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Optimization of a Combined Heat and Power Plant for the Future Electricity Market

A casestudy conducted at Söderenergi AB

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Abstract

The Swedish energy system is changing and two major events that are taking place are the phase out of nuclear power and the increase of wind power. The associated changes affect the electricity market and the electricity producers, including combined heat and power plants. This thesis evaluates the Swedish energy system of 2025 with focus on electricity spot prices. It also investigates how a combined heat and power plant might perform in the future, given certain changes in the electricity price.

Six different scenarios are developed where the electricity price is modified according to findings with regards to the influence of wind- and nuclear power. A model of a combined heat and power plant and a district heating network is created in BoFiT. The scenarios are applied to the model and results are analyzed in terms of heat production, choice of operational mode, merit order and economical performance.

Major findings show a more volatile electricity price in 2025. Low price hours (<100SEK/MWh) occur throughout the year, while high price hours (>640SEK/MWh) take place mostly during winter - the season during which the heat demand is at its peak. Results show that the developed electricity prices require much more regulation from the modelled power plant and that the power plant is more adapted to handling high price hours than low price hours. The district heating network is also affected by the volatile electricity prices, and more frequent and greater variations are observed in the merit order. This suggests that in the future, the electricity prices will need to be followed more actively, and that a strategy will need to be developed, allowing for quick adaptation to the prices - communication and cooperation between the different actors in the network will be needed.

Keywords

energy, CHP, electricity prices, modeling, BoFiT, optimization

Sammanfattning

Sveriges energisystem är i förändring där avvecklingen av kärnkraft och ökad implementering av vindkraft är i fokus. Konsekvenserna av dessa förändringar kommer påverka elmarknaden och därmed elproducenterna, bland dem kraftvärmeverk. Detta examensarbete utvärderar energisystemet i Sverige 2025 med fokus på elmarknaden. Arbetet undersöker också hur ett kraftvärmeverk kan prestera i framtiden baserat på förändringar i elpriset.

Sex olika scenarios har utvecklats där elpriset har modifierats baserat på analysen av vind- och kärnkraftsutvecklingen i Sverige och dess påverkan på elpriset. Ytterligare skapas en modell av ett kraftvärmeverk och ett fjärrvärmenät i BoFiT. Scenarierna implementeras i modellen och resultat extraheras och analyseras baserat på värmeproduktion, val av driftläge, körordning i systemet samt ekonomisk prestanda.

Resultaten visar främst att volatiliteten i elpriset ökar till 2025. Låga elpristimmar (<100SEK/MWh) visar sig inträffa under hela året medan höga elpristimmar(>640 SEK/MWh) dominerar under vintern - säsongen där efterfrågan på värme är som högst. Resultaten visar att det förväntade elpriset kräver högre reglering av det modellerade kraftvärmeverket och att anläggningen idag är anpassad för att hantera framförallt höga elpriser men inte låga elpriser. Även fjärrvärmenätet i sig påverkas av volatilitet i elpriserna och mer frekventa och större variationer observeras i körordningen. Detta antyder att elpriserna i framtiden måste följas mer aktivt och att en strategi, som möjliggör snabb reglering för anpassning av elpriserna, måste utvecklas. Kommunikation och samarbete mellan parterna i fjärrvärmesystemet kommer därmed vara av hög betydelse.

Nyckelord

energi, kraftvärmeverk, elpriser, modellering, BoFiT, optimering

Extent of work

This project is a master thesis conducted at the Energy Department of the Royal Institute of Technology (Kungliga Tekniska Högskolan, KTH) in Stockholm. The thesis is concluding a five year long Energy and environment engineering-program.

It is performed by two students, Linnéa Karkulahti and Monika Mizgalewicz, who have been working full time with the thesis between the 9th of September 2019 until the 14th of February 2020. The work consists of both a qualitative and a quantitative analysis - the first one including an evaluation of trends and policies in the energy market, working as a base for scenario creation, and the second one containing modelling of a heat and power facility, as well as modelling of a district heating network. As part of the work, time and effort has also been put into validating the model and the obtained results. A technical and economical analysis has been done based on the performance of the heat and power facility and the district heating network. Additionally, it was investigated whether a heat dump would be of profit for the heat and power plant or not.

The time frame and the tasks performed correspond to a workload of 60 credits. No division was not applied to any specific parts of the thesis - both authors contributed to each stage of the work in an equal amount.

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We would like to show our appreciation to the people whose assistance during the project has been of great value for the outcome of this thesis. Firstly we would like to express our deepest gratitude to our supervisor at Söderenergi Viktor Johansson, for invaluable support, knowledge and constant engagement throughout the project. Working with you has been both educational and fun. Further, we would like to recognize our supervisor at KTH, Monika Topel, for guiding us through our thesis, and providing support when it comes to modelling and reasoning.

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Abbreviations

BP	Bypass
DH	District Heating
CHP	Combined heat and power
EB	Electric boiler
ERU	Emission reduction unit
FGC	Flue gas condenser
HOB	Heat-only boiler
HP	Heat pump
IGV	Igelsta heating plant
IKV	Igelsta heat and power plant
KPI	Key Performance Indicator
MC	Main heat condenser
MFA	Mixed fatty acids
SRF	Solid recovered fuel
STD	Standard deviation
SöE	Söderenergi
TSO	Transmission system operator

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1 Introduction

In a world where sustainability is becoming an increasingly significant aspect of development, energy systems across the globe are undergoing changes. The energy system of Sweden is no exception, facing challenges that come along with an increasing demand and a transition to new energy sources.

This project aims to evaluate how the performance of a combined heat and power plant will be affected by changes in the Swedish electricity market in 2025. By investigating the Swedish energy system where the share of renewable energy sources is expected to increase and the nuclear power is going to be, to some extent, phased out, scenarios for the future electricity price will be developed.

The project is done in collaboration with Söderenergi - an energy producer in the south of Stockholm. The combined heat and power plant analyzed is a part of the company's portfolio of heat-producing facilities. A detailed model of the combined heat and power plant called Igelsta Kraftvärmeverk (IKV) as well as a simplified model of the entire network, which Söderenergi is connected to, is created. This, in order to optimize the performance of the plant for given constraints and economic conditions together with developed future electricity price scenarios. Results are obtained in terms of production and economic performance.

1.1 Background

The energy system in Sweden is characterized with stable energy resources and high integration of renewable energy where hydro and nuclear power constitutes 80% of the electricity mix. With hydro power being the regulating technology, nuclear has up until now, secured the base load in the system.[21]

Historically, Sweden has been highly reliable on nuclear power, having at one point been the country with the largest consumption of nuclear energy per capita in the world, producing around 1000 W per person [26]. In 2004, the highest electricity generation from nuclear power was reached and amounted to 75 TWh, which in turn corresponded to 46% of the total generation within the country

[17].

Nuclear power has thus constituted a major support in the Swedish energy system, however, due to political decisions taken in the 1980s, a process of phasing out of the energy source has been taking place during the past couple of years. Looking forward, after the planned termination of nuclear reactor Ringhals 2, in 2020, Sweden will be left with six nuclear reactors. The loss in production, along with an increasing electricity demand [7], will result in a restructuring of the country's energy system. The gap between the demand and supply will need to be addressed by the introduction of other energy sources. A large development of renewable energy sources, mainly wind power, is going to be undertaken [14]. These sources are however often characterized by large variability in production, which is different from the stable nuclear power, and possesses new challenges that need to be dealt with.

Additionally, the electricity price is expected to be influenced - it is now going to be heavily affected by the increase of undispatchable renewable energy [14]. The variable power production will also affect the frequency balance of the power system and facilities with stable and controllable energy productions might become of great value. Such facilities include combined heat and power plants(CHP plants) running on bio fuels which can regulate their production relatively fast. These facilities are able to aid the system by dampening the peaks created by a system based on variable renewable energy sources. Heat and power plants can cover the gap that might occur when the availability of wind or sun is low, but the demand for power is high. Additionally, CHP plants may become of great importance at regional level in 2025 in order to meet the challenges with the expansion of the transmission grid and expected capacity shortages.

Igelsta Kraftvärmeverk (IKV) is a combined heat and power (CHP) plant owned by Söderenergi, that is providing Stockholm and its suburban areas primarily with heat. To utilize the full capacity of the plant electricity is produced secondary and seen as a source of revenue in order to minimize the production costs. Thereby, as the electricity market becomes more volatile IKV, along with the rest of the system which Söderenergi belongs to, can be affected heavily by such fluctuations in the electricity price.

1.2 Purpose and Objectives

The purpose of this thesis is to understand how a bio-fueled heat and power plant, such as Söderenergi, can act in the future in order to economically optimize its production. Primarily, the purpose is to analyze the forthcoming electricity market and to investigate how the electricity price will change based on current trends and policies. The next task is to evaluate how this affects Söderenergi and its operation, as well as how it affects the district heating network the heat and power plant belongs to. This will be done with the help of a thermo-dynamic model which will be developed as part of this thesis. Subsequently, it will be investigated what potential changes can be done within the power plant based on current conditions, in order for the plant to be more adapted to the future needs of the market.

The aim is to provide Söderenergi with support in their decision making when it comes to production strategies. Through the project an understanding of the heat and power industry will be obtained, as well as insights will be gained with regards to the opportunities and challenges in the Swedish energy system.

In order to fulfill the purpose of the project a number of objectives are formulated:

- Develop several scenarios investigating the electricity price of the Swedish energy system of 2025, on an hourly basis.
- Evaluate the performance of IKV and changes in the production based on current technical conditions and a future electricity market.
- Based on the results suggest an action plan as well as strategies which will maximize the organization's profitability in the future.

1.3 Overall Methodology

The first part of the project will consist of literature studies. Information will be gathered with regards to the Swedish energy system, policies, market trends, development plans, trading mechanisms and other. Based on the information gathered, different electricity price scenarios will be created in order to represent the future electricity market in 2025. In parallel, hourly process data from Söderenergi and IKV is gathered forming the base of the modelling.

The obtained performance data of IKV is translated, by linearisation, to represent input data in the model of the heat and power plant which is built in BoFiT. The detailed model of IKV will be verified against data from 2018 in terms of production and associated costs. Once validated the model will be additionally developed in order to represent the rest of the network of which Söderenergi is connected to, however in a more simplified approach. Required data concerning the performance of the facilities in the network is gathered and analyzed in order to be integrated in BoFiT. Again, the expanded model is to be validated against historical data and major trends. Further, an hourly time series of the heat demand for the entire DH network over one year will be developed and implemented in BoFiT. This in order to capture the operation of IKV and the system during different seasons.

The electricity price scenarios are translated to hourly time series over one year in order for these to be implemented in the developed model in BoFiT. Simulations are conducted for each scenario and results will be retrieved and analyzed in order to see how IKV and the rest of the system is affected in a future energy system.

1.4 Delimitations

This project is performed during a limited period, meaning that some limitations need to be applied. Focus of the project is put on the CHP plant IKV, the rest of the facilities of Stockholm's DH system, amounting to over 50 units, are represented through simplified components. Further, costs related to heat production, excluding electricity prices and factors affected by those, have been assumed to remain the same in 2025 as they have been in the past. Start-up costs are disregarded for all units included in the DH system.

The heat demand is based on a temperature forecast for 2020, indicating that possible changes in heat consumption that may occur in the future are not taken into account. Additionally, the demand of external steam deliveries to the industry sector is neglected, in order to focus on the heat demand.

Additional limitation is the exclusion of the economic compensation for electrical power producing units which Söderenergi and other electricity producers in the region receive from an external part. This extra economic compensation works as an incentive for these facilities to produce electricity. This is not included in this work as the future of it is uncertain. Further, it might be interesting and helpful for Söderenergi to know how IKV would behave without compensation. Finally, excluding the this makes modelling of IKV more generic, and thus applicable to other CHP-facilities.

Another difference between the modelled work and reality is the required minimum steam flow corresponding to 1-2 MW heat that is kept streaming through the bypass (BP). In reality it is kept constant, when IKV is not operating on BP-mode, in order to enable a quick switch if needed, but in the model that constraint is excluded.

Additionally, the model does not consider any accumulators and the ramp up/down time for heat plants, excluding IKV, is not taken into account. The last one indicates that other facilities modelled can be started immediately when required. No start-up or shut down costs were included for any facility in the DH system since these were modelled with simplified components in BoFiT which limits the complexity of the rest of the system. These components are only represented by thermal output and production price. Revenues from heat sales are not taken into account - instead focus is put on minimizing the production costs of the system. Additionally, no power limits in the distribution of electricity has been taken into consideration. Limitations in the distribution grid occurs rarely to the extent that it affect the operation of IKV and is therefore, by reason excluded.

2 Theoretical Background

2.1 The Power System of Sweden

Like many other countries, Sweden is in a state of transforming its energy system due to technical development and environmental challenges. As a response to the European Union's (EU) climate action plan for 2020 and Agenda 2030 Sweden established national climate- and energy goals in order to contribute to the common EU target. These include a heavy shift from commercial energy resources to renewable energy technologies which will affect today's energy system considerably. In 2040 Sweden is expected to have 100% renewable electricity production. Sweden is expected to meet the goals for 2020 however, the consequences of policies and actions already implemented can be observed to be, to some extent, making the energy system in Sweden unstable.[22]

The electricity production in Sweden has been relying on huge capacities of hydro power and nuclear power for a long time. However, due to the policies and actions implemented a shift in electricity production is shown where base load nuclear power is expected to be phased out and intermittent renewable energy resources like solar and wind will take their place. One source of electricity production remaining stable is the combined heat and power plants which in 2017 contributed with 10% of the total electricity production.[21]

2.1.1 Nuclear Power

Sweden first introduced its first commercial nuclear power plant into its energy mix in 1972. At most, 12 nuclear reactors were later active in the country.[9]

Although nuclear power was an important contributor to the Swedish energy system, there were voices opposing it already in 1972. After the Three Mile Island accident in Harrisburg, USA, the disapproval of nuclear power grew within Sweden and a national referendum was held in 1980, during which it was decided that the nuclear power plants would be decommissioned over the upcoming decades. [9]

Today, in the midst of the process of phasing out of nuclear power, Sweden has three nuclear power plants with seven active nuclear reactors. In 2020, another one is expected to be closed down, after which Sweden will be left with six nuclear reactors that are deemed to be able to operate until 2040.[20]

Nevertheless, the dependency on nuclear power is planned to decrease and Svenska Kraftnät published in 2015 a report that estimated that the production from nuclear power will decrease from 62.2 TWh in 2014 to 48 TWh in 2025. The installed capacity will decrease from 9 528 MW to 6 700 MW between 2014 and 2025, see Figure 2.1. [19]

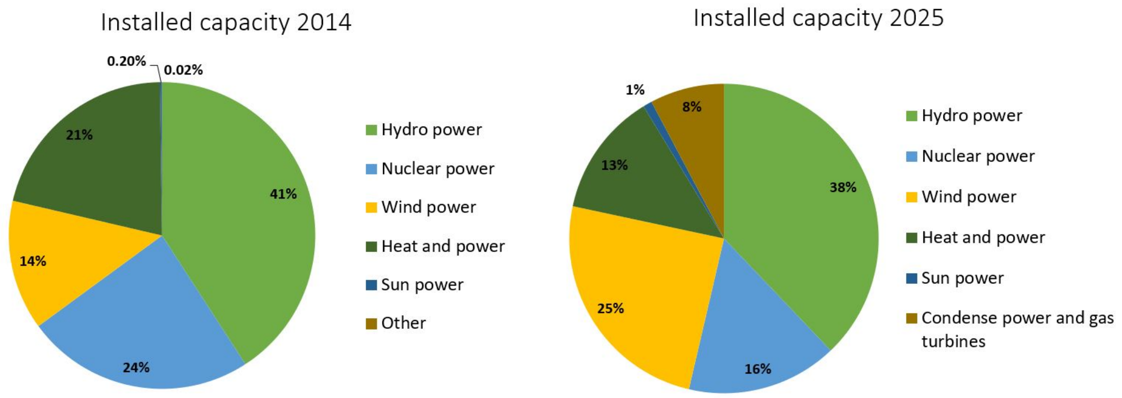

Figure 2.1: Installed capacity in Sweden in 2014 and 2025, divided based on energy sources.

2.1.2 Wind Power

The electricity production from wind power has increased significantly during recent years and is today a substantial part of the total electricity production in Sweden. In 2018, the installed capacity of wind power plants increased with 700 MW, meaning that the total installed capacity in Sweden reached 7300 MW. This resulted in a production corresponding to 11% of the total Swedish electricity production. Due to especially poor wind conditions during 2018 the turn-out was lower than expected. However, the capacity increased further in the coming years and in 2019 additional 1996 MW wind power was installed resulting in an actual production of 20.7 TWh being more than ever. The aim of the government is now to cover the upcoming losses of capacity due to the decommissioning of the nuclear power plants Ringhals 1 and 2 with renewable sources. Svenska Kraftnät estimates that the total installed wind power capacity will be 10 500 MW in 2025.[19]

The heavy increase of wind power production is partly due to the national climate- and energy goals, but it is also a result of the implementation of the electricity certificate system in 2003. The aim of implementing the system is to increase the electricity production from renewable energy sources in Sweden and in Norway by 28.4 TWh between 2012 and 2020. The purpose of electricity certificates is that it forces trading between renewable electricity producing companies and non-renewable producers together with electricity consumers, favoring the first one mentioned due to quota obligations. Electricity production from following resources generate certificates: bio fuel, solar, wind, wave, geothermal, hydro power and peat.[23]

The results of introducing the certificate system were more successful than expected and the expansion of renewable energy grew significantly - there among wind power, as described in the section above. In 2017 the Swedish government determined to expand the system additionally in order to keep favoring especially wind power. However, the supply of electricity certificates has not been following the demand which has resulted in a huge surplus of certificates lowering the prices significantly. Thereby, due to the expanded agreement, meaning more certificates, the surplus is not expected to decrease and the price of electricity certificate will continue to drop. In light of this continuous decrease the electricity certificates will assume to be zero in the scenarios of this thesis. [23]

2.1.3 Electricity Market

The production, trading and distribution of electricity is a complex system in Sweden managed and operated by several actors and companies. The transmission and distribution of electricity, occurs on three different levels of networks: The national, regional and local networks. The regional and local networks are owned by 170 different grid operators which are regulated by the Transmission System Operator (TSO) Svenska Kraftnät along with the Energy Market Inspectorate (Ei). The TSO, Svenska Kraftnät owns and operates the national transmission network as well as having the main responsibility of balancing the production and consumption of electricity in the grid, keeping the frequency on 50 Hz. [4] Additional key actors are:

- Electricity users/consumers/end customer
- Electricity producers
- Electricity traders
  - Electricity suppliers
  - Balance providers
- Network owners/grid operators
- TSO (Svenska Kraftnät)

Söderenergi is characterized as a producer selling electricity and trading of electricity is of high importance. Trading of electricity occurs on a deregulated market where competition between electricity producing companies drives the market price. The electricity market is structured by four different sub markets: the Hedging market, the Day-ahead market, Intraday market and the Balance market. They are differentiated from each other based on when in time the trading is happening.[4] Today, Söderenergi firstly acts on the day-ahead market in order to plan and optimize their production and if necessary trading on the intraday market occurs. Additionally, Söderenergi is involved in the headging market representing the financial trading of electricity. The hedging market exists in order to manage risks and secure future revenues for an electricity producer or future electricity supply for an electricity consumer. Settling future financial agreements on the hedging market is a big part of Söderenergis risk strategy but this will not be further investigated as only physical trading is of interest for this thesis.

Physical Trading of Electricity

The physical trade of electricity occurs each hour on a daily basis through the market platform Nord Pool, mainly on its submarkets: Elspot and Elbas. Elspot is the Day-ahead market where the electricity supply and consumption of tomorrow is forecasted. Nord Pool establishes the hourly electricity spot price the following day by matching supply with demand in a merit order system. The demand side depends on human behaviour and seasonal changes. The supply depends on the available technologies producing electricity and they are organized to their ascending order in price, smallest to largest. For example, nuclear power is cheap and used as base load due to its stable production and placed early in the merit order. Renewable power source such as wind and solar are also cheap but highly variable, depending only on weather conditions pushing other technologies out of the merit order when in operation. Phasing out nuclear power and increasing the amount of intermittent power producing technologies will therefore affect the electricity price to vary to a larger extent. Sweden is divided in four different electricity price zones, SE1-SE4, where Söderenergi acts in SE3. [4]

Elbas is the intraday market of Nord Pool and acts as a supplement marketplace to Elspot. Elbas allows the stakeholders to adjust their offers from the Day-ahead market, supposing the conditions for electricity production or consumption has changed. Trading is possible up to one hour before delivery which reduces the risks of being exposed to upward- or downward regulating prices which is established after the hour of operation in order to disfavour companies deviating from their proposed electricity plans.[4]

The regulating market exists in order for the TSO to keep the balance on the grid. The regulating market is only active during the hour of operation and if there is imbalance in the network the TSO has to actively regulate bids in order to correct the unwanted deviations. Only a few actors are involved in the regulating market. Today Söderenergi is not a part of this market. [4]

Due to changes in the energy system these markets are expected to adjust accordingly. In order to respond to faster variations in the electricity price Svenska Kraftnät aims to change the balance settlement period in the regulating market to 15 minutes instead of 60 minutes. Meaning, in the regulating market the regulation of balance will happen with a higher frequency in order to respond faster to changes in the system. This framework entails other changes in the marketplace including the ability to trade in the intraday market within a period of 15 minutes. These changes will be of interest, especially the intraday market, to large electrical power producing facilities such as Söderenergi which could be pushed out of the merit order if high amount of wind and solar is integrated. According to Svenska Kraftnät this will be implemented at the end of 2020. Changes in the day ahead market is not yet established.[18]

2.2 The Heating System of Sweden

The heating market is, next to the electricity market, a predominant market in Sweden. The main means of providing heat to the consumers include district heating (DH), heat pumps, electric heating and biofuel boilers. DH accounts for about 50% of the market, while electric heating and heat pump represent 30%. The rest of the heat demand is covered by oil and gas, and other biofuels.[13] The consumers consist of single- and multi-family houses, industries and premises, the latter one consisting of commercial and official buildings.

The demand for heating and heated tap water accounts for around 100 TWh per year. The largest sub-market, both in terms of turnover and energy demand, consists of single-family houses - it accounts for more than half of the economic turnover and 40% of the demand. The second largest group are multi-family houses, corresponding to a fifth of the turnover and 30% of the energy demand. Following are the premises and the industries. Historically, the market has been increasing but the increase is now slowing down due to increased efficiency of the technologies.

The Swedish heating market is, unlike the very cohesive electricity market, quite divided and consists of many smaller, locally-oriented markets. Each market is in a sense unique as it functions given different prerequisites. These variations might be noted in the geographical conditions, the demand as well as electricity- and fuel prices. The consumers are also quite heterogeneous; the customers segments range between small and large scale, new and old buildings, simple and complex systems, uninterested and knowledgeable individuals and other.

When it comes to sustainability aspects, the heating market in Sweden is regarded as having developed positively since 1970. The use of fossil fuels has decreased drastically and today only 3 TWh per year is derived from sources such as oil and natural gas, as compared to 20 years ago when the value was 30 TWh per year.

Additionally to discarding fossil fuels, the heating sector has also experienced an improvement in efficiency which has contributed to its sustainable development. The increased total efficiency has been obtained by improving the efficiency in the conversion chain and through lowering the specific heating demand of buildings.

Although a big part of the transformation towards sustainability has been done, for example by shifting to renewable- and recovered energy, studies show that the heating sector will continue to advance in regards to that aspect. The final energy use is predicted to decrease - this is due to more energy efficient houses and improved efficiency in the energy transformation technology.

The heating market is moving towards a new energy landscape. There is an increasing number of actors on the market as consumers transform into prosumers, and heat from data centers becomes incorporated in the network. Further, renewable energy sources, such as wind and solar, are increasing their share on the market which, due to their intermittency, changes the patterns of power availability and electricity prices. In the heating market, this influence facilities affected by electricity, for example heat and power facilities, which produce electricity together with heat, or electric boilers, which consume electricity in order to produce heat.[13]

2.2.1 District Heating

District heating expanded greatly in Sweden during the 1960s, when it became attractive to replace oil-fired boilers placed in each house with a uniform system, where production from a few boilers could serve multiple houses. Nowadays, DH is dominating the heating market - in 2012, the production reached 48 TWh. It has become a valuable system, not only because it supplies the society with heat, but also because it has become a resort for waste management. Certain facilities get rid of the municipal and other waste, which is not possible to recycle, by burning it. When burning the waste energy is extracted and the waste is used to its full potential.

The heat distribution system is influenced by a number of trends including global warming, sustainable development, increased competition from heat pumps, new system configurations as well as new actors on the market. It is also influenced by technology development. According to Värmemarknad, research is, among other, investigating how one can lower the temperatures in the network grid in order to minimize the losses that occur during the distribution. In an overall review of the Swedish heating market, Värmemarknad states that what DH needs to do in the upcoming future in order to keep its competitiveness is to standardize components to lower the production costs, address the increasing demand for individually adjusted comfort, tackle the changed heat load profile in the upcoming low-energy houses and investigate the possibilities of absorbing surplus electricity from intermittent production (for example from wind power) into the DH network.

The future of DH is difficult to predict as there are many factors pointing at different paths of development. For example, when it comes to the delivered energy it is predicted to decrease due to energy efficiency measures, which, in consequence will lead to decreased costs. On the other hand, advancing the technology to achieve such efficiency levels will implicate increased costs. DH is also facing competition from heat pumps, which will benefit if the electricity prices decline.

Värmemarknad is expecting the heating demand to decrease in the upcoming years. The total heating demand is estimated to be between 70 and 90 TWh in 2030, and 27 and 51 TWh in 2050. [12]

2.2.2 Production Planning

Söderenergi is a part of a large DH network including Stockholm Exergi and Norrenergi. Together they constitute a complex system of heating and electricity producing facilities connected to each other with the common goal of ensuring a stable supply of heat, fulfilling the customers heating demand to as low cost as possible. Obtaining this goal requires close cooperation between the companies and an optimization of the production, which is done through production planning.

The production planning is firstly based on the expected heat demand for the system which varies throughout the year. The variations are based on two depending factors: Physical and social parameters. Seasonal variations such as change of outdoor temperature along with change of wind and solar conditions over the year are characterised as physical parameters. Social load is due to human behaviour such as social patterns and changes on a daily basis [3].

The relation between the outdoor temperature and the heat load is the most significant parameter affecting the variations. The heat demand has an inverse correlation to the outdoor temperature which can be seen in a characteristic load curve, also called energy signature, shown in Figure 2.2. Figure 2.2 represents the energy signature for Telge nät, a part of the DH network connected to Söderenergi. Therefore, a prognosis of the required heat demand is often based on a temperature forecast. Thereafter, the production is allocated to different facilities in a prioritized order, based on production costs, called the merit order effect.

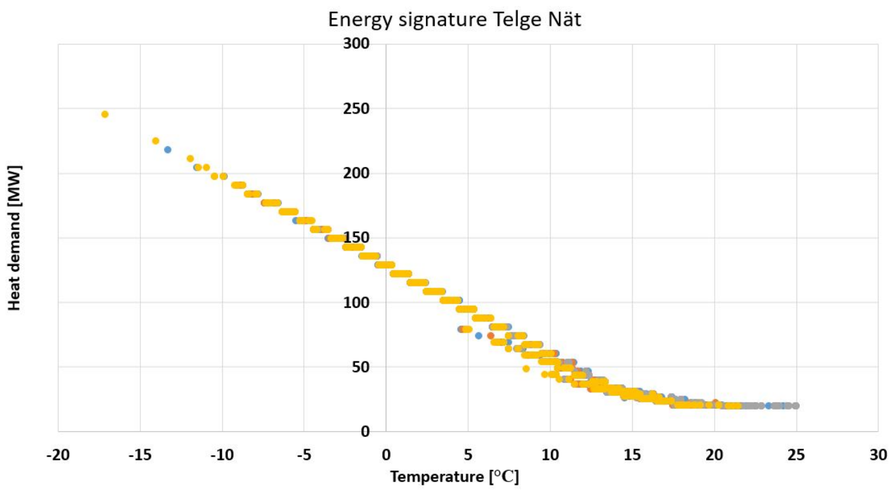

Figure 2.2: Energy signature for Telge Nät showing the correlation between heat demand and temperature.

The merit order effect organize facilities that are connected to the same DH network based on the production cost for one unit of heat (SEK/MWh), which varies among the facilities. Firstly, the costs varies depending on parameters such as fuel price, operation and maintenance and taxation. Secondly, the heat production varies from each facility depending on capacities, mode of operation and plant design. Furthermore, considering facilities producing heat and electricity the sales of electricity is seen as a revenue. This reduces the production cost significantly and places the facility further down in the merit order.[8]

Up until now the merit order for the entire system has been relatively simple to forecast and rather stable. Knowing the choice of fuel and thermal capacity, the facility could easily be placed in the merit order. For example, it is known that the cheapest facilities in the DH system, acting as base load, are represented by production facilities using waste as fuel. With waste as fuel the production cost even gets negative. It is also known that electricity producing facilities are placed early in the dispatch order while facilities using fossil fuel are pushed outside the merit order and only used as peak load facilities. However, with changes in the power system the electricity price will come to affect the electricity producing facilities to a higher extent and make the merit order more dynamic and volatile.

2.3 Söderenergi AB

Söderenergi is a part of a compound of organizations operating one of the largest and most complex DH networks in the world with a yearly production of 9 TWh representing 20% of the total DH in Sweden. Together with Stockholm Exergi and Norrenergi they own and operate over 50 facilities in order to provide the entire Stockholm region with DH (their geographical distribution is visualized in figure 2.3). The three companies optimize the heat production and supply by using the merit order principle. The facility with lowest production costs is put into operation first in order to fulfill the entire heat demand to as low cost as possible. On average, about a third of Söderenergi's heat production is exported to these partners.[16]

Söderenergi AB is owned by the companies Telge AB and Södertörn Fjärrvärme AB which, in turn, are owned by the municipalities of Södertälje, Huddinge and Botkyrka. Just by itself, Söderenergi provides 100 000 households with DH all year around. The company operates several facilities and has a yearly production of 2500 GWh heat and 550 GWh electricity. Additionally, Söderenergi delivers steam to nearby industries. Söderenergi's facility portfolio includes Igelsta combined heat and power plant (IKV), Igelsta heating plant and Fittjaverket. Further, the company operates Huddinge Masincentral (HCM), Geneta Panncentral (GPC) and Skogås facility which are backup power plants operating only in extreme cases, such as unusually cold temperatures or when one of the main power plants have been damaged. [16]

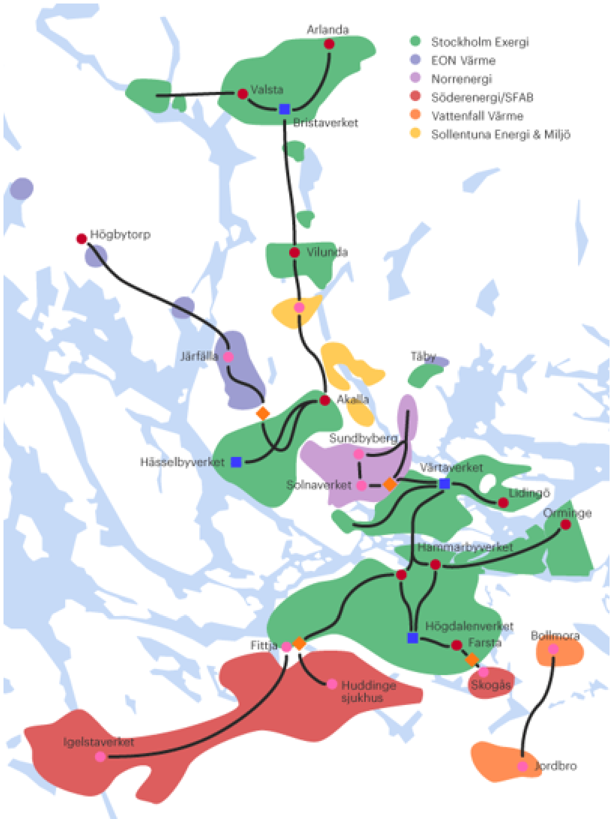

Figure 2.3: Visualization of the total District Heating network

Igelsta heating plant

Igelsta heating plant consists of three heat-only boilers (HOB); IGV 1, IGV 2 and IGV 3. The plant was originally fueled with carbon powder but went through a reformation during the 1990's where it was reconstructed so that it would be able to run on biofuels. IGV 1 is a HOB which is a part of Söderenergi's base production - on average it operates around 6000 hours per year[16]has a capacity of 92 MW including its flue gas condenser (FGC). The main fuel used is solid recovered waste, including paper, wood and plastics, which represents 80% of the mix, the remaining 20% consists of rubber. Additionally, IGV1 generates steam which is transported to local industries placed nearby.

IGV 2 is a HOB fueled by tall oil. It has a production capacity of 95 MW but it is not included in Söderenergi's base production - the facility is instead only used occasionally during the winter season, when the heating load is exceptionally high. [16]

IGV3 is the final HOB in the Igelsta complex. It is fired by recycled wood and has a capacity of 95 MW. The boiler consists of a bubbling fluidized bed and the unit includes a FGC.[16]

2.4 Combined Heat and Power Plant - IKV

IKV is a combined heat and power plant (CHP plant) meaning the plant produces both heat and electricity. The process of a CHP plant consists of an energy source, that can be represented by different types of fuels, that is combusted in a energy conversion process, in order to extract heat for both electric power production and heat supply. By integrating both heat and electricity production the full capacity of the plant is exploited making the total efficiency of a CHP plant very high.[24]

Igelsta CHP plant was founded in 2009 and is today in operation 6 200 hours per year, which in turn signifies an annual production of 1 400 GWh heat and 550 GWh electricity. Fuel is being fed in for combustion in a circulating fluidized bed (CFB). In the boiler the fuel is combusted in order to convert the chemical stored energy to thermal energy which evaporates the water in the tubes surrounding the boiler. The fuel fed into IKV consists of a mix of recycled wood waste (30%), forest residues (60%) and solid recovered fuel (SRF) (10%), and the fuel consumption reaches roughly 600 000 tons per year. [16]

The generated steam in the boiler is then transferred to the turbine which enters with a temperature of 540°C and a pressure of 90 bars. In the turbine the thermal energy is converted to mechanical energy and electricity is generated with a power capacity of 84 MW and then distributed to the electricity grid with a frequency of 50 Hz. This reduces the temperature and the pressure in the turbine so the remaining heat can be exchanged in the main heat condenser (MC) following the turbine. By transferring the remaining heat towards the DH network the steam is condensed and returned to the feed water tank which pushes the water back into the boiler, closing the cycle. The MC has a thermal output of 154 MW, heating the DH water to a supply temperature of 75-95°C.

Lastly, a CHP plant is equipped with an additional heat condenser with a possible thermal output of 240 MW which can be used without using the turbine, called the BP-condenser. By redirecting the steamflow the turbine can be bypassed and heat can still be produced when electric power is not required. IKV is also designed to allow the two condensers to operate together, further called regulating hours in this thesis. However, the majority of the time the most economically viable option for IKV is to operate with the MC due to electricity production and sales. Especially when receiving the extra economic compensation favouring electricity production even more.[6]

The primary purpose of a CHP plant is to produce heat to the DH system and electricity is produced secondly. Meaning, the plant firstly responds to the heat demand rather than electricity demand and the electricity production is instead seen as a revenue in order to lower the production cost of the plant. In order to describe how much electrical power that is produced at a given unit of heat a common performance factor used in CHP plants is α. The α represents the ratio between the electricity production P, and the heat production Q, see equation 1.[24]

$$\alpha = P/Q \tag{1}$$

Lastly, IKV is equipped with a FGC increasing the exchange of heat further. An additional heat exchanger with a thermal output of 57 MW extracts the heat from the steam in the flue gases. The heat is transferred to the return water from the DH network which becomes preheated before entering the main heat exchanger.[6]

3 Building the Model

The model used for this project was built in BoFiT - a software developed by ProCom, which uses mathematical optimization methods to imitate heat and power plant operation. The objective of the optimization in BoFiT is to minimize the production costs of the facility. The construction of IKV was the main focus of this work - the rest of the DH system of Stockholm and its suburb area was thus represented by economic operators and trading components.

BoFiT will optimize the entire system in order to achieve as low costs as possible during each hour of operation. For IKV this means four different modes of operation: operate only the MC and produce electricity (path 1 in figure3.1), operate only the BP condenser (path 2 in figure 3.1), regulating the MC with BP (path 1 together with path 2) or being shut down. IKV can also use the FGC (path 3) in combination with the MC and BP. In the past, for IKV independently it has been, most of the time, most economically viable to operate the MC and receive revenue from the sold electricity and thereby reducing the production cost. However, since IKV has also been connected to the rest of the system, at times the system would find it more profitable to switch the mode of operation from the MC to the BP condenser in order to gain more heat, especially with large heat demand.

Additionally, BoFiT can choose to operate the FGC together with the MC or the BP condenser or turn it off.

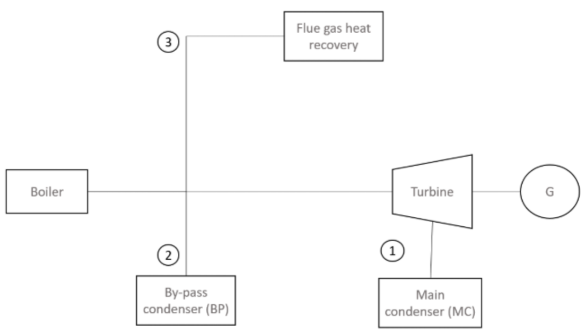

Figure 3.1: Basic operation modes of IKV

3.1 Modeling - IKV

Firstly, a base model of IKV in its current state was built in BoFiT. Components such as a boiler and a turbine were added in a way so that they would mimic the real-life flows and energy transfer processes. The data used for inputs for the model was extracted from Söderenergi's database, mainly from PI ProcessBook. The data consisted of recorded performance during 2018. The finished model is displayed in Appendix C in figure C.6 and C.7.

BoFiT assumes linear dependence between inputs, meaning that for the data where linear relationships were observed from start to end, it was sufficient to only insert the minimum and maximum values. In cases where linearity was not observed for the whole operation range of the component, the range was broken down into sections in which linear relationships existed. The values which were then inserted into BoFiT consisted of the breaking points. The correlations and final input data for BoFiT is further presented in Appendix C. Details with regards to values can be found in figure C.8-C.9 in Appendix C.

Some components of the model required or performed in a more accurate manner with time series as inputs. The inputs developed as time series include cost for fuel, operation and maintenance cost of MC and BP as well as FGC, electricity price, steam demand and heat demand. More details about how these were obtained can be found in chapter 3.1.1.

Various constraints were implemented in the model. The main one was the heat supply which is representing the heat demand, and is required to be met by the DH network. A demand was developed for the whole region of Stockholm by dividing the network into subareas - a description of the process can be found in chapter 3.2.2.

After adding the main components and the constraints, the model was refined so that it would include the limits of the real-life heat and power plant, for example a ramp up time. Additionally, the relation between the MC/BP production and FGC output needed to be locked. In practice, this means that a certain load of the boiler correlates with the production in MC- or BP-lead which corresponds to a certain production in the FGC; the FGC cannot regulate its output without considering the production in the other two heat-generating components. In the model, this relation was achieved by an operation component, which restricted the FGC heat exchanger in relation to the output of the MC or the BP heat exchanger.

Another modelling measure which was implemented in the FGC-flow was the addition of a steam supply, which serves as a fictional steam dump. The fictional steam dump represents the chimney and would the steam dump not be in place, the model would be forced to always use the FGC when using the MC or the BP. Now it can be regulated.

The FGC-component was also refined by a signal profile. It was added because the FGC performs differently depending on the time of the year, and the signals help mimic that. The amount of energy extracted from the flue gases depends on the moisture content of the fuel as well as the return temperature of the water coming back from the DH network which varies throughout the year. To model that, the efficiency of the FGC in real life throughout a year was obtained from Söderenergi's database and a different rate between fuel input and RGK output was set for each month with the help of the signal profile component. Each monthly value is presented in table C.5 in Appendix C.

3.1.1 Creating time series

Inputs which were built as time series consist of the cost of the fuel mix (recycled wood waste, forest residues and solid recovered fuel), the operation and maintenance costs for MC, BP and FGC, the cost of electricity and the heat demand of the Stockholm region.

The time series for the fuel cost consisted of the acquisition price of the fuel mix and the cost related to emission allowances. The acquisition prices of 2018 were obtained from Södernergi's economical records and the price of emission allowances was taken from January 2018 [1]. The cost of emission allowances was adjusted with an emission factor that stated how much carbon dioxide was emitted per MWh fuel burned. The adjusted emission costs were then added to the fuel acquisition cost on hourly basis for a year, which created the time series connected to the fuel input-component in BoFiT. Details with regards to prices obtained are presented in table C.6 in Appendix C

Another time series that was created for the model was the maintenance and operation cost used for the MC and BP condenser. This cost was assumed to consist of the operation and maintenance cost (O&M) related to the heat production, that was obtained from Söderenergi's past data. Additionally, the fees related to emission of nitrogen dioxide were added to the O&M costs, as Söderenergi counted those per unit heat produced. A corresponding time series for O&M costs for the FGC was also added to the model (see table C.6 in Appendix C for all details).

For the input to the power trading component in BoFiT a time series consisting of costs related to electricity production were included. These consisted of the electricity spot price, the O&M cost for electricity production, grid revenues and nitrogen dioxide fees added together. The values for each can be found in table C.6 input in the Appendix C.

The time series creation is summarized by equations 2, 3, 4 and 5. Time series 2 correspond to the input given the fuel-related components in BoFiT, Time series 3 was added as input to the main- and BP condenser in the model, Time series 4 was added to the FGC and Time series 5 was added to the power trading components connected to the turbine in BoFiT.

$$Cost_{fuel} = Cost_{fuel\ acquisition} + Cost_{emission\ allowance} \tag{2}$$

$$Cost_{heat} = Cost_{O\&M\ heat} + NO_x - fees \tag{3}$$

$$Cost_{FGC} = Cost_{O\&M\ FGC} \tag{4}$$

$$Cost_{turbine} = El.\ spot\ price - Cost_{O\&M\ el} + revenue_{grid} + NO_x - fees \tag{5}$$

Additionally, to the above, the heat demand was developed as a time series, with hourly input. The details of the process behind the development of it can be found in section 3.2.2.

3.2 Modeling - DH network

In the model created for the purpose of this thesis it was necessary to develop a heat demand for the whole Stockholm region as well as modeling the other heat-producing facilities constituting parts of the DH network. This was required in order to capture the dynamics of the system - it was of interest to know how Söderenergi's IKV would perform in comparison to the rest of the system as well as where it would end up in the merit order.

3.2.1 Components

Modelling all the other facilities at such a detailed level as the one that was applied to the IKV-model was outside of the scope of this study, which is why simplifications were made. Other facilities than IKV, that are a part of the DH network, were firstly divided into two categories; facilities which had their heat production cost affected by the electricity price and those that did not. Within those categorizations, facilities were then sorted based on what type of plant they were (for example heat only boiler or heat pump), then arranged according to their production costs and fuel type - facilities with similar characteristics were grouped into one block. For example, if there were 5 different electric boilers, with similar production costs in the original outline, they were grouped into one block.

Each block was then represented in BoFiT by components which import heat. These types of components were given maximum thermal output (MW) and cost of heat rate (EUR/MWh) as inputs. Additionally, the capacity of block S, see table 3.1, is adjusted and reduced during the summer period in order to mimic the revision period which occurs in reality once a year. This adjustment is only taken into consideration for block S being the cheapest facility in the system and placed in the bottom of the merit order and thereby affecting the operation of IKV during the summer.

The maximum thermal output for each block, shown in table 3.1,represents the sum of each of the capacities connected to the facilities incorporated in that block. The heat rate was either given as a constant value or time series - the latter one was used if the rate varied with the electricity price. For block which were not affected by the electricity price (block A-M in table 3.1), for example, oil-fueled boilers, a static heat rate, was used. The heat rate for those blocks was determined by first deriving a production cost from past data for each facility included in the block, then calculating the weighted average of those costs.

When it comes to blocks that included facilities that were affected by the electricity price (block N-T in table 3.1), three types were identified; CHP-facilities, heat pumps and electric boilers. Due to similar production costs, all heat pumps were put together as one block (block O) and all electric boilers were put together as another block (block Q). The production cost, SEK/MWh for the block with the heat pumps was later derived according to equation 6:

$$Cost_{production\ HP} = \frac{El.\ spot\ price + 356}{3.35} \qquad [SEK/MWh] \tag{6}$$

Table 3.1: Units representing the heat-producing facilities in the DH system of Stockholm and their production costs

Unit	**Type**	**Fuel**	**Cost [SEK/MWh]**
A	HOB	Recovered fuel	97.70
B	HOB	Pellet	511.91
C	HOB	MFA, tall oil	580.06
D	HOB	MFA, bio-oil	656.22
E	HOB	tall oil	691.88
F	HOB	e05	708.67
G	HOB	bio-oil	907.41
H	HOB	e05	932.01
I	HOB	e01	1068.17
J	HOB	flue gas	1.00
K	HOB	bio-oil	597.78
L	HOB	e01	1082.47
M	HOB	wood chips	150.00
N	CHP	wood fuel mix	varying
O	HP	electricity	varying
P	HOB	loss of electricity	varying
Q	HOB	electricity	varying
R	CHP	bio-oil	varying
S	CHP	waste, recovered fuel	varying
T	HOB	loss of electricity	varying

The remaining units with CHP-facilities and electric boilers had their production cost obtained based on data from past years; recorded production costs were obtained for each facility and electricity spot prices which corresponded to the dates during which the production costs were recorded were extracted from Nord

Pool. The two values were then plotted against each other. A linear relationship between the electricity spot price and the production costs was assumed (see figure 3.2 and 3.2).

There were two units, unit P and T, which represented the cost of BP-mode operation for certain CHP-facilities from the DH network. This cost was essentially put as the lost value of electricity revenues, that occurred when one was not running the turbine. The production cost for those units was set according to equation 7. The element "ranking factor" shown as RF in equation 7 indicates the relative order respective unit is positioned at in the system merit order of the DH system.

$$Cost_{production\ DH} = El.\ spot\ price + Revenue_{grid} + RF \tag{7}$$

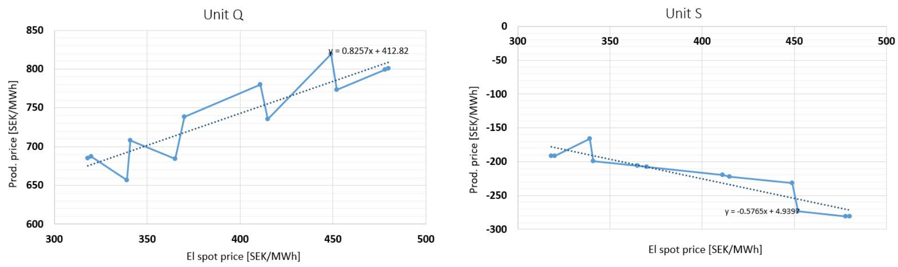

Figure 3.2: Relation between the electricity spot price and the production cost of unit Q and S, based on recorded data.

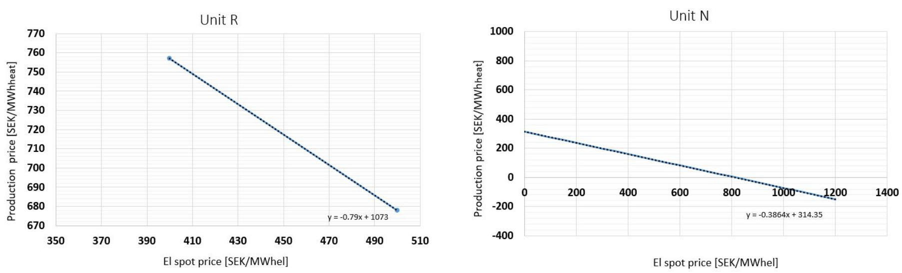

Figure 3.3: Relation between the electricity spot price and the production cost of unit R and N, based on recorded data.

3.2.2 Heat Demand

In cooperation with Söderenergi a heat load representing the entire system each hour of the year has been developed based on future forecasting temperatures for 2020 and existing power signatures for the entire network.

Firstly, Söderenergi shared a forecast for daily temperature means in 2020 which has been developed in cooperation with Stockholm Exergi based on historical data and visible trends. With BoFiT requiring hourly resolution additional data from 2016 showing hourly temperatures, retrieved from the measurement station Observatorielunden in Stockholm, were given by SöE.

Uncertainties in forecasting the temperature will always occur and therefore, the 2020 forecast was assumed to be the same in 2025. The 2016 was used in order to capture daily variations. Given the average daily temperatures in the 2020 forecast, days corresponding to the same average temperature could be identified in the year of 2016. The daily pattern from 2016 could thereby be implemented on the 2020 forecast and daily outdoor temperature variations were taken into account. However, each average occurred several times during the year of 2016 and the daily pattern for the same average could differ significantly. This happened especially during the Spring and Autumn where daily temperature variations were higher. In order to develop a representative time series additional analysis was made.

Average value occurring less than five times an arbitrary day was chosen. Values happening more than 5 times were additionally analyzed based on standard deviation, see equation 8. The standard deviation (STD) measures the spread of a set of values and quantifies the variations. A higher STD indicates high deviations from the mean value while a low STD shows that the set of values are close to the mean. A daily pattern with a standard deviation between 1-3 was considered to be representative for the values happening more than five times.

$$STD = \sqrt{(}\sum(\frac{(x-x)^2}{n}) \tag{8}$$

This resulted in a yearly time series with outdoor temperatures for each hour in

2020. The final step in deriving the heat demand of the system was to translate the temperature time series into a heat demand for the entire network. This was done by using an already existing excel model based on energy signature profiles for each sub network including Telge nät, Södertörn Fjärrvärme, Stockholm Exergi and Norrenergi. The energy signatures can be found in Appendix B. The yearly temperature series together with the heat demand is plotted in figure 3.4 as blue and green respectively.

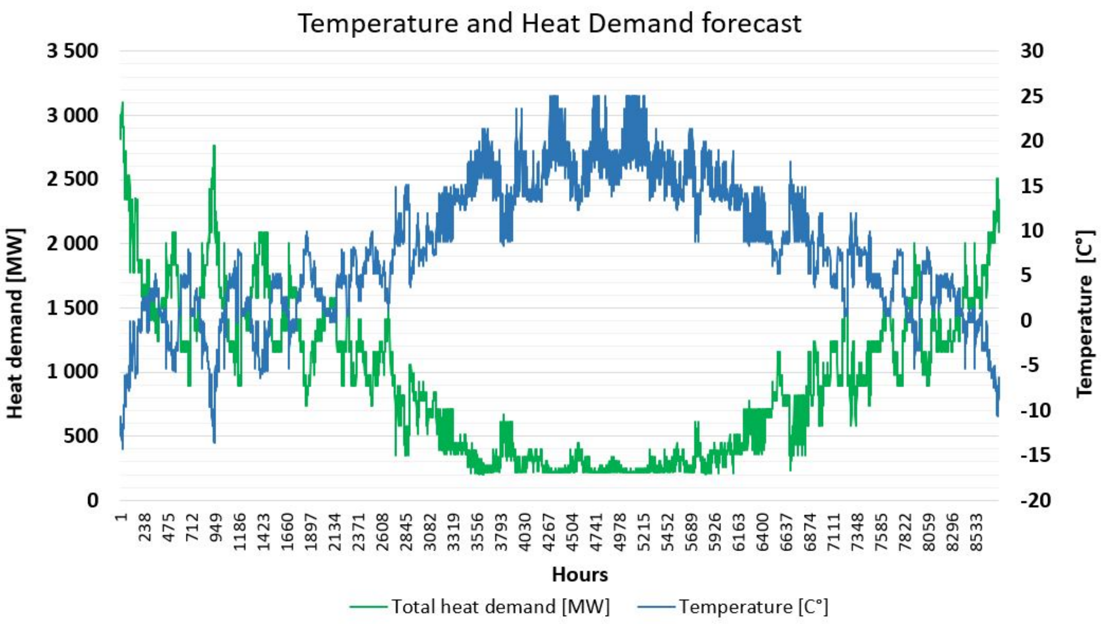

Figure 3.4: Hourly time series of temperature and heat demand forecast based on 2020 temperatures

4 Verification

In order to ensure accuracy of the results from the created model the performance of the model needs to be validated. In the following chapter the production and costs of the detailed model of IKV will be verified towards empirical data of 2018. Additionally, the expanded model, including the rest of the system, will be verified as well based on general trends and rules from reality.

4.1 Production - IKV

A validation was performed with hourly resolution against historical data retrieved from Söderenergi's database, PI processbook. The model in BoFiT was decided to be compared with the outcome of IKV in 2018. The total production of heat 2018 was therefore set as the heat demand in BoFiT and the spot price from Nordpool 2018 as the electricity price. Thereby, the mode of operation used by the model, in order to fulfill the demand, could be confirmed by comparing the production from each component with the outcome of 2018. The components analyzed were the MC, BP, FGC and the electricity production from the turbine.

In the following graphs the historical data regarding the production of IKV is compared to the production of BoFiT. BoFiT is an optimization tool forecasting the entire heat demand and electricity prices in order to run the power plant optimally which is impossible in reality. Therefore, some differences are acceptable. Figures 4.1-4.4 shows the production in BoFiT compared to the real production with values retrieved from PI Processbook. These following graphs present two weeks of the year in the beginning of March where the heat demand is reduced and IKV is regulated. Each component is represented in one graph. A verification of the entire year has been made and can be seen in Appendix B.

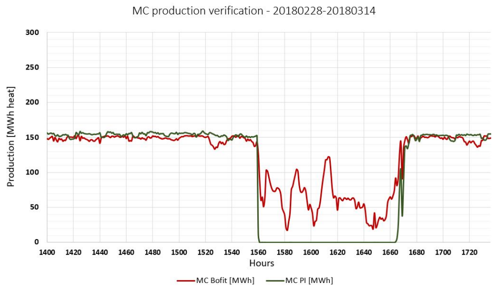

Figure 4.1: MC production

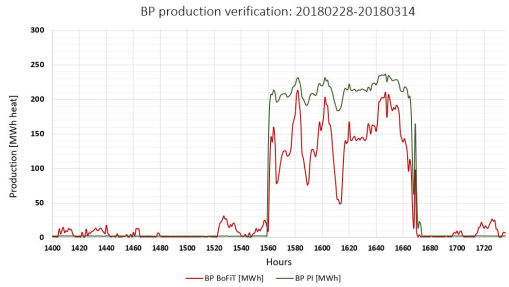

Figure 4.2: BP production

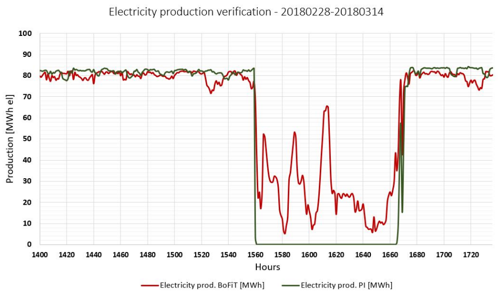

Figure 4.3: Electricity production

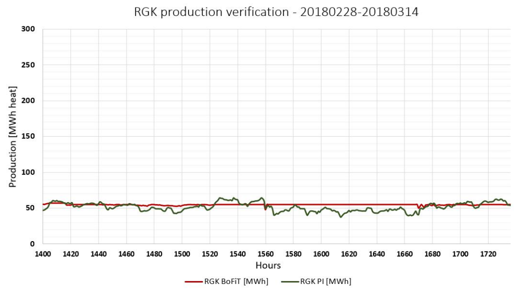

Figure 4.4: FGC production

The production between BoFiT and PI Processbook differs from each other significantly from hour 1550 to 1660 where BoFiT has an increased production from the MC which is completely shut down in the outcome of 2018, the same difference is consequently shown in the electricity production. The increased use of the MC results in a decreased use of the BP condenser compared to the data from PI. These differences can be explained by disturbances in the turbine in reality resulting in a shut down of the MC. BoFiT however, sees this as an opportunity to regulate the MC together with the BP in order to produce as much electricity as possible. The unpredictable occurrences disturbing the turbine in the reality cannot be taken into consideration when modelling BoFiT which results in some differences between the BoFiT model.

Additional deviations are due to BoFiT being a modeling tool and not affected by external parameters which makes the production fluctuate slightly in reality. This is especially noticeable in the FGC which fluctuates quite heavily during the season, see figure B.5 in Appendix B.

The total differences over one year is presented in table 4.1. In table 4.1 it can be confirmed that the major differences are between the BP condenser as well as the FGC. All differences found in the year could be explained with disturbances in the production and the model was therefore confirmed verified.

Table 4.1: Total production (Prod), Difference between BoFiT and PI(Diff)

Totals	**Prod. [GWh]**	**Diff. [GWh]**
Total BP BoFiT	54	-13
Total BP PI	68	
Total MC BoFiT	1024	3
Total MC PI	1021	
Total El. BoFiT	544	-5
Total El. PI	549	
Total FGC BoFiT	290	10
Total FGC PI	280	

4.2 Production - DH network

Once the detailed model of IKV was verified against the turnout of 2018 as well as the costs, the rest of the DH system was modelled and verified.

In table 4.2 the total heat production of IKV as well as each block importing heat is presented in total volume in GWh as well as the total share of operational hours during one year of each block. The hours of operation is defined as the number of hours the block is in operation and presented as percentage of the year. Due to the rest of the system being simplified only the major trends are verified. The entire system operates following the principle of merit order, meaning the cheapest block goes first. In this case S, representing facilities with waste as fuel. Unit S is in operation 100% of the year acting as base load for the system. Facilities such as E-I, corresponding to the peak load facilities, using oil, of the system, are not used due to their expensive production cost.

In order to verify the operation of the model in Bofit additional analysis of the BP condensers has been made, including block P, block T and IKV. In reality the optimal merit order of the BP condensers is block T as a primary choice followed by block P and lastly IKV due to production prices where block T is the cheapest one. In table 4.3 the total production of each block along with the hours of operation during the year in percentage is presented. Looking at operational hours the yearly results certify that block T is most often used with 23% closely followed by block P and lastly IKV. A few exceptions in the results that IKV is chosen before P and T.

However, this happens only a few times a year and is explained with IKV requiring ramp up and ramp down times and these occurrences are therefore disregarded in the upcoming analysis. Ramping times only affects IKV due to IKV being modelled in detail, considering the rest of the system, being simplified, ramping times are excluded.

Table 4.2: The total production volume and hours of operation for the entire network in respective blocks.

Unit	**Capacity [MW]**	**Tot prod [GWh]**	**Hours in Op. (year) [%]**
IKV	240	1 574	88%
A	95	592	79%
B	273	179	11%
C	358	90	5%
D	120	6	1%
E	95	2	0%
F	160	0	0%
G	52	0	0%
H	713	0	0%
I	94	0	0%
J	53	400	99%
K	75	8	1%
L	139	0	0%
M	95	521	64%
N	308	924	42%
O	537	2 162	58%
P	85	112	18%
Q	451	16	1%
R	200	2	0%
S	194	1 556	100%
T	54	86	23%

Table 4.3: Loss of electricity (BP)

Unit	**Capacity [MW]**	**Tot. prod. [GWh]**	**Hours of operation (during a year) [%]**
IKV BP	240	257	14%
P	85	112	18%
T	54	86	23%

4.3 Costs

Cost verification was performed in order to confirm that the model calculated the costs and revenues in a correct way. For the cost verification the results from BoFiT were compared to the results obtained from Söderenergi's cost calculation scheme. Inputs were kept the same for both approaches and the production was taken as the one obtained from BoFiT when running the 2018 production verification case. The costs obtained are presented in table 4.4.

Table 4.4: Comparison of cost calculation between BoFiT and Söderenergi's scheme (SöE).

	BoFiT	**SöE**	**Difference**
Average prod. cost [SEK/MWh]	110.47	110.47	0.00
Total cost [MSEK]	295.66	295.66	0.00
Cost heat [MSEK]	65.35	368	-302.35
Cost fuel [MSEK]	319.49	-	319.49
Netto cost turbine [MSEK]	-89.18	-72.03	-17.14
SUM	**295.66**	**295.66**	**0.00**

The cost calculation performed by BoFiT was deemed correct, as the average production cost and the total cost proved to be equal to their counterparts obtained in Söderenergi's calculation scheme. In the table, it can be observed that there are differences between BoFiT and Söderenergi's costs when it comes to *Cost heat, Cost fuel* and *Netto cost turbine*, but that the total of those is the same for both cases. This can be explained by the fact that the fuel costs, *Cost fuel*, were allocated differently in the two approaches - in BoFiT, fuel costs were calculated separately, while in SöE, fuel costs were incorporated in the costs of heat, *Cost heat*, and costs of turbine, *Netto cost turbine*.

Figure 4.5 shows the difference between heat production costs between the costs obtained from BoFiT and costs obtained from Söderenergi's calculation scheme. The figure shows the hourly difference between the two values throughout the whole year, and the small differences further confirm the calculations of BoFiT.

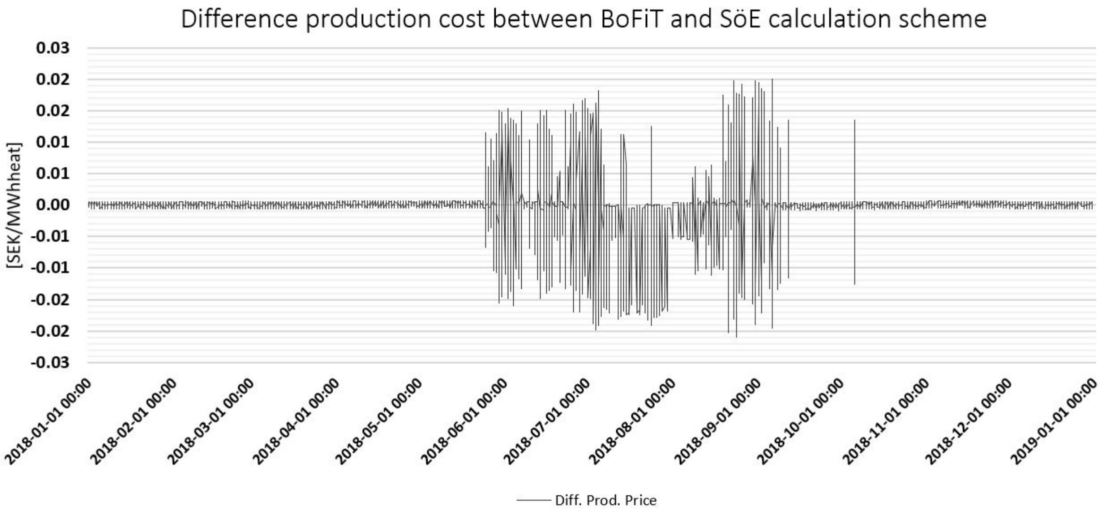

Figure 4.5: Difference in heat production cost between costs obtained from BoFiT and costs calculated with Söderenergi's cost calculation scheme.

5 Scenario Creation

For the scenario creation for this project focus was put on electricity prices, meaning that the scenarios obtained differed only by electricity price and components affected by it. The heat demand of Stockholm and its suburban areas was kept the same as the one developed in section 3.2.2 and all the components which were not affected by the electricity price were kept unchanged. The task for the scenario creation was to develop a number of hourly electricity price time series for the whole year of 2025, for Sweden. This was to be done based on the findings with regards to current and future trends in the energy system as described in section 2.1.

The scenarios created in this project were based on two major movements that are currently occurring in Sweden; the phasing out of nuclear power and the increasing share of wind power in the energy mix. This change in the energy mix indicates a shift from stable, relatively controllable energy source to more varying, unpredictable ones, and both processes possess the capability of influencing the hourly electricity price greatly.

When researching how a nuclear- and wind power affect the electricity prices it was then found that a decreased amount of adjustable and controllable electricity producers, for example nuclear power plants, led to periods with elevated or highly elevated electricity prices. Findings also showed that an increased share of wind power in the Swedish energy system resulted in longer and more frequent periods with low electricity prices [15].

The literature study performed for this project showed that the Swedish energy mix in 2025 is estimated to include 6 700 MW of installed wind power capacity and 6 800 MW nuclear power (see section 2.1. The wind power is determined to contribute with around 40 TWh of electricity. The scenarios created were thus based on these amounts. In the following sections a more detailed description of each scenario is presented.

5.1 Scenario A. 2017

Scenario A was constructed as a reference scenario. It was built based on the 2017 spot price of SE3. The price of 2017 was deemed more suitable than 2018, as 2018 was an unusually dry year, which, in a country that relies on hydropower, resulted in elevated electricity prices. This effect was especially noticeable during the summer [25]. The effect is also illustrated in figure 5.1.

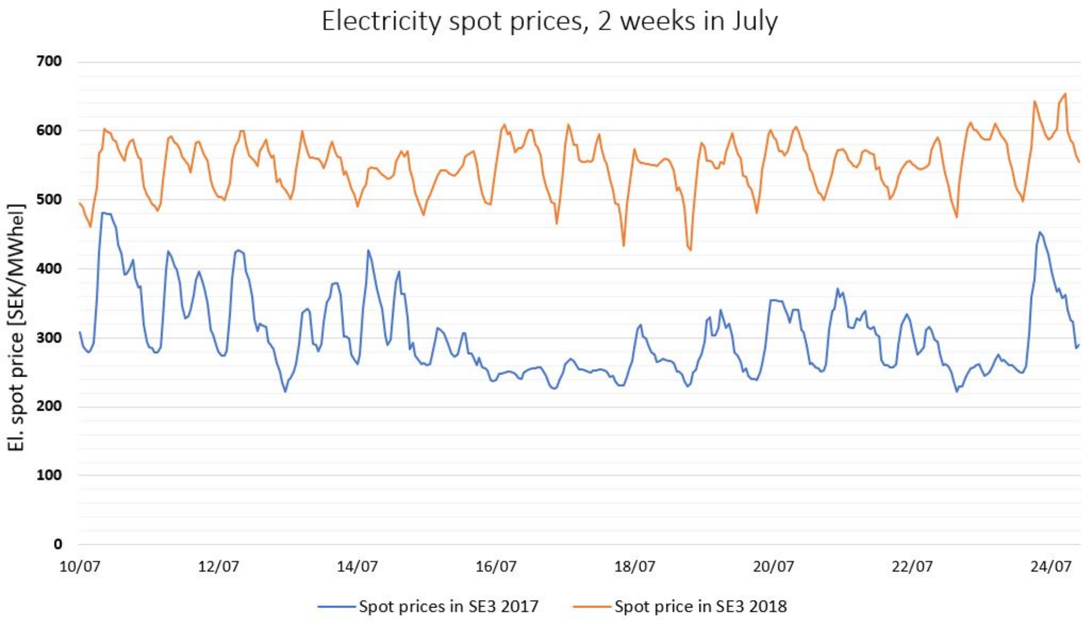

Figure 5.1: Comparison between electricity spot prices of 2017 and 2018 in SE3 during two weeks [11]

5.2 Scenario B. Profu

Scenario B - “Profu” - was built on input data from Profu. The company published a number of reports as part of a research project called “Fjärrsyn” from which insights were gained as to what factors will influence the future electricity price and in what way. Figure 5.2 shows a duration curve of electricity prices that have been forecasted by the company. The figure presents the result from various scenarios but the one which was determined to be particularly interesting for this project was RESVind. It consisted of 35 TWh wind, 5 TWh solar,15 TWh combined heat and power. It also assumed a nuclear power capacity of 4 600

MW. Out of all scenarios created by Profu, *RESVind* aligned the best with the characteristics of the future energy mix estimated in this project. The total amount of renewable, variable energy production from Profu (wind and solar) added up to 40 TWh, which was assumed to be equivalent to the 40 TWh wind mentioned in the beginning of this chapter. The nuclear power capacity differed more (6 800 MW as estimated in this project and 4 600 MW as estimated by Profu in their work). This was however condoned by the fact that Profu assumed a large availability of reserve power, among other in the form of gas turbines, which in turn could correspond to the larger share of nuclear power assumed in this project. [15]

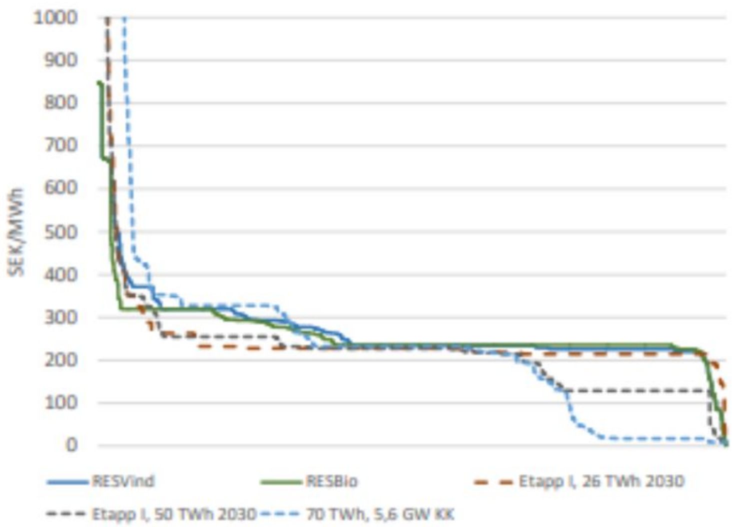

Figure 5.2: Figure from Profu's report "El och fjärrvärme - samverkan mellan marknaderna, etapp 2" (2017) showing a duration curve of the electricity prices of the future.

The duration of the curve of *RESVind* was therefore applied to the 2017 SE3 electricity spot prices. This was done by translating the plots in figure 5.2 into data (see figure A.1 in A) and then extracting a frequency matrix from it, with the step size 20 SEK/MWh.The duration curve of *RESVind* gave insights on how many times each electricity price occurred during a year, and the electricity prices of 2017 were modified accordingly. The modification was done through raising and lowering of hourly electricity prices. If prices needed to be raised, the raising was enforced on the prices that were already relatively high. If prices needed to be lowered to fit the frequency matrix of *RESVind*, the prices which were already relatively low were lowered. The effects of these measures was an hourly electricity price, for the total duration of one year, with a duration curve almost identical to the one of *RESVind* (see Duration curve B. Profu and Duration curve *RESVind* in figure 5.3).

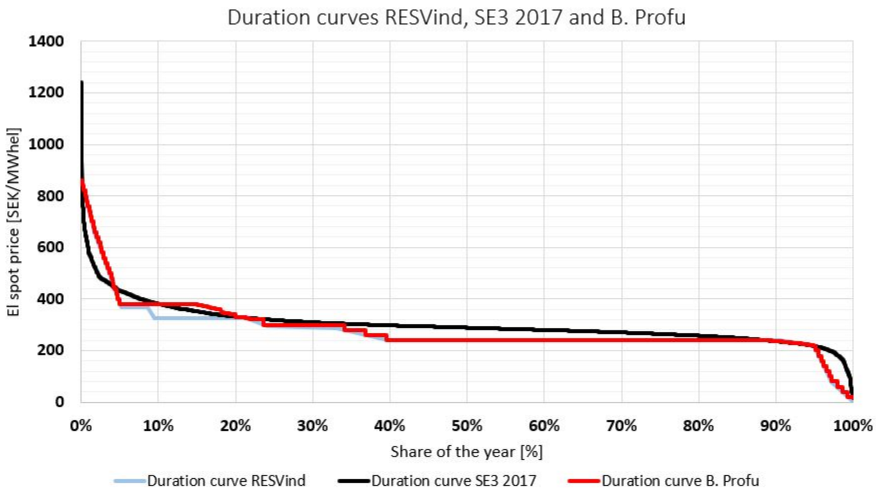

Figure 5.3: Duration curves for electricity prices, for scenario A, based on 2017 electricity prices, Profu's scenario *RESVind*, and the obtained scenario B. Profu.

Additional information that was then obtained from Profu was a seasonal distribution of "high price"- and "low price"-hours (see figures A.3 and A.2 in A). The distribution indicated how common hours where the electricity price was relatively high or low were depending on the season. Winter consisted of the months of December, January and February, spring was defined as March, April and May, summer as June, July, August and autumn as September, October, November. High price hours were, for the purpose of this project, defined as equal to or higher than 640 SEK/MWh, while low price hours were defined as prices below 100 SEK/MWh.

The high- and low price hours from the hourly prices obtained from the duration curve were then re-distributed so that they would fit the seasonal distribution presented in figures A.3 and A.2 in A. The obtained amount and seasonal distribution of high priced (≥640 SEK) and low price (<100 SEK) hours for Scenario B. Profu is presented in figure 5.4. The seasonal distribution is also compared to the two scenarios developed by Profu which had the most similar amount of wind power as assumed in this project, in figures A.4 and A.5 in Appendix A.

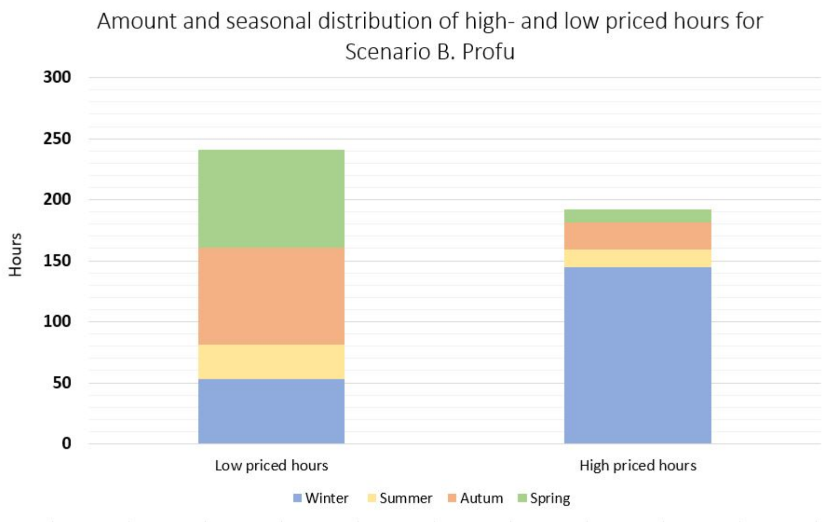

Figure 5.4: Amount of high- (≥640 SEK) and low priced (<100 SEK) hours during a year in Scenario B. Profu.

5.3 Scenario C. High price

Scenario C. High price was created as it was of interest to see how the IKV facility would behave in case the high price hours were more frequent in the future, in case, for example, the share of nuclear power would be lower than expected.

As a base for this scenario, the electricity price obtained after applying the *RESVind* distribution curve to the 2017-electricity price was used. The seasonal distribution applied in Scenario B. Profu was omitted as it was befitting to see high priced hours with different levels of heat demand, and as the latter varies greatly depending on the season, a more even distribution of high price hours was applied than the one in Scenario B. Ensuring that high price hours occurred during the summer in at least one scenario was especially of interest as the heat load then is the lowest and IKV may vary between its operational modes and shut down.

In order to exemplify the effects of single high price hours on IKV the share of high price hours was increased from 0.7% to 20% in Scenario C, as compared to the reference scenario, Scenario A. The increase was thus applied to only a certain share of the hours, which were already relatively high - this means that 80% of the year was kept the same, and that the average spot price was not affected much. An example where the raising of prices during certain hours occurs is presented in figure 5.5.

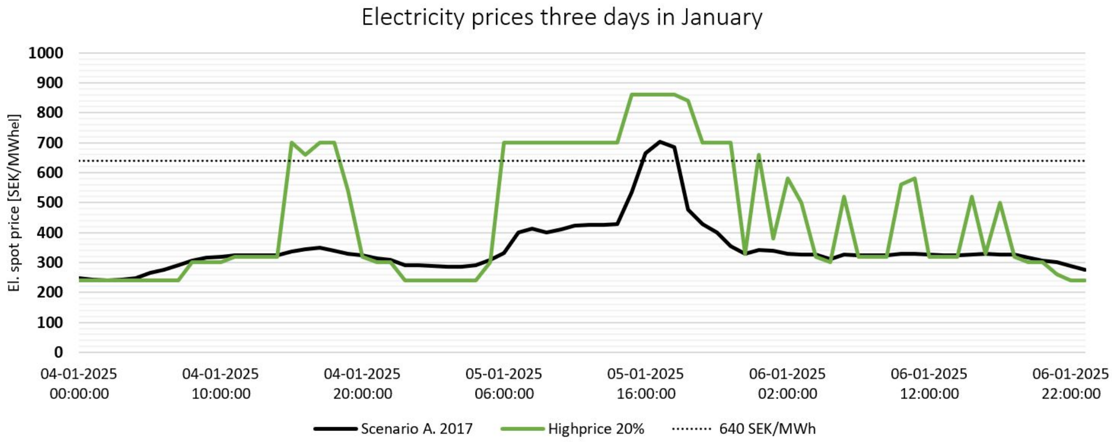

Figure 5.5: Electricity prices of Scenario A and various shares of high priced hours over three days in January.

5.4 Scenario D. Low price

The low price scenario was created as a set-off for the high price scenario. It was of equal interest to see how IKV would perform in really low electricity prices, as it would in high ones.

For Scenario D. Low price the share of low priced hours was increased from 0.5% as in Scenario A, to 20%. 1 744 hours from Scenario A had their price lowered so that they would become low price hours, that is, correspond to an electricity price below 100 SEK/MWh. The hours that were lowered had in the original set up a price above 100 SEK/MWh but were still relatively low - the modification is illustrated in figure 5.6 where it can be seen that the pattern of the original electricity price is maintained, with the difference that the dips are deeper.

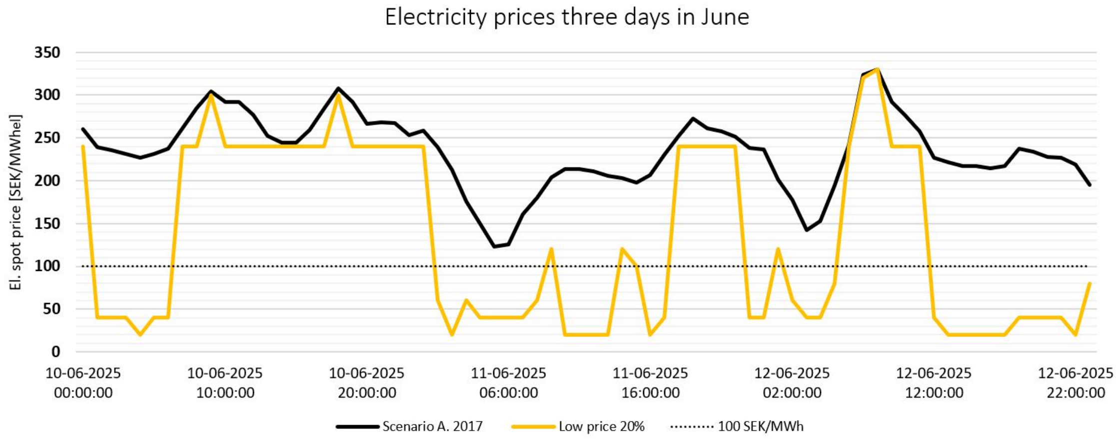

Figure 5.6: Electricity prices of Scenario A and various shares of low priced hours over three days in June.

5.5 Scenario E. Negative

Another case which was interesting to study was negative electricity prices. At the time of writing, Sweden has not yet experienced negative electricity prices but in systems where the penetration of fluctuating energy sources (such as wind- and solar power) it has been known to take place occasionally [2]. If Sweden increases its share of wind power negative electricity prices might become relevant there as well. As it is a phenomenon that has not yet taken place in Sweden or Stockholm, Söderenergi have not yet dealt with such situations, and it is therefore interesting to evaluate how IKV would operate during negatively priced hours.

For Scenario E. Negative, Denmark's turnout in terms of electricity price was used. In 2017 Denmark had 43% of its power originating from wind energy sources [5]. Denmark has also experienced negative electricity prices during the same year. Therefore, the electricity spot price of Denmark's zone DK1 from the year 2017 was taken as a basis to determine the frequency and magnitude of negatively priced hours (see table A.1 in Appendix A).

Once the frequency and the magnitude of negative electricity prices was known the obtained outcome was applied to the electricity price time series from Scenario B. Profu. The lowest priced hours from Scenario B. were thus altered to be negatively priced, in a similar manner that the hours were raised in Scenario C. High price and lowered in Scenario D. Low price. By doing so, it was assumed in the project that the hours which would be the most likely to become negatively priced were those that were the lowest in the original hourly price set-up. No additional analysis with regards to seasonal distribution of negatively priced hours was thus done.

In figure 5.7 one can observe the low-priced hours from Scenario A. 2017 have been converted into negatively priced hours.

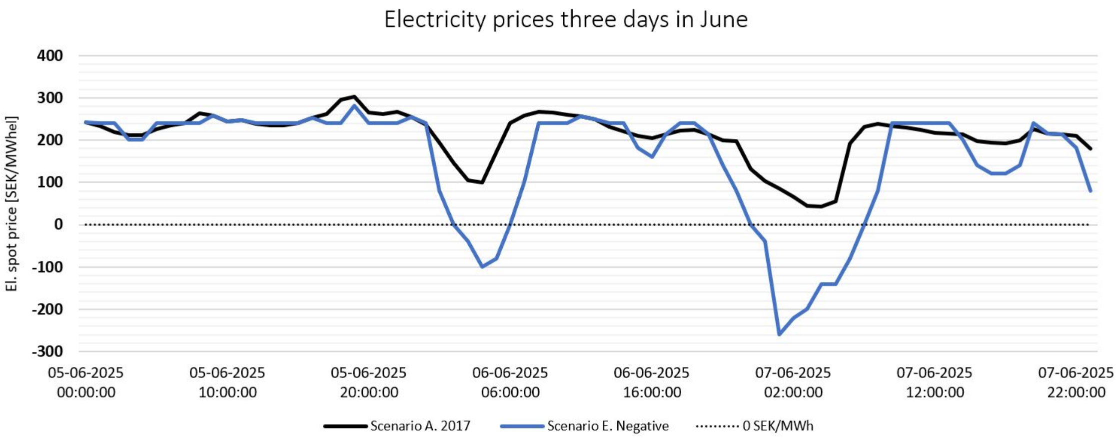

Figure 5.7: Electricity prices of Scenario A and E over three days in June.

5.6 Scenario F. Volatile

Electricity prices vary in terms of scale (low- and high prices) but also in terms of volatility. A CHP plant such as IKV might operate differently if the prices are relatively flat, not changing much from hour to hour, than if the prices are volatile, going from, for example, low prices below 100 SEK/MWh to high prices above 640 SEK/MWh between two consecutive hours. Different prices might be attractive for different modes of operation, but the plant might not be able to always operate in the optimal mode for each hour, due to technical constraints. If IKV wants to switch from MC-mode to BP-mode due to a change in electricity prices for the next hour it might not be able to do so quickly enough for it to be worth it - the plant is a subordinate to the ramp up- and ramp down-rates for example.

In Nordpool's regulating market, up- and down-regulating prices are presented for each hour of intraday trading. The market is set up so that if some producers fail to produce according to the plan determined the day before, for the spot market, other producers, with more flexible production facilities can act as a buffer for those changes, and either ramp up or down their production. The up- and down-regulating prices ensure that there incentive to produce according to the plan so that the balance is maintained in the grid.

Up- and down regulating prices are often more volatile than the spot price, thus, they were used as a foundation for the creation of Scenario F. Volatility. The regulating prices from 2017 were extracted from Nordpool, and an hourly time series was set up where for the hours where the up-price was different from the spot-price, the up-price was chosen and vice versa with down-price.

After compiling the up- and down-regulating prices for a whole year, a period where the prices were particularly volatile was extracted and duplicated so that it would represent a whole year. The original year with up- and down prices showed that the volatility did not vary much from the 2017 spot price in some periods, thus a two month-period where the volatility in the up- and down-regulating prices was significantly greater than in the spot price was used as a representative for the whole year in the volatile scenario. The period chosen was from August to October - in figure A.6 in Appendix A it can be seen that during this time the spot price and the regulating prices differed, and that the regulating price was quite volatile.

Figure 5.8 illustrates the increased volatility of Scenario F, as compared to the reference Scenario A.

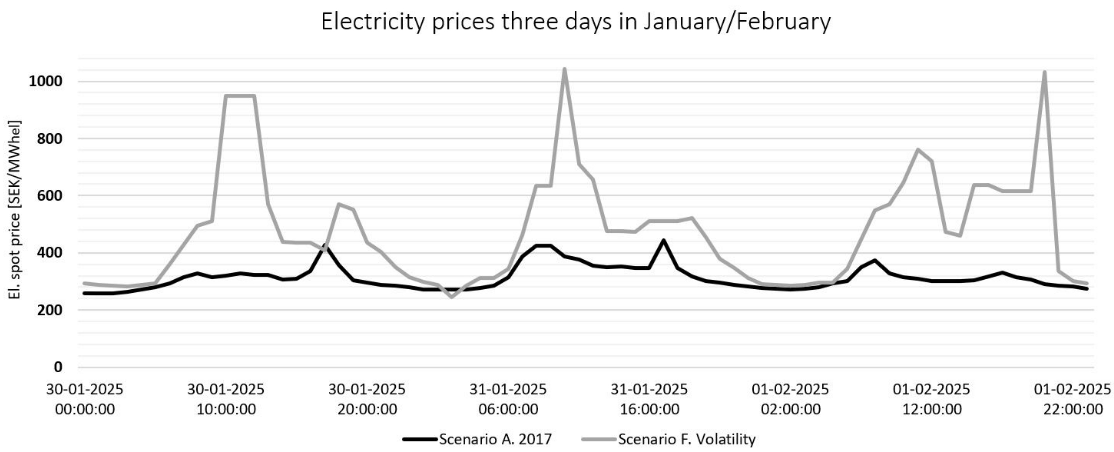

Figure 5.8: Electricity price of Scenario A and F over three days in January/February.

5.7 Addition of a ”heat dump”

A “heat dump” might become of interest for a CHP-plant in case there are situations when it is profitable to produce and sell electricity, but at the same time, there is no demand for additional heat production. For IKV, it is impossible to produce electricity without producing heat, meaning the only way to utilize those situations is to get rid of the heat produced through other means than through sending it to the DH network. A heat dump acts as a receiver of unwanted heat, and can be seen as a solution to the problem.

Currently, IKV has no heat dump installed at its premises. Additional analysis was thus performed in this project in order to investigate the profitability of installing a heat dump at IKV. A heat dump-component was added in the BoFiT-model for Scenario B. Profu. The model was then run for the year 2025, and data was extracted with regards to how often the heat dump was used. Results are presented in section 6.5.

6 Results and Analysis

In the following section, results from the development of the electricity prices, as well as results from the modelling work are presented. The results for the latter are presented in the form of production and costs. Analysis is performed parallel to the presentation of the results. With Scenario A as reference the remaining scenarios will be compared to this one in order to analyze differences. Additionally, as the electricity price of Scenario B is the most profound and reliable for 2025 the results from this scenario is of most value. However, the remaining scenarios is of great importance, representing a sensitivity analysis of scenario B.

6.1 Electricity prices

A summary of characteristics of the developed electricity prices for the different scenarios is displayed in table 6.1.In the table, the columns, A, B, C and D represent the following:

- A: Average difference between consecutive hours [SEK]
- B: Average spot price [SEK/MWh]
- C: Hours above average difference between consecutive hours [h]
- D:Hours below average difference between consecutive hours [h]

The amount of hours where the electricity price is high (640 SEK/MWh or above), low (below 100 SEK/MWh) and negative is presented in the first columns *High price*, *Low price* and *Negative*. The average difference in electricity price between two consecutive hours is then shown in column A. The average value of the reference scenario, Scenario A (14.75 SEK), is taken to determine the amount of consecutive hours between which the difference in electricity price has been greater or lesser than the average (last two columns).

It can be observed from table 6.1 that, compared to the reference scenario, all scenarios have an increased share of high price hours, even Scenario D. Low price. The reference scenario, Scenario A, also has the second to lowest amount of low

Table 6.1: Characteristics of the electricity prices developed for the different scenarios

	Highprice [h]	Lowprice [h]	Negative [h]	A [SEK]	B [SEK/MWh]	C [h]	D [h]
A. 2017	59	45	0	14.75	300.90	2 441	6 317
Scenario B. Profu	192	241	0	20.16	285.64	2 955	5 802
C. High price	1 748	243	0	40.44	351.83	2 995	5 764
D. Low price	193	1 789	0	28.22	241.35	3 119	5 640
E. Negative	192	285	70	20.78	283.54	2 998	5 759
F. Volatile	378	12	0	39.89	363.06	4 169	4 590

priced hours. This suggests that the reference scenario is the most moderate in the magnitude of electricity prices. All the other scenarios, even if they have not been created specifically with the goal of increasing the volatility, are more widespread on the scale. This is also supported by the value which gives the average difference in price between two consecutive hours - for Scenario A the average difference was 14.75 SEK which was the lowest value among the scenarios.

Other observations which can be made based on table 6.1 is that the scenarios are quite true to their names/given characteristics; the high price scenario has the greatest amount of high priced hours, the low price scenario has the greatest amount of low priced hours and the negative scenario is the only one with negatively priced hours. It might be surprising that the volatile scenario, Scenario F, does not have the greatest average difference between two consecutive hours. Instead it is Scenario C. High price that possesses that quality - although it is not far from Scenario F's value (40.44 SEK and 39.89 SEK respectively). This can be explained by the fact that the high price-scenario was created not in a way that raised all prices for every hour - instead, the share of high price hours was increased. Some hours were thus raised, while the hours occurring directly before or after were left unchanged which affected the volatility indirectly.

Similarly, it can be observed that the volatile scenario, Scenario F, has the greatest average spot price among the scenarios. It is, again, due to the way the scenarios were created - Scenario F was made out of regulating prices which were elevated as compared to the spot prices, causing a higher average. The whole year was affected, as opposite to the high price scenario, where only 20% of he hours were modified.

In terms of average difference in price between consecutive hours, the volatile scenario appears to be the second most volatile scenario, but putting it in relation to the reference scenario and evaluating it in terms of hours where the average difference in price between consecutive hours is above or below the average (14.75 SEK from the reference scenario) it appears that Scenario F is the most volatile one. Using the definition of high volatility from Nationalencyklopedin [10], which states that high volatility indicates that a price varies greatly from the average one, one can deduce that Scenario F is the most volatile one. This is as it has the greatest amount of hours where the difference in price between consecutive hours is above the average. Simultaneously, it has the least amount of hours where the difference in price between consecutive hours is below the average.

Figure 6.1 and 6.2 give insight on how the high- and low priced hours are distributed depending on the season, and how that relates to the average heat demand. It should be noted that the scale on the left y-axis is logarithmic.

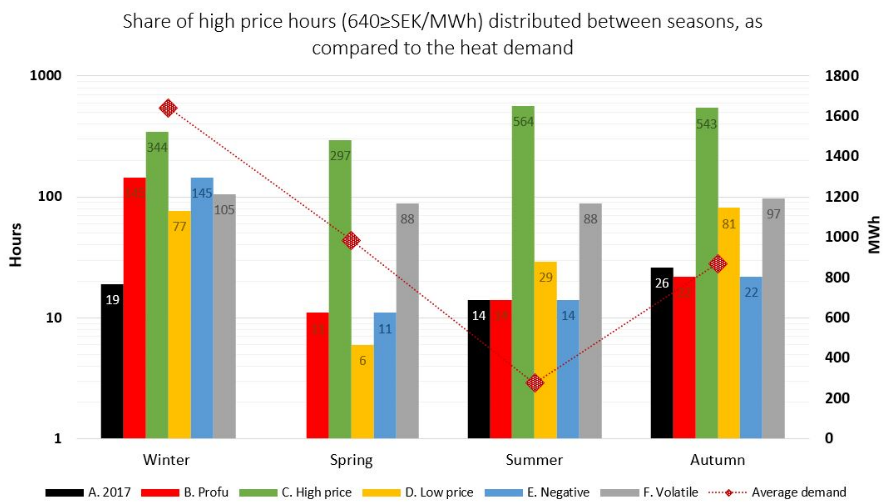

Figure 6.1: Distribution of high priced hours (≥640 SEK/MWh) between seasons as compared to the average heat demand of each season.

Figure 6.1 shows the amount of high priced hours for each scenario, in each season. It can be noted that most scenarios have their greatest share of hours where the electricity price is equal to or above 640 SEK/MWh take place during the winter season (Scenario B, E and F). Then follows the autumn season (Scenario A and D) and the summer season (Scenario C).

Further observations include the fact that the amount of high priced hours differs quite a lot for each scenario depending on the season, with the exception of Scenario F, which has a relatively even distribution of high priced hours over the year.

The heat demand varies greatly with the seasons, going from an average of 1 642 MWh during the winter season, to 277 MWh during the summer season. What can be seen in figure MMM7 is that relatively large as well small amounts of high price hours have taken place at each average heat load. Taking the winter season as an example, there is a high demand but depending on the scenario, the amount of high price hours is both relatively high (Scenario C) or low (Scenario A).

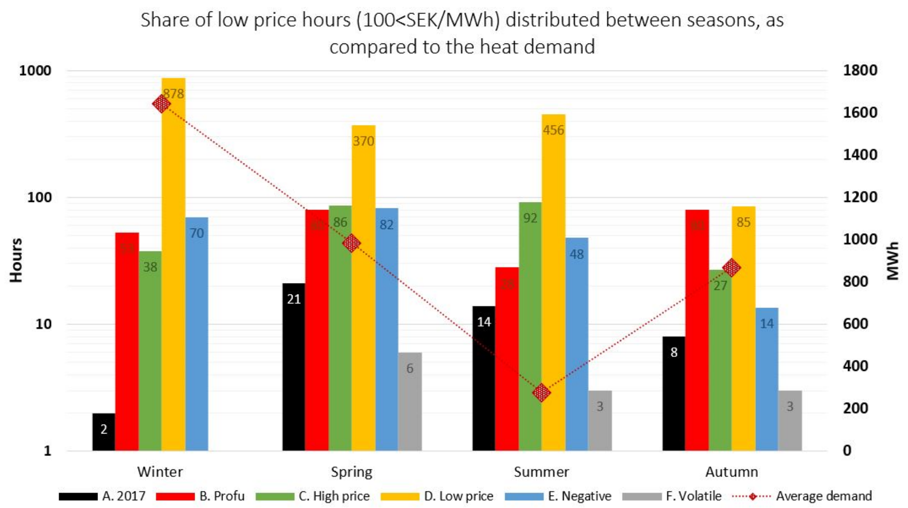

Figure 6.2: Distribution of low priced hours (<100 SEK/MWh) between seasons as compared to the average heat demand of each season.

Figure 6.2 shows the amount of low priced hours (that is hours at which the electricity price is below 100 SEK/MWh) distributed between seasons and scenarios. The low priced hours are more evenly distributed between seasons than the high priced hours. Further, most scenarios (Scenario A, B, E and F) have their greatest share of low priced hours in the spring.

The heat demand is displayed for each season, similarly as in figure 6.1. Each season has a very contrasting amount of low priced hours, depending on the scenario - there is at least one scenario that has a significantly larger and lesser amount of low priced hours than the other scenarios, for each season. The season which is the least contrasting, that is where the scenarios are the most alike in terms of number of low priced hours is autumn. The average heat demand is quite similar to the spring demand then, but Scenario D has a lot less low priced hours during autumn than in spring.

Figure 6.1 and 6.2 show that there is diversity within the scenarios, but also that there are many combinations of different heat demands with different amounts of high- and low priced hours.

6.2 Production - IKV

The detailed model of IKV makes it possible to retrieve specific results for each component. The production is therefore analyzed for each component (MC, BP and turbine) both based on a yearly total and on a seasonal basis - the latter analysis is conducted in order to capture the changes in production based in the light of different heat demands. The key performance indicators(KPI's) for the production are presented in table 6.2 and they are investigated for each scenario in every season, as well as for the entire year. All scenarios are compared with the reference Scenario A which represents a production year for IKV given current electricity prices. These comparisons are presented as differences where a positive difference indicates higher production than in the reference scenario, and a negative difference indicates a lower production. Scenario B is seen as the most profound and reliable scenario for 2025 and the results retrieved from this is of great interest.

Table 6.2: Presentation and explaination of KPI's regarding production

KPI	Unit	Comment
Total production	[GWhheat]	Summerized heat production from MC, BP and FGC. -
Total production MC	[GWhheat]	Total heat production from MC -
Total production BP	[GWhheat]	Total heat production from BP condenser -
Total production El	[GWhel]	Total electricity production from turbine -
Total production FGC	[GWhheat]	Total heat production from FGC -
Hours in operation	[%]	The share of hours IKV is in operation based on the amount of hours in the year or in each season
MC + BP regulation	[%]	The share of hours where MC and BP are both in operation, also called regulating hours
Average heat demand	[MW]	Average heat demand for each season. -

6.2.1 Total production

In table 6.3 the total production of heat and electricity from IKV over one year is presented for each scenario together with differences from the reference scenario, Scenario A. From the table it can be concluded that the total heat production is generally lower in each scenario except for Scenario F where a positive difference is observed. The results show that the MC is the main heat-producing component in all scenarios. This is expected due to the incentive of the parallel production and sale of electricity, that reduces the production costs of IKV. To be noted is also a significant production of the BP condenser in each scenario which will be investigated further in this chapter. Additionally, the hours where IKV is in operation is reduced in Scenario B, D and E but increased in Scenario C and F.

The only parameter differentiating the scenarios is the electricity price, as explained in chapter 5. The change in production volumes established below is thus a direct result of the change in electricity price. Based on the results in table 6.3 it can be seen that a larger share of low electricity prices, as in Scenario B, D and E, will decrease the use of the MC - instead, the production is shifted to the BP condenser. The opposite occurs when integrating a large share of high electricity prices as in Scenario C. However, the high electricity prices do not affect the production to the same extent as the low electricity prices. This is due to the fact that IKV is already operating the MC on the majority of the hours in the reference scenario. Including more high price hours will not increase the hours of operation from the MC significantly. Additional observation concerning Scenario C is that the total production is 23 GWh less than in Scenario A, even though IKV is in operation more often in Scenario C. This indicates higher operation of IKV on part load in Scenario C, not utilizing the full potential of the power plant.

Table 6.3: Yearly result for each scenario and differences compared to scenario A.2017.

IKV	A. 2017	B. Profu	C. High price	D. Low price	E. Negative	F. Volatility
Total prod. [GWhheat]	1 574	1 546	1 551	1 517	1 547	1 584
Difference from 2017		-27	-23	-56	-27	10
Total prod. MC [GWhheat]	939	918	963	728	916	980
Difference from 2017		-21	25	-210	-23	42
Total prod. El [GWhel]	506	493	517	389	492	527
Difference from 2017		-13	11	-117	-14	21
Total prod. BP [GWhheat]	257	257	225	441	260	227
Difference from 2017		0	-32	184	3	-30
Total prod. FGC [GWhheat]	378	372	362	348	371	377
Difference from 2017		-6	-16	-30	-7	-1
Hours in operation (year) [%]	88%	86%	88%	81%	86%	89%
MC + BP regulation (year) [%]	3.7%	5.4%	5.0%	8.0%	5.4%	4.1%

6.2.2 Seasonal Division

In order to see how the differences in electricity price affect the behaviour of IKV a more detailed investigation has been made and the year has been divided into seasons, similarly as for the creation of Scenario B. The seasons consist of the following:

- Winter: Jan,Feb, Dec
- Spring: Mar, Apr, May
- Summer: Jun, Jul, Aug
- Autumn: Sep, Okt, Nov

The operation of IKV differs significantly during the seasons. The following duration diagrams, figures 6.3,6.5, 6.7 and 6.8, represent the total production of IKV as well as the mode of operation during each season. From the figures it can be distinguished how often IKV is operating on maximum load, part load or how long it is shut down. Additionally, it is possible to identify periods of BP and MC operation from the straight lines in the figures. Maximum BP operation, 240 MW of heat, including the FGC operation, 57 MW of heat, will reach a total thermal output of 297 MW. Maximum MC operation, 154 MW, along with the FGC operation 57MW, makes IKV reach 211 MW of heat. The minimum possible load of IKV is 46.5 MW heat.

Winter

Table 6.4 shows a summary of the KPI's for the production of IKV during the winter. IKV is operating almost 100% of the season in all scenarios and the production volume is divided evenly between the BP condenser and the MC. In table 6.4 it can be seen that Scenario D is shut down 2.3% of the hours during the winter - the shut down is investigated further in this chapter. IKV being in operation the entire winter is a result of the high heat demand during the winter with an average of 1642 MW along with IKV being one of the cheapest facilities in the DH system, placing it far down in the merit order. During winter the risk of IKV being pushed out of production by another facility is thus small.

The winter season shows a high amount of regulating hours, which can be seen in table 6.4, ranging from 7-12%. The majority of these hours occurs due to the process of ramping up or down of the two condensers quickly. In the breaking point of heat demand and electricity price the steam flow is partly shifted, causing the MC and BP condenser to operate at the same time. A general increase of MC and BP regulation is shown in each scenario as compared to Scenario A, except in Scenario D.

Table 6.4: Summary of the production during the winter season. The two KPI's measured in % represent a share of the hours of the season

IKV - Winter (2106 h)	A. 2017	B. Profu	C. High price	D. Low price	E. Negative	F. Volatility
Total prod. [GWhheat]	532.2	526.7	520.0	550.6	526.9	523.7
Difference from 2017	-	*-5.5*	*-12.2*	*18.3*	*-5.3*	*-8.6*
Total prod. MC [GWhheat]	195.3	201.5	215.9	127.7	200.0	211.1
Difference from 2017	-	*6.2*	*20.6*	*-67.6*	*4.7*	*15.8*
Total prod. BP [GWhheat]	213.8	202.5	181.2	303.5	204.3	189.5
Difference from 2017	-	*-11.3*	*-32.7*	*89.7*	*-9.5*	*-24.4*
Total prod. El [GWhel]	105.7	108.7	116.5	68.3	107.9	114.1
Difference from 2017	-	*3.0*	*10.8*	*-37.5*	*2.1*	*8.4*
Total prod. FGC [GWhheat]	123.1	122.7	122.9	119.3	122.6	123.1
Difference from 2017	-	*-0.4*	*-0.1*	*-3.7*	*-0.5*	*0.0*

Hours in operation [%]	100.0%	99.9%	100.0%	98.7%	99.8%	100.0%
MC + BP regulation [%]	7.6%	10.4%	11.0%	11.7%	10.6%	9.8%

A visual presentation of the result from the production is also shown in a duration curve in figure 6.3 in order to complement the information in the table. Here, only the heat production is presented including MC, BP and FGC over the entire winter season showing that even if the MC and BP produce the same volumes of heat the MC is in operation a larger share of hours compared to the BP.

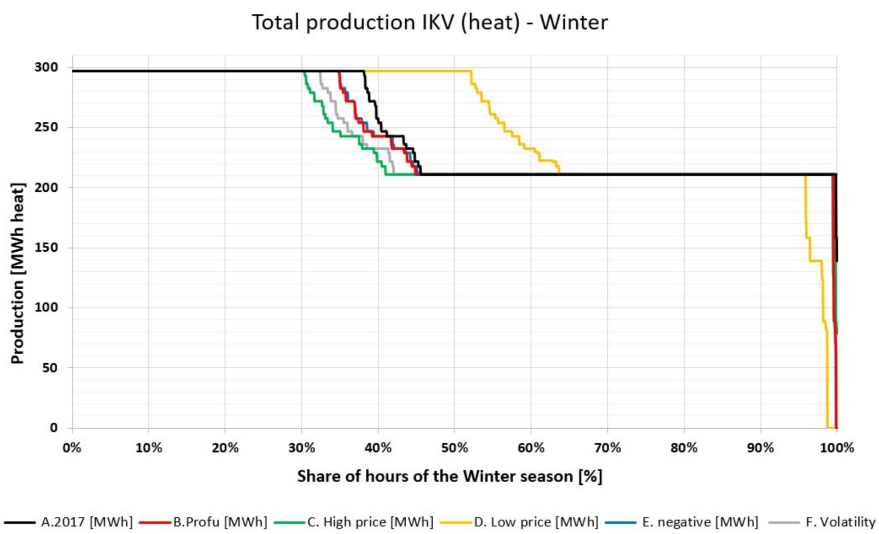

Figure 6.3: A duration diagram based on the total heat production during the winter season

As can be seen in figure 6.3 Scenario D is the scenario deviating the most from Scenario A. Scenario D generates the highest BP production due to a large amount of low price hours, making the MC non-profitable more often. The rest of the scenarios generate, in total, less heat but make use of the MC more often than in Scenario A which consequently gives a higher electricity production. These effects are observed as a result of a larger amount of high price hours.

In figure 6.3 it is shown that IKV favours the BP condenser relatively often during the winter. This is due to one main reason: High production price on the margin. A high heat demand results in the use of peak load facilities with expensive fuel such as tall oil pitch and bio oil. This increases the margin price significantly and BoFiT will try to find solutions in order to exclude these expensive facilities. Therefore, at times, BoFiT finds it more profitable to redirect the steam flow from the MC condenser, lose the revenue from the turbine and start the BP condenser instead of turning an expensive peak load plant on. During the winter this happens at an average electricity price of 330 SEK/MWh.

An example of when this happens is shown in figure 6.4 which represents the merit order of the DH system for Scenario B on the 5th of January, 2025. At 21.00 the heat demand increases pushing block C, which is fueled by tall oil pitch with a production cost of 576 SEK/MWh, to the margin. Instead of starting another block - block K, representing bio fueled burning plants, with a production cost of 598 SEK/MWh, BoFiT chooses to switch IKV's operation from the MC to the BP condenser so C is left on the margin. BoFiT deems that it is more profitable for the whole DH system for IKV to loose its electricity revenue, than to turn on facility K.

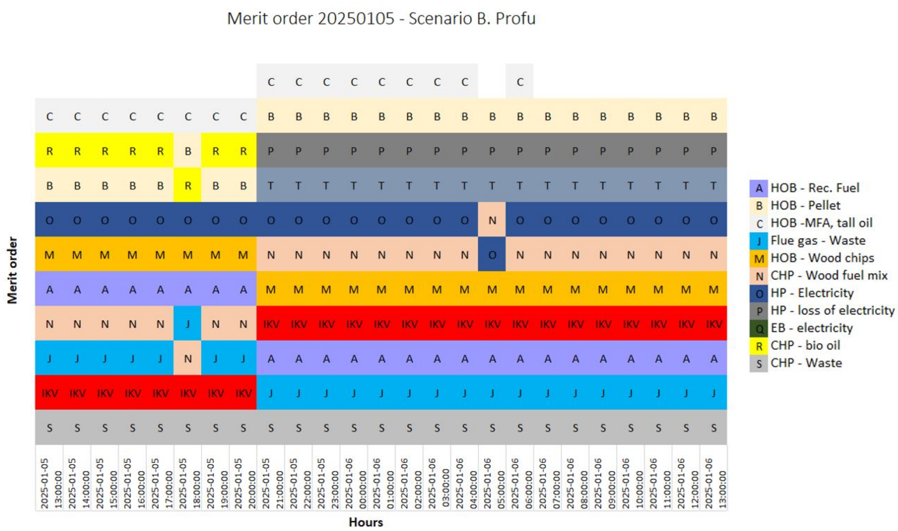

Figure 6.4: Merit order for the entire DH network at 20250105 in Scenario B

Lastly, a shut down of IKV during the winter is highly unexpected due to the high production price in the merit order. In table 6.4 it is presented that in Scenario D, IKV is being shut down 2.3% of the total time, corresponding to 28 hours. This phenomenon is divided between two different occasions; the 29th of January 2025 and the 19th of February 2025. In these cases, a combination of lowered heat demand, due to increased outdoor temperature, and low electricity prices IKV is being shut down. In the first case the combination of a heat demand of 900 MW and a electricity price of 90.2 SEK/MWh led to this shut down. In Scenario B this happens once during the winter.

Summer

The production of IKV during summer differs significantly compared to the other seasons, and in table 6.5 a summary of the production is shown. The summer season represents the period with the lowest production, largest amount of hours where IKV is operating on part load as well as being shut down. This indicates the effects of low heat demand and low electricity prices.

Table 6.5: Summary of the production during the summer season

IKV - Summer (2208 h)	A. 2017	B. Profu	C. High price	D. Low price	E. Negative	F. Volatility
Total prod. [GWhheat]	183.1	170.7	179.8	136.0	172.1	200.3
Difference from 2017	-	*-12.4*	*-3.3*	*-47.1*	*-11.0*	*17.2*
Total prod. MC [GWhheat]	147.1	136.3	149.6	109.4	137.9	163.7
Difference from 2017	-	*-10.8*	*2.5*	*-37.7*	*-9.1*	*16.7*
Total prod. BP [GWhheat]	0.2	0.2	0.4	0.6	0.1	0.0
Difference from 2017	-	*0.0*	*0.3*	*1.0*	*0.0*	*-0.2*
Total prod. El [GWhel]	76.7	70.4	76.7	56.5	71.2	84.2
Difference from 2017	-	*-6.4*	*0.0*	*-20.3*	*-5.5*	*7.5*
Total prod. FGC [GWhheat]	35.9	34.2	29.8	26.0	34.0	36.6
Difference from 2017	-	*-1.6*	*-6.1*	*-9.8*	*-1.9*	*0.7*
Hours in operation [%]	58.2%	54.7%	60.6%	44.3%	55.4%	65.9%
MT + BP regulation [%]	0.2%	0.2%	0.5%	0.7%	0.2%	0.0%

In Scenario B, D and E IKV is shut down more often than in Scenario A resulting in IKV being in operation only around 50% of the season. This is also noticeable in the production which is significantly lowered. In Scenario D the hours of operation are reduced with 14% which represents a loss of 38 GWh heat. These scenarios include a greater amount of low price hours which directly reflects in the form of a reduced production.

The opposite can be seen in Scenario C and F which include more high price hours, resulting in IKV operating more often and having a higher production. However, the high price scenarios are not as influential when it comes to change in operation mode as the low price scenario. Further, the BP production is close to zero in all six scenarios which indicates no regulation between the BP condenser and the MC. The few GWh of production are connected to ramp up and ramp down times which are not taken into account for the summer season.

In figure 6.5 the operation of the MC is visualised in a duration diagram. Full load operation (211 MW) occurs around 10% of the time during the entire summer season in each scenario, meaning IKV is either shut down or operating on part load. This is especially noticeable in Scenario D where IKV is on part load or is shut down 91% of the time - far below equivalent values for Scenario A. Scenario D includes a large amount of low price hours which consequently gives this result.

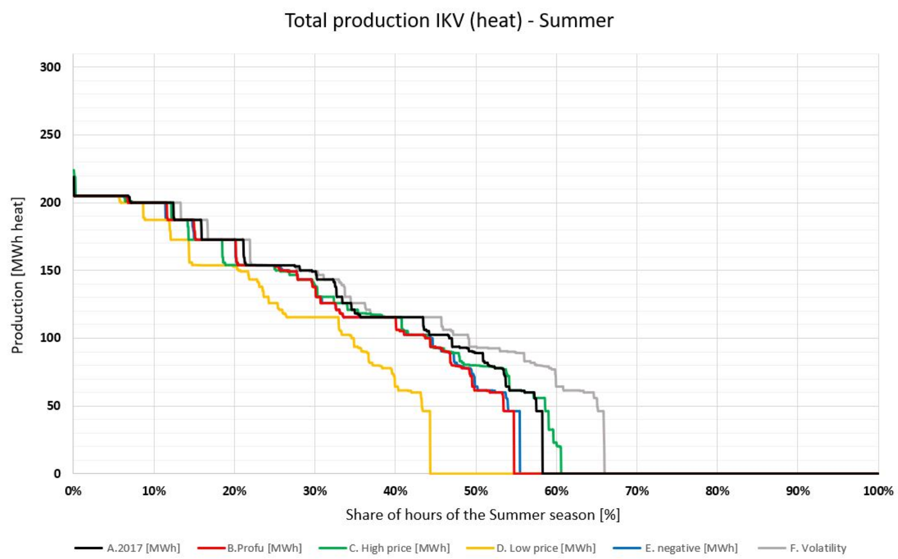

Figure 6.5: A duration diagram based on the total heat production during the summer season

IKV operating on part load is explained by IKV being placed as the margin producing facility in the merit order of the DH system. The average heat load during the summer season is 277 MW which is, considering to the other seasons, very low. At normal circumstances this demand is primarily covered by block S, see table 3.1 in chapter 3.2.1, which is, in general, the cheapest block in the system.

However, throughout the summer season, block S is partly under maintenance and holds a total capacity ranging between 120-200 MW, meaning another plant needs to cover the rest of the demand. Generally this plant is IKV placed as the second cheapest facility in the merit order. Thereby, IKV is placed on the margin which explains the operation on part load. However, due to changes in electricity prices, other facilities becomes economically competitive and pushes IKV outside the merit order, resulting in IKV operating on minimum load more often as well as being shut down.

In figure 6.6 the operation of IKV during three days of the summer is shown. The black colour represents Scenario A and the red colour Scenario B. The solid lines show the production from the MC and the dashed lines the electricity price in each scenario.

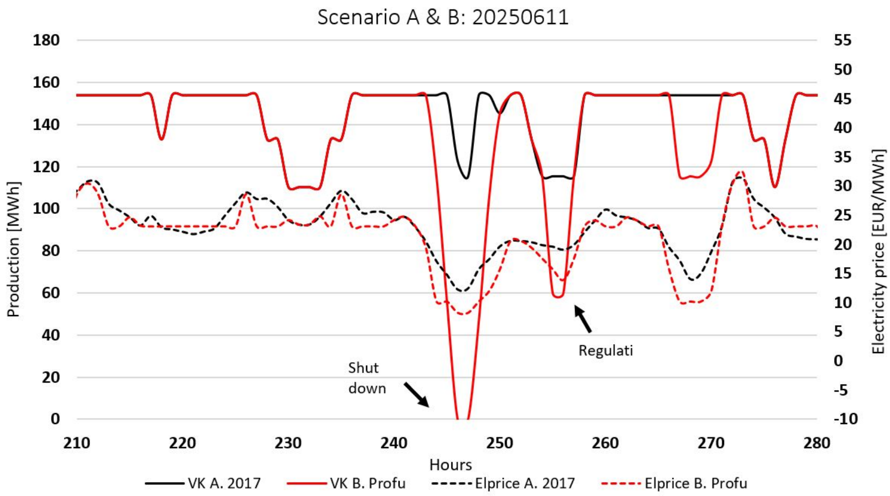

Figure 6.6: Operation of IKV during the summer showing one shut down and one part load operation in Scenario B compared to Scenario A

At hour 249 in figure 6.6 an example of IKV being shut down in Scenario B is shown. Due to a combination of a low electricity price of 90.2 SEK/MWh and a heat demand of 560 MW the MC is forced down to zero. Even if IKV would have fit in the system demand-wise it is not profitable for BoFiT to choose IKV. Secondly, in hour 258 an additional dip is market in figure 6.6 which represents a case where IKV is operating on part load. Comparing Scenario A and B the load of IKV is reduced in Scenario B due to lower electricity price.

Instead of IKV, options independent of the electricity price become more economically viable, for example block A, P, T and O, and pushes IKV outside the merit order. These blocks are shown to increase their hours of operation as the operation of IKV is decreased. During summer the production price of IKV is frequently shifting due to varying electricity prices. This requires a high flexibility of IKV as well as the rest of the DH system. In reality, the flexibility shown in figure 6.6 is however not realistic which reveals one of the major limitations of the developed model - the exclusion of start-up costs. A quick shut down is neither technically or economically feasible in the reality due to start up costs as well as component limitations. In Söderenergi these fluctuations are partly suppressed today by a small accumulator. This has also been neglected in the model of IKV in BoFiT. In table 6.6 this occurrence is further clarified.

The first row of table 6.6 presents the share of hours in the summer season where IKV is shut down. The second row is defined as the share of time where IKV is shut down for more than 72 hours which is deemed a realistic operation of IKV due to the required start up time in real-life. The difference on row three therefore indicates how large share of the season where IKV is shut down unrealistically fast. An increase in each scenario compared to Scenario A can be seen indicating a future requirement of IKV to become quicker and more flexible.

Table 6.6: Shut down of IKV during summer

IKV - Summer (2208 h)	**A. 2017**	**B. Profu**	**C. High price**	**D. Low price**	**E. Negative**	**F. Volatility**
IKV shut down [%]	42%	45%	39%	56%	45%	34%
Shut down >= 72 h [%]	25%	25%	13%	25%	25%	17%
Difference [%]	16%	21%	26%	31%	20%	17%

Spring

The spring season is characterized by a high production from the MC which can be seen in all scenarios based on the summary in table 6.7. The BP condenser is also in operation during the spring but not to the same extent. However, in Scenario D a significant increase of the operation from the bypass condenser can be seen representing the biggest difference between the scenarios during the spring since the other scenarios operate very similarly to the reference scenario. The spring season represents a transitional season in-between the two extremes in terms of heat demand - winter and summer - and has an average heat demand of 985 MW which is significantly lower than during winter.

Table 6.7: Summary of the production during the Spring season

IKV - Spring (2208 h)	**A. 2017**	**B. Profu**	**C. High price**	**D. Low price**	**E. Negative**	**F. Volatility**
Total prod. [GWhheat]	445.0	443.0	442.3	428.5	442.2	445.5
Difference from 2017		*-2.0*	*-2.7*	*-16.5*	*-2.8*	*0.5*
Total prod. MC [GWhheat]	301.9	297.8	297.3	211.1	296.3	310.0
Difference from 2017		*-4.2*	*-4.7*	*-90.8*	*-5.6*	*8.0*
Total prod. BP [GWhheat]	31.3	34.6	35.3	117.9	35.5	24.5
Difference from 2017		*3.3*	*4.0*	*86.6*	*4.2*	*-6.9*
Total prod. El [GWhel]	163.8	161.2	161.0	113.3	160.5	168.3
Difference from 2017		*-2.6*	*-2.8*	*-50.6*	*-3.3*	*4.5*
Total prod. FGC [GWhheat]	111.7	110.6	109.8	99.4	110.4	111.0
Difference from 2017		*-1.1*	*-2.0*	*-12.3*	*-1.3*	*-0.7*
Hours in operation [%]	97.4%	97.3%	97.0%	90.3%	96.8%	97.8%
MC + BP regulation [%]	3.6%	4.3%	4.3%	9.6%	4.4%	3.2%

A decreased heat demand indicates a lower production price on the margin in the DH system which partly explains the high production from the MC. With lower margin price IKV operates more independently of the rest of the DH system, and the MC can operate in a larger range of electricity prices. This means that, during spring, the electricity price can go as low as 250 SEK/MWh and the MC can still be profitable. The transitional seasons are shown to have the optimal conditions for IKV to be most profitable and thereby resulting in a high electricity production.

In figure 6.7 it can be observed that IKV is on part load during 10% of the time throughout spring. The part load operation is tracked to the end of the season, when approaching summer, which is a season with low heat demand. Additional regulation between the MC and the BP condenser is mainly due to ramping up of the BP which in opposite to the previous happening, takes place in the beginning of the season due to higher heat demand. This happens around 4% of the time in each scenario.

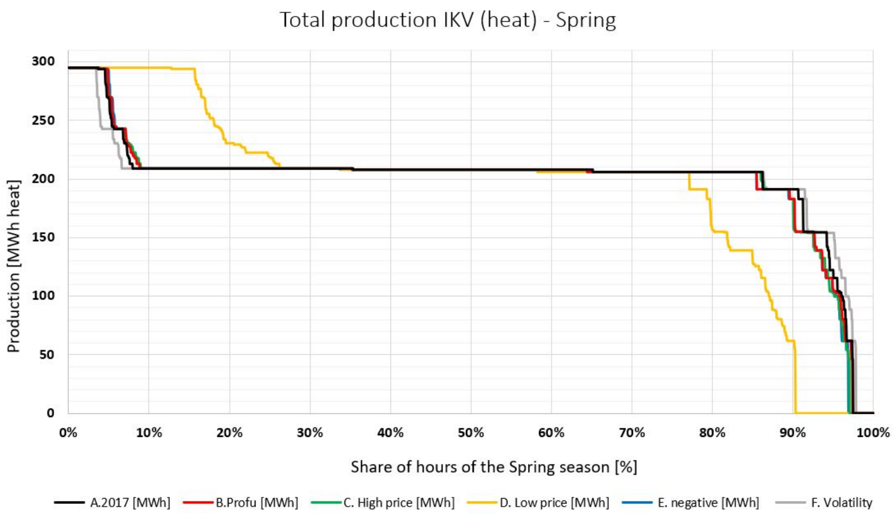

Figure 6.7: A duration diagram based on the total heat production during the spring season

Autumn

Autumn is the second transitional season which results in an outcome similar to the spring season, as shown in table 6.8, with high production from the MC and a small production from the BP condenser. The operational hours of IKV are less than during the spring season but still relatively high and IKV running on part load is more common during autumn than during spring.

Table 6.8: Summary of the production of IKV during the Autumn season

IKV - Autumn (2185 h)	A. 2017	B. Profu	C. High price	D. Low price	E. Negative	F. volatility
Total prod. [GWhheat]	413.3	406.1	408.7	402.0	405.5	414.2
Difference from 2017		*-7.2*	*-4.5*	*-11.3*	*-7.8*	*0.9*
Total prod. MC [GWhheat]	294.2	282.3	300.4	279.8	281.6	295.4
Difference from 2017		*-11.9*	*6.2*	*-14.4*	*-12.6*	*1.2*
Total prod. BP [GWhheat]	11.7	19.5	8.3	19.0	19.9	12.7
Difference from 2017		*7.8*	*-3.4*	*7.4*	*8.2*	*1.1*
Total prod. El [GWhel]	159.4	152.4	162.4	150.9	152.0	160.1
Difference from 2017		*-6.9*	*3.0*	*-8.4*	*-7.4*	*0.7*
Total prod. FGC [GWhheat]	107.4	104.3	100.0	103.2	104.0	106.1
Difference from 2017		*-3.1*	*-7.4*	*-4.2*	*-3.3*	*-1.3*
Hours in operation [%]	94.7%	93.1%	95.6%	92.2%	93.1%	94.1%
MC + BP regulation [%]	1.7%	4.0%	2.4%	4.3%	3.8%	2.0%

The average heat demand during autumn is 870 MW which is slightly lower than in spring, which explains the lower BP production. However, the demand also ranges between 200-2000 MW and IKV is therefore regulated a few times during the end of the season by using the BP condenser.

As can be seen in figure 6.8, all scenarios have a shut down of 5-10% of the total time during autumn. These hours are mainly happening in the beginning of the season, closely to summer, where the heat demand is still quite low. This period of time also explains the 20% of IKV operating on part load. Generally the differences are very small during autumn and all the scenarios are similar to the reference scenario.

6.3 Production - DH network

In figure 6.9 the total production volume from each block in the entire system is presented together with the share of operational hours showing how often each

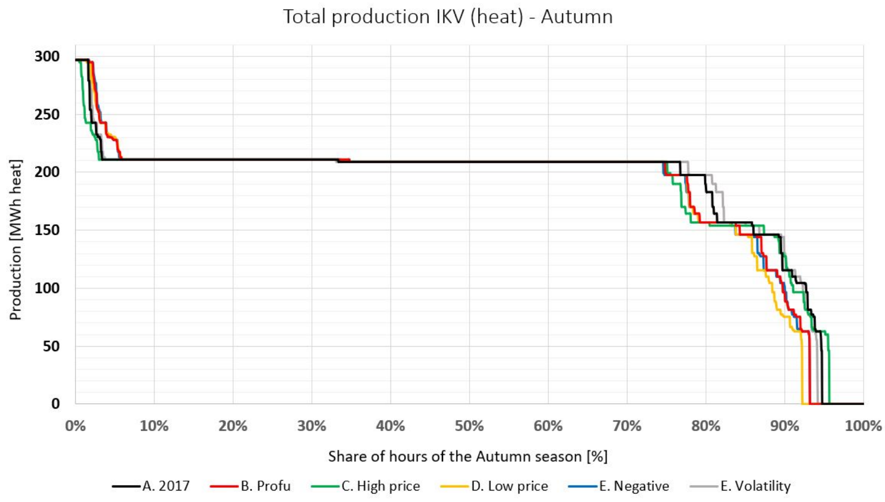

Figure 6.8: A duration diagram based on the total heat production during the summer season.

block is used. Overall, the differences are quite small and comparing Scenario A and Scenario B, no significant changes are visible in terms of total volumes. The major differences can be observed in Scenario C, D and G.

In the low price scenario, Scenario D, the middle price-blocks, such as B, M and N, representing facilities with pellets of wood fuel mixes, have their production reduced. These facilities are pushed out of the merit order more often and replaced by the cheaper facilities with BP productions. In the low price scenario, it is more profitable for the system to switch the operation mode of the CHP plants from MC to BP-mode due to low electricity prices.

Additional observation is a small increase of the O- and Q-block. These blocks represent heating pumps and electricity boilers respectively. Increased number of low price hours favours O and Q, as they are essentially electricity-consuming facilities.

In Scenario C and G, representing a electricity price characterized by high electricity price hours, the opposite strategy is chosen. These scenarios are not as heavily affected in change of operational mode as the low price scenario but the results indicate higher production from the electricity-producing facilities, showing a more stable production and indicating quite small differences as compared to Scenario A. Overall, a larger spread over the use of different facilities is to be expected as well as higher volatility in the merit order in the DH system of

2025.

Unit	A.2017		B. Profu		C. High price		D. Low price		E. Negative		G. Volatile	
	Tot prod [GWh]	Hours in operation(year) [%]	Tot prod [GWh]	Hours in operation(year) [%]	Tot prod [GWh]	Hours in operation(year) [%]	Tot prod [GWh]	Hours in operation(year) [%]	Tot prod [GWh]	Hours in operation(year) [%]	Tot prod [GWh]	Hours in operation(year) [%]
IKV BP	257	14%	257	15%	225	13%	441	26%	260	15%	227	13%
IKV MC	939	77%	918	76%	963	79%	728	62%	916	76%	980	80%
IKV El	506	77%	493	76%	517	79%	389	62%	492	76%	527	80%
IKV FGX	378	83%	372	82%	362	79%	348	77%	371	82%	377	83%
IKV Tot	1574	88%	1546	86%	1551	88%	1517	81%	1547	86%	1584	89%
A	592	79%	600	80%	567	75%	603	80%	596	80%	575	76%
B	179	11%	178	11%	184	11%	129	7%	178	11%	188	12%
C	90	5%	90	5%	92	5%	74	4%	90	5%	88	5%
D	6	1%	6	1%	6	1%	6	1%	6	1%	5	1%
E	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%
F	0	0%	1	0%	0	0%	1	0%	1	0%	0	0%
G	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
H	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
I	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
J	400	99%	400	99%	381	93%	400	99%	400	99%	391	97%
K	8	1%	8	1%	8	1%	7	1%	8	1%	8	1%
L	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
M	521	64%	516	64%	494	61%	462	59%	515	64%	506	63%
N	924	42%	851	40%	908	43%	727	37%	846	40%	1247	54%
O	2162	58%	2238	59%	2237	59%	2259	59%	2243	59%	1860	52%
P	112	18%	118	18%	108	17%	233	34%	120	19%	102	16%
Q	16	1%	16	1%	16	1%	83	4%	20	1%	21	1%
R	2	0%	13	1%	36	3%	7	1%	13	1%	20	1%
S	1557	100%	1556	100%	1556	100%	1555	100%	1556	100%	0	100%
T	86	23%	89	24%	83	22%	165	37%	91	24%	78	21%

Figure 6.9: Table of the total production of each scenario for the entire DH network

6.4 Negative electricity prices

For Scenario E, 70 hours of negative electricity prices were implemented. Apart from these hours the rest of the electricity price was identical to Scenario B and therefore, none or very small differences in total volumes could be seen in the analysis of the scenarios. Referring to the duration curves in each season, figure 6.3,6.5, 6.7 and 6.8, Scenario E is presented in blue and barely visible due to following the red line representing Scenario B.

Analysing the specific hours during which negative prices occur it was found that, in the DH system the electricity producing block including CHP plants and IKV would become unprofitable if they were to produce electricity. These facilities are instead switching their production to the BP condenser or being shut down. Additionally, block that become competitive are the electricity-consuming facilities such as heating pumps and electrical boilers. During negative hours, these facilities are placed early in the merit order. However, the amount of negatively priced hours is little and will not affect the system in significant volumes in 2025.

6.5 Heat dump

Outputs from BoFiT showed that the heat dump was used 160 hours during a year for Scenario B. Profu. The heat dump was active during the period between May and September, mostly during the summer months. When it was in use, the MT either increased or remained the same as when the heat dump was not present (figure 6.10). During the majority of the time when MT was increased, the heat from it was directed to the heat dump. Either all additional heat was dumped, or more than the actual increase was dumped, causing another facility to start operation, supplying the heat demand. During the rest of the time, the additional heat produced was partially dumped and partially sent to the DH network grid, causing another facility in the system to shut down or decrease its production (figure 6.11 to the left).

When MT remained the same, as compared to the operation when the heat dump was not included, what happened was that MT sent some or all of its heat to the dump, causing a start of another facility in the system (as the heat demand still needed to be fulfilled) (figure 6.11 to the right).

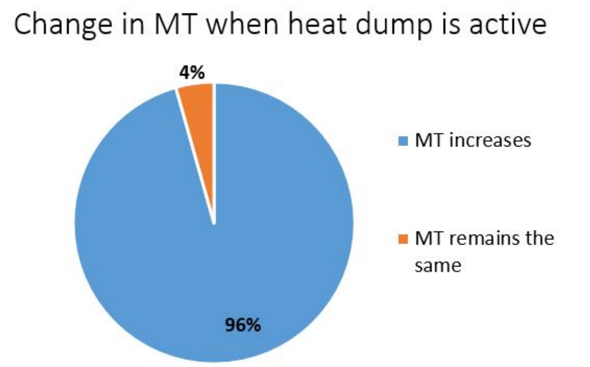

Figure 6.10: Change in MT when heat dump was used

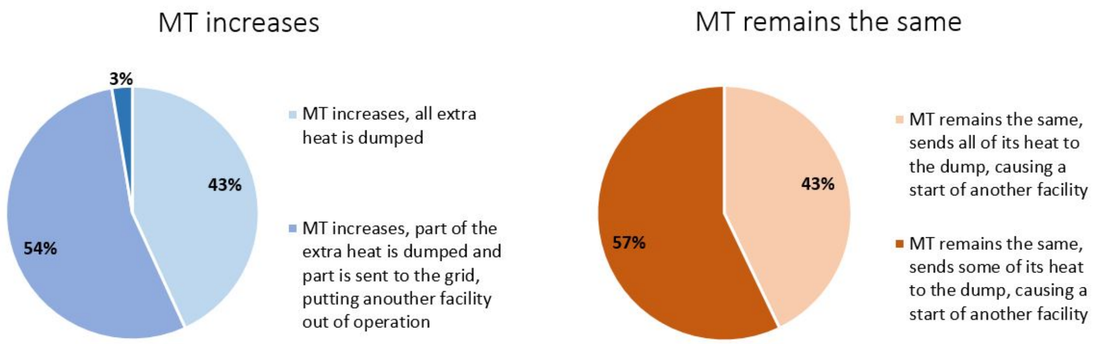

Figure 6.11: What happens with the additional heat when MT changes

6.6 Costs

The costs obtained for IKV and the DH system are presented in table 6.9 and 6.11 respectively.

Table 6.9: Costs of IKV

IKV cost [MSEK]						
	A. 2017	B. Profu	C. High price	D. Low price	E. Negative	F. Volatile
BP	45.29	45.51	43.70	77.22	46.07	39.88
MC	245.72	240.17	242.26	192.73	239.55	256.29
FGC	0.76	0.74	0.74	0.70	0.74	0.75
El.	-159.95	-151.85	-158.85	-120.31	-151.74	-202.11
SUM	**131.81**	**134.57**	**127.85**	**150.33**	**134.63**	**94.81**

For costs related to IKV it can be observed that Scenario F has the lowest total cost, which can be explained by the high amount of revenue obtained from the sale of electricity. This can be explained by the fact that Scenario F has the highest average spot price - Scenario C has the most hours where the price is equal to or above 640 SEK/MWh but for the hours below, it can be stated that Scenario F has the highest electricity price. This indicates highest electricity revenues, which in turn mean lowest heat production cost.

Scenario C has both higher average spot price and greater amount of high price hours but a lesser revenue from electricity sales, as compared to Scenario A. The total cost for IKV is however lower than in Scenario A - this can be explained by the lower production in Scenario C. Lower production might very well indicate lower total costs, if the production cost per block heat is similar between the compared cases (see table 6.9). In terms of cost, low production, or even no production at all, might seem like the best option, as it costs nothing, however, things might present themselves differently when considering the sales of heat.

Table 6.10: Heat production cost for IKV

IKV Production cost [SEK/MWh]	
A. 2017	83.77
B. Profu	87.02
C. High price	82.82
D. Low price	99.10
E. Negative	87.05
F. Volatile	59.87

Table 6.10 shows the production cost of heat for IKV in the different scenarios. It can be observed that going from the cheapest to the most expensive production cost ranks the scenarios in the same way as going from the highest average spot price to the lowest: Scenario F, Scenario C, Scenario A, Scenario B, Scenario E, Scenario D. The reference scenario, Scenario A, places itself around the middle, and Scenario B indicates higher production costs in 2025.

When looking at the DH system costs, the ranking of cheapest to most expensive scenario presents itself a bit differently (see table 6.11). Scenario F and Scenario C are still the cheapest ones, but Scenario D, which is the most expensive when looking at IKV alone, turns out to be the third cheapest scenario when considering the whole system. The DH system adapts in a better way to low electricity prices than IKV - this is because the system includes components such as electric boilers, which can directly utilize the low prices to their advantage.

Table 6.11: Costs of the DH system

Total cost [MSEK]						
	A. 2017	**B. Profu**	**C. High price**	**D. Low price**	**E. Negative**	**F. Volatile**
IKV	131.81	134.57	127.85	150.33	134.63	94.81
A	57.86	58.64	58.21	58.88	58.26	56.18
B	91.71	91.24	93.11	66.12	90.97	96.41
C	52.17	52.44	52.53	43.10	52.44	51.01
D	4.11	4.02	4.08	3.89	4.02	3.59
E	1.11	1.66	1.65	1.53	1.68	1.31
F	0.07	0.45	0.44	0.43	0.46	0.35
G	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00
J	0.39	0.39	0.39	0.39	0.39	0.38
K	4.94	5.01	5.03	4.10	5.01	4.74
L	0.00	0.00	0.00	0.00	0.00	0.00
M	78.11	77.38	76.70	69.29	77.25	75.96
N	176.75	164.31	161.94	150.95	163.38	203.53
O	417.74	419.24	420.34	379.04	417.72	390.26
P	32.80	28.15	27.80	30.70	27.18	32.85
Q	10.27	9.78	9.76	39.05	10.90	12.33
R	1.15	6.42	6.40	3.68	6.44	5.68
S	-262.59	-248.63	-255.63	-208.11	-246.93	-320.30
T	24.98	21.57	21.27	22.12	20.95	25.04
SUM	**823.38**	**826.63**	**811.87**	**815.50**	**824.74**	**734.14**

7 Discussion

High- and low priced hours and their effects on IKV’s operation mode

This project evaluated the energy system of Sweden in 2025 and the expected changes in the electricity price. It was found that two major happenings in the system were a decreasing share of nuclear power and an increasing share of wind power. What was significant in those changes was that the energy system of the future shifted from stable, controllable energy source to varying, unpredictable ones. The effects of these changes, which are not necessarily limited to nuclear- and wind power, were, among other, that the electricity price became more volatile. The electricity prices for Scenario B were deemed as the most sound prediction and it showed an increase of both high- and low price hours. These occurred both during winter and summer - extreme months in terms of heat demand, which lead to interesting cases for a CHP plant like IKV to handle.

The operation of IKV was investigated for high- and low electricity prices and the general observation was that IKV chose to run on MC-mode the majority of the time, in all scenarios, due to sales of electricity. Even at electricity prices lower than 640 SEK/MWh, defined as high electricity prices, MC-mode was more profitable and therefore chosen. Meaning, the high price hours being defined as 640 SEK/MWh does not necessarily represent a breaking point between MC and BP-mode. In fact, Scenario A, which had the least amount of high price hours (59 as seen in table 6.1) produces only 24 GWh of heat than Scenario C with 1 748 high price hours. Therefore, increasing the share of high price hours, with this definition, will not affect the share of hours which IKV runs on MC. A lowered definition of high price hours could have shown greater effects. The effects of high price hours are instead noticeable when looking at costs - the higher the electricity price, the greater the revenue.

Low price hours, on the other hand, seemed to have more impact when it comes to the share of the different operational modes - the low price scenario, Scenario E, has a significantly increased share of BP-mode in its production. This suggests that electricity prices below 100 SEK/MWh do have an effect on IKV´s operational mode and that the breaking point where IKV switches from one mode to another lies somewhere between 100 SEK/MWh and 640 SEK/MWh. That point is however hard to define, as it does not only depend on the electricity price but also on the heat demand and the rest of the DH system.

Looking at the total in terms of production and costs, Scenario F, stands out in quite a lot of aspects. It has, for example, the highest share of MC heat production, and the lowest production and overall costs. This can be explained by the fact that for this scenario, the electricity price was changed for every hours of the year. Meaning, the average spot price was raised significantly which could not be seen in the other scenarios. Scenario C and D only had 20% of the year changed so in order for the yearly result to be significantly affected, the electricity price during longer time periods need to be changed.

IKV's adaptation to negatively priced hours

During negative hours, IKV chose to switch do BP-mode, avoiding the situation where producing electricity became a cost. In this way, IKV has the means to guard itself against negative electricity prices. It is possible for the power plant to avoid the related costs, however, there is no way for the facility to use negative prices to its advantage. When low or negative prices occur it cannot switch to a mode which is benefited from low prices, because it does not contain components which consume electricity in order to produce heat. In order to profit from electricity prices an electric boiler or heat pump is of interest which was present in the DH network.

The DH system did have the electricity-consuming components IKV lacked - electric boilers and heat pumps - which resulted in the DH system not being as badly affected by low price hours, and even in some cases performing better during those conditions. This showed that although very connected, IKV and the DH system are different in some aspects, and what is disadvantageous for one might be beneficial for the other.

Increased collaboration within the DH system

The results obtained from the analysis of IKV's performance showed that the heat and power plant was regulating by operating part load on MC and part load on BP for some time. As for today, IKV has been mostly ran on MC mode as the electricity prices have been relatively stable and due to the economical compensation for producing electricity it has been receiving. With more volatile electricity prices, there was a need to switch between modes and to combine modes, which, if it happens in the future, will require an active and frequent observation of electricity prices. This would be even more crucial if the economical compensation for electricity production would, for some reason, end.

Further, the volatile electricity prices not only affected IKV but also the rest of the DH system. The results showed that the usually quite stable merit order was much more dynamic, and many facilities switched their position greatly, if the electricity price changed a lot. This implies that in the future there will be a need of great collaboration within the DH system, as well as communication - the facilities need to update each other of their changing production costs if the goal of providing heat at as low costs as possible is to be maintained.

The profitability of a heat dump The analysis of the heat dump showed that it was used only 160 hours throughout a year. A heat dump became advantageous during the hours when IKV was on the margin in the merit order - these, however, proved to be not that many. IKV was instead early in the merit order, leaving few openings to utilize a heat dump.

The majority of the hours when the heat dump was used was during summer, when the heat demand was low. During this period, IKV usually needs to undergo a revision, requiring it to shut down for a couple of weeks. This decreases the operation of the heat dump even further, making it usefulness quite small.

Other

When analysing the results and applying them into IKV's operation, it is important to remember that there are difference between the modelled reality and the actual one. The results from the model are affected by various limitations and assumptions and can thus be seen as indicators on what may happen in the future. For example, the IKV model did not include any start- or shut down costs, and the other facilities did not include any ramp up/ramp down times. This allowed for very quick regulations and changes in the merit order, however, an exact replica of the operation would probably not be possible in real life, even if one knew about the electricity prices beforehand. Nevertheless, even though the same amount of regulation will not be possible, an insight is gained, showing that more regulation than today will be needed and that the facilities will need to cooperate more actively.

Future studies

As the energy system of Sweden is undergoing major changes which affect the electricity and DH market there are a lot of studies that can be done in order to make use and adapt to these changes. During this project, some questions arose, which could not be covered due to time and work load limitations. These are instead recommended for future studies and consist of the following:

- Investigation of breaking points between MC and BP-mode; at what electricity price in combination with certain heat demands does IKV change from one to another?
- Examination of how fast IKV can regulate its operation in case of volatile electricity prices.
- Evaluation of the cooperation between the different actors in the DH network and the necessary means that need to be taken in order to ensure quick action in the merit order.

8 Conclusion

With this thesis the changes in energy system of Sweden in 2025 have been investigated in order to see how a combined heat and power plant might perform in the future. It can be concluded that along with high implementation of renewable energy sources and decreased nuclear power capacity the electricity market will change. The prices of electricity will be highly influenced by the intermittency of wind power resulting in higher volatility. Low electricity prices will occur during the entire year while high prices will be dominant during the winter. However, the price will not vary to the extent that negative price hours will occur in a significant volume in 2025.

Further, it can also be concluded that changes in electricity price will affect the operation of IKV. The results obtained showed that volatile electricity prices lead to high regulation between the main heat condenser and the BP condenser implying the importance of flexibility in operation, in the future.

Additionally, the study showed that the low price hours had a greater impact on the operation of IKV than high price hours. During these hours, IKV often chose to switch from the MC to the BP condenser, or to shut down. Seeing that IKV will regulate and operate on the BP condenser more often, as compared to today, it is recommended for Söderenergi to develop operational strategies that will allow for a smooth transition to BP mode.

When it comes to costs, these decreased for IKV when increasing the electricity price but increased significantly when low prices occurred and the power plant ran on BP-mode. For the DH system, no such clear trend could be observed. A common effect on the system was however more frequent and greater changes in the merit order, due to the increased volatility in the electricity prices. This leads to the recommendation of investigating the ramp up and ramp down possibilities of the individual facilities in the system, as well as the system's regulation characteristics as a whole. In the future, it will be even more crucial to have updated technical data of the facilities and the network, as they might be needed to be pushed to their limits when it comes to regulation in order to operate optimally.

References

[1] Advantag. *Emissions Trading / Carbon Market News (2018-01-18)*. 2018. URL: https://advantag.de/en/emissions-trading-carbon-market-news-2018-01-18. (accessed: 14.11.2019).

[2] Alpman, M. and Hållén, J. *Köp el - få betalt*. NyTeknik. 2010. URL: https://www.nyteknik.se/energi/kop-el-fa-betalt-6420565. (accessed: 25.11.2019).

[3] Gadd, H. and Werner, S. *Daily heat load variations in Swedish district heating systems*. In: Applied Energy, pp. 47-55. DOI:10.1016/j.apenergy.2013.01.0307. 2013. (accessed: 03.11.2019).

[4] Goding, L. et al. *The Swedish Electricity and Natural Gas Market 2017*. Swedish Energy Markets Inspectorate, Eskilstuna, Sweden. 2018. (accessed: 20.09.2019).

[5] Jacobsen, S. *Denmark sets record with 43 percent of power from wind in 2017*. Reuter. 2018. URL: https://uk.reuters.com/article/uk-denmark-renewables-windpower/denmark-sets-record-with-43-percent-of-power-from-wind-in-2017-idUKKBN1F01VD. (accessed: 26.11.2019).

[6] Johansson, V. *Interview*. Continous interviews during autumn 2019. 2019.

[7] Kungliga Ingenjörsvetenskapsakademien (IVA). *Framtidens elanvändning - En delrapport*. 2016. URL: https://www.iva.se/globalassets/info-trycksaker/vagval-el/vagvalel-framtidens-elanvandning-delrapport.pdf. (accessed: 04.01.2020).

[8] Kvarnström, J., Dotzauer, E., and Dahlquist, E. *Produktions - och distributionsplanering av fjärrvärme*. Värmeforsk, Stockholm, Sweden. 2006. (accessed: 03.11.2019).

[9] Nationalencyklopedin. *Kärnenergifrågan*. n.a. URL: https://www.ne.se/uppslagsverk/encyklopedi/%C3%A5ng/k%C3%A4rnenergifr%C3%A5gan. (accessed: 10.10.2019).

[10] Nationalencyklopeding. *Volatilitet*. n.d. URL: https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/volatilitet. (accessed: 27.11.2019).

[11] Nordpool. *Historical Market Data*. n.d. URL: https://www.nordpoolgroup.com/historical-market-data/. (accessed: 18.11.2019).

[12] Sköldberg, H. and Rydén, B. *Värmemarknad i Sverige - en samlad bild*. 2014. URL: http://www.varmemarknad.se/pdf/Varmemarknad_Sverige_sammanfattning.pdf. (accessed: 14.10.2019).

[13] Sköldberg, H. and Rydén, B. *Värmemarknaden i Sverige - en samlad bild*. Värmemarknad Sverige, Eskilstuna, Sverige. 2014. (accessed: 10.10.2019).

[14] Sköldberg, H., Unger, T., and Holmström, D. *El och fjärrvärme - samverkan mellan marknaderna*. Energiforsk. 2015. URL: https://energiforskmedia.blob.core.windows.net/media/19560/el-och-fjarrvarme-energiforskrapport-2015-223.pdf. (accessed: 04.01.2020).

[15] Sköldberg, H., Unger, T., and Holmström, D. *El och fjärrvärme - samverkan mellan marknanderna, etapp 2*. Energiforsk. 2017. URL: https://energiforskmedia.blob.core.windows.net/media/22176/el-och-fjarrvarme-samverkan-mellan-marknaderna-energiforskrapport-2017-346.pdf. (accessed: 04.01.2020).

[16] Söderenergi. *Teknik i framkant*. 2020. URL: http://w3techs.com/technologies/overview/content_language/all. (accessed: 20.09.2019).

[17] Statistiska Centralbyrån (SCB). *Tillförsel och användning av el 2001-2018*. 2019. URL: https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/tillforsel-och-anvandning-av-energi/arlig-energistatistik-el-gas-och-fjarrvarme/pong/tabell-och-diagram/tillforsel-och-anvandning-av-el-gwh/. (accessed: 04.01.2020).

[18] Svenska Kraftnät. *Finer - 15 minuters avräkning*. 2018. URL: https://www.svk.se/finer. (accessed: 05.01.2019).

[19] Svenska Kraftnät (SvK). *Nätutvecklingsplan 2016-2025*. Svenska Kraftnät, Stockholm, Sweden. 2015. (accessed: 10.10.2019).

[20] Svt Nyheter. *Kärnkraftens framtid i Sverige osäker*. 2018. URL: https://www.svt.se/nyheter/inrikes/karnkraftens-framtid-i-sverige-osaker. (accessed: 10.10.2019).

[21] Swedish Energy Agency. *Energy in Sweden 2019. An overview*. 2019. URL: https://energimyndigheten.a-w2m.se/Home.mvc?resourceId=133464. (accessed: 27.09.2019).

[22] Swedish Energy Agency. *Sveriges Energi- och Klimatmål*. 2019. URL: https://www.energimyndigheten.se/klimat--miljo/sveriges-energi--och-klimatmal/. (accessed: 27.09.2019).

[23] Swedish Wind Energy Association. *Vindkraftsstatistik 2018*. SWEA, Eskilstuna, Sweden. 2019. (accessed: 20.09.2019).

[24] Thorin, E., Sandberg, J., and Yan, J. *Combined Heat and Power*. In:Handbook of Clean Energy Systems, pp.1-11. DOI:10.1002/9781118991978.hces021. 2015. (accessed: 05.01.2020).

[25] Vattenfall. *Elmarknaden just nu: Högsta elpriset på tio år*. Vattenfall. 2018. URL: https://www.di.se/pressreleaser/2018/8/31/vattenfall-elmarknaden-just-nu-hogsta-elpriset-pa-tio-ar/. (accessed: 20.11.2019).

[26] Wetterstrand, M. et al. *Högre säkerhet i svenska kärnreaktorer (väckt enligt 3 kap. 13 § riksdagsordningen med anledning av händelse av större vikt)*. Motion to the Parliament. 2010. URL: https://www.riksdagen.se/sv/dokument-lagar/dokument/motion/hogre-sakerhet-i-svenska-karnreaktorer-vackt_GY02N5/html. (accessed: 04.01.2020).

Appendices

A Complementary figures and tables

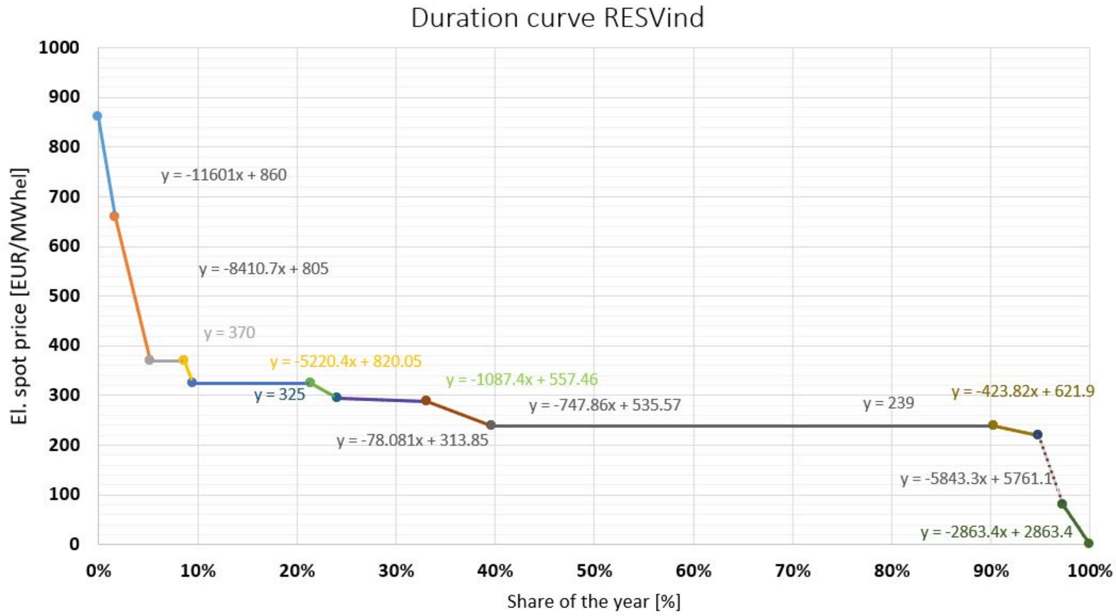

Figure A.1: Duration curve of Profu's scenario RESVind approximated with linear relations and equations.

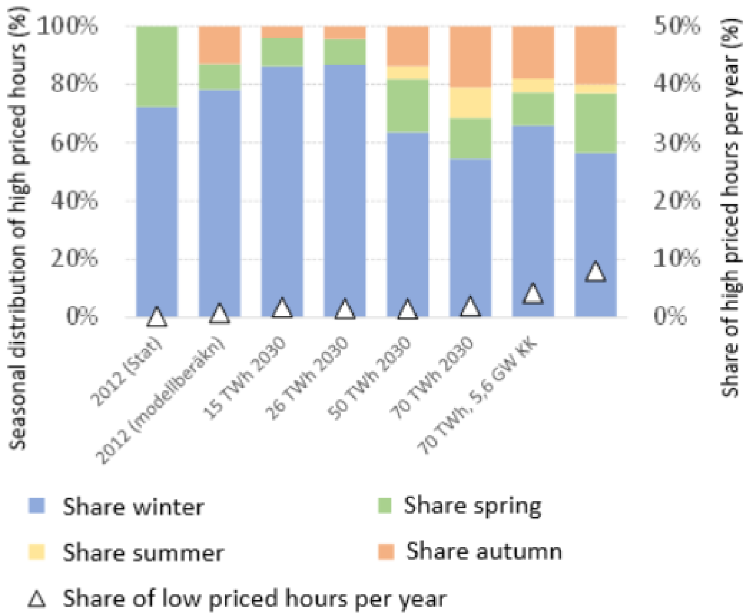

Figure A.2: Seasonal distribution of high price hours throughout a year from Profu.

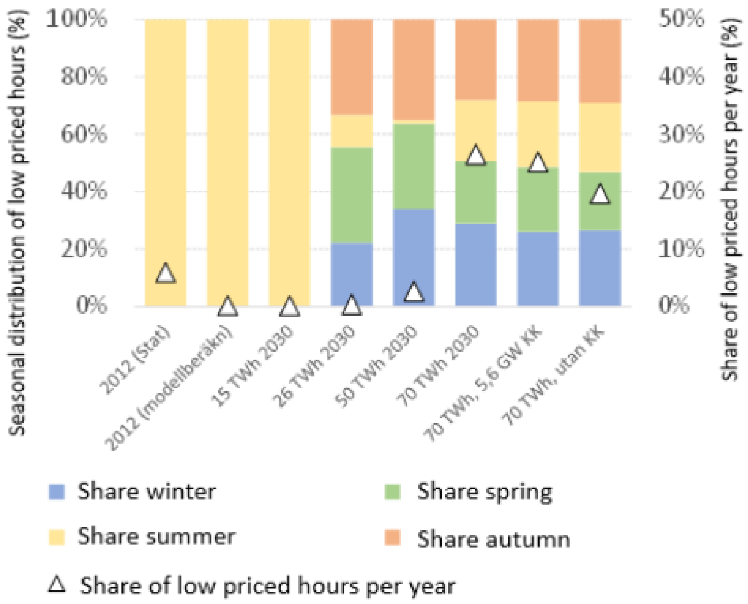

Figure A.3: Seasonal distribution of low price hours throughout a year from Profu.

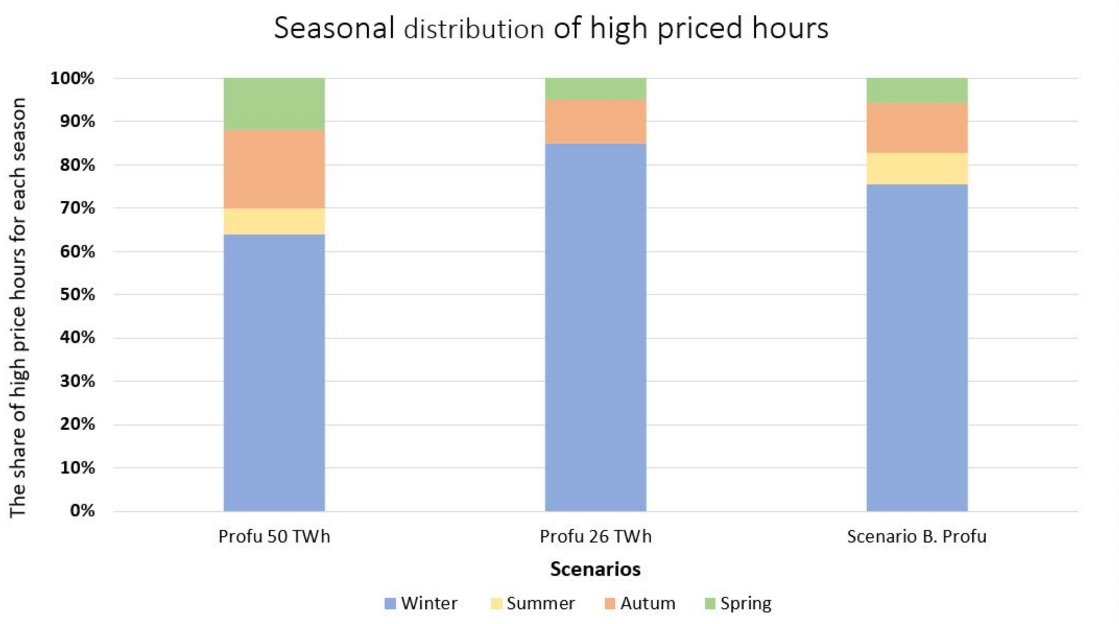

Figure A.4: Comparison of seasonal distribution of high price hours throughout a year between data from Profu and Scenario B.

Figure A.5: Comparison of seasonal distribution of low price hours throughout a year between data from profu and Scenario B.

Table A.1: Frequency of negatively priced hours in DK1 in 2017.

Magnitude [SEK/MWh]		Frequency
-500	-520	0
-480	-500	1
-460	-480	0
-440	-460	0
-420	-440	1
-400	-420	2
-380	-400	1
-360	-380	0
-340	-360	0
-320	-340	0
-300	-320	0
-280	-300	0
-260	-280	0
-240	-260	0
-220	-240	2
-200	-220	2
-180	-200	0
-160	-180	1
-140	-160	12
-120	-140	5
-100	-120	11
-80	-100	7
-60	-80	6
-40	-60	10
-20	-40	6
0	-20	23

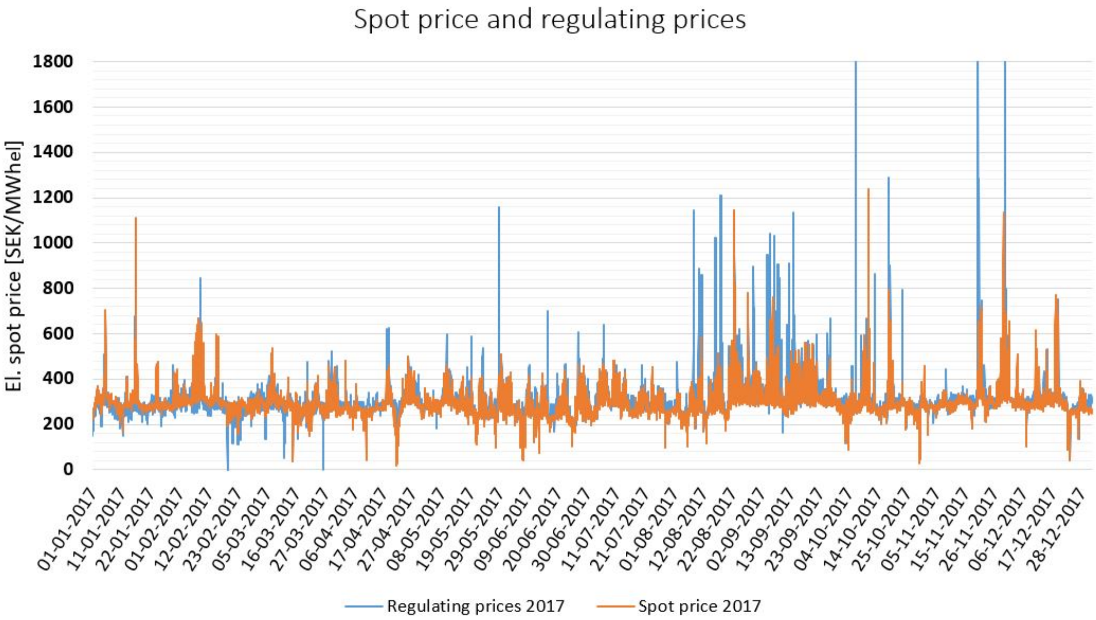

Figure A.6: Spot and regulating prices of 2017.

Table A.2: Frequency table and comparison of electricity price for SE3 2017 and Profu electricity price

Electricity price		Frequency SE3	Frequency Profu
From	To	[hr]	[hr]
860	880	9	-
840	860	2	15
820	840	2	15
800	820	2	15
780	800	5	15
760	780	2	15
740	760	2	15
720	740	7	15
700	720	6	15
680	700	10	15
660	680	12	15
640	660	10	21
620	640	8	21
600	620	11	21
580	600	25	21
560	580	23	21
540	560	26	21
520	540	27	21
500	520	37	21
480	500	91	21
460	480	82	21
440	460	133	21
420	440	155	21
400	420	205	21
380	400	291	21
360	380	361	1148
340	360	598	161
320	340	1178	161
300	320	1941	161
280	300	1609	920
260	280	899	234
240	260	513	234
220	240	210	4845
200	220	95	30
180	200	59	30
160	180	25	30
140	160	23	30
120	140	20	30
100	120	16	30
80	100	4	30
60	80	10	60
40	60	14	61
20	40	2	61
0	20	0	61

B Complementary figures heat and production

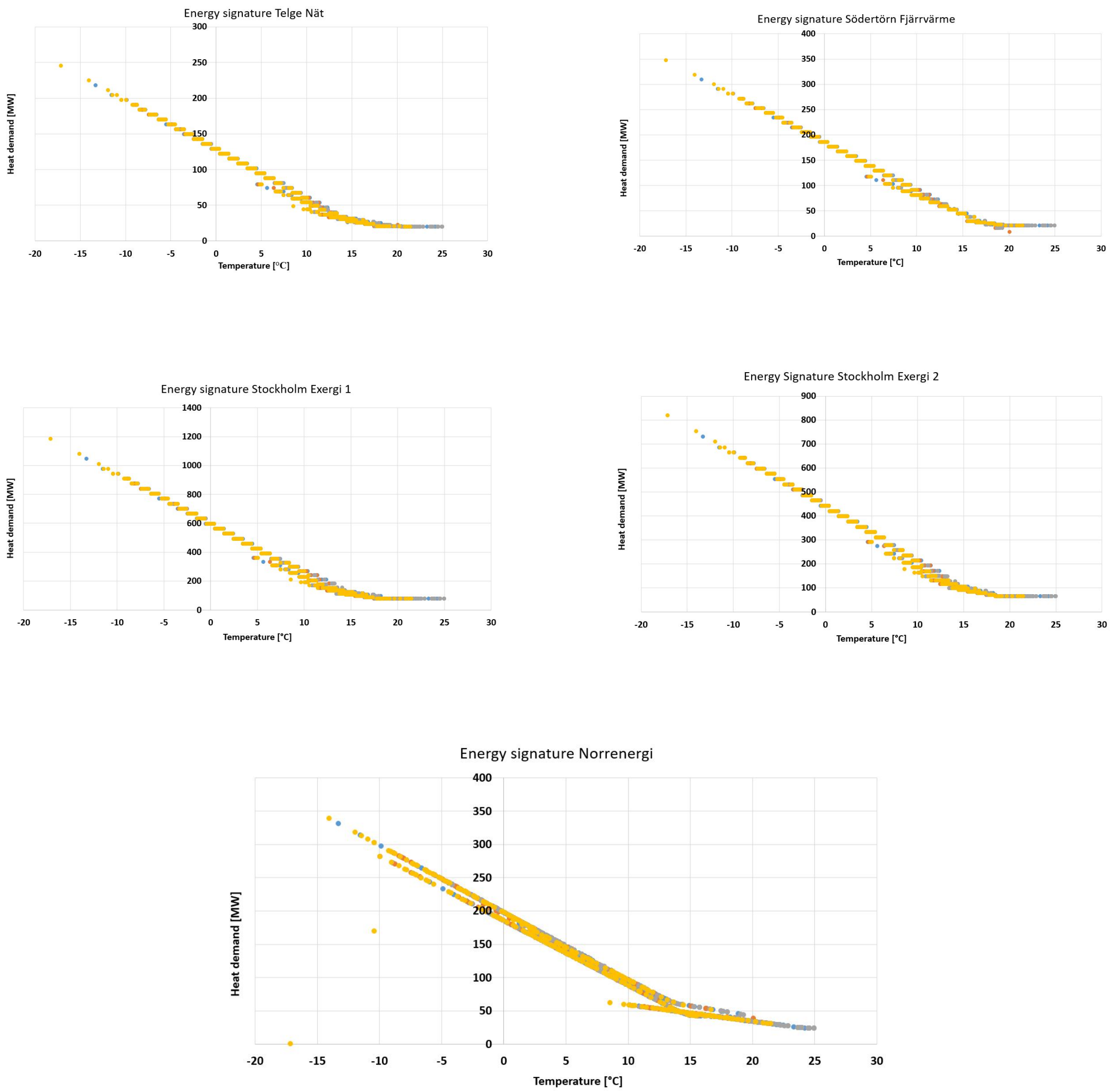

Figure B.1: Energy signature curves.

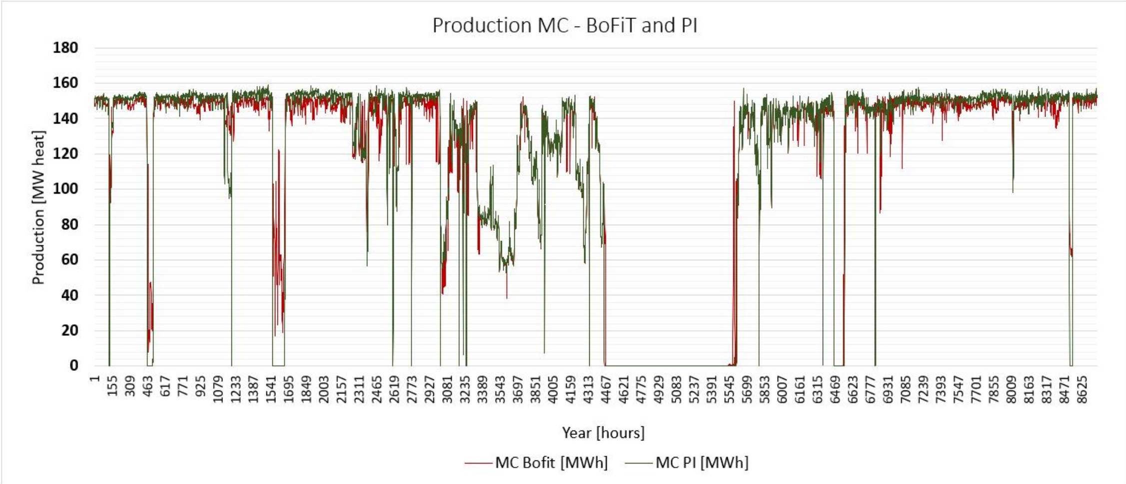

Figure B.2: Production from MC, comparison between output from BoFiT and PI.

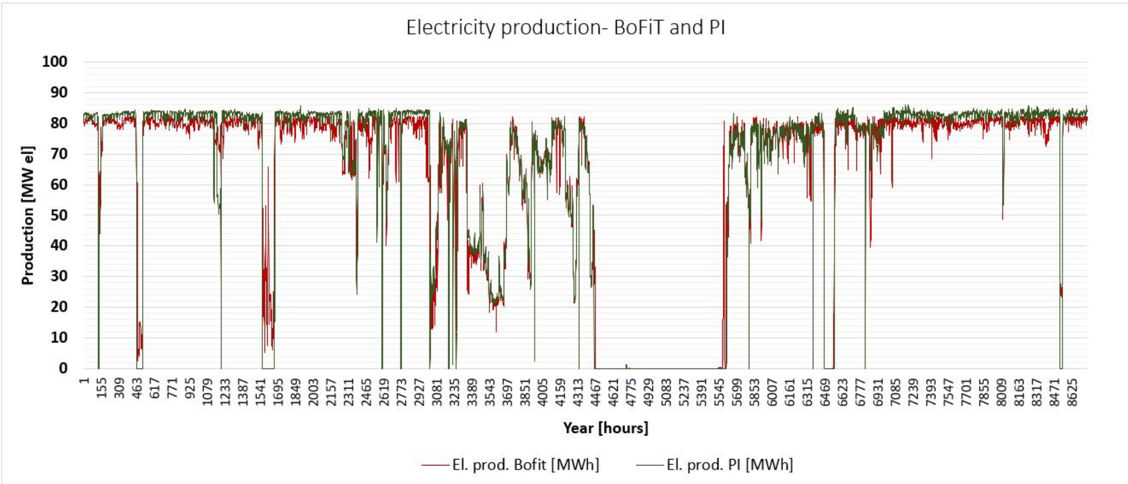

Figure B.3: Production of electricity, comparison between output from BoFiT and PI.

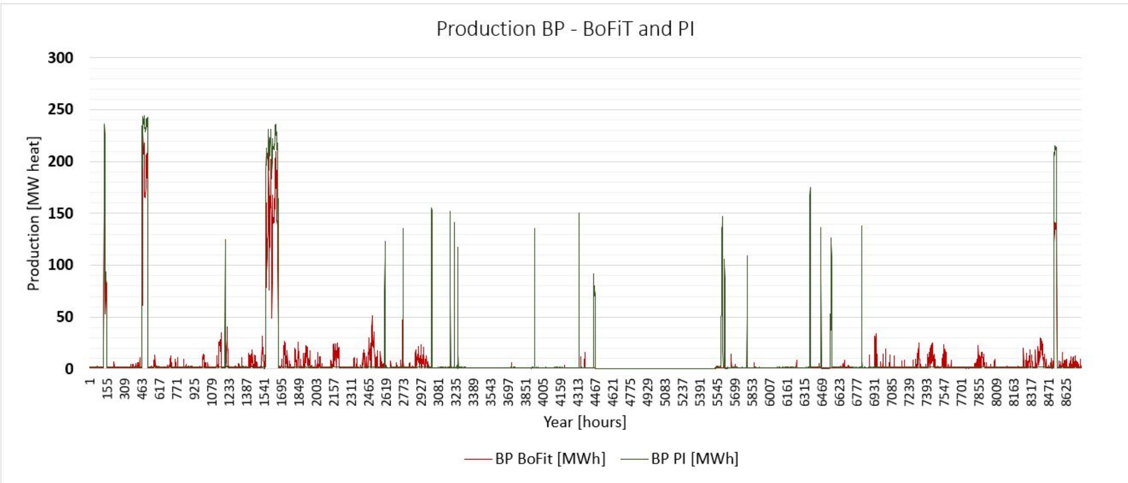

Figure B.4: Production from BP, comparison between output from BoFiT and PI.

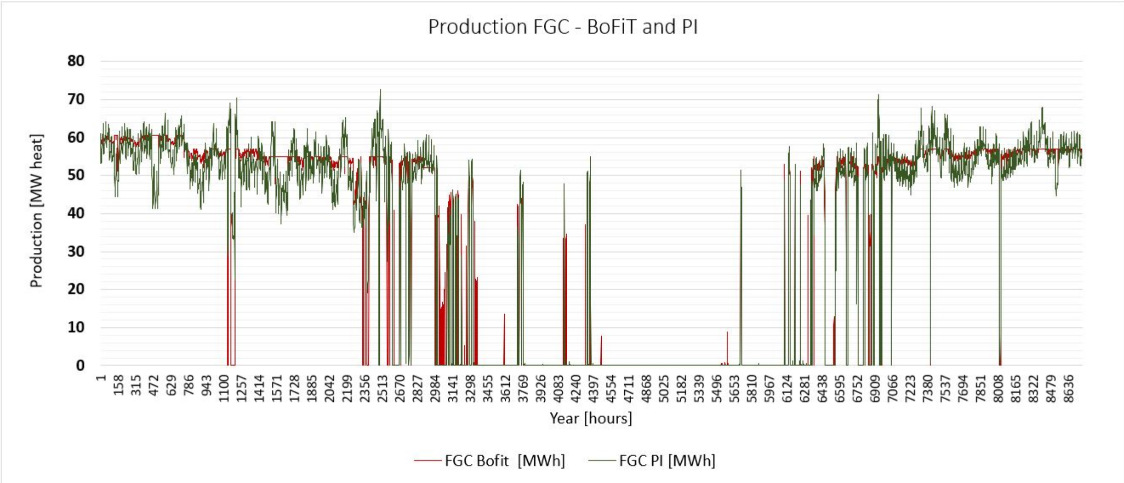

Figure B.5: Production from FGC, comparison between output from BoFiT and PI.

C Modelling BoFiT

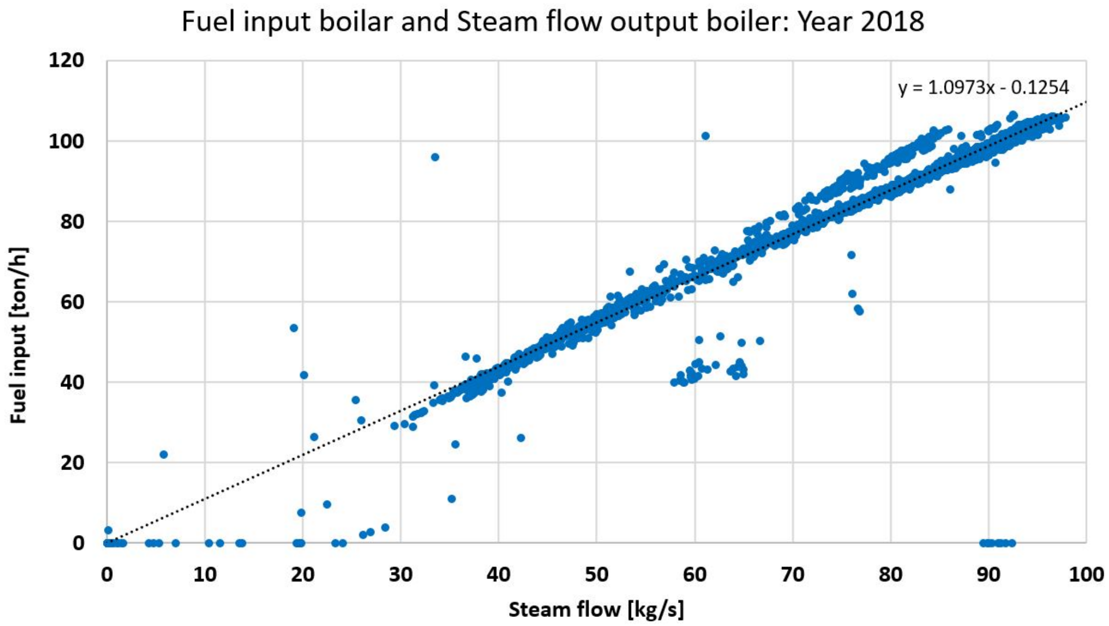

Figure C.1: Fuel input plotted against the steam flow output showing a linear correlation.

Table C.1: Input in BoFiT for steam generator/Boiler

Denotation in BoFiT:Steam Generator Denotation in project: Boiler				
Name of input	**Unit**	**Value 1**	**Value 2**	**Source**
Fuel input	[MW]	0	286	Figure B.1
Steam output	[kg/s]	0	100	Figure B.1
Start-up fuel demand cold start	[MWh]	400	-	Wallin, 2019
Add. start-up fuel warm start add. Firing	[MWh]	600	-	Wallin, 2019
Max. standstill period warm start	[hr]	72	-	Wallin, 2019

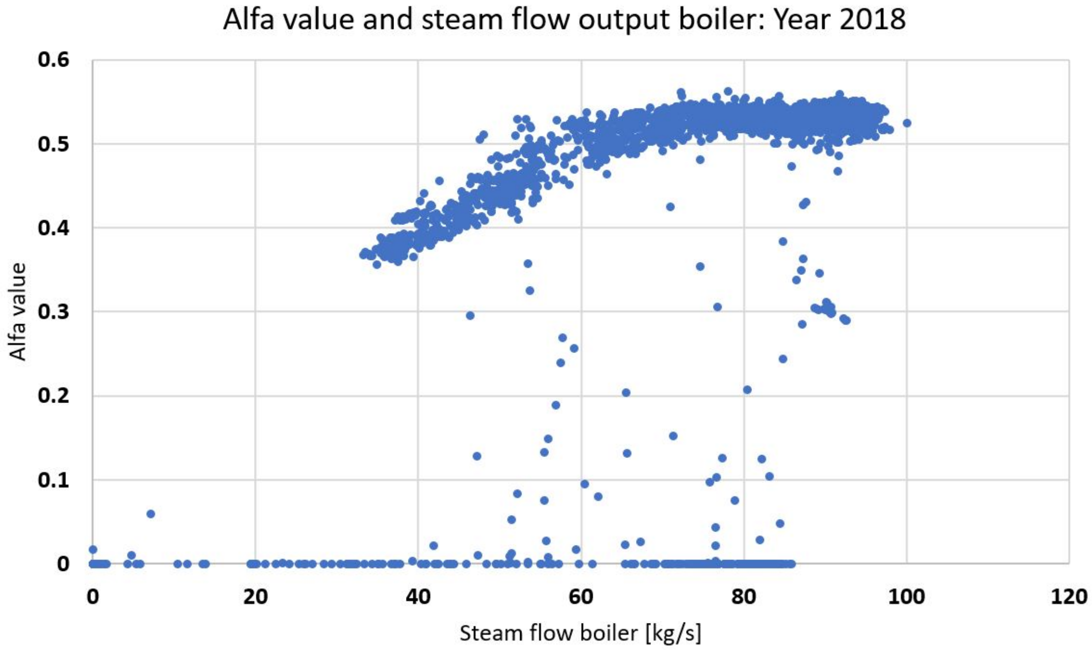

Figure C.2: Alfa value plotted against the steam flow output from the boiler showing a non linear correlation.

Table C.2: Input in BoFiT for partial turbine/turbine based on alpha values and steam output from boiler.

Denotation in BoFiT: Partial turbine Denotation in project: Turbine							
Name of input	**Unit**	**Value 1**	**Value 2**	**Value 3**	**Value 4**	**Value 5**	**Source**
Steam input	[kg/s]	0	30	50	75	100	PI
Generator output	[MW]	0	14.5	32	62	84	Calc
Alfa without RGK	-	0	0.314	0.416	0.538	0.538	SöE

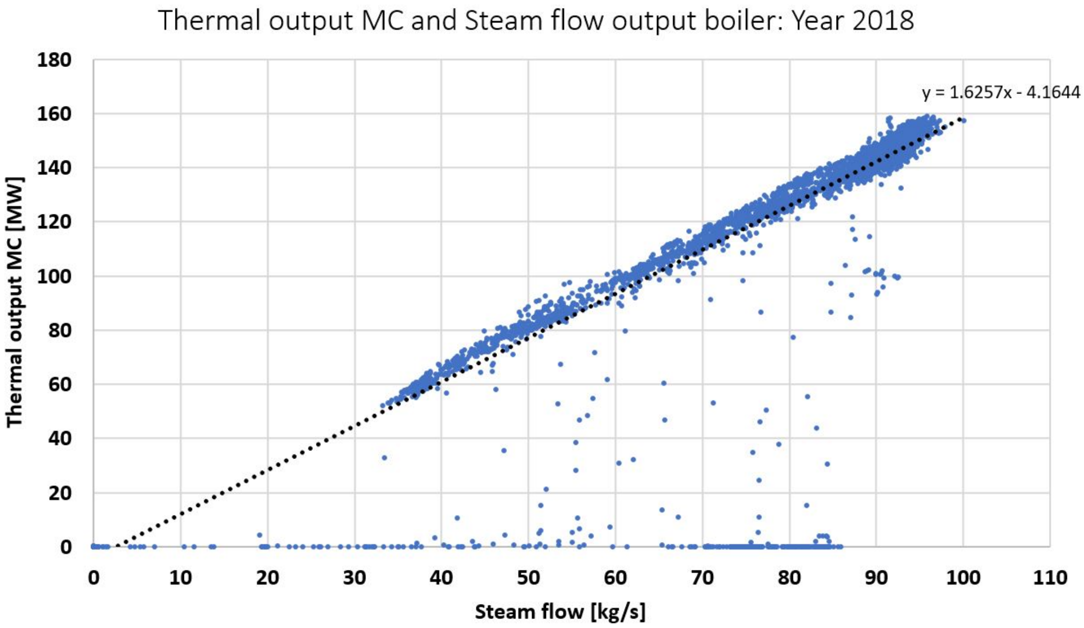

Figure C.3: Thermal output from the MC plotted against the steam flow from the boiler showing a linear correlation.

Table C.3: Input to BoFiT for MC

Denotation in BoFiT: Heat Exchanger Denotation in project: MC				
Name of input	**Unit**	**Value 1**	**Value 2**	**Source**
Thermal output	[MW]	0	154	Figure C.1
Steam input	[kg/s]	0	100	Figure C.1

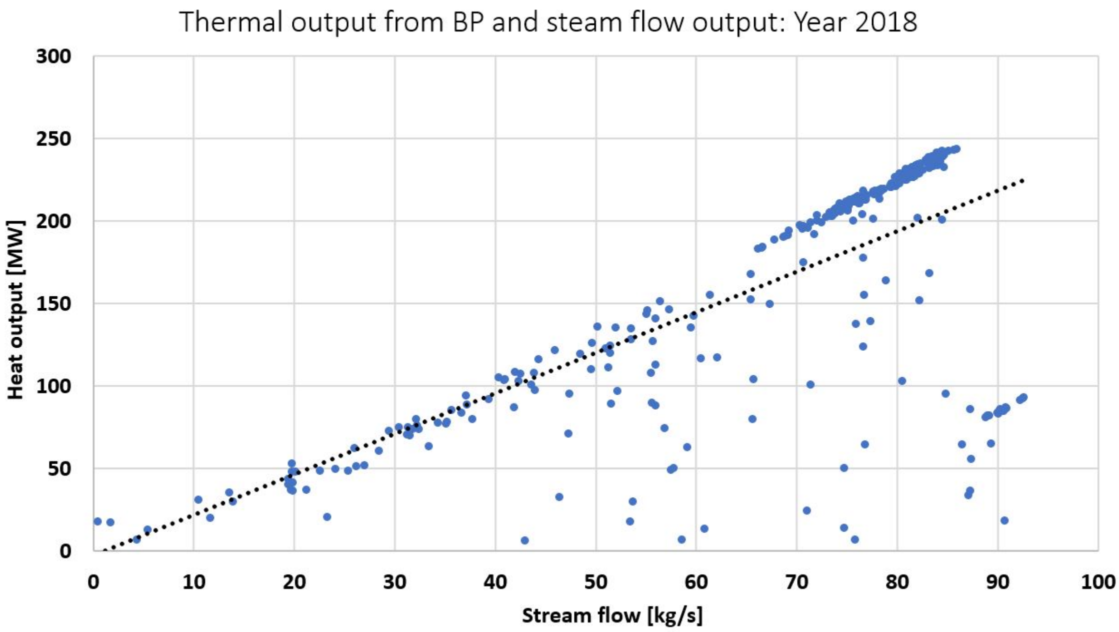

Figure C.4: Thermal output plotted against the steam flow output from the boiler assuming a linear correlation where the scarcity of measurement points is due to the infrequent use of the BP in 2018

Table C.4: Input to BoFiT for Heat exchanger/BP

Denotation in BoFiT: Heat Exchanger - Nr 4 Denotation in project: BP Heat condenser (BP)				
Name of input	**Unit**	**1**	**Value 2**	**Source**
Thermal output	[MW]	0	240	Figure B.4
Steam input	[kg/s]	0	100	Figure B.4

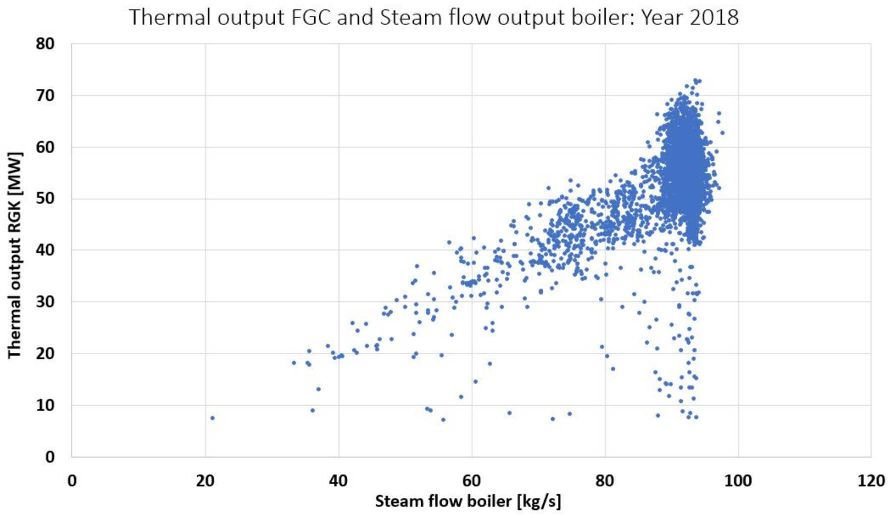

Figure C.5: Thermal output from FGC plotted against the steam flow output from the boiler.

Table C.5: Input to BoFiT for Heat exchanger/ FGC, average thermal output for each month.

Denotation in BoFiT: Heat Exchanger Denotation in project: FGC				
Name of input	**Unit**	**Value 1**	**Value 2**	**Source**
Steam input	[kg/s]	0	100	Figure B.5
Thermal output	[MW]			Table B.5
Jan	[MW]	0	57	-
Feb	[MW]	0	57	-
Mar	[MW]	0	55	-
Apr	[MW]	0	54	-
Maj	[MW]	0	52	-
Jun	[MW]	0	46	-
Jul	[MW]	0	50	-
Aug	[MW]	0	51	-
Sep	[MW]	0	55	-
Okt	[MW]	0	55	-
Nov	[MW]	0	57	
Dec	[MW]	0	57	-

Table C.6: Time series input

Time series	Cost	Unit	Comment
Acquisition price, fuel mix	114.20-148.60	SEK/MWh	Varies
Emission allowance cost	76.18	SEK/tonne carbon emitted	Constant
Heat (MC & BP) O&M cost	39	SEK/Mwhheat	Constant
NOx fee	-6.28	SEK/MWhheat	Constant
O&M FGC	2	SEK/MWhheat	Constant
Grid revenues	5.9	MWhel	Constant
Electricity O&M cost	2	MWhel	Constant

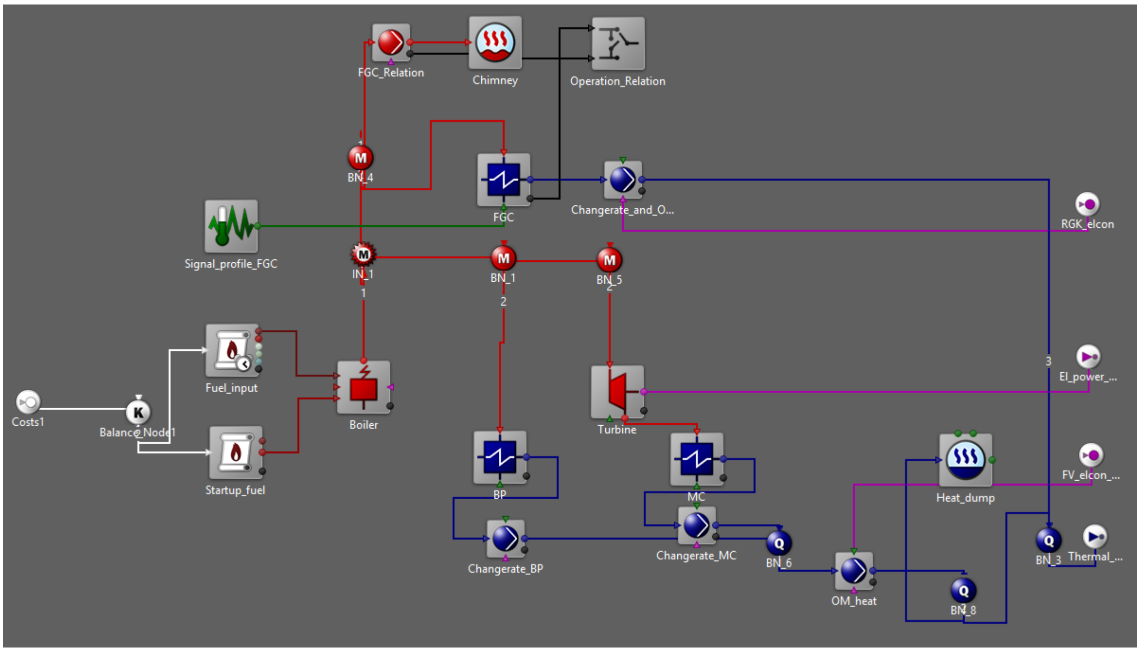

Figure C.6: Picture of the model from BoFiT

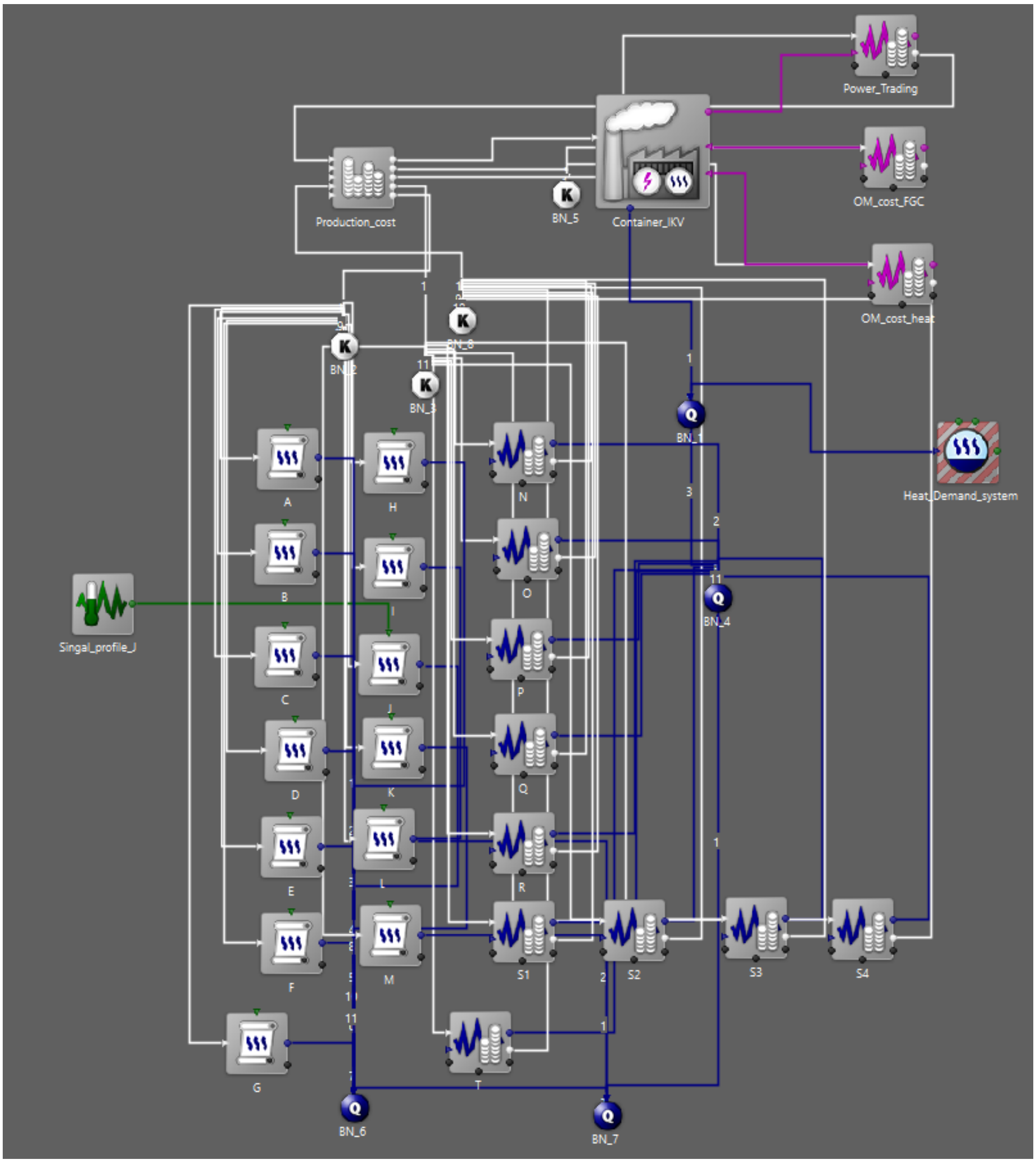

Figure C.7: Picture of the model from BoFiT

Component	Boiler
Input	**Value**
Steam output	0; 0.01; 29.99; 30; 100 kg/s
Fuel input	0; 100 000; 100 000; 81.15; 270.50 MW
Own power consumption	Default
Start-up fuel demand warm start	400 MWh
Addition start-up fuel demand cold start	600 MWh
Start-up fuel warm start add. firing	0 MWh
Start-up fuel cold start additional	0 MWh
Max. standstill period for warm start	72 hr
Min. standstill period	0 hr
Min. running time	0 hr
Max. output changing rate of fuel input	-1 MW/h
Output change	Standard
Characteristic fuel consumption	Auto
Characteristic own power consumption	-
Planning interval	-1 hr
Min. steam flow amount	-
Max. steam flow amount	-
Predet. steam flow amount	-
Min. use frequency	-
Max. use frequency	-
Predet. use frequency	-
Min. utilisation period	-
Max. utilisation period	-
Predet. utilisation period	-
Component	BP
Input	**Value**
Thermal output	0; 240 MW
Steam input	0; 100 kg/s
Operation	100
Characteristic model	Auto
Component	MC
Name of input	**Value**
Thermal output	0; 154 MW
Steam input	0; 100 kg/s
Operation	100
Characteristic model	Auto
Component	FGC
Input	**Value**
Thermal output	0; 57; 55; 54; 52; 46; 50; 51; 55 MW
Steam input	0; 100 kg/s
Operation	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12
Characteristic model	Auto
Component	Change rate BP
Input	**Value**
Max. changing rate of thermal output	70 MW/h
Heat Flow	0; 240 MW
Power Consumption	0 MW

Figure C.8: Input IKV

Component	Change rate MC
Input	**Value**
Max. changing rate of thermal output	60 MW/h
Heat Flow	0; 154 MW
Power Consumption	0 MW
Component	Change rate and O&M FGC
Input	**Value**
Max. changing rate of thermal output	50 MW/h
Heat Flow	0; 60.60 MW
Power Consumption	0; 60.60 MW
Component	O&M heat
Input	**Value**
Heat flow	0; 394 MW
Power Consumption	0; 394 MW
Component	FGC Relation
Input	**Value**
Steam output	0, 100 kg/s
Power Consumption	0 MW
Characteristic model	Auto
Component	Turbine
Input	**Value**
Steam input	0; 30; 50; 75; 100 MW
Generator output	0; 14.50; 32; 62; 84 MW
Operation	100
Min. standstill period	0 hr
Min. running time	0 hr
Max. steam mass flow changing rate	-1 kg/s/hr
Ouput change	Standard
Operation limit	Inactive
Characteristic model	MC
Component	Chimney
Input	**Value**
Steam demand (load)	-
Component	Operation Relation
Input	**Value**
Option	Not more than one component may be used
Component	Signal profile for FGC
Input	**Value**
Temperature forecast	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12

Component	Fuel input
Input	**Value**
Max. Fuel Input	1000 MW
Fuel-specific Emission Factor CO2	0 t/MWh
Fuel-specific Emission Factor SO2	0 t/MWh
Fuel-specific Emission Factor NOx	0 t/MWh
Operation Limit	Inactive
Planning interval	-1 hr
Energy Rate	Time series 1
Min. Fuel Output	-
Max. Fuel Output	-
Predet. Fuel Output	-
Min. Fuel. Quantity	-
Max. Fuel Quantity	-
Predet. Fuel Quantity	-
Component	Start up fuel
Input	**Value**
Operation Limit	Inactive
Planning interval	0 hr
Energy Rate	97 EUR/ MWh
Min. Energy Quantity	0 MWh
Max. Energy Quantity	-1 MWh
Min. Power Output	0 MW
Max. Power Output	1000 MW
Component	Target Function
Input	**Value**
-	-
Component	Power Trading
Input	**Value**
Price forecast Power	Time series 4
Min. Power Purchase	0 MW
Max. Power Purchase	1000 MW
Min. Power Sales	0 MW
Max. Power Sales	1000 MW
Component	O&M cost FGC
Input	**Value**
Price forecast Power	Time series 3
Min. Power Purchase	0 MW
Max. Power Purchase	1000 MW
Min. Power Sales	0 MW
Max. Power Sales	1000 MW
Component	O&M cost heat
Input	**Value**
Price forecast Power	Time series 2
Min. Power Purchase	0 MW
Max. Power Purchase	1000 MW
Min. Power Sales	0 MW
Max. Power Sales	1000 MW

Component	Heat Demand system
Input	**Value**
Return temperature	50 oC
Flow temperature	100 oC
Temperature forecast	-
TF Heating Curve	-
Component	Heat dump
Input	**Value**
Return temperature	50 oC
Flow temperature	100 oC
Temperature forecast	-
TF Heating Curve	-
Component	A
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01;95 MW
Heat rate	0; 8.98; 8.98 EUR/MWh
Operation	100
Component	B
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 273 MW
Heat rate	0; 47.05; 47.05 EUR/MWh
Operation	100
Component	C
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 385 MW
Heat rate	0; 53.31; 53.31 EUR/MWh
Operation	100
Component	D
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 120 MW
Heat rate	0; 60.31; 60.31 EUR/MWh
Operation	100
Component	E
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 95 MW
Heat rate	0; 63.59; 63.59 EUR/MWh
Operation	100
Component	F
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 160 MW
Heat rate	0; 65.14; 65.14 EUR/MWh
Operation	100

Component	G
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 52 MW
Heat rate	0; 83.40; 83.40 EUR/MWh
Operation	100
Component	H
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 713 MW
Heat rate	0; 85.66; 85.66 EUR/MWh
Operation	100
Component	I
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 94 MW
Heat rate	0; 98.18; 98.18 EUR/MWh
Operation	100
Component	J
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 53 MW
Heat rate	0; 0.09; 0.09 EUR/MWh
Operation	100
Component	K
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 75 MW
Heat rate	0; 54.94; 54.94 EUR/MWh
Operation	100
Component	L
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 139 MW
Heat rate	0; 99.49; 99.49 EUR/MWh
Operation	100
Component	M
Input	**Value**
Min thermal output	0 MW
Thermal output	0; 0.01; 95 MW
Heat rate	0; 13.79; 13.79 EUR/MWh
Operation	100
Component	N
Input	**Value**
Price forecast district heating	Time series N [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	308 MW
Min. district heating sales	0 MW
Max. district heating sales	308 MW

Component	O
Input	**Value**
Price forecast district heating	Time series O [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	536.95 MW
Min. district heating sales	0 MW
Max. district heating sales	536.95 MW
Component	P
Input	**Value**
Price forecast district heating	Time series P [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	85 MW
Min. district heating sales	0 MW
Max. district heating sales	85 MW
Component	Q
Input	**Value**
Price forecast district heating	Time series Q [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	429 MW
Min. district heating sales	0 MW
Max. district heating sales	429 MW
Component	R
Input	**Value**
Price forecast district heating	Time series R [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	200 MW
Min. district heating sales	0 MW
Max. district heating sales	200 MW
Component	S1
Input	**Value**
Price forecast district heating	Time series S1 [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	194 MW
Min. district heating sales	0 MW
Max. district heating sales	194 MW
Component	S2
Input	**Value**
Price forecast district heating	Time series S2 [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	158 MW
Min. district heating sales	0 MW
Max. district heating sales	158 MW
Component	S3
Input	**Value**
Price forecast district heating	Time series S3 [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	134 MW
Min. district heating sales	0 MW
Max. district heating sales	134 MW

Component	S4
Input	**Value**
Price forecast district heating	Time series S4 [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	96 MW
Min. district heating sales	0 MW
Max. district heating sales	96 MW
Component	T
Input	**Value**
Price forecast district heating	Time series T [EUR/MWh] - hourly interval
Min. district heating purchase	0 MW
Max. district heating purchase	54 MW
Min. district heating sales	0 MW
Max. district heating sales	54 MW

Figure C.9: Input IKV 7

D Electricity prices

	Highprice [h]	Lowprice [h]	Negative [h]	Avrg diff. between consecutive hrs [SEK]	Hours above avrg difference between consecutive hrs [h]	Hours below avrg difference between consecutive hrs [h]	Average spot price inbetween hours [SEK/MWh]	Average spot price high price hours [SEK/MWh]	Average spot price low price hours [SEK/MWh]
Scenario A. 2017	59	45	0	14.75	2 441	6 317	299.07	756.07	59.24
Scenario B. Profu	192	241	0	20.16	2 955	5 802	285.64	743.73	50.38
Scenario C. High price	1 748	243	0	40.44	2 995	5 764	351.83	877.81	49.90
Scenario D. Low price	193	1 789	0	28.22	3 119	5 640	241.35	758.57	53.28
Scenario E. Negative	192	285	70	20.78	2 998	5 759	283.54	743.78	11.64
Scenario F. Volatile	378	12	0	39.89	4 169	4 590	363.06	743.71	92.79

Figure D.1: Yearly statistics with regards to the obtained electricity prices for each scenario.

	Highprice [h]	% of yearly value	Lowprice [h]	% of yearly value	Negative [h]	% of yearly value	Average diff. between consecutive hrs [SEK]	Hours above average difference between consecutive h [h]	Hours below average difference between consecutive h [h]	Average spot price [SEK/MWh]	Average spot price inbetween hours [SEK/MWh]	Average spot price high price hours [SEK/MWh]	Average spot price low price hours [SEK/MWh]
WINTER													
A. 2017	19	32%	2	4%	0	-	13.01	412	1748	307.03	303.58	721.84	64.19
B. Profu	145	76%	53	22%	0	-	21.45	690	1469	298.12	271.55	748.10	50.62
C. Highprice	344	20%	38	16%	0	-	32.88	664	1496	339.97	265.16	766.22	50.60
D. Lowprice	77	40%	878	49%	0	-	26.59	674	1486	220.17	298.94	737.44	66.70
E. Negative	145	76%	70	25%	34	49%	22.15	702	1457	293.85	271.81	748.10	-29.71
F. Volatile	105	28%	0	0%	0	-	41.04	1110	1050	379.69	355.90	845.22	-
SPRING													
A. 2017	0	0%	21	47%	0	-	12.44	597	1610	284.62	286.91	-	45.70
B. Profu	11	6%	80	33%	0	-	16.49	669	1538	265.31	270.89	758.11	50.03
C. Highprice	297	17%	86	35%	0	-	34.85	700	1507	308.87	254.34	721.68	48.80
D. Lowprice	6	3%	370	21%	0	-	26.45	754	1453	199.47	253.06	650.02	47.34
E. Negative	11	6%	82	29%	3	4%	16.77	676	1531	264.97	270.93	758.11	47.10
F. Volatile	88	23%	6	50%	0	-	40.53	1020	1187	357.78	335.55	909.56	92.79
SUMMER													
A. 2017	14	24%	14	31%	0	-	16.46	810	1398	293.94	292.00	823.54	80.14
B. Profu	14	7%	28	12%	0	-	19.28	787	1420	283.03	283.61	658.63	50.04
C. Highprice	564	32%	92	38%	0	-	48.00	833	1375	368.40	248.59	752.48	51.78
D. Lowprice	29	15%	456	25%	0	-	32.50	892	1316	247.05	294.21	771.09	35.54
E. Negative	14	7%	48	17%	20	29%	20.34	800	1407	280.46	284.78	658.63	-22.91
F. Volatile	88	23%	3	25%	0	-	38.42	1004	1204	355.06	333.53	881.92	92.79
AUTUMN													
A. 2017	26	44%	8	18%	0	-	17.56	625	1559	318.30	314.12	744.76	56.96
B. Profu	22	11%	80	33%	0	-	23.95	811	1374	296.49	301.02	761.71	50.69
C. Highprice	543	31%	27	11%	0	-	46.38	800	1385	390.19	266.42	780.22	46.00
D. Lowprice	81	42%	85	5%	0	-	27.67	802	1383	298.82	291.91	746.98	35.79
E. Negative	22	11%	85	30%	13	19%	24.40	822	1363	295.20	301.16	761.71	30.99
F. Volatile	97	26%	3	25%	0	-	39.97	1039	1146	360.05	336.22	880.55	92.79

Figure D.2: Seasonal statistics with regards to the obtained electricity prices for each scenario.

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