the simulation is illustrated in table 1. The feed that has been used in the simulation is recycled wood. The required parameters for heat production are 100 MW and for electricity 50 MW (Mälarenergi, 2020).

Table 1 Parameters used in the Aspen plus simulation program for boiler 7

Type	Boiler 7
Feed	Recycle wood
Steam flow	57
Steam temperature, °C	520
Steam pressure, bar	92
Heat production, MW	100
Electricity production, MW	50

Aspen plus has been used for the modelling of boiler 7. Recycled wood is used as an input in the model. Elemental composition of recycled wood is presented below in table 2.

Table 2 Wood composition for boiler and gasification

Wood composition (boiler and gasification)	Water %	Dry basis
Moisture	40 wt%	-
Ashes	5 wt%	Dry basis
Carbon [C]	49,6 wt%	Dry basis
Hydrogen [H]	5,80 wt%	Dry basis
Nitrogen [N]	1,02 wt%	Dry basis
Chlorine [Cl]	0,04 wt%	Dry basis
Sulfur [S]	0,11 wt%	Dry basis
Oxygen [O]	38 wt%	Dry basis

The model is developed as per methodology explained in the article written by Salman et al. (2018), The figure 5 below was provided for us from C.A. Salman, (2020).
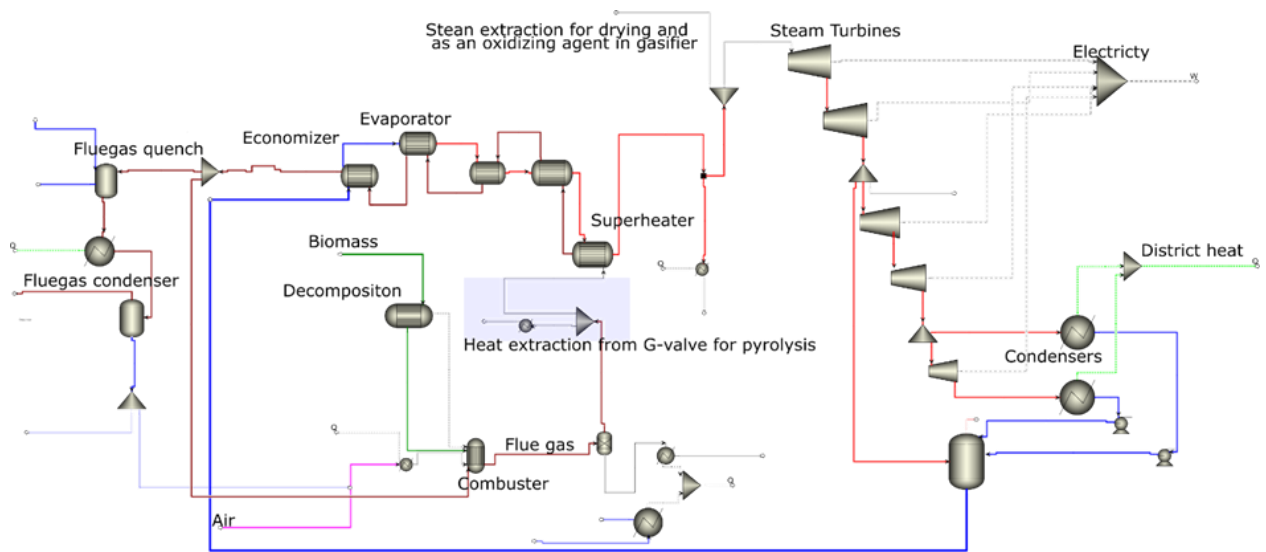
Figure 5 CHP model developed in Aspen Plus (C.A.Salman, M. Naqvi, E.Thorin, and J.Yan, 2018)

Pyrolysis modelling

Wood pellets has been used as the input material for pyrolysis. The pyrolysis model was based on the cellulose, hemicellulose and lignin content of the wood as explained in the article written by Mobolaji et al. (2014), as shown below in table 3.

Table 3 Pyrolysis hemicellulose and lignin content for pyrolysis modelling

Proximate analysis	wt.%ar	Subcomponent composition	wt.%ad
Moisture content	25	Cellulose	42
Fixed carbon	20	Hemicellulose	23
Volatile matter	55	Lignin	24
Ash	0,7	Water	10

Model for pyrolysis has been previously developed in python in the article written by Salman et al. (2017), which has been used in this thesis. Results from python has been transferred to Aspen plus for process integration with G-valve of CHP plant.

Modelling of Gasification

Gasification model has been developed in Aspen plus with accordance in the article written by Salman et al. (2017), which was integrated with CHP plant. Steam from CHP plant has been used for as an oxidizing agent.

Modelling of Electrolyser

Aspen plus does not have the required components for the modelling of electrolyser, so for simplicity, the power required to produce 1 kg of hydrogen has been used to generate the mass and energy balance of integrated processes. 42 kWh of power is required to produce 1 kg of hydrogen (IRENA, 2018).

Economic analysis

The economic analysis will be based on cost and profit estimations. These estimations are based on various price scenarios that can occur during the application such as electricity and fuel price. Thanks to these scenarios a mean cost and profit value can be used for the calculation of the annual net balance and by this see the annual loss or profit for each implementation.

3 LITERATURE STUDY

A literature study has been concluded in order to strengthen the theoretical foundation within the field. The most relevant literature includes scientific articles, previous studies and sources referenced in this study were found using online research database MDH-diva, ScienceDirect, Scopus ResearchGate and books within the field. The more detailed purpose of the literature study was to provide in depth knowledge of modern combustion technology, current research, and future development with special focus on pyrolysis gasification and electrolyser.

According to goals and visions set by Energimyndigheten in 2012, the production of biofuels should increase. Based on this theory, we have tried to identify several methodologies that could enable a cost friendly way of increasing the production of biofuels. We came into a conclusion that it could be increased with the help of CHP plants, by making the plants more efficient and implementing new techniques to produce biofuel. The current goal is to make the small CHP plants in Sweden more efficient, but the future goals with CHP plants is to implement new methods that can eliminate the CO_2 emission. A future vision is to expand the production of biofuel, eliminate the CO_2 emission and use the fuel in different sectors such as transport and industry (Energimyndigheten, 2012). This could potentially satisfy the high demand of energy in multiple sectors, limit pollution, and allocate all the resources effectively.

3.1 Pyrolysis gasification

Sweden is well established in the CHP sector. In this literature study we will further investigate the possibility to implement pyrolysis gasification.
Wang, Zhang, Qi, (2020) describes that pyrolysis occurs with the help of heat decomposition of different types of biomass resulting in syngas or liquids. When pyrolysis is combined with gasification and it is implemented in a CHP this could result in a more efficient plant. Pyrolysis can generate liquid and fuel gas. The liquid can be refined to produce for example bio-oil or diesel oil. This liquid could also supply the boiler or steam turbine which gives the plant power. Gasification can generate fuel gas which can be used for the steam turbine or the

combustion engine, it can also be used during chemical synthesis which can give essential chemicals that could be used in other sections of the CHP plant.
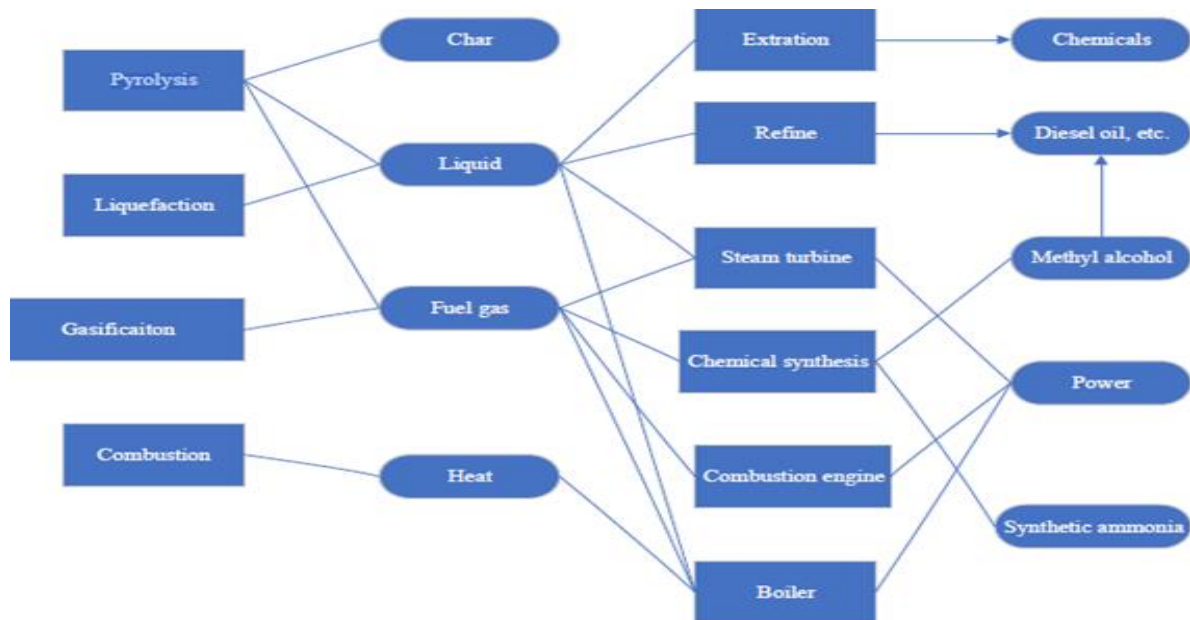
Figure 6 A description on thermo-chemical process Source: (Research Status and Analysis of Biomass Pyrolysis Gasification, 2019)

According to the article "*Future directions for CHP plants using biomass and waste*" written by Salman et al. (2019), states that in CHP plant pyrolysis utilizes heat that comes from sand in the combustor, during this process vapor is created from the pyrolysis. Thanks to the condensation process, the vapor is converted to bio-oil and the gas that could not be condensed is sent back to the boiler, the sand and biochar is sent back to the boiler in the CHP plant. The bio-oil can be transformed into fuels that could be used in vehicles, but the bio-oil needs to be hydrotreated before it can be used. This is when oxygen in the bio-oil is removed as water and carbon dioxide with the help of hydrogen at a high-pressure level. The hydrogen needed to execute hydrotreating is 4-5% of the bio-oils weight. This hydrogen can either be bought or produced in the CHP plant, but purchasing the hydrogen for this process is very expensive. This is where gasification comes in and during the gasification the amount of hydrogen needed for the upgrade of bio-oil is produced. The steam from the CHP plant is used and applied during the oxidation which results in syngas being collected from the gasifier and converted to hydrogen.

According to Sharma et al. (2014), the positive aspect of pyrolysis and gasification is that conversion between solid components into gases and vapours results in a cheaper plant since gases and vapour are easier to store, transport and handle. With pyrolysis and gasification heat is needed to drive the chemical reaction that produces the syngas if the plant does not have an overload of energy production this will results in fuel being needed to generate the gas.

3.2   **Electrolyser**

According to the article *"Hydrogen production by PEM water electrolysis – A review"* written by Shiva Kumar and V. Himabindu (2019), in a CHP plant hydrogen is required during the different processes. For example, when the bio-oil is converted into fuel, most of the cases it requires a purchase of hydrogen. The article states that hydrogen is the future and it is a clean energy that has water as a by-product. Today, there are different types of electrolysis methods such as water and alkaline water electrolysis.

Water electrolysis process is when the water molecule becomes the reactant and dissociates to hydrogen and oxygen through electricity. The electricity can come from renewable energy sources such as wind, solar or hydropower. Alkaline water electrolysis is another way to produce hydrogen this method uses an alkaline solution as an electrolyte to create hydrogen molecules and hydroxyl ions throughout electricity. These methods are effective and have a high cell efficiency and a higher hydrogen production with increased level of purity. However, the disadvantages with this technique is that the maintenance is expensive, and the transportation and storage still must be improved.

Table 4 Comparison between different methods

Production Method	Benefits	Difficulties	Efficiency (%)	Price $/kg
Pyrolysis	Cheap feedstock and environmentally friendly CO_2 neutral	Tar formation and irregular amount of H_2 levels storage still must be improved	35–50	1.70
Gasification	Cheap feedstock and environmentally friendly CO_2 neutral	Tar formation and irregular amount of H_2 levels storage still must be improved	30–40	2.05
Electrolyser	No emission and O_2 as by product	Transportation and storage still must be improved	60–80	10.30

As shown in table 4, the pyrolysis is cheaper to maintain and use, but it is not as efficient as the electrolyser. The electrolyser has a higher efficiency, but it is expensive to maintain, another positive aspect with electrolysis is that the product is O_2 which is environmentally friendly. When a solution for reduction of the cost during the electrolysis comes up then this method will be very efficient in the future.

4 CURRENT STUDY

4.1 Circulating fluidized bed boilers (CFB)

CFB type boilers are the most appropriate for large-scale applications, primarily because of its high investment cost. As the name suggests, the bed material in CFB type boilers is not restricted to the bottom of the furnace, but instead swirls around in the entirety of the boiler. Achieving the circulating effect is possible by increasing the velocity of the primary air to a point where the bed surpasses the bubbling state. By design, a CFB boiler is very similar to Bubbling Fluidized Bed (BFB) boiler, but since the thermal bed covers a wide area of the boiler, the heat transfer to the cooling water reaches a higher efficiency and CFB type boilers can reach an efficiency up to 95 % (José & Pascual, 2011).

As figure 7 shows, at the bottom of the boiler there is a bed made of inert material. Bed is where the sand and fuel are located. The air comes from under the bed thanks to high pressure. When the air comes at high pressure this results in the bed material and coal particles lifts and its kept in suspension, thereafter combustion occurs in the suspended condition.
The nozzles have a special design at the bottom of the bed which results in a smooth air flow without any clogging. The bed has a primary and secondary fan, the primary fan supports the heated fluidizing air and the secondary air fan supports the heated combustion air. The nozzles built in the walls at different heights spreads the combustion air inside the furnace.

Because of the flue gases particles from the burned coal, ash and bed material travels up to the upper area of the furnace which results into a cyclone. During the cyclone separation occurs between the heavy particles and the gas falls as shown in the figure 7.

The bed material is composed of sand and a portion of this sand is lost in the ash due to the process, this sand needs to be refilled. Fuel fired boilers use the ash from the combustion of the fuel to refill the sand in the bed. Boilers that use biofuels which give low ash content then sand will be the material used to refill the bed. If the fuel for example has a high value of Sulphur limestone is added to the bed material which reduces the emission of SO_2 (Brighthubengineering, 2020).
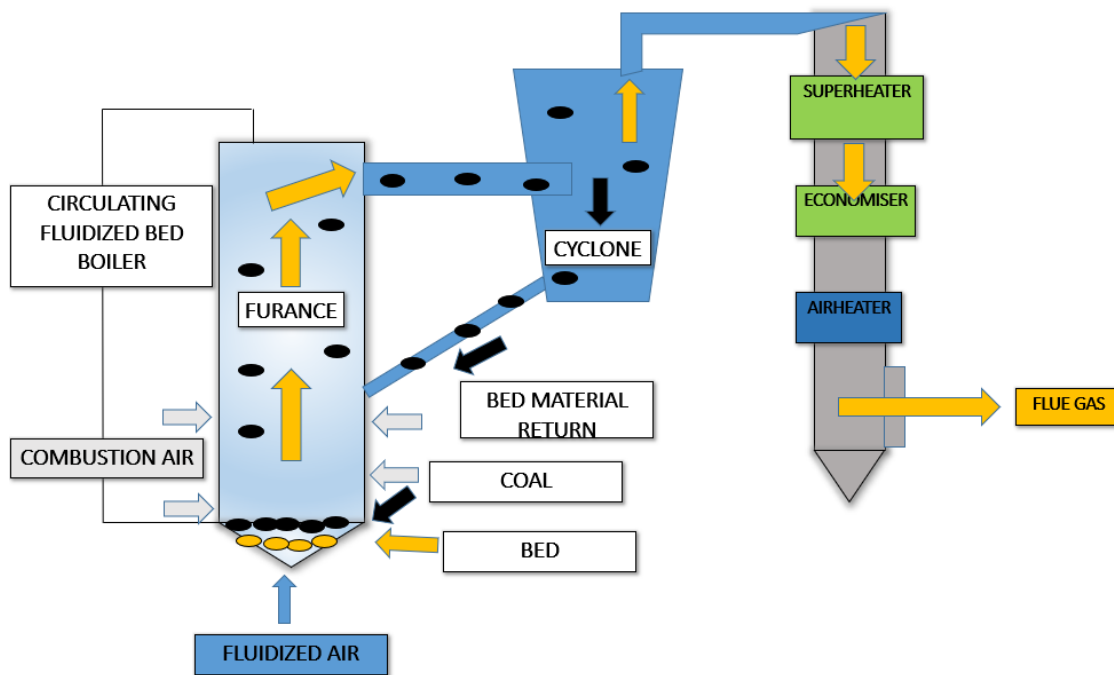
Figure 7 Circulating fluidized bed boiler (CFB) – Schematic

4.2 Description of Unit 7

Unit 7 (Boiler 7) is the newest boiler in Mälarenergi, Västerås and began operation in 2020. Boiler 7 is a CFB-boiler with capacity of 150 MWh thermal power. The annual fuel consumption is 250 000 tons of recycled wood, sawmill by products, wood chips, barks of trees, energy forest and peat. Boiler 7 has an operating time of about 5 500 hours annually, with full load the equivalent operating time is 4 500 hours annually. Heat and electricity production are 600 GWh and 250 GWh respectively (Mälarenergi, 2020).

Boiler 7 works in accordance with CFB technology, a combustion technique that is well suited for biofuel firing. The CFB technique allows firing with fuel with a high moisture content and varying particle size, which provides considerable flexibility as regards the choice of fuel. The boiler is primarily fired with recycled wood, sawmill by products, wood chips, barks of trees, energy forest and peat. When the fuel enters the boiler room, it is divided into two fuel compartments and then transferred via worm conveyors forward to the fuel feeders at the bottom of the boiler. Air is supplied at several levels in the boiler, which causes the sand and ash from the fuel to be blown upwards along with the flue gases and on to the cyclones, where they are separated and returned to the bed. The flue gases that are formed during combustion are routed upwards in the boiler house, before proceeding through the intermediate and final superheaters, dust cleaning and the flue gas condenser, and out through the chimneys. The flue gas temperature reaches a maximum of around 850°C inside the boiler.

Figure 8 CHP plan Unit7 Source: (Mälarenergi, 2020)

5 RESULTS

5.1 Pyrolysis gasification for Unit 7

The table below illustrates monthly forecast production of heat and power for unit 7 at Mälarenergi in Västerås. The data has been provided to us by Mälarenergi (2020), based on figure 1, the blue section of the table shows the heat production and the red section shows the power production for each month.

Table 5 Average monthly forecast production of heat and power for unit 7

Time	Heat, MW	Power, MW	Average total generated heat & power, MW
January 2021	100	49	149
February 2021	101	49	150
March 2021	99	48	147
April 2021	49	22	71
May 2021	40	19	59
June 2021	0	0	0
July 2021	0	0	0
August 2021	0	0	0
September 2021	42	20	62
October 2021	70	32	102
November 2021	94	45	139
December 2021	85	41	126

The table below shows the results obtained from Aspen plus simulations when pyrolysis gasification is implemented, the simulation has been done by C.A. Salman (2020). The blue section shows heat production, red section shows power production and green section shows the biofuel production. The table also shows how much biomass is needed to implement pyrolysis gasification and the hydrogen production with help of gasification.

Table 6 Result from simulation of CHP plant with integration of pyrolysis gasification

Biomass without integration, kg/s	Biomass with integration, kg/s	Heat, MW	Power, MW	Gasoline and Diesel, MW	Biomass for pyrolysis, kg/s	Biomass for gasification, to produce required H2, kg/s
16	16	101	47	0	0	0
16	16	101	47	0	0	0
16	16	101	47	0	0	0
8	11	49	24	40	6	4
7	10	41	20	40	6	4
0	4	3	4	40	6	4
0	4	3	4	40	6	4
0	4	3	4	40	6	4
7	10	42	21	40	6	4
11	14	70	33	40	6	4
15	16	101	47	0	0	0
14	16	87	41	40	6	4
Tot, MWh		467 933	226 000	213 373		

Figure below shows monthly comparison between heat and power productions forecast, without integration of pyrolysis gasification and electrolyser, the values can be seen in table 5.
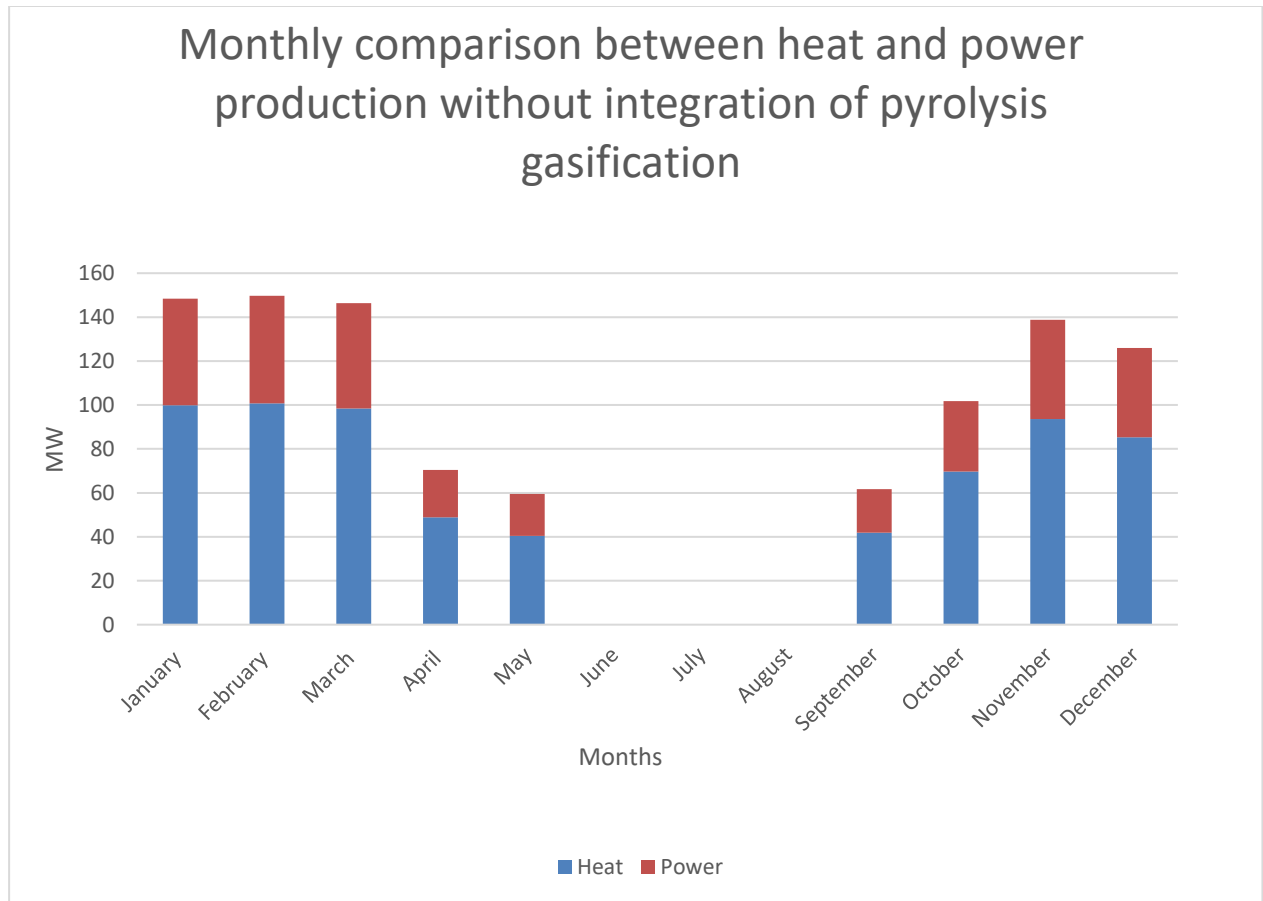
Figure 9 Monthly comparison between heat and power production in unit 7

Figure below shows monthly comparison between production of heat, power and biofuel obtained from the Aspen plus simulation when implementing pyrolysis gasification method, the values for this figure can be found in table 6.
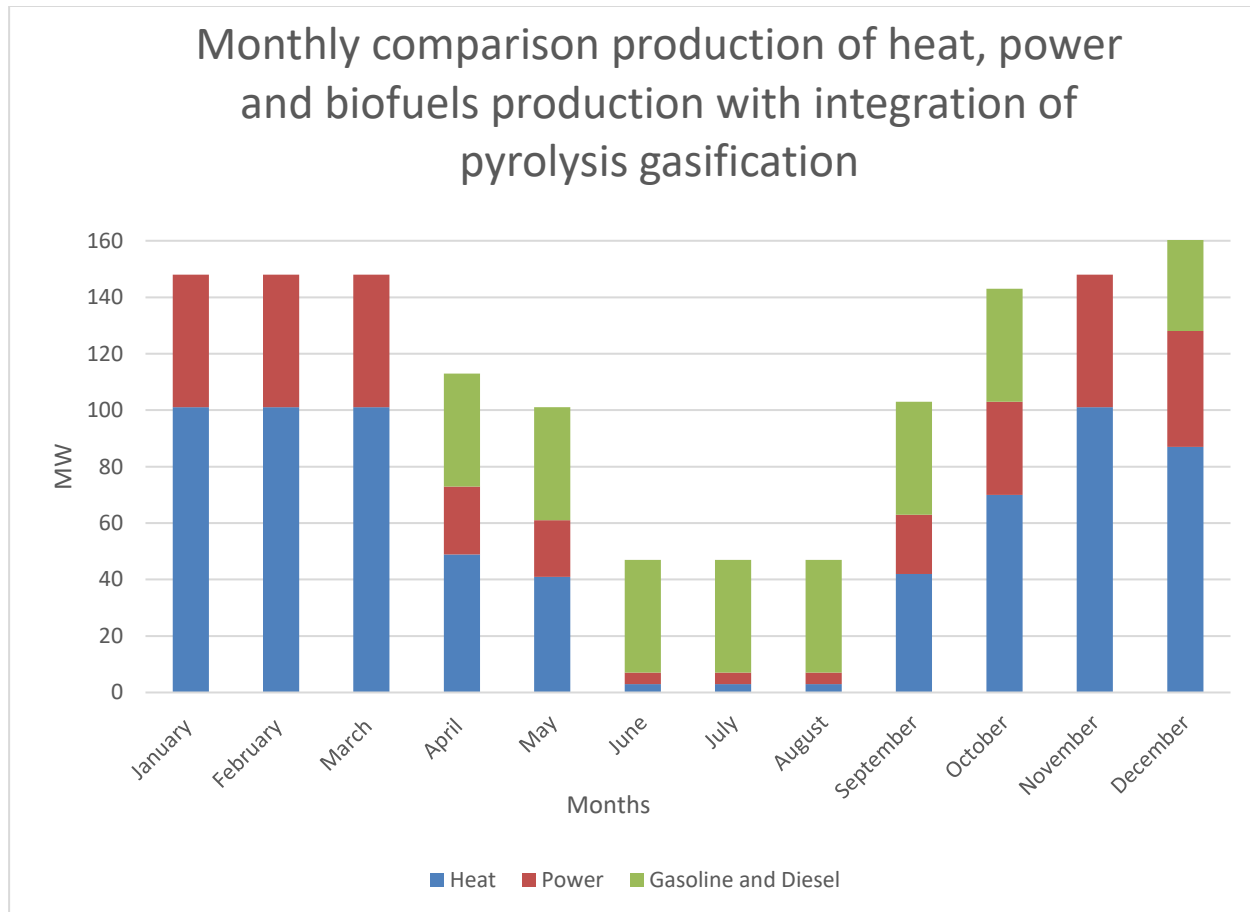
Figure 10 Monthly comparison production of heat, power and biofuels production

5.2   **Electrolyser gasification for Unit 7**

The table below shows the results obtained from Aspen plus simulations provided by C.A. Salman (2020), when electrolyser gasification is implemented. The blue section shows the heat production, red section shows power production and green section shows biofuel production. The table also shows how much biomass is needed to implement pyrolysis gasification and the hydrogen production with help of gasification.

Table 7 Result from simulation of CHP plant with integration of Electrolyser gasification

Biomass without integration kg/s	Biomass with integration kg/s	Power, MW	Heat, MW	Net power	Gasoline and diesel, MW	Biomass for pyrolysis kg/s	Power required, MW
16	16	47	101	47	0	0	0
16	16	47	101	47	0	0	0
16	16	47	101	47	0	0	0
8	16	43	92	14	40	6	29
7	16	43	92	14	40	6	29
0	11	29	59	0	40	6	29
0	11	29	59	0	40	6	29
0	11	29	59	0	40	6	29
7	16	43	92	14	40	6	29
11	16	43	92	14	40	6	29
15	16	47	101	47	0	0	0
14	16	43	92	14	40	6	29
Tot, MWh		325 867	694 400	173 333	213 373		152 533

Figure below shows monthly comparison between production of heat, power and biofuel obtained from the Aspen plus simulation when implementing electrolyser method, the values for this figure can be found in table 7.
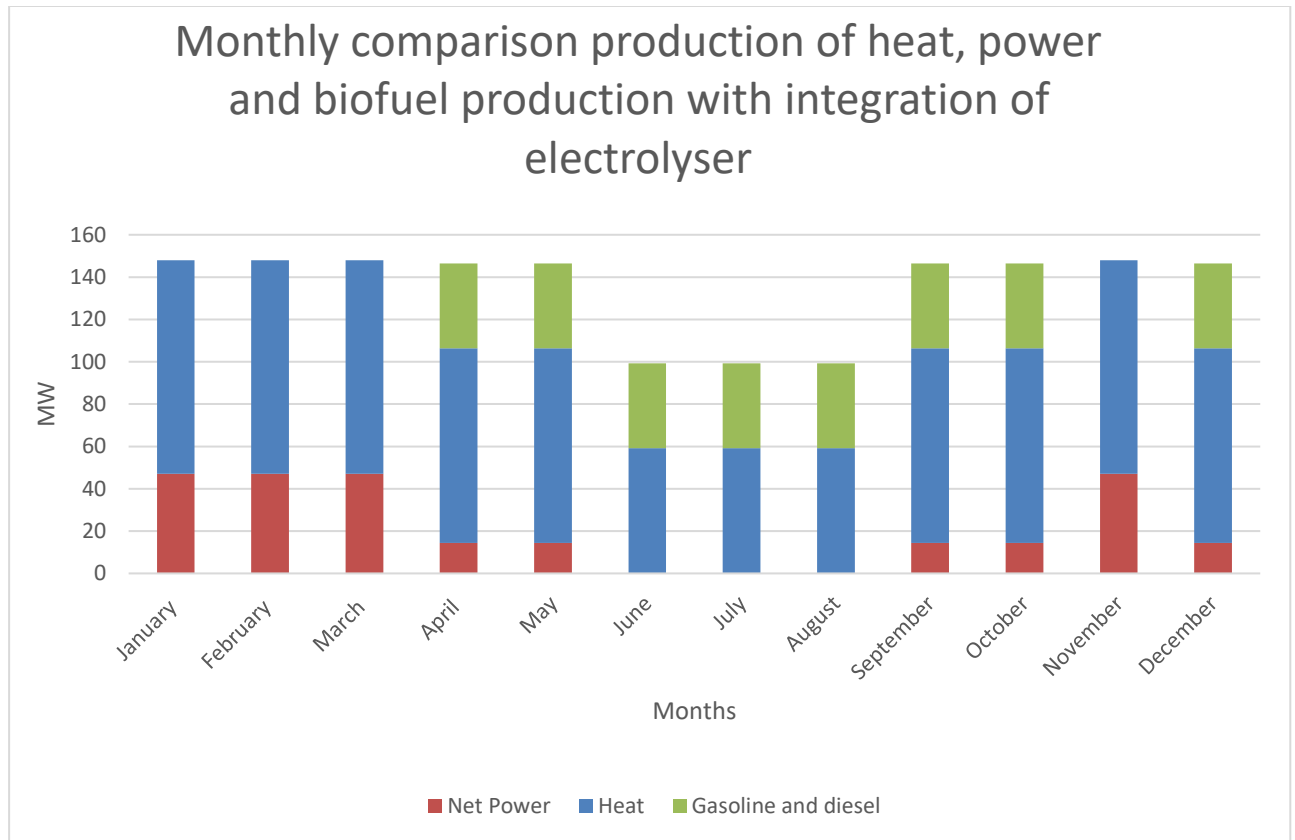

Figure 11 Monthly comparison production of heat, power and biofuel production in unit 7

5.3 Comparison HEAT and POWER production between Electrolyser and Pyrolysis gasification

The table below illustrates monthly comparison heat production between electrolyser and pyrolysis gasification results obtained after the simulations. The green section shows heat values for electrolyser and blue section shows heat values for pyrolysis gasification.

Table 8 Monthly comparison heat production between Electrolyser and Pyrolysis Gasification

Time	Heat, MW Electrolyser	Heat, MW Pyrolysis gasification
January 2021	101	101
February 2021	101	101
March 2021	101	101
April 2021	92	49
May2021	92	41
June 2021	59	3
July 2021	59	3
August 2021	59	3
September 2021	92	42
October 2021	92	70
November 2021	101	101
December 2021	92	87
Total, MWh	694 400	467 933

Figure below shows monthly comparison between heat production with electrolyser and pyrolysis gasification, based on the values from table 8.
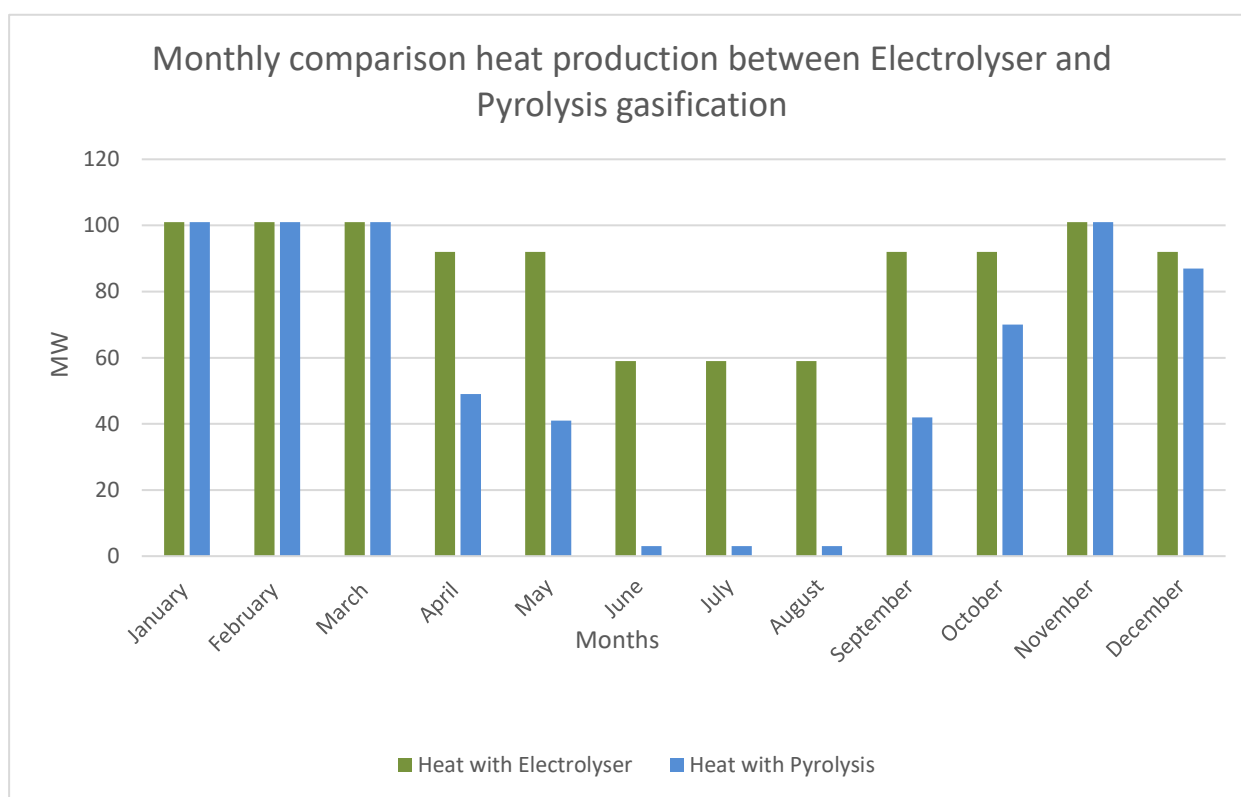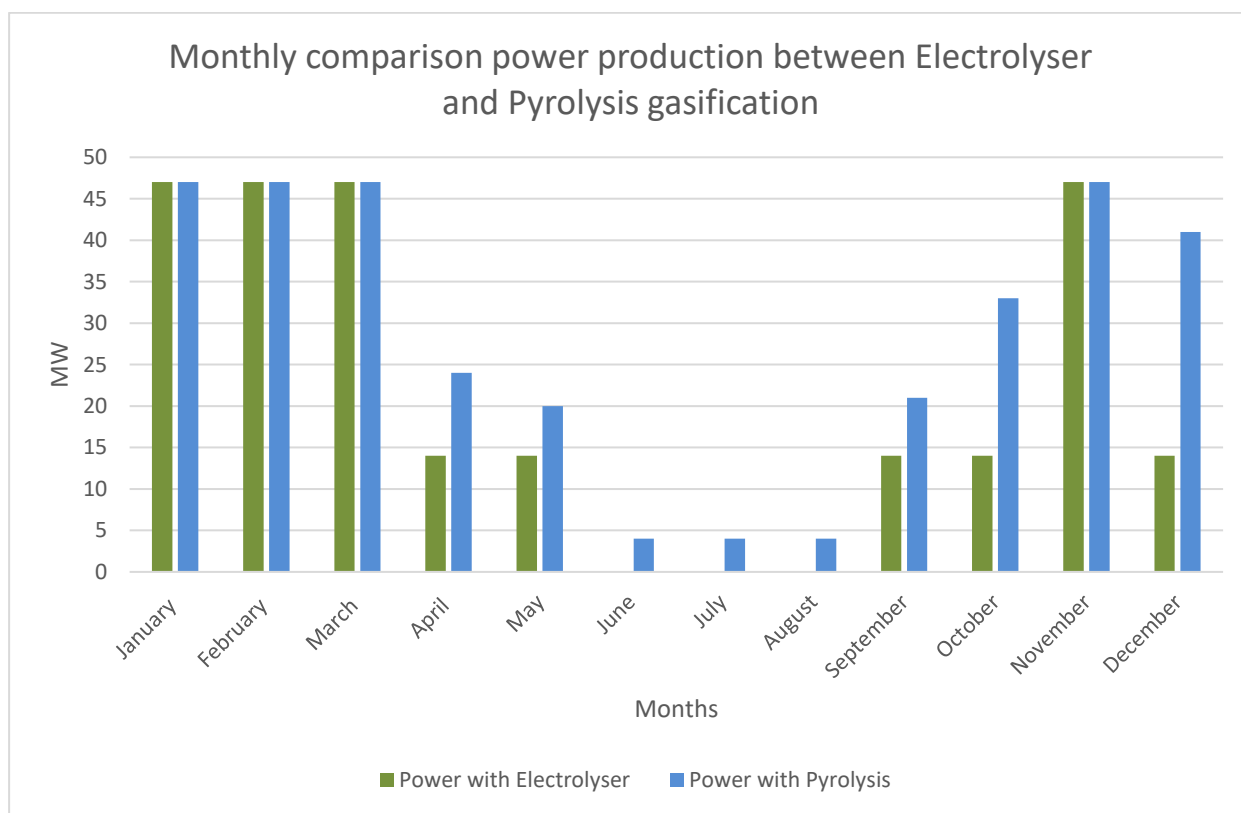

Figure 12 Monthly comparison heat production between Electrolyser and Pyrolysis gasification

The table below illustrates monthly comparison power production between electrolyser and pyrolysis gasification results obtained after the simulations. The green section shows power values for electrolyser and blue section shows power values for pyrolysis gasification.

Table 9 Monthly comparison power production between Electrolyser and Pyrolysis Gasification

Time	Net Power, MW Electrolyser	Power, MW Pyrolysis gasification
January 2021	47	47
February 2021	47	47
March 2021	47	47
April 2021	14	24
May 2021	14	20
June 2021	0	4
July 2021	0	4
August 2021	0	4
September 2021	14	21
October 2021	14	33
November 2021	47	47
December 2021	14	41
Total, MWh	173 333	226 000

Figure below shows monthly comparison power production between electrolyser and pyrolysis gasification, based on the values from table 9.

Figure 13 Monthly comparison power production between Electrolyser and Pyrolysis gasification

5.4   Costs and income for the implementations

5.4.1 Cost estimations

The table below demonstrates the total investment cost for the implementation of pyrolysis gasification and electrolyser. The investment costs are based on different price scenarios for each step during the application. The prices for gasification are taken from the article "*Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant*" written by H. Thunman et al. (2018) and the prices for electrolyser was provided to us by E. Dahlquist (2020).

Table 10 Investment costs for the implementation of gasification and electrolyser

Investment costs	
Pyrolysis gasification	**Electrolyser**
87 030 000 kr	49 060 000 kr

The table below illustrates annual electricity cost to maintain the electrolyser based on multiple price scenarios. The prices are provided to us by E. Dahlquist (2020), an estimation has been done on how much the electricity the electrolyser needs to function and based on that a calculation has been done with the help of the different price scenarios.

Table 11 The annual electricity cost to maintain the electrolyser based on different price scenarios

Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Price	0,15 kr	0,50 kr	1,00 kr	1,50 kr
Cost	22 880 000 kr	76 266 667 kr	152 533 333 kr	228 800 000 kr

Table below illustrates annual fuel cost to maintain the electrolyser and pyrolysis gasification based on different price scenarios. These price estimations have been used to see how the cost would change with different price ranges. The prices are provided to us by E. Dahlquist (2020), based on the simulation data for the total production in MWh an estimation can be done on the price for the fuel by using the cost of wood chips kr/MWh.

Table 12 The annual wood chips cost for different implementations based on different price scenarios

Scenarios	Scenario 1	Scenario 2	Scenario 3
Wood chips (kr/MWh)	190	180	170
Electrolyser	164 869 333 kr	156 192 000 kr	147 514 667 kr
Pyrolysis gasificaion	131 847 333 kr	124 908 000 kr	117 968 667 kr

The table below shows annual cost for an extra employee to maintain different implementations such as electrolyser or pyrolysis gasification. The annual payment is extracted from Alla studier *(Alla studier, 2020).*

Table 13 The annual cost for an extra employee to maintain the different implementations

Pyrolysis gasification and Electrolyser	Annual payment
Operating technician	388 800 kr

The table below highlights the total annual cost for each implementation based on mean values from different price scenarios. The cost values have been calculated with the help of the scenarios presented above.

Table 14 The total annual cost based on mean values from the different scenarios

Implementations	Pyrolysis gasification	Electrolyser
Total costs	125 296 800 kr	276 700 800 kr

5.4.2 *Profit estimations*

The table below demonstrates annual profit when selling heat at a fixed price that is produced in the CHP plant with the help of different implementations. The fixed price is provided to us from Mälarenergi AB (2020). Thanks to the fixed price at 440 kr/MWh a profit estimation can be done by looking at the produced heat MWh from the Aspen plus simulations.

Table 15 The annual profit when selling the heat that is produced with a fixed price

Implementations	Electrolyser	Pyrolysis gasification
Selling fixed price	440 kr	440 kr
Profit	106 937 600 kr	92 650 800 kr

Table below illustrates annual profit when selling the electricity produced in CHP plant with the help of different implementations at different price ranges. The prices are provided to us by E. Dahlquist (2020). With the help of the simulation data, the produced electricity in MWh can be obtained, this was used when calculating the profit.

Table 16 The annual profit when selling the electricity based on different electricity price scenarios

Price	0,15 kr	0,50 kr	1,00 kr	1,50 kr
Electrolyser	9 100 000 kr	30 333 333 kr	60 666 667 kr	91 000 000 kr
Pyrolysis gasification	11 865 000 kr	39 550 000 kr	79 100 000 kr	118 650 000 kr

The table below illustrates annual profit for each implementation when selling the biofuel that is produced in the CHP plant with the help of the different implementations, at different price ranges the prices are provided to us by E. Dahlquist (2020). With the produced biofuel obtained from the Aspen plus simulation, a profit analysis can be done by using the different price ranges.

Table 17 The annual profit for electrolyser and pyrolysis gasification when selling the produced biofuels based on different price scenarios

Selling price (kr/L)	2,00 kr	3,50 kr	5,00 kr
Profit	43 105 745 kr	75 435 055 kr	107 764 364 kr

The table clearly shows the total profit for each implementation based on mean values from the different price scenarios.

Table 18 The total annual profit based on mean values from the different scenarios

Implementations	Pyrolysis gasification	Electrolyser
Total costs	230 377 105 kr	230 147 655 kr

The table below illustrates the annual net balance based on equation 2, like mentioned above in the methodology under the subtitle equations. For each implementation based on investment, cost, and profits. The net balance uses the average profit and costs for the different implementation based on the simulations and price scenarios, the annuity based on equation 1 is used in this formula as with an interest of 6%.

Table 19 The annual net balance for the implementations

Implementations	Electrolyser	Pyrolysis gasification
Net balance	-50 390 948 kr	98 272 233 kr

6   DISCUSSIONS

The results that have been achieved from the Aspen plus simulations and data from Mälarenergi AB provide are positively promising of how a CHP plant with integrated solutions such as pyrolysis gasification and electrolysis gasification would work. The data provided from Mälarenergi in table 5 illustrates the average monthly production of heat and power for Unit 7. There is no heat or power production in unit 7 between the months June to August, this can be utilized better by applying pyrolysis gasification to maximize the efficiency of the plant. Moreover, figure 9 demonstrates this very clearly, high production during the winter periods and a decrease during summer seasons.

When pyrolysis gasification is implemented gasoline and diesel can be produced during the year especially during the summer period from June to August. This is very beneficial since the CHP plant did not generate heat or power during summertime. Table 6 shows the result obtained from the simulation for pyrolysis gasification. The monthly heat and power production when implementing pyrolysis gasification is almost the same compared to the scenario without pyrolysis gasification demonstrated in table 5. Meanwhile, the production for heat and power increases significantly during the periods from June to August, from 0 kg/s to 4 kg/s, this can be seen in table 6 with the titles Biomass without integration in June month was 0 kg/s and Biomass with integration of pyrolysis gasification same month for June increased to 4 kg/s. This means an increase of biomass is needed for the implementation of pyrolysis gasification for every standard input is increased with roughly about 4 kg/s. This growth is due to the production of hydrogen with the support of gasification and the addition of more biomass to the process to make it work.

Furthermore, figure 10 demonstrates the production of heat, power and gasoline and diesel and from April to October and December the CHP can produce gasoline and diesel. However, according to the results obtained from the simulation except for the month November no production of fuel occurs. The simulation shows that in December fuel can be produced, but this can be changed due to the cold temperature level it reaches during the winter. That is why November and December will be neglected; thus, this result of fuel production of fuel can occur during the period April to October. This technique can be very beneficial for unit 7 to implement when the plant is not in function during the summertime. Fuel can be generated which can give a positive economical outcome by selling or using the biofuel, compared to a

scenario where the implementation is not implemented which results to no production during the summer periods.

When Electrolyser gasification is implemented gasoline and diesel can be produced during the year especially during the period from April to October and December a total of 213 373 MWh. Especially during the summer periods from June to August monthly the CHP plant can produce 40 MW of gasoline plus diesel and 59 MW of heat this shows in table 7.

Table 7 explains the simulation result regarding the implementation of electrolyser. The study shows different types of production scenarios that occurs during the process, what is interesting to see with this outcome is the net power during the summer period. The net power during the period June to August is equal to zero, this is because the monthly power production during June to August is on 29 MW and the monthly required power run the electrolyser during the same period is on 29 MW which can be seen as a consequence. Table 7 shows also monthly gasoline production, gasoline production occurs during the whole year except for January, February, March, and November this is because more heat is required to produce during the cold periods. Production of gasoline occurs during December but if the winter is harsh this needs to be neglected due to heat production will increase instead. During the months from April to December monthly can be produced 40 MW of biofuels such as gasoline and diesel and totally 213 373 MWh.

Table 8 shows monthly comparison of heat production between Electrolyser gasification and pyrolysis gasification. From the table 8 we can conclude that implementing electrolyser gasification to the CHP plant results to a higher production of heat compared to pyrolysis gasification. The total heat production with electrolyser is on 694 400 MWh and 467 933 MWh by implementing pyrolysis gasification. This is because heat production during the summer period June to August for electrolyser is high compared to the pyrolysis. For electrolyser the heat production during this period is 59 MW and 3 MW for pyrolysis. This is a consequence for electrolyser a high heat production during the summer period is not beneficial due to the climate being hot, a solution to this is to cool down the heat with the help of a close by river but with pyrolysis gasification this issue does not occur.

In Table 8 monthly heat production remain the same as implementing pyrolysis gasification until the month of march, but then from April CHP plant heat production implementing electrolyser produce almost double heat than pyrolysis gasification, we can produce 92 MW of heat implementing electrolyser and 49 MW of heat implementing pyrolysis gasification. However, the production of heat increases significantly during the period from June to August

and implementing electrolyser we get 59 MW of heat compared of only 3 MW implementing pyrolysis gasification. This increase is due to the production of hydrogen with the help of gasification, more biomass is needed to add for the process to work.

Figure 11 shows the result obtained from the simulation which shows monthly comparison production of heat, power and biofuels production in unit 7 from April to October and December the CHP plant can produce biofuels like gasoline and diesel. However, according to the result from the simulation except for the month November no production of fuel occurs. The simulation shows that in December fuel can be produced but this can be changed due to the weather, how cold it becomes during the winter. That is why November and December will be neglected, this results to production of fuel can occur during the period April to October. This technique can be very beneficial for unit 7 to implement when the plan is not in function fuel can be generated which can give a positive economical outcome.

Table 9 shows monthly comparison power production between Electrolysis and Pyrolysis gasification. We can conclude that by implementing pyrolysis gasification we produce more power a total of 226 000 MWh than implementing electrolyser gasification which is 173 333 MWh. Especially from June to August we do not produce any power figure 13 shows clearly these differences. As mentioned before this is due to electrolysing consuming the production of power to maintain the biofuel production.

After our analysis regarding the economic aspect, we have learned that the investment costs for pyrolysis gasification is higher than the investment costs for electrolysis which is illustrated in table 10. The annual cost for pyrolysis gasification is cheaper when compared to the annual cost for electrolyser which are illustrated in table 11 this is because of the required electricity needed to maintain the electrolyser which results to a higher annual cost compared to pyrolysis.

In the future, when Sweden becomes more dominant in for example wind power the electricity price will fall, and this will result to a cheaper maintenance of the electrolyser. This will be a very good environmentally friendly option. The downside with electrolyser based on our simulation is that lots of heat is produced during the summertime which is not needed due to the hot climate. Therefore, the heat generated through this period is not profitable as there is no demand for it. When we look at the heat production scheme, pyrolysis gasification is

more efficient. This efficiency is due to the fact that heat is produced only when needed during the wintertime. This results in a low heat production during the summer times which is a better economic scenario compared to electrolyser, these results to that the pyrolysis gasification has an annual profit compared to electrolyser.

7 CONCLUSIONS

In conclusion, the implementation of the techniques is rather similar, but pyrolysis gasification is found to be the most suitable and advantageous for now. The electrolyser needs more research and elaboration for it to be implemented in a CHP plants. The electrolyser according to our simulations results needs further development to be more efficient, because especially during the summer period a lot of heat is produced and in combination with high maintenance cost pyrolysis gasification economically is more convenient for now. Thus, for cost related purposed we have decided to use to continue with the implementation of pyrolysis gasification process rather than pyrolysis electrolyser.

The annual net balance for each implementation is illustrated in table 19, for pyrolysis gasification in conclusion can be made that it has an annual profit compared to electrolyser. This is because as mentioned above the electrolyser produce lots of heat during the summer period that cannot be sold also in combination with the electricity prices in Sweden results into an economic loss.

8   SUGGESTIONS FOR FURTHER WORK

The suggestion for further work is to evaluate these scenarios over a longer period of time to be able to achieve a more accurate analysis regarding the implementation. Additionally, more research is needed to be conducted for electrolysis in CHP plants as this subject does not have many scientific reports to conclude and hopefully in the future this will change. The economical aspect uses reference prices and costs which can change over time and this needs to have further work on as well in the future.

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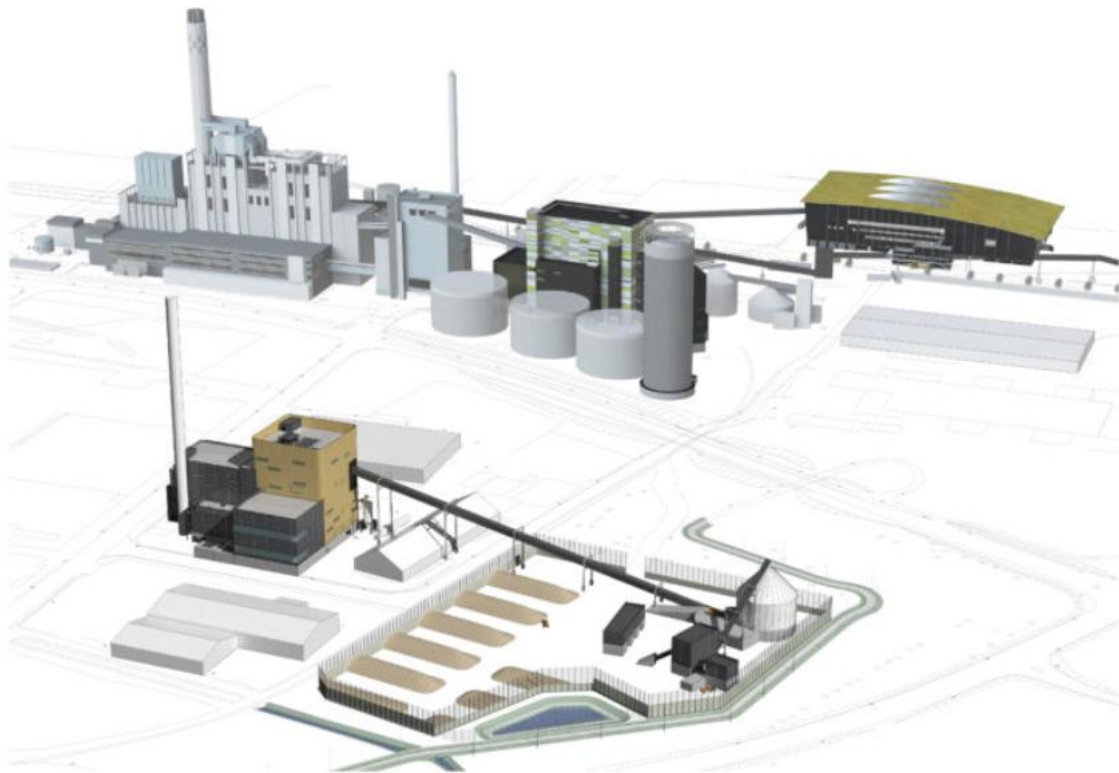
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APPENDIX 1 CHP UNIT 7