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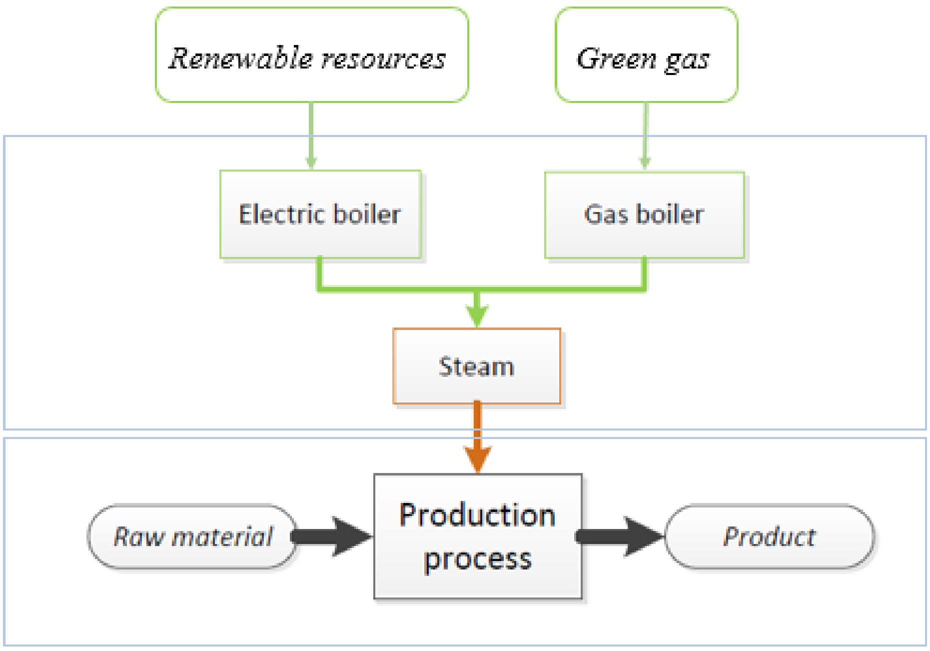

Evaluation of Electric and Hybrid Steam Generation for a Chemical Plant under Future Energy Market Scenarios

Innovative and Sustainable Chemical Engineering

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Department of Space, Earth and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2019

MASTER'S THESIS

Master's Thesis within the *Innovative and Sustainable Chemical Engineering* programme

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Cover: Schematic picture representing a hybrid steam generation system for a chemical plant

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Abstract

The reduction of greenhouse gas emissions is one of the largest environmental challenges in modern time, in particular the reduction of fossil CO_2. The industry is a large source of CO_2 emissions and the chemical process industry will be in focus of this master thesis project. Nouryon´s site in Stenungsund is dependent on steam for their production of specialty chemicals. Steam production is energy demanding and fossil-based gases are used as fuel for the process. Nouryon's ambition is to reduce their carbon footprint and therefore different alternatives for producing steam is investigated.

The aim of this master thesis project is to investigate the possibility to implement new technologies for steam production and to identify options to reduce the fossil CO_2 emissions in the future at the lowest possible cost. Power-to-heat is one promising concept of electrification and therefore the implementation of an electric boiler is investigated. The other boiler of interest is a gas boiler, similar to the existing steam boiler on-site. A hybrid system of these two boilers is also considered.

A model to calculate the total annualized cost at different capacities of the boilers was developed and used for optimisation in which the optimal capacities with the lowest total annualized cost were identified. A reference scenario for current market conditions, and two future scenarios were evaluated. A sensitivity analysis of the Capex was conducted to the reference scenario in order to estimate how sensitive the model is to changes in Capex. Two future scenarios from World Energy Outlook 2017 were evaluated, one new policies scenario where current policies and announced polices were used to predict the future and a sustainable development scenario that reflects a future focusing on reducing the fossil CO_2 emissions. In addition, a fixed capacity of 36 MW and 29 MW for an electric boiler and a gas boiler respectively, was compared to only having a gas boiler. Constraints on fossil CO_2 emissions were implemented as well in this comparison between a fixed capacity and a gas boiler.

Results from the model show that for the reference scenario and the new policies scenario a combination of technologies is the most profitable. In the sustainable development scenario a larger amount of electricity is incorporated and in the future only using an electric boiler is the most feasible.

In comparison between the fixed capacity and a gas boiler the gas boiler is more expensive. When constraints to the CO_2 emissions are added the cost for the fixed capacity becomes higher, since it incorporates more electricity. For the gas boiler the cost becomes significantly higher since it incorporates more bio-methane as fuel which has a higher cost than electricity.

Key words: Electric steam generation, Gas boiler, Fossil CO_2 emissions, Chemical plant

Acknowledgements

This thesis work was carried out at Nouryon in Stenungsund, during the period September 2018 to March 2019. The purpose of the thesis was to investigate possible options for replacing the site's main steam boilers which are near the end of their useful service life.

I would like to thank my supervisors at Nouryon, Charlotte Bergek and Peter Strunk for answering all my question and providing me with information about the site and all the process data necessary for this thesis. I would also like to thank the entire staff at Nouryon, their knowledge and help was essential for this work.

I would like to thank my examiner Simon Harvey and especially my supervisor Holger Wiertzema at Chalmers for helping me with theoretical questions and guidance in this thesis.

Göteborg, March 2019

Malin Kerttu

Contents

Notations

Roman upper case letters

Q_{Steam}	Boiler steam output	[MWh/h]
C_E	Investment cost of boiler with capacity Q	[MSEK]
C_B	Investment cost of boiler with capacity Q_B	[MSEK]
M	Cost capacity exponent	[-]
Q_{EB}	Steam produced by electric boiler	[MWh/h]
Q_{GB}	Steam produced by gas boiler	[MWh/h]
$Q_{naturalgas}$	Steam produced by gas boiler from natural gas	[MWh/h]
$Q_{bio-methane}$	Steam produced by gas boiler from bio-methane	[MWh/h]
Q_{tot}	Total steam production	[MWh/h]
$Q_{max,EB}$	Maximum capacity of electric boiler	[MW]
$Q_{max,GB}$	Maximum capacity of gas boiler	[MW]
$Q_{max,tot}$	Total maximum steam capacity	[MW]
$Capex_{EB}$	Capital cost for electric boiler	[MSEK/year]
$Capex_{GB}$	Capital cost for gas boiler	[MSEK/year]
$Opex_{EB}$	Operating cost for electric boiler	[MSEK/year]
$Opex_{GBs}$	Operating cost for gas boiler	[MSEK/year]
$FixCost_{EB}$	Fixed operating and maintenance cost for electric boiler	[SEK/kW/year]
$FixCost_{GB}$	Fixed operating and maintenance cost for gas boiler	[SEK/kW/year]
$VarCost_{EB}$	Variable operating and maintenance cost for electric boiler	[SEK/MWh]
$VarCost_{GB}$	Variable operating and maintenance cost for gas boiler	[SEK/MWh]
$Price_{naturalgas}$	Fuel price for natural gas	[€/MWh]

$Price_{bio-methane}$	Fuel price for bio-methane	[€/MWh]
$Price_{el}$	Electricity price	[€/MWh]

Roman lower case letters

m_{steam}	Flow rate of steam	[kg/s]
h_s	Enthalpy of steam	[MJ/kg]
h_{fw}	Enthalpy of feedwater	[MJ/kg]
i	Discount rate	[%/year]
n	Economic lifetime of plant	[year]
r	Annuity factor	[1/yr]
η_{EB}	Efficiency of electric boiler	[%]
η_{GB}	Efficiency of gas boiler	[%]

Abbreviations

GB	Gas boiler
EB	Electric boiler
EFAB	Ethylene terminal
EMU	Emulgol plant
EO	Ethylene oxide
EU	European Union
ETS	Emissions Trading System
MEA	Monoethanolamine
STF	Specialty surfactants plant

1 Introduction

The economic growth in the world results in an increased demand for energy. To satisfy this demand the use of fossil fuels, especially natural gas and oil, has increased [1]. Non-renewable resources in industrial production processes lead to negative environmental effects such as the release of carbon dioxide, nitrous oxide, sulphur dioxide and particles into the atmosphere. These emissions have a negative impact on the environment including higher global temperature, air pollution, acid precipitation and stratospheric ozone depletion.

The Paris agreement stated in 2015 that the global temperature increase should be kept below 2 degrees Celsius above pre-industrial levels [2]. As a response to the Paris agreement, in 2018 a Swedish climate law came into force, stating that Sweden will be carbon neutral by 2045 [3]. An intermediate step on the way to the target in 2045 is that by 2030 Sweden should have reduced the emissions of greenhouse gases by 63 % compared to 1990 levels, excluding sectors covered by the European Union's emission trading system [3]. The United Nations have sustainable development goals worldwide, two of them are affordable and clean energy and climate action. These are clearly connected to the industrial energy sector, since by 2030 two of the targets are increased shares of renewable energy and improvements in energy efficiency. These actions and legislations make clear that a transition to clean energy is important and necessary not just for Sweden but globally as well.

In Sweden, the industry accounts for about a third of the total carbon dioxide emissions and the highest emissions are within the sectors of iron and steel, mineral (cement), refineries and chemical industry [4]. They all have an impact on the greenhouse gas emissions, but their processes differ a lot. In this thesis, the focus will be on the energy demand for heat production within a chemical plant.

Electrification of the heat production (so called Power-to-heat) is one possible way to reduce emissions. This is especially true for Sweden where there is a high amount of renewable production of electricity (wind and hydro power). Increased use of biomass-based fuels in process utility steam boilers is a further way to reduce the carbon dioxide emissions, either by using wood chips or bio-methane gas as fuel.

1.1 Background

Nouryon operates one out of six process plants within the chemical complex in Stenungsund, which is one of the largest in Sweden. Nouryon is a global producer of specialty chemicals that are used in other products such as plastics, paper, building materials, pharmaceuticals and personal care items. Nouryon's sustainability goal is to be carbon neutral and to use 100 % renewable energy at all sites by 2050 [5].

Many chemical industries are dependent on steam for their process applications. Two main measures to reduce the emissions from steam production are energy efficiency measures and substitution of fossil fuels to renewable alternatives. Both of these measures can be applied in at the Nouryon site in Stenungsund since the steam producing boilers are getting old and need to be replaced. Using bio-methane as a substitute for fossil natural gas fuel is also one possibility to reduce fossil greenhouse gas emissions.

Industrial decision makers need to comply with legislation regarding reduced emissions of greenhouse gases in the most cost-effective way. For steam production it is possible to combine different types of boilers to constitute a hybrid boiler system that can achieve emissions at the lowest possible cost. A promising technology are electric boilers with no local emissions and carbon neutrality in case the electricity is produced from renewable sources.

1.1.1 Previous work

A recent study that was made over the whole chemical complex in Stenungsund produced several reports describing options to increase the energy exchange between the industrial plants with the objective of decreasing the site's total fuel usage. The steam excess and deficit at each company was established, as well as energy saving options if there was an energy system integration. One report in this study is "Investigation of opportunities for implementation of proposed category - A energy efficiency measures" [6] which shows that low pressure steam of 3 MW could be exported from Borealis to Nouryon, which would affect the steam generation at Nouryon's production on site. Nouryon could also deliver 0.5 MW of hot water to a future hot water circuit that redistributes the water within and between the companies in the cluster. This energy is currently cooled away and wasted. The study examined heat exchange of low-pressure steam whereas this thesis focuses on production of high pressure steam. The hot water can be redistributed and does not affect the steam production of the boilers on-site.

Another report in this study is "TSA II Final Report: Methodology development for efficient integration of energy-intensive climate friendly processes in industrial clusters" [7] in which payback periods of different heat recovery systems are presented. Nouryon is part of "system 54", a site-wide combination of energy efficiency measures that could reduce the site's heat demand by 54 MW. This option importing steam from Borealis' cracker plant to the Nouryon site. The payback period was estimated at approximately four years and is slightly higher than the other systems in the report because of the high cost associated with infrastructure. Detailed cost estimates associated with the steam link to the Borealis cracker plant were not available at the time when this thesis was initiated. Furthermore, for operability reasons, it was decided to prioritize an investigation of how Nouryon can produce stream for their processes on-site.

Another report that examines a hybrid boiler concept is the master thesis "Financial feasibility of using an electric steam boiler in a multifuel steam production set and providing grid flexibility" [8]. It was written in 2015 and examines the financial feasibility of a Multifuel Steam Production Set (MSPS). A bio boiler is used for the base load of steam production and combined gas and electric boiler are used for the peak demand of steam. This study shows that a combination of technologies is profitable and therefore a combination of technologies is considered in this thesis as well.

1.2 Aim

The aim of this master thesis is to identify and evaluate possible future options to replace the existing steam boilers at Nouryon in Stenungsund in compliance with corporate and legislative requirements. Since the Swedish climate goals are stricter than EU´s climate goals the Swedish goals will be used in this thesis. The goal in Sweden is to have net zero net emissions of greenhouse gases by 2045. Boiler concepts with different types of fuel (electricity, natural gas and bio gas) as well as different operating characteristics are included in this analysis. Particular attention is paid to the significant variations of the steam demand in the correspondent processes to evaluate if the boilers can handle these variations.

The evaluation of the boiler concepts takes into account technological aspects (boiler efficiency), cost (Capex and Opex) as well as the greenhouse gas emissions consequences (in terms of changes in CO_2 emissions) for different future energy market scenarios.

1.3 Limitations

The scope of this thesis is limited to the steam production and not the optimisation of the use of steam in the process or the optimisation of other utilities such as feedwater. The focus is on on-site solutions and the option of importing steam from neighbouring plants within the chemical complex in Stenungsund is not considered.

Solid biomass fuel is not be included in this study since the Nouryon site lacks logistic capacity to handle such material at the site.

2 Steam boiler technologies

Many chemical industries are dependent on steam for their process applications. Steam is delivered through a steam boiler that converts water to steam at a certain pressure that is appropriate for the process. The heat source can be combustion of fuel, electricity or waste heat. Various fuels can be fired and most of the boilers are built for a specific fuel, so that a change in fuel often requires a rebuild. The fuel can for example be coal, oil, gas, peat, municipal waste or wood chips.

2.1 Gas fired steam boilers

There are two basic types of gas fired steam boilers, namely fired tube boilers or water tube boilers. In fired tube boiler the combustion takes place in a number of tubes and the water is located outside the tubes. In the water tube boiler, the combustion takes place in a furnace and the water is located in tubes surrounding the furnace. Water tube boiler is the most common technology for large utility steam boilers and will be described further.

Figure 1 shows a simplified configuration of a water tube boiler. The combustion takes place in a furnace and heats the water in the surrounding tubes, referred to as riser tubes. The feedwater to the boiler goes through an economizer to be preheated before entering the steam drum, located at top of the boiler. The steam drum separates the saturated steam from the saturated condensate. The water goes to the riser tubes via a downcast pipe and is heated and converted to steam and returns back to the steam drum. The saturated steam can then be further heated to superheated steam in superheaters.

Mixing of gas with air is important for the combustion process. The mixing could occur before the burner tip or just at the burner tip. The amount of air has to be higher than the theoretical amount since the combustion process is never ideal. Thus, an amount of 10 % excess air is normal operating conditions for natural gas [9].

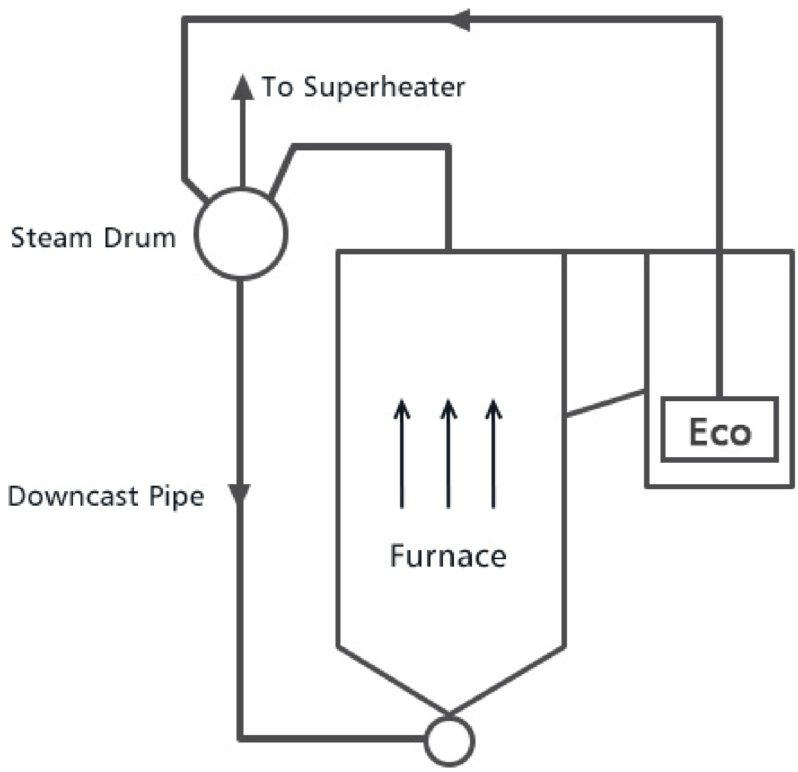

Figure 1: Schematic configuration of a gas-fired water tube steam boiler [10].

2.2 Electric steam boilers

Electric boilers have a high efficiency of up to 99 % with losses connected primarily to pumps and radiation losses. No local emissions occur [11], however emissions from production of the electricity could still exist. Common sources of renewable energy are wind, water and solar power. The two most common types of electric boilers are the electrical resistance boiler and the electrode boiler.

Electric resistance steam boiler

As the name implies the heat is generated through resistance in banks of fixed heating elements surrounded by electrical insulation. The electric current passes though the tubes in the banks and heat is created due to the resistance of the tubes. Hereby, the surrounding water is heated and converted to steam. However, this technique is mostly used for hot water production and will not be described further.

Electrode resistance steam boiler

In an electrode boiler a current is applied directly to the water by electrodes and the water provides the necessary resistance to produce heat. It is easy to scale up since adding more electrodes will produce more heat. This is the most common type of electric boiler on the market and is therefore explained in more detail. In Figure 2, the different parts of the boiler are shown.

The boiler has an inner vessel mounted on ceramic insulators which in turn are attached to the outer vessel. In Figure 2, three electrodes are used and located in the inner vessel. The power output is regulated by the water level and thus the coverage of the electrodes with water in the inner vessel.

The water level in the inner vessel is regulated by the amount of water pumped in by a circulating pump from the outer vessel and there is also a possibility to drain out water to the outer vessel again.

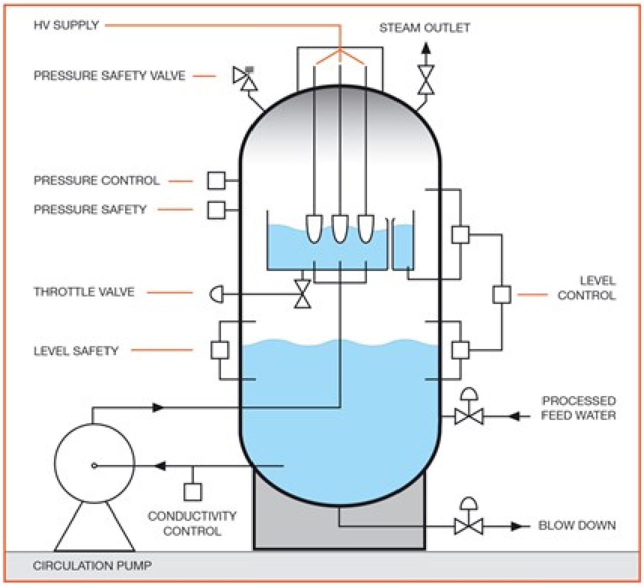

Figure 2: Electrode boiler configuration [12].

The feedwater has to be of high quality in order to use the boiler as efficient as possible. Electrical conductivity of the water is an indicator for the amount of dissolved salt in the water and is measured before entering the inner vessel. The conductivity should be low since the electricity should heat the water and not the minerals in the water. At high conductivity the efficiency decreases due to blow down of water to maintain the appropriate conductivity. High concentrations of salts can also cause scaling and lead to corrosion. This can damage the electrodes and reduce their lifetime. The pH of the water should be alkaline in order to avoid corrosion, however not too alkaline since that leads to attack of the porcelain insulators [13].

2.3 Emissions related to steam boilers

Depending on the fuel type and available technology the environmental impact is different. Combustion of fuel produces flue gases that cause emissions. Carbon dioxide, nitrogen oxides, sulphur dioxide and products of incomplete combustion are examples of common emissions [14]. The combustion of bio-based fuels does not add carbon dioxide to the atmosphere since carbon dioxide was taken up from the atmosphere during growth. However, during combustion of bio-based fuels local emissions will still occur. For electric boilers, emissions associated with the production of electricity need to be taken into account. The efficiency of the boilers has an impact as well since higher efficiencies lead to lower energy demands. Reduction of emissions can be done by cleaning or preparing the fuel before the combustion or by flue gas treatment after combustion.

Emissions related to gas steam boilers

Carbon dioxide (CO_2)

CO_2 is formed during combustion of fuel and is the primary greenhouse gas. In 2010, it accounted for 76 % of the global greenhouse gases of which 65 % came from fossil fuel [16]. In order to curb global warming, reduction of CO_2 emissions is a necessity. New technologies to reduce the CO_2 in the atmosphere are under development and techniques like CO_2 capture and storage are promising [17]. Changing from fossil fuel to a renewable fuel source is also an important measure.

Nitrogen oxides (NO_x)

NO_x contributes to acid rain, formation of photochemical smog and also affects the tropospheric ozone [18]. Nitric oxide (NO) and nitrogen dioxide (NO_2) are examples of NO_x, formed either from nitrogen in combustion air or nitrogen bound in the fuel. To some extent N_2O is formed in combustion and this is a strong greenhouse gas that affect the stratospheric ozone layer [14].

Sulphur dioxide (SO_2)

SO_2 is an air pollutant and precursor to acid rain and thereby acidification of the soil. With water in the flue gas or in the atmosphere the SO_2 transforms to sulphuric acid (H_2SO_4) that can be carried by the wind for long distances [19]. Sulphuric acid falls down on the ground, which lead to reduced photosynthesis and growth for plants. The human health is also affected since the respiratory system can be harmed by short-term exposures. This has led to emission regulations and over the last 20 years the emissions were reduces by 84 % [20].

Emissions related to electric steam boilers

Electricity can be produced from coal or gas fired boilers that run a turbine and these technologies releases emissions stated in the previous section. However, new technologies to produce clean and cost-competitive electricity are upcoming on the market. Solar and wind power are penetrating the market since the Swedish government energy polices has encouraged renewable energy. The wind power has increased from 0.5 TWh in 2000 to 17.5 TWh in 2017 and the solar power has become more cost-effective [21]. The largest part of the renewable sources is hydro power that stands for around 40 % of the total electricity production [22]. The part in electricity production that comes from CO_2 neutral sources like wind, solar, hydro power and biofuel is constantly increasing [23]. There are no local emissions produced when using the electricity even if it comes from non-renewable sources.

3 Nouryon in Stenungsund

Nouryon produces specialty chemicals at three different plants, the ethylene oxide (EO) plant, the amine plant and the surfactant plant. The EO plant is important since EO is a raw material for the other plants on site. The amine plant produces ethanol amines by the reaction between EO and ammonia. One of the products is monoethanolamine (MEA) which reacts further with ammonia to form ethylene amines. The surfactant plant has two units, the emulgol (EMU) and the specialty surfactants (STF). Both EMU and STF produce a large variety of products. A flow chart of the different products can be seen in Figure 3.

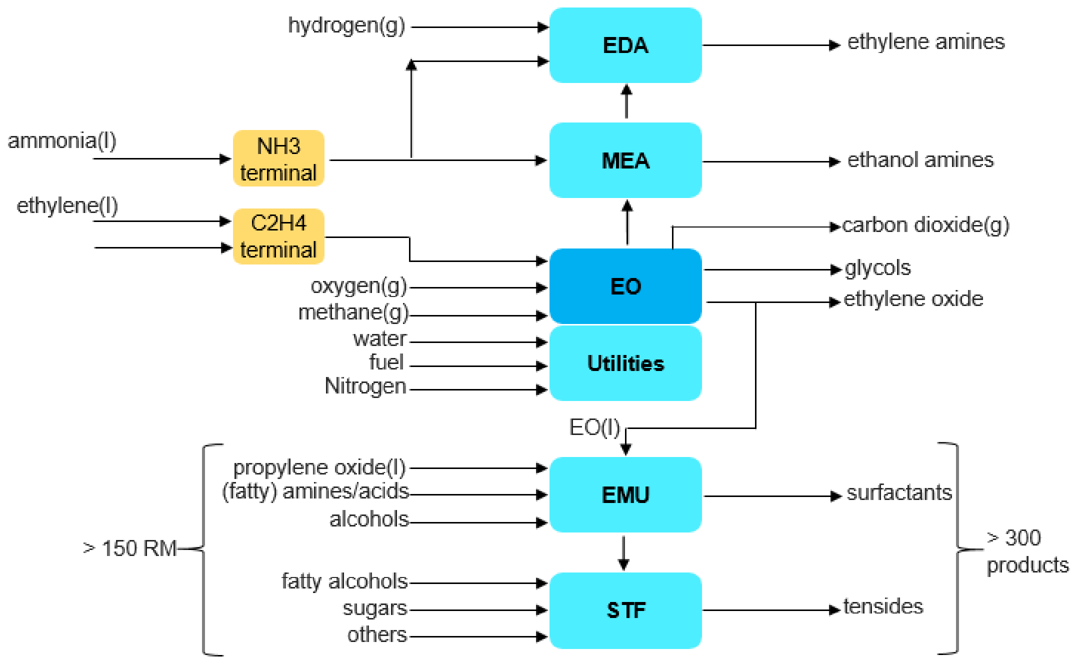

Figure 3: Schematic overview of the material flows at site Stenungsund.

The amount of products in tonnes for the years 2016 and 2017 is given in Table 1.

Table 1: Production in tonnes for the different material flows in Stenungsund *[24]*.

Plant	Material	Production [tonnes]	
		2016	2017
EO	Ethylene oxide / Glycol	100 811 / 3 537	105 729 / 4 796
Amine	Amines	70 679	77 052
STF and EMU	Surfactants and tensides	60 732	68 638

3.1 Steam system at Nouryon's site in Stenungsund

The utility system at Nouryon's plants in Stenungsund, includes steam, compressed air, cooling water from sea water, freshwater from a nearby lake, ammonia from the ammonia terminal and ethylene from a nearby plant and/or from the ethylene terminal (EFAB). The ammonia and ethylene terminal are storage tanks for ammonia and ethylene on site.

To provide the necessary steam to the different plants there are two main steam boilers on site, boiler 2 and boiler 3. Boiler 2 runs on oil and can produce steam at 28 bar(g) while boiler 3 uses gas as main fuel but can be run on oil if necessary to produce steam at 40 bar(g). There is also a waste incineration boiler, called boiler 4, that produces steam at 40 bars(g). The production of ethylene oxide (EO) is strongly exothermic and during cooling of the reactors, steam is produced and can feed the 20 bar(g) network. Boiler 2 is not run under normal conditions but works as a back-up boiler. Boiler 2 and 3 are reaching the end of their useful lifetime and need to be replaced or extensively refurbished within the next years.

The steam pressure levels in the system are 40, 28, 20, 6 and 1 bar(g). Steam is used throughout the different plants with the amine and EO plants as largest consumer. The 40 bar(g) steam is primarily used in the amine plant for heating different parts of the process. The surfactant plant uses the 28 bar(g) steam and some is sent to a nearby plant. From the 28 bar(g) network it is reduced to 20 bar(g) by a valve and is used in the amine and EFAB plants. Some of the products are highly viscous and need to be heated in order to be handled and pumped to the tanks where heating is done with 6 bar(g) steam. The boiler feedwater tank is in connection with the 1 bar(g) steam. A simplified representation of the steam system is shown in Figure 4.

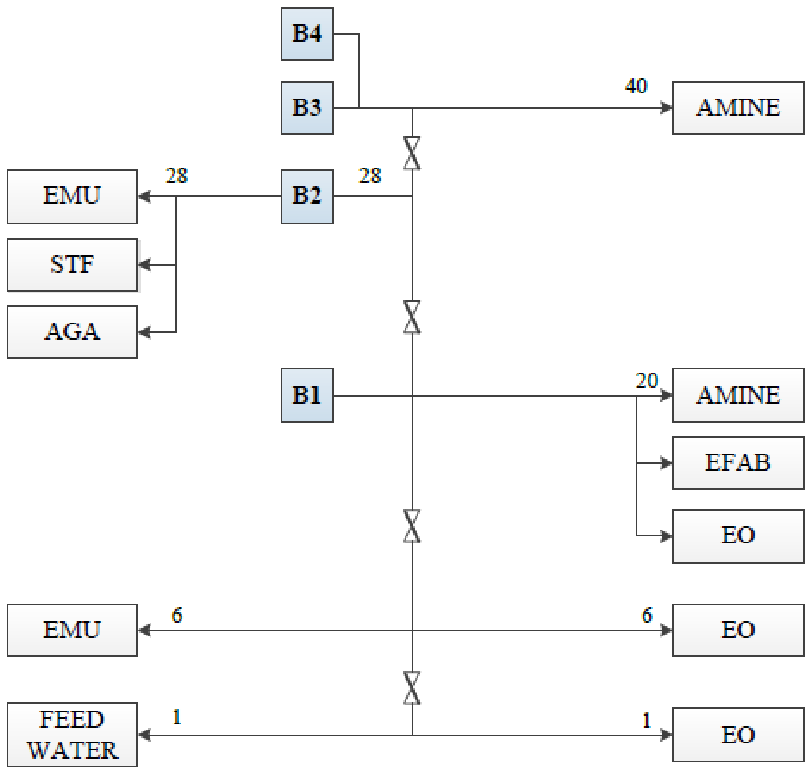

Figure 4: Overview over the steam systems where B1 = EO reactor, B2 = Boiler 2, B3 = Boiler 3, B4 = Waste incinerator boiler and AGA = nearby company. The pressure levels are given in bar(g).

3.1.1 Feedwater

The feedwater must be of high quality to prevent damage to the tubes in the boiler. The incoming water is filtrated water taken directly from a nearby lake and must be treated before it can be used to produce steam. First, magnesium and calcium are removed to avoid scaling. The water is then heated through a heat exchanger before entering the storage tank where it is heated even more to remove dissolved oxygen and carbon dioxide since it lowers the pH and causes corrosion. Oxygen and carbon dioxide are vented either to the atmosphere or are used in a heat exchanger. A precoat filter is used to remove iron, copper and other soluble particles. The last step before the steam drum is to add chemicals to remove magnesium and calcium ions. It is a closed system and approximately 80 % of the feedwater is returned and can be used again.

3.1.2 Steam boilers on site

Boiler 1 (EO reactors)

The reaction between oxygen and ethylene is strongly exothermic and during cooling of the reactors steam is produced that is used in the process. A more detailed description is not be provided since it is not part of the thesis work.

Boiler 2

The construction of boiler 2 is very similar to boiler 3 (see below). Some differences are that boiler two produces steam at 28 bar(g), has a lower capacity, uses fuel as oil and that there are only two burners instead of three.

Boiler 3

Boiler 3 consists of a furnace, burners, a steam drum, as well as an economiser and has a capacity of slightly less than 100 t/h of steam at 40 bar(g). In the furnace area, combustion of the fuel occurs. To achieve a good combustion the fuel has to be well mixed with incoming air. In the boiler there are three main burners and one for the ventilation gases. In the steam drum water is stored and the separation between water and steam occurs here as well. From the steam drum the water goes to the corners of the boiler before it is distributed to the tubes of the boiler. The feedwater is preheated by the flue gases in the economiser, in this way the efficiency of the boiler is increased.

Boiler 4 (Waste incinerator)

The main purpose of the waste incineration boiler is to burn organic residues and ventilation gases from the whole site and to produce steam from the hot flue gases. Waste burned in the incinerator comes from water and organic waste from the process, high and low-pressure ventilation gases and in addition fuel gas is burned.

The organic waste and process water is evaporated by two evaporators before entering the destruction furnace in order to facilitate combustion. The flue gases then enter the steam boiler where the steam is produced. Cleaning of the flue gases begins after the steam boiler with a dust separator cyclone and then a quench to cool the gases and remove excess water in a following separation step. The last cleaning step for the flue gases are the electrostatic filter that removes the remaining particles by electricity.

3.1.3 Steam demand

The production of steam varies depending on the demand and since there are several boilers producing steam on site, their individual production depends on each other. If the steam producing plant reduces the production the other boilers need to be able to respond quickly and increase production if the rest if the plants are able to continue the production. Disturbances in the production of the plants on site causes the boilers to decrease the steam production.

Since the main function of boiler 4 is to burn organic waste and not produce steam the variations are regulated by boiler two and three. These factors cause large variations in the steam demand.

3.1.4 Fuel

Both oil and gas can be used as fuel in boiler 3, only oil in boiler 2 and only gas in boiler 4. Fuel gas is provided by a nearby plant within the chemical cluster in Stenungsund. A small stream of ventilation gases is also used as fuel in boiler 3 and these gases come from the Nouryon site. Both the lower heating value and the composition of the fuel gas day by day are reported at the end of the month by the provider of the gas. The main components of the gas are hydrogen, methane, ethane and propane. The emissions associated with the fuel used are shown in Table 2.

Table 2: Amount of fuel used and emissions from combustion to atmosphere on a yearly basis [24].

Fuel	[tonnes/year]	Sulphur [kg/year]	NOx [kg/year]	CO_2 [tonnes/year]
Fuel gas	18 358	400	48 800	52 000
Oil	486	50	4 000	1 600
Sum 2017	18 844	450	52 800	53 600
2016	17 627	130	50 200	47 000

3.1.5 Flue gas

In a complete combustion only water and carbon dioxide are formed. However, this is not the case and among others carbon monoxide, nitrogen monoxide and nitrogen dioxide are also formed. These are measured and controlled since they are regulated. The oxygen, carbon dioxide and smoke formation are also measured.

4 Methodology

This section describes the methodology of the thesis. As can be seen in Figure 5, the work is divided into three main parts. The first part was to gather information about electric and gas steam boilers and to collect process data that is necessary for the model and optimisation section. In the optimisation, different energy market price scenarios were evaluated in order to determine the capacities for the boiler technologies to reach minimum total cost. After that, an analysis for fixed boiler capacities for different energy market price scenarios and emission constraints was performed.

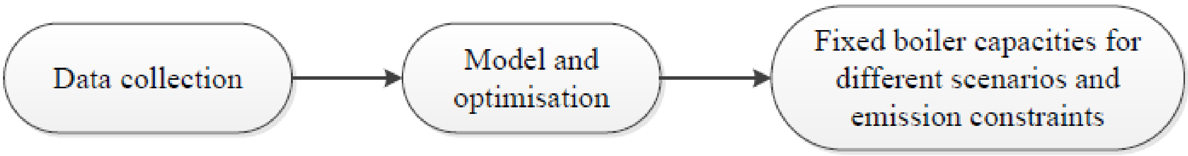

Figure 5: Flowchart over the three main parts of methodology.

4.1 Data collection

Data was collected from tags in the process at Nouryon to estimate the future steam demand. Information regarding the characteristics of electric and gas boilers was also investigated.

4.1.1 Data collection at Nouryon

Recent steam production data at Nouryon was used to forecast the expected future steam demand. Data gathered from August 2015 to August 2018 was collected directly from the plant's process database EPI (Enterprise Process Information).

Data tags collected were steam production of boilers 2 and 3, temperature and pressure of feedwater, as well as temperature and pressure of steam at the outlet of boiler 3. Boiler 3 was used for pressure and temperature collection since this boiler produces steam at 40 bar(g) which is the pressure level at which the new boilers are supposed to operate. Data was collected with a daily resolution as an interpolated value. However, since Capex was calculated on a yearly basis, the year of 2017 was used as a reference year of normal production in the cost calculations. The maximum produced steam value occurred during 2017 and to ensure that this could be handled in the future as well this year was chosen. For the cost calculations, data was collected with an hourly resolution as an interpolated value. The tags used are for steam production in boilers 2 and 3. The higher resolution was necessary to be able to investigate the variations in steam production and to investigate if the boiler technologies could handle the variations.

Data points with bad values and outliers were excluded from the data set. Bad values refer to bad connection for a short period of time for the measurement instrument and no data was collected for that time slot. Values considered unreasonable and values around maintenance stop were also excluded since these were not obtained under normal operating conditions.

4.1.2 Future steam demand

To simulate future need of steam and to make sure that a new system of producing steam is sufficient an increase of 20 % in the production was considered. A factor of 1.2 was applied to the current steam production every hour and thereby an increase in the steam production was achieved.

The following formula was used to calculate the steam demand in terms of power from the steam mass flow.

$$m_{steam}(h_s - h_{fw}) = Q_{Steam} \tag{1}$$

To extract the enthalpy the pressure and temperature of the feedwater and steam were used. The enthalpy content in the steam was 2800.82 kJ/kg and for the feedwater it was 525.0 kJ/kg. This resulted in an increase of enthalpy of 2275.82 kJ/kg across the boilers.

4.1.3 Boiler technologies

An electrical steam boiler, gas steam boiler or a hybrid system of boilers were considered to be the technologies to replace boilers 2 and 3 on-site. Properties about technical data such as efficiencies, minimum load and ramp-up properties were collected from literature and vendors. Some operational characteristics like temperature and pressure levels were based on specifications from the current boilers at the Nouryon site.

4.2 Model and optimisation

An economic analysis was conducted to be able to evaluate and decide when the different boiler technologies become profitable. In this master thesis the lowest total annual cost with different boiler technology was determined. The program used for this analysis was Excel. The calculation procedure for estimating the minimal total annualized cost follows the flowchart in Figure 6 and is further described in this section.

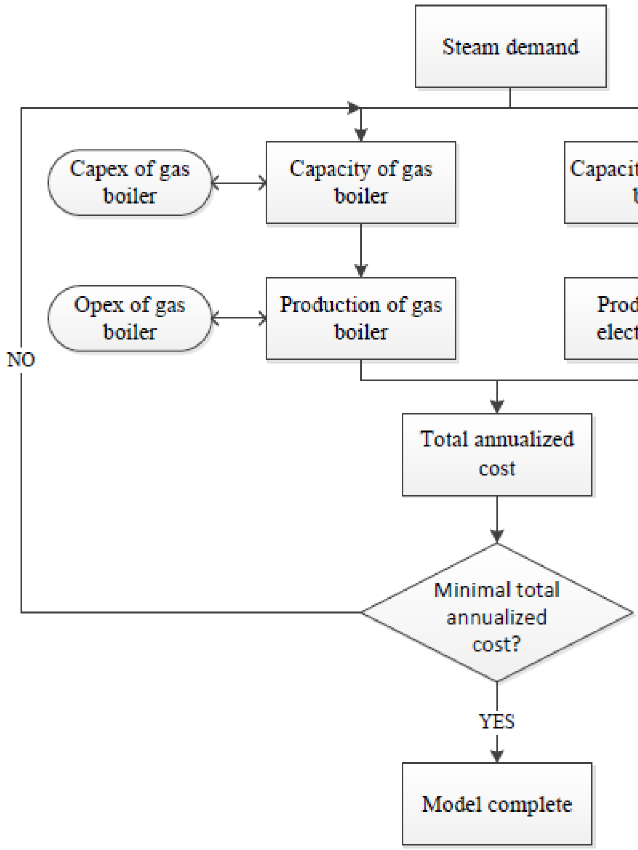

Figure 6: Flowchart over the calculation procedure and optimisation.

4.2.1 Objective function

The total annualized cost was the objective function to be minimized. The summation of the Capex and Opex over one year is the total annualized cost, as shown in equation (2).

$$Min. Total\ annualized\ cost = minimize\ (Capex_{GB} + Capex_{EB} + Opex_{GB} + Opex_{EB}) \quad (2)$$

4.2.2 Capex and Opex

Equipment costs were obtained from vendors and average values were used when multiple cost estimates were available. The equipment cost for the boilers provided by vendors were for a certain capacity and corrections were made to the different capacities. Equation (3) shows how the cost for a new capacity was calculated.

$$C_E = C_B * (\frac{Q}{Q_B})^M \quad (3)$$

The cost capacity exponent *M* was assumed to be equal to 0.7.

Equipment costs were increased to account for additional costs such as site preparation, installation and additional pumps using standard investment cost factors. A factor of 4 times the equipment cost of the boiler was used to cover installation cost [25]. Equations (4) and (5) show thethe annualized capital cost.

$$Capex_{GB} = (C_{GB} * 4 * r) \tag{4}$$

$$Capex_{EB} = (C_{EB} * 4 * r) \tag{5}$$

The annuity factor *r* was calculated according to equation (6), where *i* is the discount rate and *n* the economic lifetime of the boiler.

$$r = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

The Opex depends on the fuel prices, efficiencies and the fixed and variable operating and maintenance cost. The operating cost can be computed by summing the hourly operating costs for each hour of the year, and then adding the fixed annual operating cost, see equations (7) and (8). The gas fuel price of the gas was assumed to be equal to that of natural gas. In practice, the boilers are fired with fuel gas from the neighbouring cracker plant, and natural gas is only purchased from the gas grid when there is a deficit of fuel gas. Furthermore, it is assumed that the gas boiler can be operated interchangeably on natural gas or bio-methane fuel.

$$\begin{aligned} Opex_{GB} = \sum_{j=1}^{8760} \Bigg(& \left(\frac{Price_{naturalgas}}{\eta_{GB}} + VarCost_{GB}\right) * Q_{natural\ gas,j} \\ & + \left(\frac{Price_{bio-methane}}{\eta_{GB}} + VarCost_{GB}\right) * Q_{bio-methane,j} \Bigg) \\ & + (FixCost_{GB} * Q_{max,GB}) \end{aligned} \tag{7}$$

$$Opex_{EB} = \sum_{j=1}^{8760} \left(\left(\frac{Price_{el}}{\eta_{EB}} + VarCost_{EB}\right) * Q_{el,j} \right) + (FixCost_{EB} * Q_{max,EB}) \tag{8}$$

4.2.3 Optimisation variables

<u>Capacity of boilers</u>

The maximum capacity of the two boilers combined is the maximum of the steam production, which was 65 MW. The minimum capacity per technology was zero. When one boiler capacity increases the other one will decrease since the maximum steam demand is a fixed value, as can be seen in equation (9). Constrains of non-negative values are shown in equations (10) and (11). The capacities are the optimisation variables changing in the model to reach the minimal annualized total cost.

$$Q_{max,EB} + Q_{max,GB} = Q_{max,tot} \tag{9}$$

$$Q_{max,EB} \geq 0 \tag{10}$$

$$Q_{max,GB} \geq 0 \tag{11}$$

Steam production of boilers

The steam demand data was available on an hourly basis for a complete year. For each hour, the amount of steam delivered by each boiler technology and the Opex were determined. The steam demand at a certain time slot was a fixed value and the combined production by the boilers equalled the total steam demand, see equations (12) and (13). This is the demand constraint.

$$Q_{el} + Q_{gas} = Q_{tot} \tag{12}$$

Where:

$$Q_{gas} = Q_{naturalgas} + Q_{bio-methane} \tag{13}$$

In the model the production by the gas and the electric boilers was determined based on the price of fuel, efficiencies, fixed and variable operating and maintenance costs for the corresponding technology and the total steam demand. The production was constrained by the maximum capacity of the boilers and was not allowed to go below zero. The amount of produced steam from the gas or electric boiler depended on the energy price, efficiencies, fixed and variable operating and maintenance cost for a gas boiler in comparison to the electric boiler. If the gas boiler was the cheapest to operate the gas boiler would produce steam until the maximum capacity was achieved. If there was a higher steam demand than the gas boiler could produce the electric boiler to cover the remaining load. If the opposite situation occurs the electric boiler was run until its maximum capacity was achieved and if there was more steam demand the gas boiler would take the rest.

4.2.4 Energy market price scenarios

To predict and evaluate the minimal total annualized cost, different future energy market scenarios were evaluated. A reference case based on the year 2017 and two different future scenarios were considered.

Reference scenario

In the reference scenario, current steam loads were increasd by 20%. The prices of fuel were set to average prices for year 2017, including taxes but not VAT [26]. The taxes included for natural gas were energy tax and CO_2 tax. However, since Nouryon is included in the EU ETS and does not pay CO_2 tax, the tax was subtracted from the gas price collected and a CO_2 charge representative of EU ETS [27] was added instead. The taxes of electricity are reduced for industry and this was considered in the electricity price. Since Nouryon consumed around 100 GWh [24] in addition to a possible electric boiler, a higher user category was assumed when collecting prices [26].

Since the equipment cost for an electric boiler varied between vendors a sensitivity analysis was conducted by raising the equipment cost of the electric boiler by 50 %. The equipment cost collected from suppliers of a gas boiler was in the same price range so that it was sufficient to raise the equipment cost by 20% for the sensitivity analysis.

Future scenarios

For predicting the optimal mix of technology in the future, an analysis of two different scenarios based on scenarios presented in the IEA's World Energy Outlook 2017 were considered. The resulting prices for electricity and natural gas were generated using the ENPAC model [28] that is an energy market tool developed at Chalmers which uses data from World Energy Outlook as input. The higher investment cost for the electric and gas boiler was not considered in the future scenarios. The two different scenarios used were the "New policies" and the "Sustainable development" scenario. The "New policies" scenario is based on legislation and measures that are implemented as of mid-2017 and takes into consideration announced policies of governments. This scenario attempts to predict the likely effect of these implementations even if they may not have been incorporated yet. The "Sustainable development" scenario shows one possible way of achieving the energy-related sustainable development goals set up by the United Nation, i.e. the goals that include climate change, air quality and universal access to modern energy. This scenario involves a major increase of renewable energy sources and a substantial reduction of greenhouse gas emissions.

Predictions of fuel prices were taken for the years 2025, 2030 and 2040. The prices of natural gas and electricity were regional prices for Europe and the CO_2 charge for EU ETS was added to the fuel price. The bio-methane price was a prediction from a report [29] that used ENPAC. In the report, prices for 2018, 2030 and 2043 were provided and prices for 2025 and 2040 were calculated by linear interpolation.

EU Emissions Trading System (EU ETS)

The EU Emissions Trading System (EU ETS) is the European Union´s system to reduce the carbon dioxide emissions within the union. It was launched in 2005 and is a "cap and trade" system, in which a maximum amount of carbon dioxide is decided. Companies receive a certain number of free shares for their emissions and must obtain additional emission right certificates when emitting more. The current system has four phases with a decrease in every phase in how much carbon dioxide that is allowed to be emitted. The last and fourth period is from 2021 to 2030 and the aim is to reduce the emissions by 43% compared to the levels in 2005. This is equivalent to an annual rate of 2.2% [15]. The companies that are part of this system do not pay carbon dioxide tax in Sweden, but instead they are required to hold so-called European Emission Allowances (EUA) corresponding to their emissions. All installations that have a total combustion capacity of over 20 MW are included in this system.

4.2.5 Assumptions

The calculations were performed for boilers 2 and 3 as they deliver steam at different pressure levels. All steam that is produced from boilers 2 and 3 was assumed to be at 40 bar(g) because the main steam demand is at 40 bar(g). The feed water was assumed to be saturated water at 124 ˚C. The energy added to the water by the pumps is small compared to the energy added in the boiler, so it was neglected since it would not affect the results.

In reality, some ventilation gases are burned in boiler 3 as well, but since it is a small part of the total amount of burned gas it was neglected. The ventilation gases need to be combusted. If a gas boiler is not present on-site these ventilation gases must be taken care of in another way. The minimum load of the boilers was not taken into consideration in the model. The CO_2 charge was included in the natural gas price as an average per MWh, in reality the CO_2 charge is only paid for the amount of CO_2 that is over the share that Nouryon has been assigned by EU ETS.

4.3 Fixed boiler capacity for different scenarios and emission constraints

The "New policies" scenario was assumed to be the most likely future scenario since it proceeds from current and future legislations. Therefore, fixed capacities were determined as the average of the optimal capacities from the different years of this scenario. A total cost for the fixed capacities was calculated by the model and this cost was compared to a case with the same capacities but with constraints on the fossil CO_2 emissions. The constraints on fossil CO_2 emissions were in compliance with Sweden's goal of being carbon neutral by 2045. To reach this goal a linear reduction by the same amount every year from 2021 to 2045 was applied. 2021 was taken as starting year since the boilers were assumed to be up and running by then. The emissions of fossil CO_2 in 2021 were assumed to be the same amount of fossil CO_2 produced in 2017 according to the model if the steam demand was covered by a gas boiler running on natural gas only. The electricity was assumed to be carbon neutral.

A gas boiler is interesting to compare with since the infrastructure of a gas boiler is already in place and the current system uses gas steam boilers. It is possible to reach the emission goals of CO_2 with a gas boiler if it can be run on bio-methane. The cost for a gas boiler that runs on natural gas is therefore compared to a gas boiler that runs on both natural gas and biomethane in order to reach the emission goals.

When restrictions of emissions are added the boiler is assumed to be run on natural gas until the limit of emitted fossil CO_2 is reached and then a switch to either electricity or bio-methane for the rest of the year is done in the model. The cost for these two cases is compared with the fixed capacities. The different cases are evaluated for the two future scenarios, the "New policies" and the "Sustainable development" scenario in 2025, 2030 and 2040.

5 Model input data

5.1 Steam demand

Average, maximum, minimum and standard deviation for the new steam demand used in the optimisation are presented in Table 3.

Table 3: Characteristics of reference steam demand (average, maximum, minimum and standard deviation)

Value	Steam demand [tonne/h]	Steam demand [MWh/h]
Average	42	27
Maximum	105	65
Minimum	12	8
Standard deviation	10	6
Max. hourly variation	42	32

Figure 7 shows the new steam demand in a load duration curve for one year. The maximum value is 65 MWh/h and then there is a steep decline since the high production only happens few times of the year. The steam demand is between 25 and 35 MWh/h for most of the year.

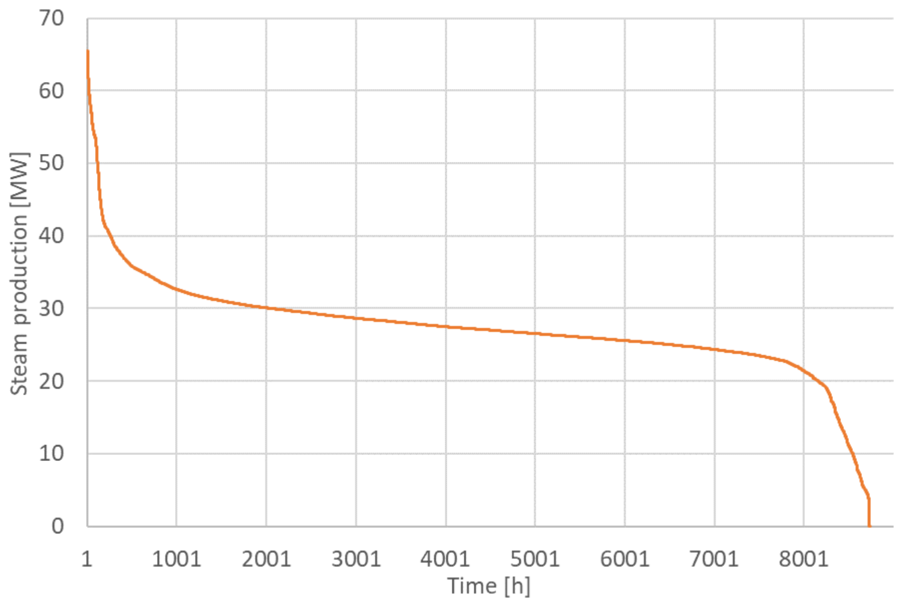

Figure 7: Load duration curve for the new steam demand in MWh/h.

5.2 Boiler technology

The boilers in use today have a minimum load of approximately 16 % of full capacity and a new gas boiler is assumed to operate at the same minimum load. The electric boiler can however go lower, to 4 % of full capacity. The minimum load is not been taken into consideration in the model. The electric boiler can increase the steam production very fast with only five minutes from standby to full load. The boiler could go even faster but the steam system cannot change that fast and for security reasons 5 minutes are recommended by manufactures. The electricity grid has to be able to support such a fast ramp up of electric boilers as well, this was assumed to be the case. The production of CO_2 from the gas boiler is 0.202 ton/MWh fuel and for the electric boiler no CO_2 is produced since it was assumed that the electricity is produced from renewable sources. The economic lifetime of a steam boiler was set to 20 years. The maximum demanded ramp up of steam in the production was 32 MW/h which was lower than the maximum ramp up of the boilers listed in Table 4. Therefore, there was no need of having this as a constraint in the model.

Table 4: Operating characteristics for a gas boiler and an electric boiler.

Parameter	Quantity	Value	Source
Gas boiler			
Max Pressure	[bar(g)]	40	Based on current system
Max Temp	[˚C]	250	Based on current system
Min load	[%]	16	Based on current system
Ramp up	[MW/h]	210	Product information*[1]
Efficiency η_{GB}	[%]	90	[8]
CO_2 production	[ton CO_2/MWh]	0.202	[30]
Economic lifetime	[years]	20	Provided by Nouryon
Electric boiler			
Max Pressure	[bar(g)]	40	Based on current system
Max Temp	[˚C]	250	Based on current system
Min load	[%]	4	Product information*[2]
Ramp up		5 min from standby to full load up	Product information*[2]
Efficiency η_{EB}	[%]	99	[12]
Economic lifetime	[years]	20	Provided by Nouryon

*[1] Provided by vendor (Valmet)

*[2] Provided by vendor (Elpanneteknik)

5.3 Capex and Opex

In Table 5 the equipment cost for the different boiler technologies are presented for a specific capacity.

Table 5: Average values of equipment cost for a specific capacity collected from industry.

Technology	Capacity [MW]	Equipment cost [MSEK]
GB	47	44.5
EB	15	7

To annualize CAPEX costs a discount rate of 8 % was assumed. Where conversion of currency was needed, the assumed rate was 1 EUR = 10 SEK.

In Table 6, fixed and variable operating and maintenance cost are presented for the different boiler technologies.

Table 6: Assumed data for fixed and variable operating and maintenance cost from [31].

Technology	Fix O&M cost [SEK/kW, year]	Var O&M cost [SEK/MWh]
GB	25	15
EB	15	10

5.4 Energy market price scenarios

5.4.1 Reference case

The natural gas and electricity prices for the reference case in 2017 are given in Table 7.

Table 7: Prices collected for natural gas and electricity for industrial customers [26], CO_2 tax withdrawn from natural gas price and a CO_2 charge added instead [27].

Source	Price [SEK/MWh]
Natural gas with CO_2 charge	305
Electricity	385

5.4.2 New policies scenario

The prices in the new policy scenario for CO_2 charge, natural gas, bio-methane and electricity are given in Table 8.

Table 8: Assumed prices for CO_2 charge and energy for the years 2025, 2030 and 2040 of the new policies scenario, prices comes from ENPAC model [28]. The bio-methane price is collected from [29].

	Unit	2025	2030	2040
CO_2 charge	[€/tonne]	22	29	43
Energy prices:				
Natural gas incl. CO_2 charge	[€/MWh fuel]	37	41	48

Bio-methane	[€/MWh fuel]	75	82	92
Electricity	[€/MWh-el]	52	54	59

5.4.3 Sustainable development scenario

The prices in the sustainable development scenario for CO_2 charge, natural gas, bio-methane and electricity are given in Table 9.

Table 9: Assumed prices for CO_2 charge and energy for the years 2025, 2030 and 2040 of the sustainable development scenario, generated using the ENPAC model [28]. The bio-methane price is collected from [29].

	Unit	2025	2030	2040
CO_2 charge	[€/tonne]	56	80	126
Energy prices:				
Natural gas incl. CO_2 charge	[€/MWh fuel]	42	48	61
Bio-methane	[€/MWh fuel]	87	95	102
Electricity	[€/MWh-el]	54	54	63

5.5 Fixed boiler capacity for different scenarios and emission constraints

Prices for the new policy scenario and sustainable development scenario are presented in Table 8 and in Table 9 and were used as data for the different cases. The amount of fossil CO_2 that should be reduced in order to reach the goal of being carbon neutral by 2045 is presented in Table 10.

Table 10: The allowed emission amount of fossil CO_2 from the steam system. From 2021 to 2040, in order to be carbon neutral by 2045.

Years	Allowed amount of emitted fossil CO_2 [tonnes/year]	Total reduction [tonnes/year]
2021	53 726	0
2025	44 772	8 954
2030	33 579	20 147
2040	11 193	42 533

6 Results

This section presents the results from the reference case in 2017, the two different future scenarios (new policies scenario and sustainable development scenario) and the fixed capacity in comparison with a gas boiler.

6.1 Reference case

For the reference case, the total annualized cost for different boiler capacities is shown in Figure 8 and the most economically feasible combination of boiler technologies in Table 12. Figure 8 shows different combinations of boiler capacities at a total annualized cost. The most expensive option is a gas boiler at 107.5 MSEK/year. The cost is then decreasing until the optimal option of gas and electric boiler at 27 MW and 38 MW respectively at total minimum cost at 103.3 MSEK. This option is marked with a circle in Figure 8. The cost is then increasing again for the mix of technologies and then decreases for an electric boiler of 65 MW at 103.4 MSEK/year.

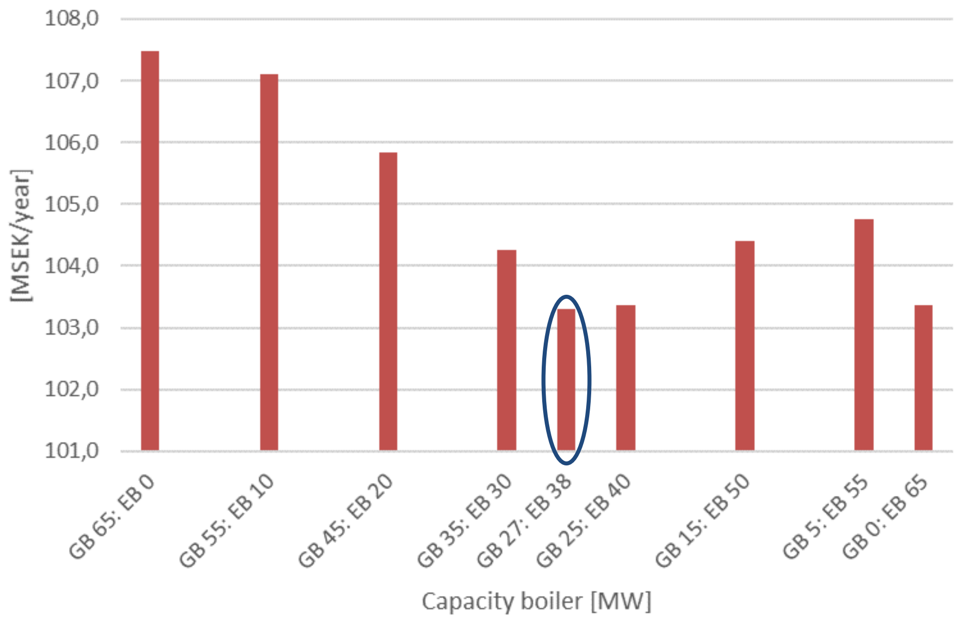

Figure 8: The total cost for the reference case at different boiler capacity combinations. Note that the total cost axis does not start at zero.

In Table 11, a more detailed view of the cost for the different capacity combinations is shown, including the total annualized cost, Capex and Opex for the different technologies. The decrease in total cost for the electric boiler is due to the fact that Capex is only made for one boiler and the decrease in this cost makes up for the increase in Opex (see Table 11). The approach taken so far is not an optimisation but gives an overview of how the cost varies with the different capacities.

Table 11: Total cost, Capex and Opex for different boiler capacity combinations in the reference case.

Capacity GB [MW]	Capacity EB [MW]	Total cost [MSEK/year]	Capex GB [MSEK/year]	Capex EB [MSEK/year]	Opex GB [MSEK/year]	Opex EB [MSEK/year]
65	0	107.5	22,9	0	84.6	0
55	10	107.1	20.4	2.2	84.5	0.1
45	20	105.8	17.7	3.5	84.1	0.6
35	30	104.3	14.8	4.7	83.1	1.7
27	38	103.3	12.2	5.6	77.0	8.5
25	40	103.4	11.7	5.7	73.8	12.1
15	50	104.4	8.2	6.7	45.6	43.9
5	55	104.8	3.8	7.6	15.4	77.9
0	65	103.4	0	8.1	0	95.3

Detailed results for the optimal capacity mix consisting of a gas boiler of 27 MW and an electric boiler of 38 MW are presented in Table 12. Since there are great variations in the steam production, the electric boiler will only produce steam for peak load and therefore the steam produced by the electric boiler is only 9 % of the total steam produced. However, 58 % of the time during the year the electric boiler is in operation, mostly on part load.

Table 12: Results for parameters of different boiler technologies for the reference scenario in 2017.

Parameter	Unit	Technology	2017
Capacity	[MW]	GB	27
		EB	38
Total minimal cost	[MSEK/year]	GB+EB	103.3
Capex*	[MSEK/year]	GB+EB	17.8
Opex	[MSEK/year]	GB+EB	85.5
Amount of steam produced	[%]	GB	91
		EB	9
Time in operation	[%]	GB	100
		EB	58
Natural gas used	[MWh/year]	GB	219 675
Electricity used	[MWh/year]	EB	21 225
CO_2 emissions	[tonnes/year]	GB	48 863

* 20 years economic lifetime and 8 % discount rate

Figure 9 shows the Capex and Opex cost for the boiler technologies at optimal capacity. The dominating part of the total cost is made up by the Opex of the gas boiler. The Capex for the gas boiler is higher than for the electric boiler even if the capacity of the electric boiler is higher. The Opex is higher per unit of energy for the electric boiler than the gas boiler, see Table 7. However, in Figure 8, the higher operating cost for the gas boiler is due to the amount of steam produced by the gas boiler which is considerably higher than the electric boiler.

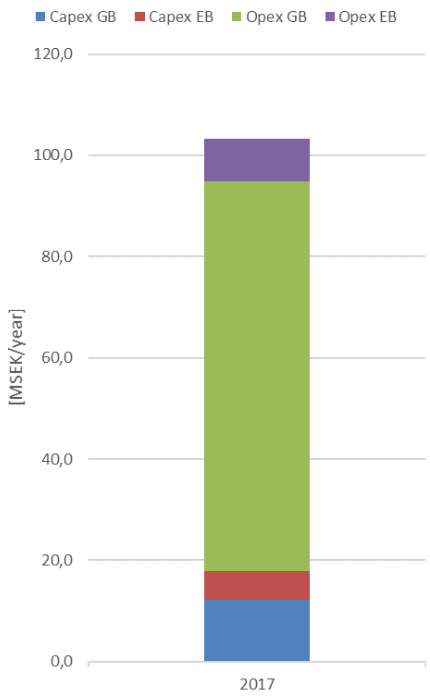

Figure 9: Capex and Opex for gas and electric boilers at optimal capacity in the reference scenario in 2017.

The sensitivity analysis of raising the equipment cost for the electric boiler by 50 % gives a higher capacity in the gas boiler by 1 MW and the electric boiler reduces its capacity by the same amount, see Table 13. The total minimal cost is slightly higher since the equipment cost is higher. The time in operation and amount of steam produced from the electric boiler is reduced compared to the reference case without the 50 % raise in equipment cost of the electric boiler. This shows that the model is not very sensitive to changes in equipment cost for the electric boiler.

Table 13: Results for parameters of different boiler technologies for the reference scenario in 2017 with 50 % higher equipment cost for an electric boiler.

Parameter	Unit	Technology	2017
Capacity	[MW]	GB	28
		EB	37
Total minimal cost	[MSEK/year]	GB+EB	106.0
Capex*	[MSEK/year]	GB+EB	20.8
Opex	[MSEK/year]	GB+EB	85.3
Amount of steam produced	[%]	GB	93
		EB	7
Time in operation	[%]	GB	100
		EB	44
Natural gas used	[MWh/year]	GB	223 017
Electricity used	[MWh/year]	EB	15 913
CO_2 emission s	[tonne/year]	GB	58 414

* 20 years economic lifetime and 8 % discount rate

The raise in equipment cost by 20 % for the gas boiler results in the electric boiler providing the whole steam demand as can be seen in Table 14.

Table 14: Results for parameters of different boiler technologies for the reference scenario in 2017 with 20 % higher equipment cost for a gas boiler.

Parameter	Unit	Technology	2017
Capacity	[MW]	GB	0
		EB	65
Total minimal cost	[MSEK/year]	GB+EB	103.4
Capex*	[MSEK/year]	GB+EB	8.1
Opex	[MSEK/year]	GB+EB	95.3
Amount of steam produced	[%]	GB	0
		EB	100
Time in operation	[%]	GB	0
		EB	100
Natural gas used	[MWh/year]	GB	-
Electricity used	[MWh/year]	EB	239 382
CO_2 emissions	[tonnes/year]	GB	-

* 20 years economic lifetime and 8 % discount rate

6.2 Future scenarios

Since the price for bio-methane is higher than the price for natural gas and the minimal total annualized cost is determined the cheapest fuel is used and therefore bio-methane will not be incorporated in these scenarios for optimal capacities. When comparing a fixed capacity with a gas boiler, restrictions of fossil CO_2 emissions are introduced, the use of bio-methane becomes of interest and is incorporated.

<u>New policies scenario</u>

The result for the new policies scenario is that the optimal capacities decrease by 1 MW for the gas boiler between the years stated in Table 15 and an increase for an electric boiler by the same amount. The electric boiler increases its share from 4 % of the steam produced in 2025 to 7 % in 2040 and operates more throughout the year. The operating cost increases since the price of energy increases but the relationship between the natural gas and electricity prices is quite constant over the years. In Figure 10, the cost division between Capex and Opex is shown. The increased Opex over the years is due to the increasing prices for energy and thereby makes up a larger part of the total cost. The operating cost for the electric boiler increases in 2040 since it operates more compared to the previous years. The CO_2 emissions are reduced by approximately 4000 tonnes from 2021 to 2040.

Table 15: Results for parameters of different boiler technologies in production in the new policies scenario.

Parameter	Unit	Technology	2025	2030	2040
Capacity	[MW]	GB	30	29	28
		EB	35	36	37
Total minimal cost	[MSEK/year]	GB+EB	121.6	132.0	150.3
Capex*	[MSEK/year]	GB+EB	18.6	18.4	18.1
Opex	[MSEK/year]	GB+EB	103.0	113.6	132.2
Amount of steam produced	[%]	GB	96	95	93
		EB	4	5	7
Time in operation	[%]	GB	100	100	100
		EB	23	30	45
Natural gas used	[MWh/year]	GB	229 414	227 018	223 874
Electricity used	[MWh/year]	EB	9 458	11 286	16 271
CO_2 emission s	[tonnes/year]	GB	51 605	51 195	50 076

* 20 years economic lifetime and 8 % discount rate

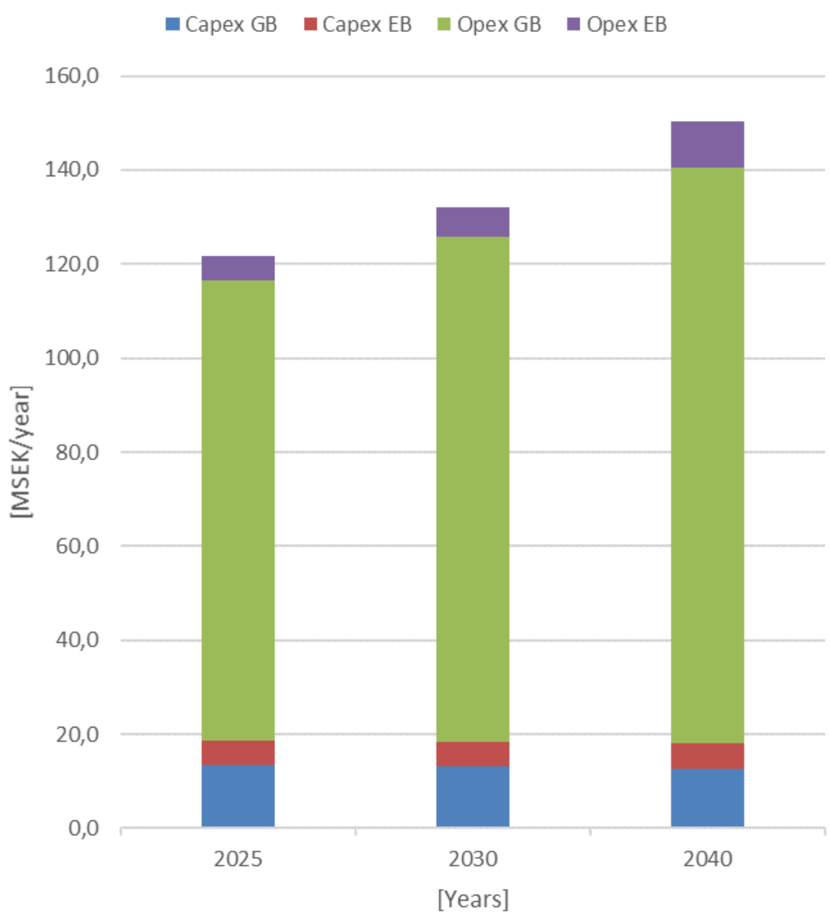

Figure 10: Capex and Opex for gas and electric boilers at optimal capacities. For the years 2025, 2030 and 2040 in the new policies scenario.

Sustainable development scenario

Figure 11 shows the results for the sustainable development scenario with respect to cost. Note that the increased Opex cost over the years is due to higher energy prices and not that the boilers produce more steam. Table 16 gives more detailed results in the sustainable development scenario. In 2025 the development is similar to the previous case, however in 2030 and 2040 the result is different. The high charge for emitting fossil CO_2 leads to a high price of natural gas compared to electricity and this makes the electric boiler feasible. The total minimal cost is increasing more for every year compared to the other scenario since the energy price is high even if the capital cost is lower. In 2030 and 2040 the site is carbon neutral.

Table 16: Results for parameters of different boiler technologies in production in the sustainable development scenario.

Parameter	Unit	Technology	2025	2030	2040
Capacity	[MW]	GB	29	0	0
		EB	36	65	65
Total minimal cost	[MSEK/year]	GB+EB	134.5	141.0	162.8
Capex*	[MSEK/year]	GB+EB	18.3	8.1	8.1
Opex	[MSEK/year]	GB+EB	116.2	133.0	154.7
Amount of steam produced	[%]	GB	95	0	0
		EB	5	100	100
Time in operation	[%]	GB	100	0	0
		EB	35	100	100
Natural gas used	[MWh/year]	GB	227 018	0	0
Electricity used	[MWh/year]	EB	12 809	239 382	239 382
CO_2 emissions	[tonnes/year]	GB	50 853	0	0

* 20 years economic lifetime and 8 % discount rate

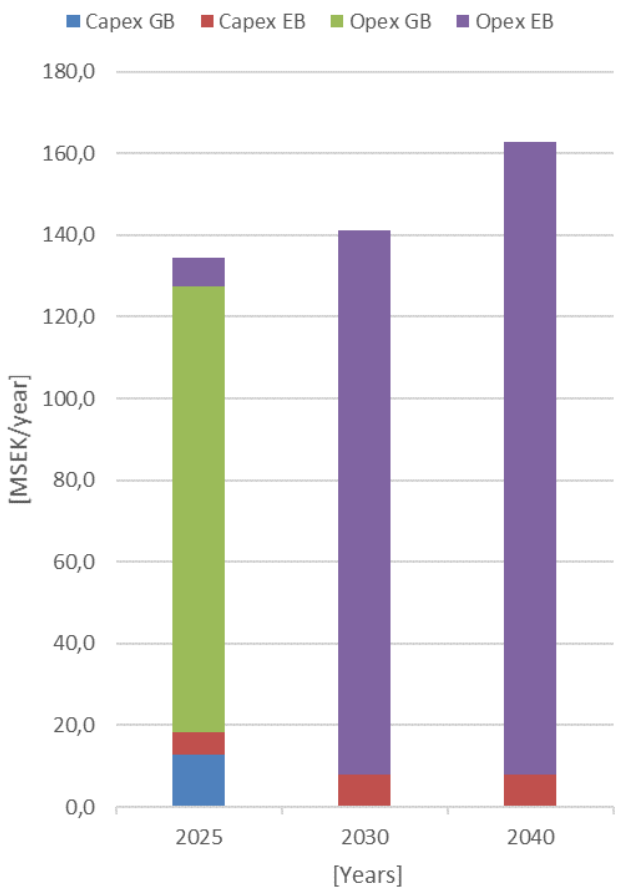

Figure 11: Capex and Opex for gas and electric boilers at optimal capacities. For the years 2025, 2030 and 2040 in the sustainable development scenario.

6.3 Fixed boiler capacity for different scenarios and emission constraints

The capacities determined are a gas boiler of 29 MW and the electric boiler of 36 MW. These capacities are chosen as an average of the optimal capacities in the new policies scenario since this is the most likely scenario in the future. The cases will be referred to as follows:

- Case A: Gas boiler of 29 MW and an electric boiler of 36 MW with no restrictions of emissions
- Case B: A Gas boiler of 29 MW and an electric boiler of 36 MW with restrictions of emissions according to Table 10
- Case C: A gas boiler run on natural gas with no restrictions of emissions
- Case D: A gas boiler run on natural gas and bio-methane with restrictions of emissions according to Table 10

New policies scenario

In Figure 12 the total annualized cost is presented in the new policies scenario for the different cases in the future. The cheapest option is case A in which the base load is covered by the gas boiler and the peak load is covered by the electric boiler in all the future years, see Figure 14 a. Case B is slightly more expensive since the electric boiler is incorporated more for every year due to the restrictions of fossil CO_2, see Figure 14 b and c. In 2040, the electric boiler covers the base load and the gas boiler covers the peak load as can be seen in Figure 14 d. Case C is more expensive than case A, however when there are restrictions on fossil CO_2 emissions the cost is considerable higher as case D shows. The emission levels for the different cases can be seen in Figure 13. Case C has the highest emissions of fossil CO_2 since it runs on natural gas only. In case A, emissions are slightly reduced compared to case C since the electric boiler covers the peak load. However, this is not enough to reach the emission reduction goals. The restriction on fossil CO_2 in case B forces it to incorporate more electricity and case D incorporates more bio-methane in the fuel every year to reduce the fossil CO_2 emission to the desired level.

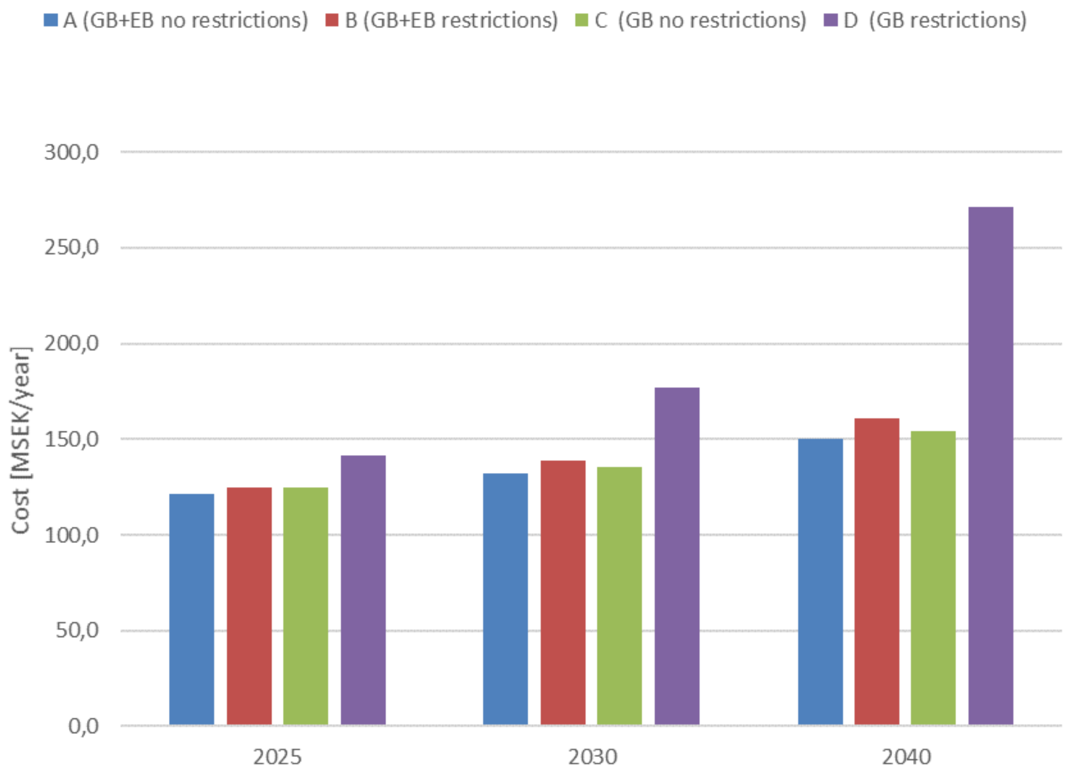

Figure 12: Comparison of total annualized cost for the four different cases A, B, C and D at three different years in the new policies scenario.

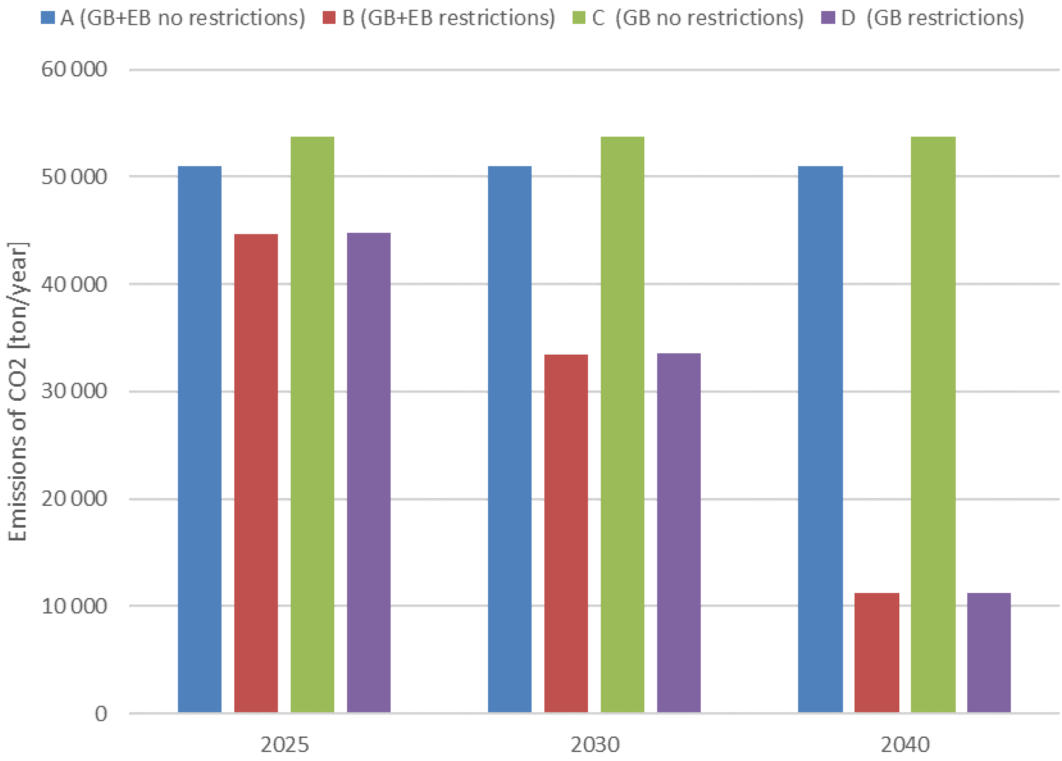

Figure 13: Emissions of CO_2 for the four different cases A, B, C, D at three different years in the new policies scenario.

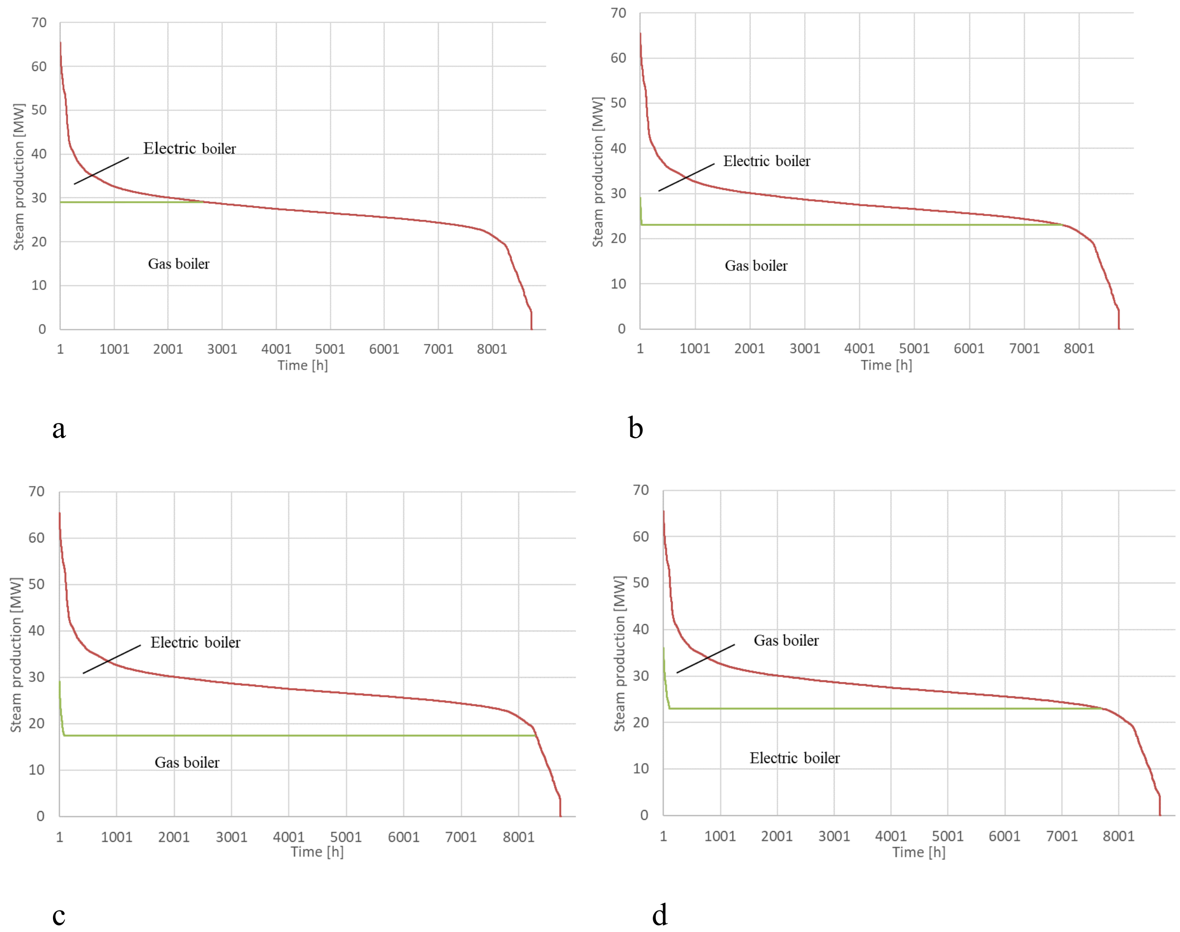

Figure 14: Load duration curves for one year in the new policies scenario showing operational loads for the different boilers a) case A in 2025, 2030 and 2040 b) case B in 2025 c) case B in 2030 d) case B in 2040

<u>Sustainable development scenario</u>

In the sustainable development scenario, Case D has a much higher cost compared to the other cases as can be seen in Figure 15. In Case A, the gas boiler covers the base load in 2025 and 2030, see Figure 17 a, but in 2040 the base load is covered by the electric boiler, see Figure 17 d. Case C is more expensive than Case A and the difference becomes more prominent in the future since the difference between the gas price and electric price decreases. The emissions from the different technologies can be seen in Figure 16 where it is similar to the new policies scenario, Figure 13, except in 2040 where the electric boiler covers the base load in Cases A and B and thereby the emissions are even lower than the goal of reduction of emitted fossil CO_2.

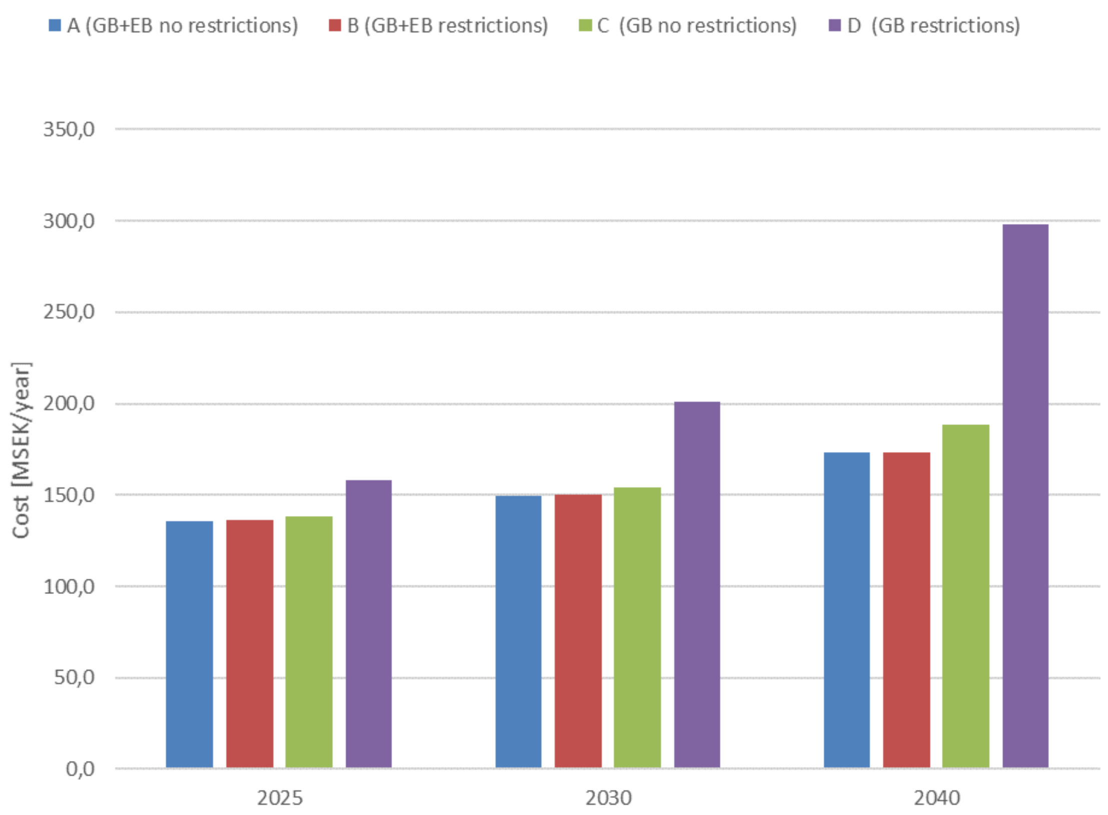

Figure 15: Comparison of total annualized cost for four different cases at three different years in the sustainable development scenario.

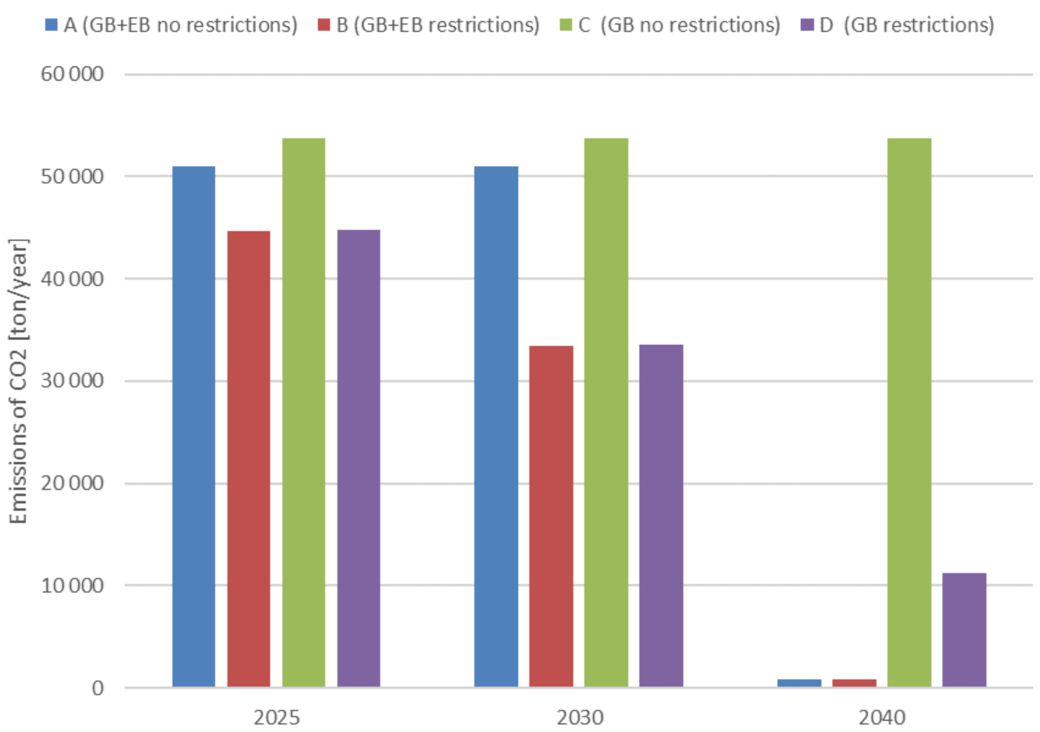

Figure 16: Emissions of CO_2 for four different cases at three different years for the sustainable development scenario.

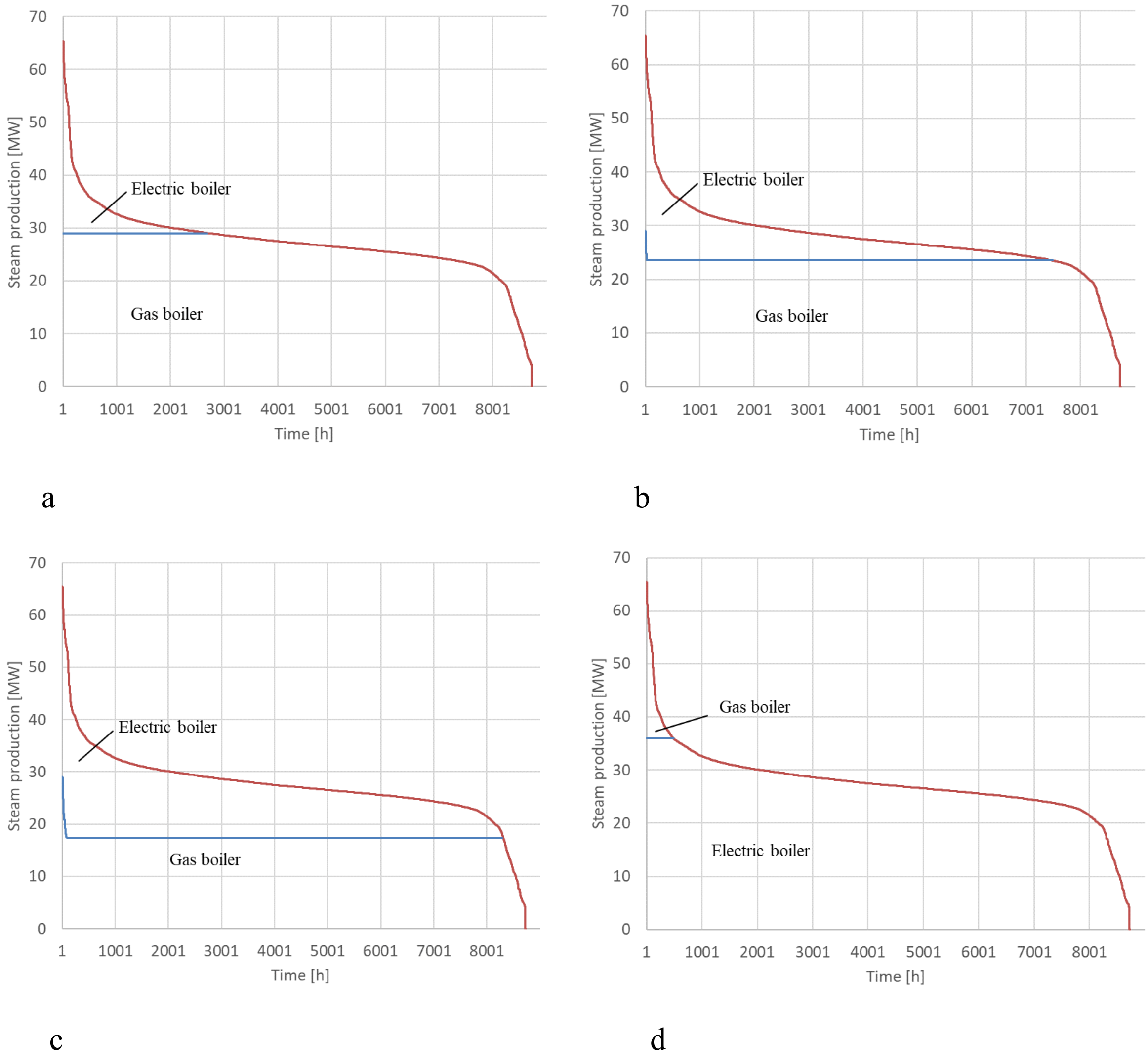

Figure 17: Load duration curves for the sustainable development scenario showing operational loads for the different boilers a) case A in 2025 and 2030 b) case B in 2025 c) case B in 2030 d) case A and B in 2040

7 Discussion

The results are discussed according to their relevance and some implications of the different boiler technologies are also mentioned. The different scenarios are compared and discussed as well.

7.1 Practical implications

There is a strong variation in steam demand and the steam supply has to be very flexible and able to increase and decrease quickly. This means that at least one of the boilers has to run on part load most of the time. This is not an optimal operation of a boiler. In the reference case and new policies scenario the gas boiler operates mostly on maximum load, however this does not apply to the electric boiler. In part load operation the electrodes in the electric boiler wear down faster and a replacement could be necessary more often. This leads to an extra cost in maintenance.

The water quality is of great importance for the durability of the boilers. The electric boiler requires cleaner water than a gas boiler and the current feedwater system is not sufficient. If the water feedwater quality is not sufficient this leads to lower efficiency of the boiler and thereby higher operating and maintenance cost. There has to be extra equipment installed for this and the pre-treatment of water could be done by reverse osmosis or ion exchanger.

At Nouryon there is a possibility to install a 10 MW electric boiler with the current power grid connection infrastructure. Higher capacities than this require new infrastructure around the boiler and additional costs for e.g. a new switchgear, power transmission and distribution network that can supply more electricity. Even if the electric boiler is not in operation the electric grid has to be able to cover the required load when needed and this constant readiness in the grid can cause the prices for electricity to go up.

Most of the infrastructure for the gas boiler is in place since the existing steam demand is produced by gas boilers. If only a gas boiler is chosen and not a combination of technologies, the higher steam demand requires more fuel gas and the pipeline has to have the capacity to supply this.

7.2 Model

The minimum load of the boiler is not taken into consideration in the model. For the base load this will not be affected since the minimum load is handled by the current system which this model is based on. This can be of importance if the peak load technology produces less than the minimum load. In reality, either the hybrid boiler system has to produce more steam than necessary or the boiler for the base load technology has to produce less steam in order for the peak load technology to at least produce at the minimum amount of steam. This may lead to a higher Opex.

The CO_2 charge is included in the price of natural gas, this charge will however only be paid for every tonne of CO_2 that is over the assigned share from EU ETS to Nouryon. The share is under negotiation and not known when this thesis was conducted and therefore this was not taken into account in the model. If this was taken into account the gas price would be cheaper than stated now, leading to that especially in the next few years the outcome could be that a bigger gas boiler is more profitable. At a longer perspective when the shares of CO_2 decline the outcome would be the same.

The model can handle variations in the incoming prices down to every hour, however in the model the energy prices are constant over the whole year. This may not be the case but can vary depending on the contract the company has with the supplier and this may lead to a different outcome. The electric prices can vary from hour to hour or day by day, unlike the gas price that is more constant. When there is too much electricity in the grid the possibility to utilise the electricity at a lower price is possible and when there is a shortage of electricity the electricity price will go up. The problem arises when the steam demand is high and there is a shortage of electricity, either the running cost will go up due to high electricity price or the production has to be reduced due to lack of electricity. The electric boiler can also be used to balance the grid. With grid flexibility there is a trade-off between savings in operational cost when electricity is cheap and additional investment cost for the boiler when it is oversized.

The variations in steam demand require the boiler technologies to be able to ramp-up and ramp-down quickly. Both technologies can handle the speed of ramp-up and ramp-down and therefore no constraints on this is added to the model. Even if the electric boiler can ramp-up quickly the power grid must be able to supply this electricity, this is something that has to be discussed with the boiler vendor and is not a technical limitation of the boiler and is therefore not a limitation in the model. One possibility could however be to include an extra cost in the model for increasing the electrical connection with a larger electric boiler.

7.3 Energy collaboration

There is also a possibility to have a collaboration with other companies in the chemical complex in Stenungsund. Steam excess from Borealis can be supplied to Nouryon that are in deficit of steam. This has some implications as well since this makes Nouryon dependent on another company. Disturbances in Borealis production will directly affect the ability to supply steam to Nouryon and the length and time of the year of maintenance stop is another issue. One solution could be to have part of the steam demand supplied by Borealis and invest in one new boiler and thereby still have the possibility to keep part of the production running even if there are disturbances in Borealis production.

Collaboration with Borealis regarding steam supply is a possibility, however these implementations are not yet established. Therefore, this was not taken into consideration in this thesis. It is however a future possible scenario.

7.4 Scenarios

The cost calculations for the different scenarios are rough estimations and could be used as guidance and basis for further investigations.

Evaluation of the reference case with historical prices shows that a combination of technologies would have given the lowest total cost even today, but the difference compared to an electric boiler only is only 0.1 MSEK/year, see Table 11. Compared to the total cost of around 100 MSEK/year, the difference is not large. There is not a lot of difference according to cost between the most expensive option either, the gas boiler which is 4 MSEK more expensive per year than the cheapest option. This is only valid for one year to give an indication of what is profitable now. With the uncertainties in the future this can change, and the future scenarios give an indication of what is profitable in the future. It should also be taken into consideration that the model is sensitive to an increase in equipment cost for the gas boiler, and a different outcome can be expected with small changes in the investment cost. The model is not sensitive to an increase in equipment cost for the electric boiler. This can however be more thoroughly investigated when more specific offers have been examined.

In the sustainable development scenario, the focus is on the environment and there is a high CO_2 charge which will highly affect the price of natural gas and make the electric boiler feasible. The total cost is higher than the total cost in the new policies scenario due to higher energy prices and CO_2 charges, leading to higher Opex while Capex is the same in both scenarios. The optimal capacities of the different technologies in the sustainable development scenario are difficult to assess since for the year 2025 the result is so different. However, in this scenario the policies of high CO_2 charge will likely to continue after 2040 and since the electric boiler has a longer lifetime than the economic lifetime of the boiler, the electric boiler is the best suitable choice for this scenario in the long run. However, the scenarios are used as a sensitivity analysis since the perfect foresight into the future does not exist.

The recommendation of only having an electric boiler as in the sustainable development scenario is not recommended when evaluating and taking into account both scenarios. If only an electric boiler is selected there is no flexibility in the future which makes this option very fragile. Ventilation gases have to be burned as well and therefore a gas boiler is recommended to be on-site. In the new policies scenario both the old and new possible policies are taken into account leading to that this is a likely scenario in the future. In this scenario the boilers are of nearly equal capacities which gives some flexibility for the future in respect of choice of fuel. With high electricity prices the gas boiler takes the base load and with high gas prices the electricity takes the base load. The possibility to use the electric boiler for grid flexibility in the future is also possible as discussed earlier.

The reduction goal of fossil CO_2 emissions is not achieved for the new policies scenario even if there is a trend towards more electricity in the future. The emissions can be lower if even more electricity is incorporated, at a higher operating cost. This is possible since the electric boiler is not utilised to its full capacity. The emissions can be even lower if biogas is incorporated.

7.5 Fixed boiler capacity for different scenarios and emission constraints

A combination of technologies is chosen as a case to be compared with a gas boiler because of the implications with only having an electric boiler as discussed earlier. One more advantage of having two boilers is the flexibility of switching fuel and the capacity is an average of capacities in the new policies scenario since this is the most likely scenario in the future.

The gas boiler is a more expensive option but not by much. However, when taking into account the goals stated by Sweden, a gas boiler will most likely be very expensive to run in the future. The advantage with the combination of technologies is the flexibility which is shown with the possibility to switch base load between the boilers. The emission goals are achieved by Case B (fixed capacity with restrictions of fossil CO_2) without incorporating bio-methane but only by incorporating more electricity. This shows the flexibility of having two boilers. In order to be completely fossil free in the future bio-methane must be used. The possibility to be completely carbon neutral is also possible for the gas boiler, but the Opex for a gas boiler is considerably higher.

An interesting report of the GoBiGas demonstration plant of 20 MW that produces bio-methane shows that the technology is commercially mature and can be scaled up to a preferred size around 200 MW [32]. This will lead to a cheaper price of bio-methane at around 60 €/MWh (it should be noted that relatively low biomass feedstock costs are assumed in the report). This price will be around the same price as natural gas and electricity in the sustainable development scenario in 2040 and can therefore be an alternative to reduce the fossil CO_2 emissions. In the new policies scenario, the price of bio-methane is still too high to be an alternative without any restrictions on emissions.

8 Conclusion and future work

Options to replace the existing steam boilers at Nouryon have been evaluated. Two types of boilers have been taken into consideration, an electric boiler and a natural gas fired boiler. Information and investment cost for the boilers have been collected through correspondence with manufacturing companies and in literature study. A model based on the collected information has been developed to determine the total cost for steam production. The model was then used for an optimisation to identify the capacities that lead to the minimal total annualized cost. One reference scenario using historical prices of energy and two future scenarios have been evaluated with the help of the model.

For the different scenarios, optimal capacities and operating times for the different boilers have been determined to the lowest cost. The reference case shows that a combination of boilers would have been profitable already in 2017. In the two future scenarios, electricity is incorporated more and the electric boiler is utilised to a higher extent, since there will be more focus on the environment and therefore higher charge for emitting fossil CO_2.

The reference case and the new policies scenario have similar results, namely that a combination of technologies is most profitable. The “Sustainable development” scenario has a different result because the electric boiler produces most of the steam and covers the base load in the years 2030 and 2040. This is due to the high charge for emitting fossil CO_2. This leads to the achievements of the fossil CO_2 emission reduction goal in this scenario. In the new policies scenario, the goal is not reached, but there is a possibility to operate the electric boiler more or to fire more bio-methane in the gas boiler to reduce the emissions and reach the goal with the optimal capacities.

From the results of the optimal capacities in the future scenarios a fixed optimal capacity is determined of a gas boiler of 29 MW and an electric boiler of 36 MW. This case is evaluated in comparison with only having a gas boiler. Both of these cases also investigate the possibility of reducing the fossil CO_2 emission and the cost of this. The new policies scenario and the sustainable development scenario are used as future scenarios. The combination of technologies is the most profitable in all scenarios, when comparing with a gas boiler, and this case is also flexible and robust since the cost does not go up much when there is a restriction of fossil CO_2. The gas boiler is more expensive than the combination of technologies however not by much. The case is on the other hand sensitive to the restrictions of fossil CO_2 and when this is applied the cost becomes considerably higher. The two cases can reach the reduction goals of fossil CO_2 and can also be totally carbon neutral to a higher cost.

8.1 Future work

The incoming data on Capex is based on prices from equipment vendors, however a more detailed case study should be done in order to get a more accurate investment cost. When equipment and installations around the boiler are specified, e.g. capacities, pumps and cleaning equipment for flue gas and feedwater a better estimation of Capex can be made.

For an electric boiler bigger than 10 MW some new installations have to be made and the cost for these rebuilds and new installations has to be estimated and taken into account in Capex for the electric boiler in order to get a more accurate result.

In this thesis the prices are given as an average per year, this might not be the case and a monthly or hourly price can be used depending on the contract the company has with the energy supplier. This has to be taken into account in a more detailed study. The usage of an electric boiler for grid flexibility should be investigated more.

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