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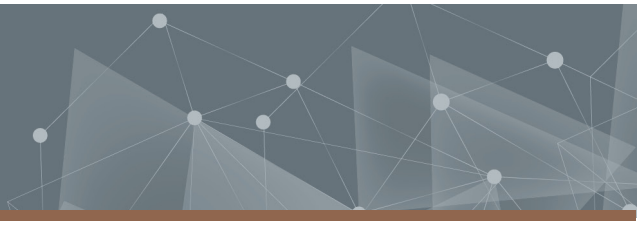

Thermal storage valuation in Gothenburg district heating system

Master's thesis in Master´s Programme Sustainable Energy Systems

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Cover: Wind visualization constructed in Matlab showing a surface of constant wind speed along with streamlines of the flow.

Abstract

Göteborg Energi has invested in an accumulator tank for their district heating system in Rya. This accumulator tank needs further investigation about cost-efficiency and best usage. The study's goal is to investigate the profitability of the installed accumulator tank and see if future accumulator tank investment is a profitable solution.

The district heating network is divided into different nodes which are connected by water pipes, and different plants/units are found at different nodes. The units have different fuels, start times, start costs, efficiencies, and limitations which makes these units more or less expensive to run. In this work, the combined heat and power (CHP) plants have decided to have a restricted minimum load, and the rest of the units have a flexible load. The different generation units are heat-only boilers (HOB), CHPs, and heat pumps (HP).

The method was set up to calculate the minimum annual cost of generation in three different cases with different input values. These cases are *2019*, *2030*, and *2030* new investments where the differences are that *2019* is the current system and is modeled with an accumulator tank and without. The *2030* case is based on Göteborg Energi's prognosis of how the new installment of units will look in 2030. Here the comparison was made between the current accumulator installed and the possibility of new accumulator investments in the system. The last case was like the *2030* case, but instead of the 2030 prognosis of installed units, the model invested in three categories of plants (HOB, HP, and CHP), where the units still in service from 2019 remained. A sensitivity analysis was also made in all these cases where the fuel prices were varied.

The *2019* case showed a saving of 1.55 M€, and in both cases, investments in new accumulator tanks were made, especially in nodes 5 and 6, which are in the north and eastern districts of Gothenburg. The sensitivity also showed that accumulator tanks are profitable even though bigger fuel price fluctuations occur.

One important discovery in the study was that bottlenecks were decreased with the help of accumulator tanks. In contrast, plants further up the merit order decreased production when more accumulator tanks were available. Also, electricity-dependent heat generation units have good integration with this kind of thermal storage because of the higher use of heat pumps and CHPs when accumulator tank capacity increases.

One of the study's conclusions is that the current accumulator tank is profitable and has a payback of approximately 11 years, and investing in more accumulator tanks would decrease the cost of the district heating system.

Keywords: Accumulator tank, Thermal energy storage, District heating system, Node division, Bottlenecks .

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We like to thank Joel Bertilsson and Lisa Göransson at the Department of Space, Earth and Environment at Chalmers for helping us with the thesis. The Chalmers Department of Space, Earth and environment also contributed with seats and computers, which we are thankful for. We also like to thank Jonas Cognell and Per Khilström from Göteborg Energi for helping us gather the data and constraints for the thesis GAMS model and an extra thank to Jonas Cognell for also getting us in contact with the right persons at Göteborg Energi when we desired certain information.

Göteborg June 2023
Pontus Håkanson and Ludvig Johansson

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1
Introduction

The global energy system is moving away from stable fossil fuels and transitioning to more variable renewable energy sources (VRE), thereby less emitting energy sources [1]. These VREs will contribute to a more fluctuating energy system, so variation management strategies (VMS) are important. These VMSs can contribute to smoothing the load in both the electrical system and the district heating system [1]. One of these VMSs is thermal energy storage. In Gothenburg, this has already been invested in, and more precisely, a tank thermal energy storage (TTES) which works as an accumulator tank and is in the district Rya in the northwestern parts of Gothenburg. It is a 60-meter-tall structure with a storage capacity of 1000 MWh. This is one of the investments necessary to become fossil-fuel-free by 2025, according to Göteborg Energi [2].

There are different approaches to becoming fossil-fuel-free by 2025. One is to optimize the current system based on increasing the CHP usage to get a stronger dependency between heat and electricity production[3]. This will lower fossil-fuel usage because of the penetration of renewable energy sources in the electricity sector.

In the study [3], the CHP:s fuel was biomass, and biomass will be a big part of the future of the district heating systems. This biomass has its drawbacks as well, and according to [4] will the future be dependent on more biomass in many different sectors, which for the district heating sector can be problematic since it is already dependent on biomass to a larger degree. This will increase the demand and, thereby, the cost of biomass. In [4], it is also mentioned that biomass already covered a quarter of the Swedish heat demand in 2013. Many old CO2-intensive plants with oil as a fuel are replaced by either biomass or electrification. This is also the case for Gothenburg, where the latest biomass plant was taken into operation in 2022 [5]. In Gothenburg, the existing biomass plants are the HOB8 in Rya[6] which runs on pellets, and the CHP in Sävenäs, which runs on wood chips[7]. If biomass becomes expensive because of higher demand, as explained above, or because of low supply, some plants may be limited yearly in how much heat they can generate.

District heating networks can be divided into nodes to make the system more manageable, and with these multiple nodes, some sort of transfer between these nodes is necessary because the generation is not always at the location the demand is. These transmission pipes that link the system together can create limitations within the district heating system where a more expensive plant is forced to run because of limited transmission capacity [8]. These transmission capacity limitations are based

on a high velocity in the pipes, leading to higher pressure losses. Eventually, if it is extremely high velocities, the heat delivery can decrease [8]. These limitations are called bottlenecks and are important to localize in the system. Determining bottlenecks is important to optimize the district heating system. In [8], this has been researched by either expanding the pipes from which the district heating water is supplied or raising the supply temperature. This, according to [8], could be solved by either option one, increasing the diameter of the pipes or installing one more at the affected distance, or option two, installing another plant at a location that needs a higher supply temperature, or the installment of thermal energy storage that will give the same effect as installing another plant. So, in conclusion, either better transmissions between districts or increasing the generation. It is also mentioned in [8] that planning for the future and being aware of the bottlenecks that can occur when new demand is generated is vital.

The future has uncertainties, but it will need a more flexible system since peak plants will be wanted less since it is often driven by fossil fuels or biogas/biomass, which will be needed in many sectors. Other fuels and solutions are needed. One of those could be electricity, and according to [9], heat pumps are the most relevant because of their high coefficient of performance (COP) and the flexibility of generation. The flexibility of fuel price decreases for boilers which are more even in the generation because of their independence from the electricity market [9], but HOBs can be flexible in temperature of the running flame and thereby the output energy [10]. The integration towards other energy systems, such as electricity systems, is needed. This is through heat pumps or CHPs and their flexible operation, which is the obvious one according to [11]. The different integrations between sectors are a necessity for future energy systems. These other solutions, especially the integration with electricity, create other phenomena where plants can differ in total cost.

The total cost of different plants generates what is called a merit order. Where the last one in the merit order is the most expensive and is thereby on the margin of where the demand meets the supply [12]. Critical parameters of the total cost are the energy input cost, maintenance, taxes, and so forth [13]. These input differences will then create a specific merit order. In [13], it is also mentioned that waste heat can lower the marginal cost due to its low costs and not only the input differences. The merit order changes depending on the electricity price since CHPs and heat pumps are available in many systems. Depending on how fluctuating the electricity price becomes, the more the merit order changes and the flexibility of plants is essential.

The change of merit order will cause a change in the most expensive plant needed, which is a way in for thermal energy storage into the district heating system [14]. According to [14], TES is one of the solutions to these offsets between producing cheap heat and the demand peaks. To store the cheap energy and use it for another hour. In [15], different options to solve this offset were presented by different technologies and strategies, mostly thermal energy storage. These thermal energy storages will manage the offsets and lower the maintenance of other plants since the

heat generation will be more steady. The thermal energy storage will cover more daily fluctuations according to [15]. The profitability of thermal energy storage in a district heating system is then evaluated through the usage of all other plants, and in [16] an investigation surrounding CHP profitability with thermal energy storage available, [16] then states that depending on the configuration of the CHP there are profitable solutions when integrating a TTES. This study is for the whole of Gothenburg, which can also find cost-efficiency in TTES since the amount of plants is greater than the one CHP in the study [16].

Further up the introduction, it is stated that [15] is arguing for a higher use of bio-CHP but [11] disagrees and states that bio-CHP will not be used in future cases, which then clearly shows how uncertain the future of district heating optimization is and what plants that should be installed. According to another study [17], the combination of CHP:s and thermal energy storage are well-used. This strategy is used in Gothenburg, where this study is performed since both the accumulator tank and Rya CHP are located in the district Rya along with HOB and HP. HPs in future energy systems, according to both [11] and [15], are important. The importance of heat pumps in a district heating system is, according to [18], great. That study also investigates the collaboration between HPs and thermal energy storage. It concludes that combining them is a good way to create a more flexible district heating system and use the sometimes low electricity prices to charge the storage and use at another time. Since both CHPs and heat pumps are a good combination together with thermal energy storage, the location of the current accumulator tank, according to [17], is a good option.

This is one suitable location, but there could also be other locations where an accumulator tank is beneficial. Another mention from [17] is that many aspects should be considered when assessing the suitability of installing a TES, including various configurations, depending on network topology, distribution of energy density demand, type of connected plants, control strategy, and environmental conditions. All these aspects are suitable to investigate further at the city of Gothenburg, which also is within Göteborg Energi's knowledge. The district heating system in Gothenburg has already invested in an accumulator tank with an investment cost of 16 M€ [19], but how cost-efficient is it?

1.1 Aim & Objective 2019

The goal of the study is to investigate how cost-efficient the installed accumulator tank is. Goteborg Energi wants to see how the tank is integrated into the system and how it lowers the costs of the system by erasing bottlenecks and increasing the operation of low-cost generation units.

The accumulator tank/s is one of the parameters to accomplish the goal of a fossil-free district heating in 2025, where present valuations are relevant for future investments. Erasing bottlenecks is a big part of lowering costs since these create higher costs than possible for the available generation units.

- Investigate if the installed accumulator tank was a profitable investment.
- Find patterns in generation plants that show bottleneck's existence.

1.2 Aim & Objective 2030

In the direction of the 2025 fossil-free district heating system, the goal for 2030 is to investigate how cost-efficient the investment of new accumulator tanks is. With the same aim of seeing how the tanks are integrated and investigating how these are lowering costs because of decreased bottlenecks and increased use of low-cost generation units.

This is to create a broader view of the future district heating system for Goteborg Energi and the future plants in investments of other units.

- Investigate if more accumulator tanks are suitable in the future system.
- Find patterns in generation plants that show bottleneck's existence.
- See if there are more cost-efficient combinations of new accumulator tanks and plants for the future district heating system.

1.3 Limitations

Demarcations in a larger aspect are that this study is only performed in the city of Gothenburg. This is according to Göteborg Energi´s wishes. There are also environmental impacts that the energy system will contribute to, such as CO2 emissions which will not be considered, but only the cost of emissions for 2019. Since Göteborg Energi already has a target of carbon-neutral heat generation in the year 2025. This study also focuses on district heating and not district cooling. Thermal storage is not only available VMS in a technological aspect, but buildings have an inertia that will not be included in this study. The only storage aspect included will be what Göteborg Energi has control over on the supply side. There will also be limitations regarding the kind of thermal energy storage available for future investments. This option is the current technology, accumulator tanks such as the already installed one in the Rya district. The district heating system is also limited to energy flow and not separated into mass flow of water and temperature. This is due to more complex models, longer run times, and demand side problems since the customers have different temperature demands, which are collectively added into one node.

Another limitation regarding the model is that emission rights are excluded in future cases. On the other hand, the present case has emission rights included. Still, it does not affect the case because Göteborg Energi has its emission rights allocated and does not exceed this allocation limit. The system will not account for the fixed cost of already invested plants both now and in the future, only operational and maintenance costs, because this study focuses on integrating accumulator tanks in the district heating system.

The GAMS program, precisely the model calculation, is specified to multiple integer programs (MIP), which then prohibits using marginal value, data that can be exported from GAMS output files. This is because binary values create nonlinear marginal values where marginal values must be linear.

2
Theory

This chapter will present a general theory about Gothenburg's district heating system and the modeling software GAMS. More precise information about Gothenburg heat generational units included now and planned in the future will be presented further down the chapter.

2.1 Thermal Energy Storage

Thermal storage is a way to store thermal energy. That can be collected through many diverse sources, industrial waste heat, power plants, waste management, etc. There are separate ways of storing this way, categorized into three different ways. Sensible heat storage, latent heat storage, and chemical reaction heat storage [20]. The focus of this study will be on thermal energy storage as an accumulator tank which is in the sensible heat storage category. Sensible heat storage means energy can be stored by varying the temperature of the storage materials.

2.2 District heating in general

The district heating system is divided into two inputs for households and industries. The first one is the heating of the building, and the other one is the hot water supply [21]. Heat exchange is used primarily to transfer heat from the main transmission pipes to the local heating or hot water system at each property. The most common way of the citywide distribution network is pipes planted in the ground under streets, pavements, and parks [21]. The forward temperature is the temperature given to the customer, which differs from 70-150 °C but most often around 80-90 °C. The return temperature is then the temperature back to the district heating system before heating occurs again. This return temperature varies between 35-70 °C but most often lands on 45-60 °C [21]. The operation of the district heating system is based on using four different control equipment independent of each other. The first level is heat demand control. This control is made by thermostatic valves at the radiators at the location, and mixing valves for domestic hot water [21]. The second level controls the heat transfer at customer substations and is checked with valves that adjust the flow [21].

The third level controls pressure differences between the supply and return sides in the pipes. This is done by adjusting the speed of the distribution pumps. This allows the customer substations to receive the heat necessary by adjusting the flow

through pressure differences [21]. The last level is the one that controls the supply temperature that is made by changing the generation from the heat generating plants [21].

2.3 Generation Plants

Often a company services the district heating network in a city based on several plants, waste heat, storage tanks, and pipes connecting the whole city. The system is built to supply heat to households and industries around the connected parts.

Supplying the district heating system with enough energy plants that generate heat is necessary. These plants can run on different fuels, including oil, natural gas, pellets, wood chips, biogas, or bio-oil, which all have different heating values. These fuels are then distributed through various kinds of generating plants. In this study, there are heat pumps (HP), heat-only boilers (HOB), and Combined heat and power (CHP), which have the larger focus.

The heat pumps use tempered water, which extracts the heat from and transfers the extracted heat to the district heating water. Heat pumps run on electricity, and the output is often several times larger in heat than in electrical input. This difference is called the coefficient of performance (COP-value). Heat pumps generally consist of a heat exchanger that extracts the heat and a compressor that moves the refrigerant in the refrigeration cycle[22]. The heat pumps for a district heating system require higher input temperatures than typical residential applications, which is then the sewage water in Gothenburg[22].

Next is a Heat only boiler (HOB) that heats water from a low temperature to a higher one by burning a certain fuel. This can be compared to a regular boiler, but instead of a turbine that generates electricity [23], a heat exchanger is placed to transfer the heat from the produced steam to the district heating water.

The last way for heat generation is the combined heat and power (CHP) plant that generates electricity and thermal energy, as the name says. A typical power plant can convert the fuel's energy (without any flue gas recovery) into electric energy at an efficiency of 30%. The rest is lost in the process [24], but in a CHP, the remainder of the energy becomes waste heat that is delivered to the district heating system. Of course, there will be losses, but the energy efficiency is much higher compared to an only electricity-producing power plant.

2.4 GAMS

The study will be made in a linear programming software called GAMS that allows for larger linear and non-linear equations that simulate the heating system in Gothenburg. In GAMS, some options will enable the model to be non-linear. One of these options is to insert binary variables that only can alter between 1 and 0 [25].

Other aspects can limit the model, such as positive, semi-continuous, and free variables where positive does not allow the value to be lower than 0. Semi-continuous is close to a binary value but can be 0 or a positive value within a range. Lastly free variable can take any value, positive or negative. There is an implication with using binary variables: the running time increases depending on how many, and an output called marginal value cannot be used.

2.5 District heating system 2019

Most of Gothenburg's district heat generation originates from industrial waste heat from two oil refineries, Preem and St1, and Renova, which incinerates waste. There are also connections to other municipalities such as Mölndal, Kungälv, and Ale, which is an import and export for the Gothenburg district heating system. Göteborg Energi owns several other heat production units that meet the rest of the heat demand. Gothenburg's district heating system divides its heat generation plants into different city areas to always cover the demand at various locations. Table 2.1 presents all heat generational units that Göteborg Energi operates with the unit's technical properties, maximum load, minimum load, efficiency, fuel, and start cost, where the values have been taken from [26], [27] and [28].

Unit name	Max load heat/el [MW][27]	Min load heat [MW]	Efficiency/ COP [27]	Fuel[27]	Start cost [€/ MW_{heat}]
Sor HOB2	30	0	0.92	Natural gas	30
Sor HOB4	40	0	0.92	Natural gas	30
HP1	30	0	3.6	Electricity	5
HP2	30	0	3.6	Electricity	5
HP3	50	0	3.15	Electricity	5
HP4	50	0	3.15	Electricity	5
Rya CHP GT1	98/87	31	0.49 heat +0.435 el	Natural gas	54
Rya CHP GT2	98/87	31	0.49 heat +0.435 el	Natural gas	54
Rya CHP GT3	98/87	31	0.49 heat +0.435 el	Natural gas	54
Rya HOB8	120	24	0.923	Pellet	40
Ros HOB4	140	0	0.903	Fuel oil (Eo5)	30
Ros HOB5	140	0	0.903	Natural gas	30
Save HOB1	83	0	1.024	Natural gas	30
Save HOB2	80	0	0.899	Fuel oil (Eo1)	30
Save CHP3	107/13	25	1.019 heat +0.124 el	Wood chips	83.3
Ang HOB1	38	0	0.835	Bio oil	30
Ang HOB2	33	0	0.725	Bio oil	30
Ang HOB3	30	0	0.639	Bio oil	30
Ask HOB1	10	0	0.90	Fuel oil (Eo1)	30
Ask HOB2	10	0	0.90	Fuel oil (Eo1)	30

Table 2.1: The heat generation units that Göteborg energi operates with their respective technical properties.

Gothenburg is a large city with many plants, as shown in Table 2.1, and the different

plants and waste heat connections are distributed all over Gothenburg from Angered in the north to Frölunda in the south and Sörred in the western parts. Along with waste heat generation and waste incineration in the eastern and northwestern parts.

In Appendix A.1 Table A.1 the different fuel prices with a combination of intel from the sources [29] and [28]. The waste heat cost in that table is also from a source which is [19].

From the Appendix in Section A.1, the cost for the different fuels is presented for the corresponding fuel shown in Table 2.1. With help from these tables, a method can be created and a system in the simulation tool GAMS.

2.6 District heating system 2030

Göteborg Energi aims that all district heating will originate from recycled or renewable sources by 2025 [30]. Some plants powered by fossil fuels will be retired, and others will be converted to renewable sources. Göteborg Energi has plans to invest and make changes in several more production units by 2030, presented in Table 2.2, which was given by [28], and along with [27]. The plans include several heat-only boilers, one additional bio-CHP, and one additional heat pump.

Unit name	Max load heat/el [MW][27]	Min load heat [MW]	Efficiency/ COP [27]	Fuel[27]	Start cost [€/ MW_{heat}]
Sor HOB2	30	0	0.92	**Bio gas**	30
Sor HOB4	40	0	0.92	**Bio gas**	30
Sor HOB	40	0	0.95	Pellet	40
HP6	50	0	3.4	Electricity	5
Rya CHP GT1	98/87	32	0.49 heat +0.435 el	**Bio gas**	54
Rya CHP GT2	98/87	32	0.49 heat +0.435 el	**Bio gas**	54
Rya CHP GT3	98/87	32	0.49 heat +0.435 el	**Bio gas**	54
Rya Bio-CHP	110/30	40	0.864 heat +0.236 el	Wood chips	71.4
Ask HOB1	10	0	0.90	**Bio oil**	30
Ask HOB2	10	0	0.90	**Bio oil**	30
Riskulla HOB	40	0	0.95	Pellet	40
Save HOB4	80	0	0.95	Pellet	40
Ang HOB	30	0	0.95	Pellet	40

Table 2.2: Additional units and changes to existing units planned to operate in 2030. Bold text marks changes made regarding new fuel and units, While new units are named in bold text.

In Table 2.2, all units that have a change from 2019 are presented where Sörred HOB2 (Sor_{HOB2}) and Sörred HOB4 (Sor_{HOB4}) have changed from natural gas to biogas. Then a new plant at the district Sörred in the northwestern parts called Sörred HOB (Sor_{HOB}). At the Rya district, a new heat pump is installed,

which will use low-temperature waste heat from Northvolt along with another CHP ($Rya_{Bio-CHP}$) and the units at the old CHP ($Rya_{CHP,GT1}$, $Rya_{CHP,GT2}$ and $Rya_{CHP,GT3}$) has changed fuel from natural gas to biogas. In the more southern parts of Gothenburg, the plant Askim HOB1 (Ask_{HOB1}) and Askim HOB2 (Ask_{HOB2}) have changed from fuel oil to bio-oil and then also a unit called Riskulla (Ris_{HOB}). The Riskulla plant is in Mölndal but is owned by Göteborg Energi, an additional pipe is under construction between Mölndal and Frölunda. Riskulla will mainly supply Gothenburg with heat but will also supply Mölndal. The plant will have a max capacity of 50 MW, but the pipe has a max capacity of 40 MW. Mölndal Energi will use the rest of the generated heat from Riskulla. Then there are two other installments in the eastern and northern parts, which are Sävenäs HOB4 ($Save_{HOB4}$) and Angered HOB (Ang_{HOB}).

3
Methods

The district heating system is based on supply being more or equal to the demand. The demand is based on a temperature difference between supply and return that the users require. This temperature and mass flow dependency is assumed to only consist of energy transfer from one point to the next, as explained in the introduction. This is done because the temperature and mass flow coefficients make the modeling complex in GAMS. Also, the scope of the study is not a deep dive into the function of the district heating system, but the cost-efficiency of an accumulator tank where energy flows is sufficient [19].

As explained in the section above, energy transfer will be the main driving force to overcome difficulties in managing temperature and mass flow. Again, Gothenburg will be divided into nodes not to make the model too complex or too simple with no nodes. If no nodes were implemented, a big part of the scope would vanish, which is the ability to establish bottlenecks. While not making it too complicated narrow down the number of nodes to a reasonable number which in this study will be six, which was given by Göteborg Energi and, more specifically, [28]. The reason was the similarity to the district division in the program Göteborg Energi uses, which uses the same sectioning. The nodes will have different transmission capacities from each other. There are also other problematic attributes of the district heating system. The water in the pipes does not have instant transmission from one node to the other because of the limitation in mass flow and water velocities in the pipes, unlike electricity which travels almost instantly from one point to another. This transfer must then have a time delay which also will be included.

There are not only generation plants that produce heat energy but also waste heat. The waste heat is generated throughout Gothenburg from Preem, St1, and Renova. Renova is a CHP but cannot be regulated as other units in the system because of waste limitations and will be seen as a waste heat option with low costs. Waste heat is a large contributor to the total production of heat. There are also connections to outer districts such as Mölndal, Ale, and Kungälv, which have a heat exchange with Gothenburg. All these plants, waste heat, and import/export are then allocated to the correct nodes. The nodes are presented in Figure 3.1, and the sectioning of units, waste heat, and import/export are shown further down. The pipe between Frölunda and Mölndal is under construction because of the new Riskulla plant that is located in Mölndal but will be operated by Göteborg Energi. The Riskulla plant will have a maximum capacity of 50 MW, but the pipe will have a maximum capacity of 40 MW. Because of this, the import pipe is not included in the *2019* case but in the

2030 cases.

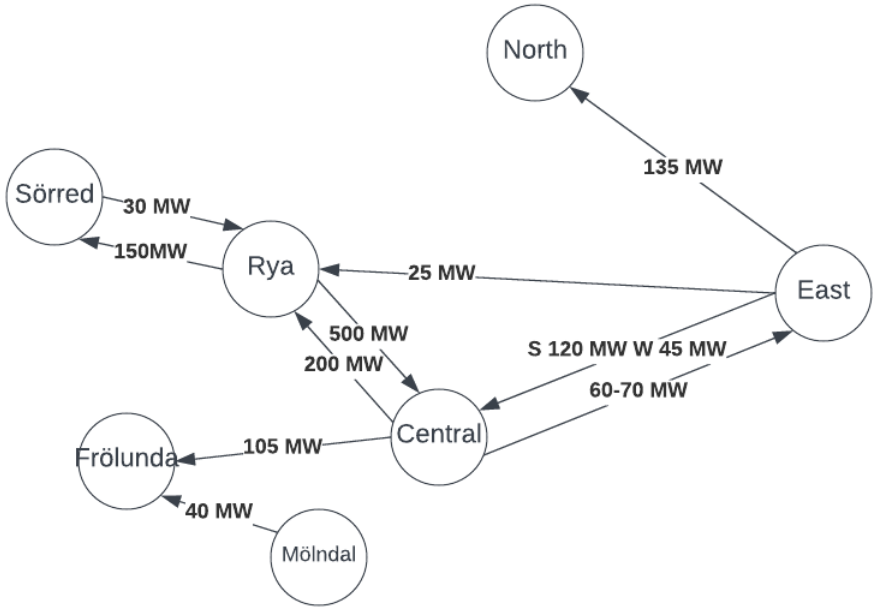


Figure 3.1: Import and export between the nodes in 2030 with additional pipe to Mölndal that is not included as a node. All plants, waste heat, and import/export with other municipalities are allocated to the node they are located in.

Three different cases will be conducted in this study, *2019*, *2030*, and *2030* new investment. The *2019* case includes all the current heat generation units and the Rya accumulator tank. The *2030* case includes all current heat generation units except the pensioned plants and includes planned new heat generation units with the possibility to invest in new accumulator tanks. The *2030* new investment case will exclude the planned heat generational units and will have the possibility to invest in both new heat generational units and accumulator tanks.

3.1 Model structure

Creating a model with the frame in 3.1 Sets, Parameters, and Variables is a vital start to create constraints and objective functions described in Section 2.4. The sets created are to create a time frame and add the units and their properties into the model along with the nodes, pipes, and their properties and the demand. The parameters are the input values for the model, such as unit costs, efficiencies, and other limitations for pipes and units. The variables created will be used to analyze the results later and are the generation of units and some generation costs. All these will be found in Table 3.1, 3.2, and 3.3 below, along with the Objective function in equation 3.1, which is to minimize the cost of generation.

3.1.1 Sets

Table 3.1 represents all the current case sets and what is needed for the model. t is the total time in which the model is run. This also is divided into two subsets called t_{winter} and t_{summer}, the corresponding time steps for summertime and wintertime necessary for certain constraints in the model. These constraints will appear further down in the method. *Pipes* and *Plantprop* describe the properties that limit the pipes and the plants concerning maximum load, minimum load, costs, and more.

Sets	Description	Unit
t	The time described by T=1,...,8760	h
t_{winter}	The time described by T=1,...,2881, 6553,...,8760	h
t_{summer}	The time described by T=2882,...,6552	h
u	Production units	-
node	Gothenburg spited in six areas	-
Demand	Demand divided into all nodes	MWh/h
Pipes	Pipe properties	-
Plant prop	Plant properties	-

Table 3.1: Current case sets for the GAMS model.

3.1.2 Parameters

The parameters in Table 3.2 are input values that are a form of limitation. Some input values are $\forall t$ which is Q_{demand} or $Q_{Wasteheat}$. Q_{demand} is dependent on outdoor temperatures, the demands curves are presented in Appendix A.2, Total demand in Figure A.1 and net demand (Q_{demand}-$Q_{Wasteheat}$) in Figure A.2. $Q_{wasteheat}$ includes the waste heat from plants like Preem, Chalmers, St1, waste incineration from Renova, and Import or export from/to other municipalities and is shown in Appendix A.3. The parameter $Spotprice_{(t)}$ for both 2019 and 2030 is shown in the Appendix A.4. These limitations for the sets are to create a model that generates similar results as in a reality where these input values are taken from an internal software called DLS in Göteborg Energi or [31]. Some of the parameters are taken elsewhere, and these are *Anglim* and *Roslim*, which [32] and [33] provided the input data regarding the environmental limitations.

3.1.3 Variables

The variables in this model are presented in Table 3.3, which are values that get simulated values in the model, such as how the plants will generate and how the accumulator tank charge and discharges and the binary plants on/off and running at a certain time t. These are the values that the result later will be based upon.

3.1.4 Objective Function

The objective function is the main equation for the model, where in this case, it is made to minimize the annual costs. In equation 3.1, the objective function is

Parameters	Description	Unit
$Q_{demand(node,t)}$	Heat demand for each node ∀ t	MWh/h
$Q_{Wasteheat(node,t)}$	Waste heat ∀ t	MWh/h
$Spotprice_{(t)}$	Price of electricity in SE3 ∀ t	€/MWh
$T_{sewage(t)}$	Temperature of sewage water ∀ t	$°C$
$P_{capacity(pipe)}$	Max pipe capacity	MW
$\eta_{(pipe)}$	Pipe efficiency	-
$acc\ maxcharge$	Limits charging of accumulator tank to 130 MW	MW
$acc\ maxdischarge$	Limits discharging of accumulator tank to 130 MW	MW
$acc\ maxlevel$	Limits storage level of accumulator tank to 1000 MWh	MWh
$\eta_{acc,sto}$	Losses in accumulator tank	-
$Anglim$	Limits operational hours to 1500	h
$Roslim$	Limits operational hours to 1500	h
$Maxload_{(u)}$	Max load for each production unit	MW
$Minload_{(u)}$	Min load (only for CHP production units)	MW
$Cost_{partload(u)}$	Cost of running HOB and HP on part load	€/MW
$\eta_{(u)}$	Efficiency ∀ u	-
$OM_{(u)}$	Operational and maintenance cost ∀ u	€/MWh
$\alpha_{(u)}$	The heat to electricity ratio	-
$Cost_{start(u)}$	The cost of starting up a plant that is not running	€/MWh

Table 3.2: Current case parameters for the GAMS model.

presented where $Q_{(node,u,t)}$ is the production from every heat production unit in every node for every timestep. The $Fuel_{(u)}$ is the representative fuel cost for every production unit that is connected to the correct generation plant, so (u) is matched for $Fuel_{(u)}$ and $Q_{(node,u,t)}$ to get the cost of generation. $\eta_{(u)}$ is the representative efficiencies for the different units, which then for every (u) is allocated to the correct plant for both $Fuel_{(u)}$ and $Q_{(node,u,t)}$. This is to get the running cost of the plant. The next part of equation 3.1 is the maintenance cost which is calculated the same way as the prior part of 3.1 where (u) matches for every plant for $Q_{(node,u,t)}$ and $OM_{(u)}-Q_{(node,u,t)}$. The next part of the objective function is if the unit also generates electricity which means it is a combined heat and power plant. Where the $\alpha_{(u)}$ is the alpha value which is the amount of generated electricity per amount of generated

Variables	Description	Unit
$Q_{(u,t)}$	Heat production for each node ∀ t	MWh/h
$On_{(u,t)}$	Switch on production unit before production	Binary
$Spin_{(u,t)}$	0 if plant not running, 1 of the plant is producing heat	Binary
$Startcost_{(u,t)}$	Cost of turning on a production unit	€/MW
$Partloadcost_{(u,t)}$	Cost of running a unit on part load	€/MW
$Q_{(pipe,t)}$	Export/Import between nodes ∀ t	MWh/h
$Q_{acc,level(t)}$	Storage level of accumulator tank ∀ t	MWh
$Q_{acc,cha(t)}$	Charging accumulator tank ∀ t	MWh/h
$Q_{acc,dis(t)}$	Discharging accumulator tank ∀ t	MWh/h

Table 3.3: Current case variables for the GAMS model.

heat. This α-value is then multiplied with the $Spotprice_{(t)}$, which is the electricity price at time t. At the end of the objective function, it is also an addition of $Startcost_{(u,t)}$ and $Partloadcost_{(u,t)}$, which represents the cost of starting the power plant unit and part load cost is used in the non-binary cases. Still, these two variables are calculated in equations 3.13 and in 3.14. The annuity factor (r) is based on an assumption which is 5 % that is used in Chalmers's research based on a social cost perspective.

$$\begin{aligned}\text{Min cost} \geq (\sum_{node=1}^{6}(\sum_{u=unit1}^{U}(\sum_{t=1}^{T}(Q_{(node,u,t)}+Q_{new(node,u,t)})*(Fuel_{(u)}/\eta_{(u)}\\ +Q_{(node,u,t)}*OM_{(u)}-\alpha_{(u)}*Spotprice(t)+Startcost_{(u,t)}+Partloadcost_{(u,t)})\\ +(Q_{inv,acc(node)}*Inv_{(acc)}+Q_{inv(node,u)}*Inv_{(u)})*r)))\end{aligned} \tag{3.1}$$

In equation 3.1 is the objective function presented where the investment opportunities for the current case are 0, so Q_{inv} variables are not used in the current case along with the Q_{new} variable. Equation 3.1 is for the model to sum up all costs of the model and minimize it to the most profitable solution.

3.1.5 Constraints

This section is about the constraints on the model to create a more realistic system. Some constraints are from conversations with Göteborg Energi [19] and [28] and some technical limitations to mirror the existing district heating system.

3.1.6 Import/export

The nodes are connected with import and export pipes according to Figure 3.1, and max capacity and direction are presented in Table 3.4. The capacity of the pipe is dependent on the mass flow and temperature of the water. Including temperature and mass flow would make the model too complicated. Hence, the capacity constraint is a simplification that still mirrors reality and makes it possible to investigate bottlenecks in the district heating system. The simplification was made by consulting [28]. These import/export pipes will not be looked at, and thereby, any expansion or decrease of the pipes is not in this study.

The first equation presented in the list below is equation 3.2, referred to as a constraint that does not allow the transfer capacity from one node to another to be higher than its capacity at any given timestep. The list of which pipes and what the max capacity of these pipes are can be found above in Figure 3.4. The second equation for the pipes equation 3.3 is a reference to pipe loss where $\eta_{(pipe)}$ is the efficiency in percentage. At one timestep later, the energy transferred is lower than at the start because of the distance between nodes.

$$Q_{(pipe,node,t)} \leq P_{capacity(pipe)} \tag{3.2}$$

$$Q_{(pipe,node,t)} \geq \eta_{(pipe)} * Q_{(pipe,node,(t+1))} \tag{3.3}$$

Pipe	Capacity
Pipe 1→ 2	30 MW
Pipe 2→ 1	150 MW
Pipe 2→ 4	500 MW
Pipe 4→ 2	200 MW
Pipe 4→ 3	105 MW
Pipe 4→ 5	70 MW
Pipe 5→ 4	120 MW Summer
Pipe 5→ 4	45 MW Winter
Pipe 5→ 2	25 MW
Pipe 5→ 6	135 MW

Table 3.4: Max capacity for export pipes between nodes. The capacity is the same throughout the year except for the pipe from East to Central, which differs between summer and winter.

3.1.7 Rya Accumulator Tank

The equations below from 3.4 to 3.7 is for the accumulator tank in the Rya district. Where the first equation is the state of charge equation where the discharge $Q_{acc,dis(t)}$ and charge $Q_{acc,cha(t)}$ for the current time step t will affect the next time step state of charge. In 3.4, there is also an efficiency called η_{hx} because of the heat exchanger between the district heating water and the accumulator tank water. The other efficiency $\eta_{acc,sto}$ is because of the heat exchange between the accumulator tank and outdoor air while it is in storage. The following equations are limitations for the accumulator tank in regards to discharge equation 3.6 and charge equation 3.7 rate and the storage level limit, which is equation 3.5. $acc\ maxcharge$, which is in 3.6 and 3.7, was given by [19] and is a known discharge and charge capacity for the accumulator tank.

$$Q_{acc,level(t+1)} = Q_{acc,cha(t)} * \eta_{hx} - Q_{acc,dis(t)} + Q_{acc,level(t)} * \eta_{acc,sto} \tag{3.4}$$

$$Q_{acc,level} \leq acc\ maxlevel(1000MWh) \tag{3.5}$$

$$Q_{acc,dis} \leq acc\ maxcharge(130MW) \tag{3.6}$$

$$Q_{acc,cha} \leq acc\ maxcharge(130MW) \tag{3.7}$$

3.1.8 Energy balances

The energy balance is done based on six nodes, all representative of the regions in Gothenburg where node 1 is "Sörred", node 2 is "Rya", node 3 is "Frölunda", node 4 is central, node 5 is East, and lastly node 6 is north. Table 3.9 then shows which plant and unit generates from which node.

The equation 3.8 is the energy balance for every node in the study. Where all plants and waste heat are included and combined with the import/export between nodes. For energy balances, there is $Q_{demand(t)}$, which is the demand profile for every node and every t. The other is once again $Q_{(u,t)}$, which is the generation from the

production units divided into the correct node, then summarized over the number of units. Then it's $Q_{(pipe(import),t)}$, which is the import from and to the specific node for every t. $Q_{(pipe(export),(t+1))}$ has a time delay of one hour at the arrival to another node, so the export from a node occurs the same hour, and the import to a node occurs the hour after. This was done with inspiration from [15], which also made the same assumption. There are also other variables included that are isolated to separate nodes. These are $Q_{ack,dis(t)}$ and $Q_{ack,cha(t)}$, which is represented by the accumulator tanks discharge and charge at a certain time t. There is also an efficiency coupled with the tank discharging since the heat exchanger between district heating water and tank water is not 100% effective and is called η_{hx}. For a deeper understanding of the equations of every node, it is presented in Appendix A.5.

$$Q_{demand(t)} \leq Q_{(pipe(import),t)} - Q_{(pipe(export)(t+1))} + Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} + \sum_{u=1}^{U} Q_{(u,t)} \tag{3.8}$$

When these equations are placed for each node, it generates storage within the system because there is space in the transmission pipes, which can be sent forward and backward between nodes, which then is taken care of by a large energy balance for the whole of Gothenburg at every hour. This is done in equation 3.9. This creates total equality for heat generated and consumed so that the total demand for every t limits the whole of Gothenburg.

$$\sum_{node=1}^{Node} Q_{demand(node,t)} \leq Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} + \sum_{u=1}^{U} \sum_{node=1}^{Node} Q_{(u,node,t)} \tag{3.9}$$

3.1.9 Binary conditions

The spin variable ($Spin_{(u,t)}$), which is in equation 3.10, is a variable that confirms if a plant is spinning and therefore is running at the moment or if the plant is not running and it is off. The On variable ($On_{(u,t)}$), which is in equation 3.11, on the other hand, is an on/off switch that happens the timestep before the $Spin_{(u,t)}$ which say which hour the plant is turned on. Then it takes a set number of time to get the plant running where $Spin_{(u,t)} = 1$ and then the $On_{(u,t)}$ turns to 0 until the next startup. Which is the conclusion of the equations 3.10 to 3.12. So $On_{(u,t)}$ and $Spin_{(u,t)}$ is working together. This variable must be binary for individual units to accomplish a correct $Spin_{(u,t)}$. In the current case, the CHP units with high starting costs, long startup times, and more restrictive minimum loads are binary. The solid fuel units are also binary in the 2019 case but not in 2030 because of model running times. The selection of solid fuels is also based on the long start times. This applies to RYA CHP all units, Sävenäs CHP, which is the third unit of the plant in Sävenäs, and also Rya HOB8. The rest are calculated through the same equations but without binary variables. This is because of much lower minimum load demands and lower startup times. To cope with the fact that without binary condition, the Spin variable can be any number between 0 and 1, a cost of the part load is set, dependent on the

power generated less than rated power. This creates a tendency to generate at-rated power for the non-binary units and is not used for binary units. Equation 3.13 is the cost of starting a plant ($Cost_{start(u)}$) at the point where it turned on ($On_{(u,t)}$) and is used both in the binary units and non-binary units. The equation 3.14 is only used for the plants with non-binary variables and is a way to avoid low generation where $Cost_{partload(u)}$ is the individual part load cost for every unit multiplied by how close to the rated power it is. The closer it is to the maximum load, the lower the cost. This will only give small costs at certain times and non at other times because the $Spin_{(u,t)}$ is a continuous variable but will put the non-binary units in the right direction. Equation 3.15 and 3.16 are values that set the minimum and maximum load of a unit. Where $Maxload_{(u)}$ and $Minload_{(u)}$ are the max capacity and min capacity of a plant (u). This method is taken from another study [34] that sets the conditions for a generating unit with restrictive minimum loads and longer starting times.

$$Spin_{(u,(t+Starttime_{(u)}))} \leq Spin_{(u,t)} + On_{(u,t)} \tag{3.10}$$

$$Spin_{(u,(t+Starttime_{(u)}))} \geq On_{(u,t)} \tag{3.11}$$

$$Spin_{(u,t)} + On_{(u,t)} \leq 1 \tag{3.12}$$

$$Startcost_{(u)} = On_{(u,t)} * Cost_{start(u)} \tag{3.13}$$

$$Partloadcost_{(u)} \geq Cost_{partload(u)} * (Spin_{(u,t)} * Maxload_{(u)} - Q_{(u,t)}) \tag{3.14}$$

$$Q_{(u,t)} \leq Spin_{(u,t)} * Maxload_{(u)} \tag{3.15}$$

$$Q_{(u,t)} \geq Spin_{(u,t)} * Minload_{(u)} \tag{3.16}$$

Startup time is a parameter that, in this study, varies and is presented in Table 3.5. These startup times have been discussed with [28]. This variation means that $On_{(u,t)}$ occurs a set hour before $Spin_{(u,t)}$ starts to cope with the downtime of larger units in the system.

Unit	**Start time [h]**
Rya CHP GT1	6
Rya CHP GT2	6
Rya CHP GT3	6
Save CHP3	10
Rya HOB8	2

Table 3.5: The start time in hours for the plants for the binary units in the current case.

These startup times are included in the equations by changing the time frame of 3.10 to increasing it one step at a time away from the original time 0. Where the allocated startup time for the generation unit is the last equation of 3.17 to 3.19 used.

$$Spin_{(u,(t+2))} \leq Spin_{(u,t)} + On_{(u,t)} \tag{3.17}$$
$$Spin_{(u,(t+3))} \leq Spin_{(u,t)} + On_{(u,t)} \tag{3.18}$$
$$\vdots$$
$$Spin_{(u,(t+10))} \leq Spin_{(u,t)} + On_{(u,t)} \tag{3.19}$$

This will then affect how long $On_{(u,t)}$ needs to fulfill the condition > 0 before the unit starts spinning and $Spin_{(u,t)}$ becomes greater than 0. To establish how long $On_{(u,t)}$ is active is done by an input called $Starttime_{(u)}$ which differs depending on the plant and is shown in equation 3.10. Where the appointed start time is put in $Starttime_{(u)}$ for the units concerned. Then equations 3.17 to 3.19 are applied and will only affect binary units.

3.1.10 Plant constraints

The constraints presented below are limitations for the plants that do not depend on capacity or efficiencies. In Appendix A.6, the equations for the restriction regarding heat generation are shown for Rosenlund, Angered, and Sävenäs. Rosenlund heat generation units have *Roslim* as the maximum allowed time to run at max load. This value is because of environmental agreements with Gothenburg City, of the largest allowed emittance. This constraint about full load hours also applies to the Angered heat generation units since they also have a roof of how much heat they can produce during a year. Sävenäs has no environmental limitation but a restriction because a change of sand in the combustion chamber is necessary once a year. This period is presented in t_{save} and is a subset of t but is only used in this equation. During this time, the generation in Sävenäs HP3 is 0 and is calculated by setting the $Spin_{(u,t)}$ for Sävenäs HP3 to zero. Another assumption regarding Sävenäs HOB1 and CHP is that the flue gas condensation is included in the total capacity for the unit.

Next up in limitations is the Rya district or node 2, where feed water is limited. This limitation makes the accumulator tank unusable if all the plants in node 2 are running at rated power simultaneously because it has no water that can be heat exchanged with the accumulator tank. A more detailed equation and presentation of this limitation is found in Appendix A.7.

The heat pump's heat production is dependent on the sewage temperature. Suppose the sewage temperature is under 8 °C. In that case, the efficiency is decreased by η_{T1} if the sewage temperature goes below 7 °C, the efficiency η_{T2} is used, and lastly, if the temperature goes below 6 °C η_{T3} is used. Which is shown in Table 3.6. If the sewage temperatures are too high, the heat pumps cannot operate. One efficiency is also called η_{T0}, which applies when the temperature is higher than 15 °C. The temperature curve of sewage water is presented in Appendix A.8, Figure A.13.

Efficiency	Value	Temperature condition $°C$
η_{T0}	0	≥ 15
η_{T1}	0,85	≤ 8
η_{T2}	0,75	≤ 7
η_{T3}	0,65	≤ 6

Table 3.6: Decreased max load for heat pumps depending on sewage temperatures.

The efficiencies η_{T0} to η_{T3} are presented in Table 3.6. The values are assumed and discussed with [19] and [28] for realistic values.

One plant is added that does not exist in the system is called the Fine plant in this study, which is exceedingly more expensive than other plants. This is not to get any errors for insufficient energy production at any given hour. This will be placed in every node and be called $Fineplant_1$, $Fineplant_2$,...,$Fineplant_6$. This is one of many ways to prove bottlenecks. These plants have maintenance and running costs that are much larger than the remaining plants. The Fine-plant has the same function as any other non-binary unit, and the costs are presented in Appendix A.9.

3.1.11 Losses in the system

Losses are included in the model to create a more real-life system. These losses for the pipes in the system ($Q_{(pipe,node,t)}$) are assumed to be a few percent but depend on the real-life distance from one node to the other. For example, does Sörred to Rya have a smaller loss than Rya to Eastern. These percentages are presented in Table 3.7 below.

Pipe	Efficiency
Pipe 1→ 2	98%
Pipe 2→ 1	98%
Pipe 2→ 4	97%
Pipe 4→ 2	97%
Pipe 4→ 3	97%
Pipe 4→ 5	95%
Pipe 5→ 4	95%
Pipe 5→ 4	95%
Pipe 5→ 2	94%
Pipe 5→ 6	96%

Table 3.7: Efficiency of the pipes when export and import are made based on assumptions.

Other losses in the system are from and to the accumulator tank and losses in the accumulator tank. The discharge and charge losses are because of a heat exchanger between the accumulator tank and the district heating system that, according to Göteborg Energi, is about 5 °C for a whole cycle which in this study have been represented as an efficiency. The second efficiency for the accumulator tank is due

to the non-adiabatic conditions that occur when hot water is stored in a "thermos". The temperature of the water will decrease slightly every hour because a hot media will transfer its heat to a colder one no matter how good the isolation is. The value of the accumulator tank efficiency is then per hour. These values are presented in Table 3.8.

Description	Value
Cha/Dis Efficiency	99,5%
Accumulator tank efficiency/h	99,96%

Table 3.8: The efficiency of the accumulator tank both in regards to storage and charge/discharge.

3.2 2019

The 2019 case is what the model structure is built upon, where all model structures are in place, and no additions nor subtractions of Sets, Parameters, Variables, units, or constraints are made. The present case is on the 2023 generation units in the Gothenburg district heating system with electricity price data from 2019 because of significant fluctuations in the energy market in recent years. These fluctuations are because of a pandemic with lower energy demand and Russias invasion of Ukraine which increased all energy prices. Both are temporary happenings that will not last. This affects the electricity price in 2019 and the demand profile to match peaks depending on the weather. The input data files regarding waste heat and import/export from and to other communes such as Mölndal, Ale, and Kungälv are also based on 2019 for the same reason. Table 3.9 presents which nodes (shown in Figure 3.1) each plant and waste are allocated to. As well as the node number and the share of total heat demand for each node demand.

Nodes	Sörred	Rya	Frölunda	Central	East	North
Node number	1	2	3	4	5	6
Share of demand [%] [28]	3.5	17.1	11.4	34.2	19.5	14.3
Production plants	Sor HOB	Rya HP Rya HOB Rya CHP TTES	Ask HOB	Ros HOB	Save HOB Save CHP	Ang HOB
Waste heat	Preem	Preem St1		Chalmers Mölndal	Renova	Kungälv Ale

Table 3.9: Nodes and plants in operation in 2023, which node they are allocated to, and the share of total heat demand each node demands.

3.3 2030

It has been assumed that in the *2030* model, the system operates with the same amount of nodes and waste heat delivered. The differences are the operating plants

where Rosenlund ($RosHOB4$ $RosHOB5$) will be pensioned, and others will be constructed in different nodes. The changes made are presented previously in Table 2.2. The second one is the electricity price based on 2019 but modeled to 2030 conditions. This is to match the peaks that the weather creates, which corresponds to the demand and input data profiles. The electricity price projection for 2030 from study [35]. The study aims to investigate the time-resolved cost of electrolytic hydrogen in a future climate-neutral electricity system with high shares of variable renewable electricity generation in which hydrogen is used in the industry and transport sectors and for time-shifting electricity generation. Prices above 500 €/MWh were reduced to 500 €/MWh to avoid investments based on unlikely predictions.

The accumulator tank at Rya will be a part of the system, and the model will have the opportunity to invest in more tank storage. This is shown in Table 3.10 and the following equations between 3.20 to 3.23. In Table 3.10, the new parameters and variables are introduced into the model, where Inv_{cost} and r correspond to the investment of the tanks and the profitability in the long run. The values of the parameters have been researched, and the C_{rate} for the new accumulator investments is the same as the current accumulator tank. The Inv_{cost} is an approximation of two sources, [19] and [36], for a reasonable 2030 value. The annuity factor (r) is based on a collective annuity factor used in Chalmers's research of 5 %, which is from a social cost perspective.

Parameters	**Description**	**Unit**	**Value**
C_{rate}	charged or discharged relative to storage capacity	MW	0.13
Inv_{cost}	Investment cost for acc-tank	€/MWh	8000
r	The annuity factor for investments	-	0.05
Variables	**Description**	**Unit**	
$Q_{inv,acc(node)}$	New storage investment between 100 and 2000 ∀ nodes	MWh	
$Q_{newacc,level(node,t)}$	Storage level of new invested acc-tank	MWh ∀ nodes and t	
$Q_{newacc,cha(node,t)}$	Charging of new invested accumulator tank ∀ nodes and t	MWh/h	
$Q_{newacc,dis(node,t)}$	Discharging of new invested acc-tank ∀ nodes and t	MWh/h	

Table 3.10: Model sets, parameters, and variables added for investment model with the values of the parameters.

3.3.1 New Equations 2030

The added equations needed for the *2030* model will be presented in this section. Equation 3.20 to 3.23 relates to new accumulator tank investments. Where equation 3.20 is the state of charge equation that lets the tank discharge and charge from the previous level to the current, which is. As explained in earlier accumulator tank equations in the current case Section 3.1.7, there are again efficiencies for the withdrawal of heat and a loss dependent on the storage time. Which are represented in η_{acceff} and $\eta_{newacc,sto}$. The equation 3.20 is also specified for each node so that the investment affects not only the total balance but also the regions, which is also a

way to see bottlenecks.

The other three equations are limitations for the tank concerning level discharge and charge capacity. Equation 3.21 is the level limitation, and equations 3.22 and 3.23 is the limitation in charge and discharge capacity based on a constant C-rate that is dependent on the size of the storage tank.

$$Q_{newacc,level,(node,(t+1))} = Q_{cha,(node,t)} * \eta_{acceff} - Q_{dis(node,t)} + Q_{newacc,level(t)} * \eta_{newacc,sto} \tag{3.20}$$

$$100MWh \leq Q_{newacc,level} \leq 2000MWh \tag{3.21}$$

$$Q_{dis(node,t)} \leq C_{rate} * Q_{newacc,level(node,t)} \tag{3.22}$$

$$Q_{cha(node,t)} \leq C_{rate} * Q_{newacc,level(node,t)} \tag{3.23}$$

The energy balance is also changed with added variables. These added variables are $Q_{newacc,cha(t)}$ and $Q_{newacc,dis(t)}$ and as explained in Section 3.1.8, the discharge rate gets affected by an efficiency since the heat exchanger between systems is not perfect. The whole energy balance for every node can be seen in Appendix A.10, where the possibility of accumulator tank investments is added to equation 3.8 for every node.

As explained in Section 3.1.8, a total energy balance is made to stop the system from storing heat within the system. The energy balance for every node at every t is $\geq$ than the demand, but also for the whole city. This one has the addition of $Q_{newacc,cha(t)}$ and $Q_{newacc,dis(t)}$ to take into account the new accumulator tanks invested in at each node.

In the 2030 case, one more heat pump is installed, which is called HP6, and this heat pump will get wastewater from a new industry called Northvolt which will have a constant temperature all year [19] and [28]. HP6 will not be included in the heat pump restrictions explained in Section 3.1.10. HP6 will be optimized to the given temperature and independent of the sewage temperature.

In the current case, a water limitation at the district Rya is created to increase the realism of the system, which is explained in Section 3.1.10, but in the *2030* case, this is assumed to have been handled, and the amount of water is no longer a restriction for district Rya (Node 2). Another thing not included in the *2030* model is the $Fineplant_{1-6}$ because there is no longer a shortage of thermal energy in the system. If there is a shortage somewhere, it can be solved by the accumulator tank investment opportunity.

3.4 2030 new investment

The future system in Gothenburg is not definite, and plans can change. Therefore this study will also focus on the opportunity to invest in new-generation plants and

not only accumulator tanks. The generation plant options that will be introduced are HP, HOB, and CHP. Which then will be additions to the current sets of heat pumps and plants.

In Table 3.11, the addition of sets, parameters, and variables is shown where the only addition is the investment opportunity for generation units.

Sets	**Description**	**Unit**
(u)	Is the same as last unit set but with addition with before mentioned units	-
Parameters	**Description**	**Unit**
$Inv_{(u)}$	The investment cost for the different generation units	$M€/MW_{heat}$
$OM_{(u)}$	The variable cost of operation	$€/MWh$
$Starttime$	The time between $On_{(u,t)}$ and $Spin_{(u,t)}$	h
$\eta_{(u)}$	The efficiency of the unit	-
$Fuel_{(u)}$	The fuel cost of the different units	$€/MWh_{fuel}$
$Cost_{start(u)}$	The cost of starting the unit	$€/MW_{rated}$
$\alpha_{(u)}$	The alpha value for the CHP unit	-
Variables	**Description**	**Unit**
$Qinv_{(node,u)}$	The newly invested generation capacity for every unit and $\forall$ nodes	MW_{heat}
$Q_{new(node,u,t)}$	The newly invested actual generation for every unit and node	MWh/h_{heat}

Table 3.11: Model sets, parameters, and variables added for investment model with the possibility for generation units.

The values of the parameters presented in Table 3.11 are shown in Table 3.12 where there are primarily similar values to the current units but with some exceptions such as $\eta_{(u)}$ and the $\alpha_{(u)}$ for the CHP which are mean values from [31] and not given values from Göteborg Energi, [19] and [28], other values are taken from the current units and fuels that already are used in the study. The investment cost which is $Inv_{(u)}$ also from [31].

Parameters	**Value HP**	**Value HOB**	**Value CHP**	**Unit**
$Inv_{(u)}$	0.76	0.42	1.24	$M€/MW_{heat}$
$OM_{(u)}$	0	3.41	1.33	€/MWh
$Starttime_{(u)}$	1	1	1	h
$\eta_{(u)}$	3.5	1.15	1.11	-
$Fuel_{(u)}$	$Spotprice_{(t)}$	30	30	€/MWh
$Cost_{Start(u)}$	5	40	83.3	€/MW
$\alpha_{(u)}$	0	0	0.37	-

Table 3.12: Model sets, parameters, and variables added for investment model with the possibility for generation units.

3.4.1 New equations 2030 new investment

In this part of the study, another set of equations will be added where most of it is additions of earlier equations for the new plants that are added. For example,

the equations 3.10 to 3.16 are applied to these new sets and parameters. The new equation is as follows.

Equation 3.24 limits the generation ($Q_{(node,u,t)}$) from the plants in regards to how much that is invested in ($Qinv_{(node,u)}$). There is also an addition to current equations, including the energy balance for each node and the objective function.

$$Qinv_{(node,u)} \geq Q_{new(node,u,t)} \tag{3.24}$$

This last energy balance has an addition of a variable. This variable is $Q_{new(node,u,t)}$ and is added to every node, which can be seen in Appendix A.11. For the equation 3.8 the variable $Q_{new(node,u,t)}$ is added along with $Q_{newacc,cha(t)}$ and $Q_{newacc,dis(t)}$ which is explained in Section 3.3.1. There is also another perspective regarding the (u) notation for $Q_{new(node,u,t)}$, which is that this is per plant, not unit, as it has been before since a limitation would require binary conditions and this longer simulation times because of 6 or more new binary plants.

The total energy balance for Gothenburg with is shown in equation 3.9 with the addition of $Q_{new(node,u,t)}$ and the previous $Q_{newacc,cha(t)}$ and $Q_{newacc,dis(t)}$ which is the newly invested plants and accumulator tanks in the system is then made. It is also detailed in Appendix A.12.

These two additions create a system that is allowed to invest in options other than accumulator tanks to see if this makes room for more accumulator tanks by increasing flexibility in the system.

3.4.2 Analysis new generation

A comparison between the *2030* case and the *2030* new generation case will be made with the accumulator tank in focus, where the analysis will surround how accumulator tanks are invested and the differences between the two cases.

3.5 Bottlenecks

One of the main ways to analyze the system is through bottlenecks. This analysis will be applied to every case, where some are more obvious than others. In the first case, the first one is when the Fine-plant is operating, described in the bottom section in Section 3.1.10. There is a bottleneck when this unit operates in any node while some other unit is not operating at full capacity.
Another possibility for finding bottlenecks is a deeper analysis of the generation of units and in which order these units are generating. The plant/units have a certain merit order, described in Section 1 and more specifically [13] is the least costly unit run first, until the last one, which covers the demand. A bottleneck is found if this merit order is not in the right order and a more costly unit generates before a cheaper one. This way creates two ways of finding these bottlenecks: looking at

deviations in the full load hours compared to merit order or hour by hour by looking at the merit order and specifically finding these deviations.

Another choice is to look at the transmission pipes between nodes and their usage of these. Where more hours of rated transfer in one pipe creates a bottleneck. There is also another way by analyzing marginal cost differences between nodes that is described in Section 1.3. But this can not be studied because mathematical limitations in the structure of the problem but in a linear problem would be possible.

3.6 Sensitivity Analysis

In the sensitivity analysis, the effects on the system are shown, and the most important aspects are the availability of the units and waste heat and the operation costs for the different plants, according to Göteborg Energi. The availability of units was a challenge in making good cases and was therefore abandoned as a sensitivity analysis case. Then there are other minor aspects, such as demand differences, transmission sizes(pipe size), and other constraints. Some of these will act differently in the different models since there are many changes from 2019 to 2030. So there will be some other waste heat availability problems that occur in 2030 that are not probable in 2019. Such as the availability of waste heat from specific areas, especially Preem, since it has particular focuses for the future. These plans involve that goes towards a carbon-neutral system. Cost of operation is one sensitivity analysis that can be divided into categories. Among these categories are fuel cost, start cost, the efficiency of the plant, and more, where the most relevant is because of recent happenings surrounding Ukraine and the renewable energy source debate. Also, what is mentioned in Section 1 regarding biomass and its future allocations. This creates a more volatile fuel cost for the plants both in regards to the solid, liquid, and gaseous fuels and also in regards to the electricity price. Which then is an essential part of the sensitivity analysis.

3.6.1 Method sensitivity analysis

To create these sensitivity analysis cases, a method was decided where the first stage was increasing the biomass fuel price by 100 % for both cases, and the second one is decreasing the biomass price to half its original cost. This exact method was also done for the electricity price. The third case is to double and increase by 1,5 times the current price of fossil fuels, which will only be relevant for the current case due to the lack of fossil fuels in the future case. The second stage of the sensitivity analysis method is to see how the system reacts to changes in the waste heat supply which will only be applied to the *2030* case because the current case is irrelevant because the waste heat contracts cover this. For 2030 there is a particular uncertainty for Göteborg Energi and the waste heat generated from especially Preem because of changes in the demand for fossil fuels and substitutions. This leads to the sensitivity analysis case surrounding what happens if Preem waste heat is no longer serviced and how that affects the system. All these cases will then be compared to each other to get a broader view of the several aspects of the cases and see what

occurs with the accumulator tank usage and investment of the accumulator tank depending on the base cases. The cases are presented in Table 3.13, and the case differences are based on relevance for the base cases.

2019 (with and without acc)	**2030**	**2030 New gen**
2x bio-price	2x solid bio-price	2x solid bio-price
0.5x bio-price	0.5x solid bio-price	0.5x solid bio-price
2x electricity-price	2x electricity-price	2x electricity-price
0.5x electricity-price	0.5x electricity-price	0.5x electricity-price
2x fossil-price	2x fluid bio-price	-
1.5x fossil-price	0.5 fluid bio-price	-
-	No preem	-

Table 3.13: The cases of the sensitivity analysis made. Solid bio refers to wood chips and pellets, while fluid bio refers to biogas and bio-oil

4
Results and Analysis

In the results, the system's total cost is a key point of every case and the comparison between every simulation. Observations of unit generation and trends will also be used to strengthen why the cost is lower or higher. The sensitivity analysis described in Section 5 is also an important part of the results since fuel prices are a volatile parameter, and those results can also broaden the analysis. More informed conclusions can be if the accumulator is a cost-efficient investment, even if the fuel price increases or decreases.

4.1 2019 case

The annual cost of generation is divided into one with an accumulator tank and one without, where the savings with an accumulator tank is 1.55 M€ per year which is a payback of 9.7 % of the total investment cost per year. The annual generation cost for the case where the accumulator tank is used is 43.3 M€, and without the usage of an accumulator is 44.8 M€.

Figures 4.1 and 4.2 present the total supply curve for the whole year for every unit. Comparing the two Figures 4.1 and 4.2, they look mostly the same. Still, some key difference is that the accumulator tank can save waste heat during the summer and does not need extra heat production, which is not the case when the accumulator tank is not included. This can be seen from approximately hour 3700 to hour 6300. The accumulator tank also reduces the need for peak production. Some clear examples are the highest peak of the year around hour 700 and hours 2900 to 3200, where all the peaks are reduced from.

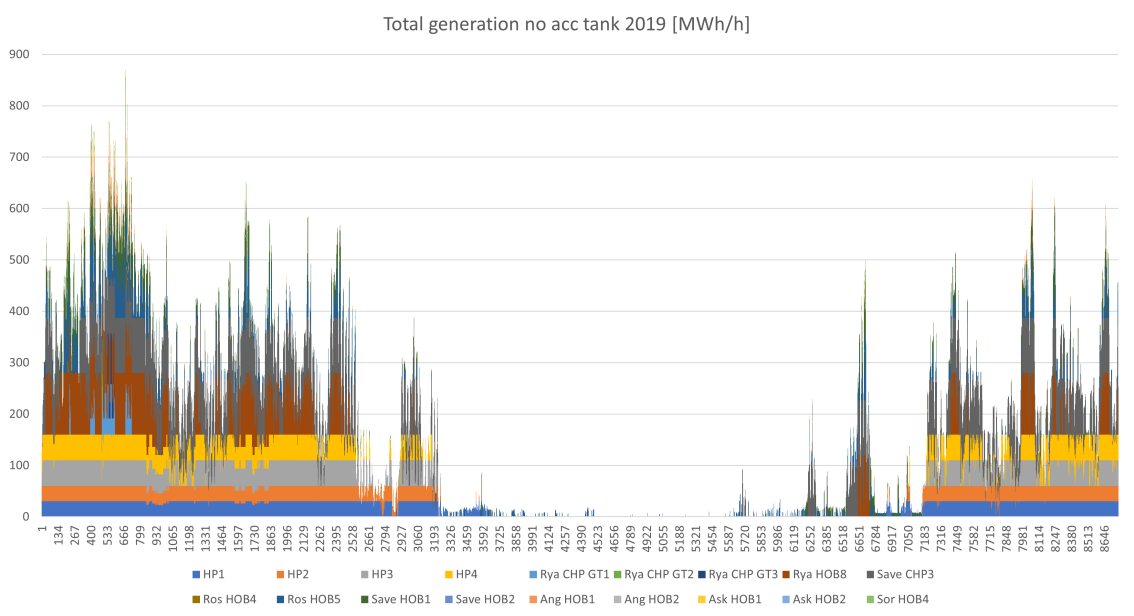


Figure 4.1: Total generation for all production units, excluding Ang HOB3 and Sörred HOB2 that are not used. For *2019* with no accumulator tank.

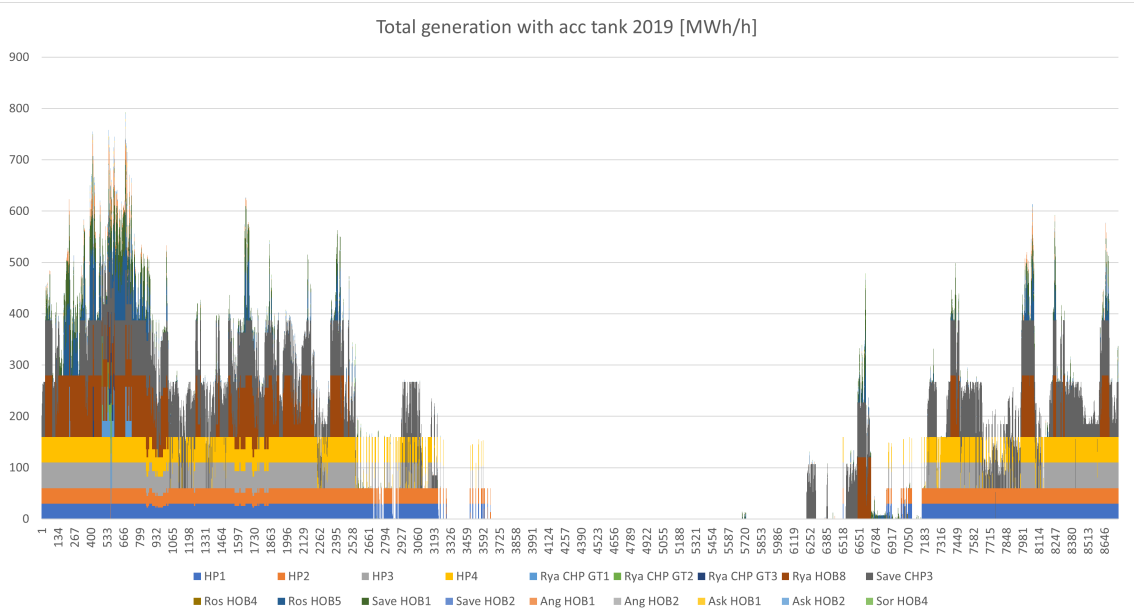


Figure 4.2: Total generation for all production units, excluding Ang HOB3 and Sörred HOB2 that are not used. For *2019* with an accumulator tank.

Table 4.1 shows the merit order at a mean constant electricity price. Of course, will HP and CHP vary in placement of the merit order depending on an increase or decrease in the electricity price. Also, the waste heat is the maximum produced during 2019. It will fluctuate during the year since it is not in Göteborg Energi's own hands but depends on the amount of waste in the industry or Renova.

Production unit	Accumulative installed capacity [MW]	Order
Waste heat	387	1
HP 1-4	547	2
Save CHP3	654	3
Rya HOB8	774	4
Ros HOB5/Save HOB1	997	5-6
Sor HOB 2,4	1067	7
Ros HOB4	1207	8
Rya CHP	1501	9
Save HP2	1581	10
Ask HOB1-2	1601	11
Ang HOB1-3	1702	12

Table 4.1: Merit order *2019* assuming average electricity price of 38.4 €/MWh and excluding startup cost. Including installed heat capacity. Sörred HOB2 is not used while units further down the merit order are, indicating a bottleneck. Ang HOB3 is not used because it is the last unit and is not needed.

In Figure 4.3, it is observed that the placement of an accumulator tank increases the use of the transfer pipes in the system seen out of the full load hours for the pipes. Where the number after *pipe* in the x-axis is from node "z" to node "y" in that order. Especially for the connections between the nodes 2, 4, and 5. This result can be related to higher usage of the units and waste heat surrounding the accumulator tank, and the energy is transferred in a higher percentage due to the availability of the accumulator tank. It can also be seen that the pipe between node 2 to node 1 is never used independent of the current accumulator tank or not. This is because the waste heat in node 1 covers the demand, and that is the cheapest heat in the system unless the CHP runs when the electricity price is extremely high.

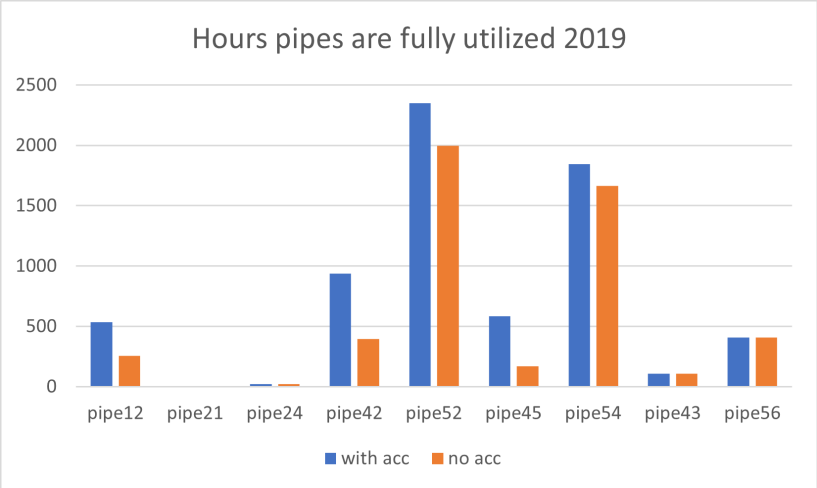


Figure 4.3: Amount of hours during the year the export pipes between nodes are fully utilized, with and without accumulator tank compared.

An important note from Figure 4.4 which is a figure of the full load hours of every unit, is the difference in usage of plants where the Rya node generates more heat with an accumulator tank than without. This can be seen by the full load hours of the heat pumps at the bottom, along with the full load hours of Rya HOB8 one step up. The two nodes, Eastern and Central, are producing less since a priority in heat generation can be applied thanks to the accumulator tank, which can be seen by the generation of Rosenlund HOB5 and Save CHP3 in the middle of the figure. One note is also made to the bigger generation from both Askim HOB1 and HOB2 and Angered HOB1, HOB2, and HOB3 at the top of the figure where these two are generating more than units lower in the merit order, such as Sor HOB2,4 and Save HOB2.

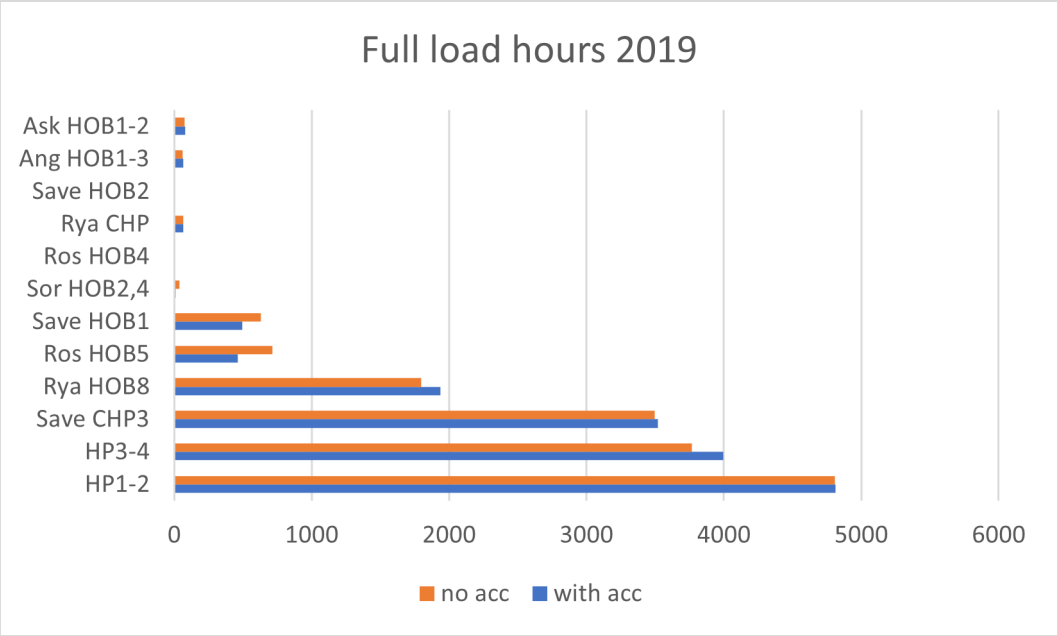


Figure 4.4: The amount of full load hours for every unit. Where units at the bottom of the figure are the lowest in the merit order up to the highest at the top of the figure.

If an observation is made on both Figure 4.3 and 4.4, it is seen to be a lower generation in node 5. However, it still exports more due to higher waste heat usage than in a no-accumulator tank case, which is then exported into Rya(node 2). Since also a higher percentage of full load hours for the pipes is seen between node 5 and node 4 and node 4 and node 2, the waste heat is transferred this way to end up at node 2. This, together with the lowered usage of the units in node 5 and node 4, which Rosenlund and Sävenäs state that the accumulator tank helps lower the cost of generation since these are as seen in Table 4.1 are more expensive units than the waste heat.

As can be seen in Figure 4.5, the Fine-plant goes in at a few hours in node 3 ($Fineplant_3$), which is a sign of a bottleneck since there are enough generations in the system to be able to avoid those but the transfer capacity is limited, and thereby the fine plant generates instead.

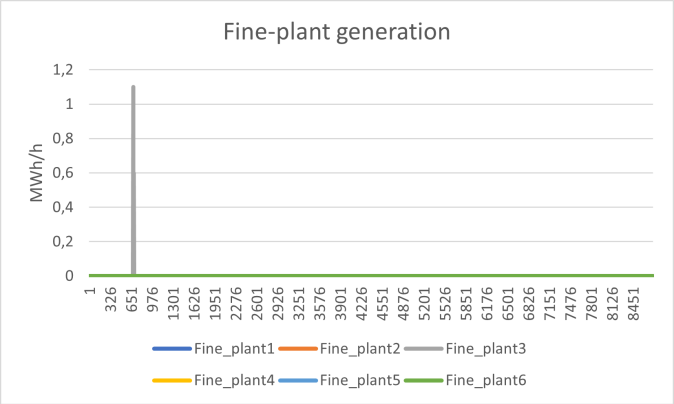
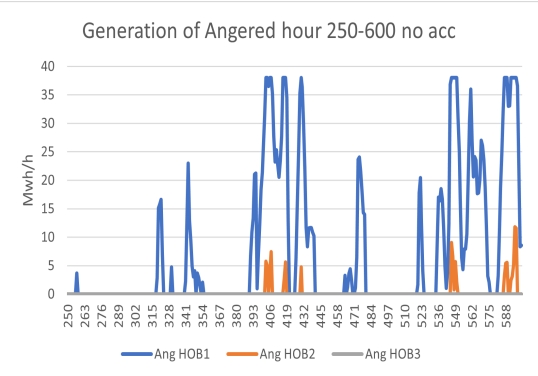


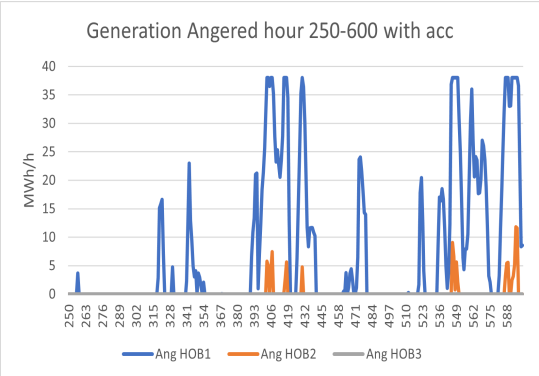
Figure 4.5: Figure of Fine-plants used, when production cannot meet the demand. The number behind the name Fine-plant is the node it belongs to.

4.1.1 2019 trends

In Figure 4.6a it can be seen that the generation during these hours is very similar in comparison with Figure 4.6b. The same does not apply to the Askim generation units. Where Figure 4.7a and Figure 4.7b have differences in generation where the generation with an accumulator tank is less than the generation without. Where a few peaks have been lowered.

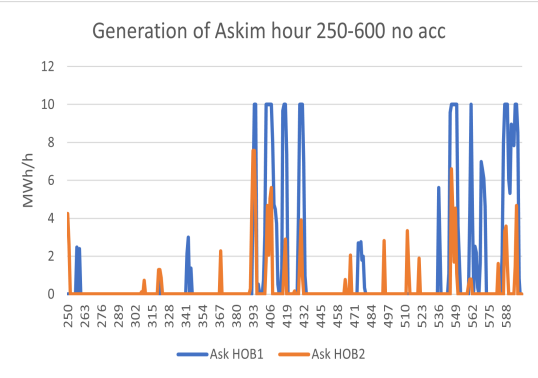


(a) Angered (node 6) generation without accumulator tank.

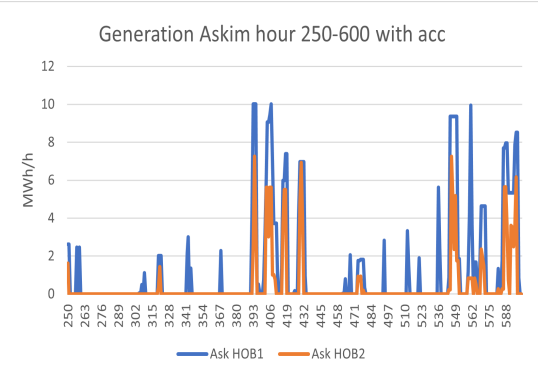


(b) Angered (node 6) generation with accumulator tank.

Figure 4.6: Generation of ang HOB1-3 with and without accumulator tank. The identical generation between the two cases because of bottlenecks.



(a) Askim (node 3) generation without accumulator tank.



(b) Askim (node 3) generation without accumulator tank.

Figure 4.7: Generation of Ask HOB1-3 with and without accumulator tank.

4.1.2 Discussion 2019

According to this study, the accumulator at Rya is a cost-efficient solution and a saving because of the lowering of the generation cost and a small decrease in bottlenecks. When the bottlenecks disappear, the cost decreases since the merit order can be followed more times during the year. Not only will the bottlenecks decrease, but the use of waste heat will increase, decreasing the use of more expensive units such as Rosenlund HOB5 and Sävenäs HOB1,2. Not only will the waste heat be a generation that the accumulator tank can benefit from, but heat pumps which are a low merit order generation, are used more when the electricity price is lower. Thereby lowering the cost of generation. The electricity price also affects the CHP, and when the price is higher, the heat from the CHP can also be used and replace more expensive generations.

Looking at Figure 4.2 and 4.1 during summer, the units do not need to generate because of the accumulator tank. This can allow maintaining the plants during summer and have fewer interruptions because of maintenance during the rest of the year. This makes room for such maintenance, which without an accumulator tank only results in a more costly unit will take its place.

The full load hours for every unit are shown in Figure 4.4, where the irregularities except the CHP are Angered´s and Askim‘s units, which are explained by bottlenecks in the system. This is the only explanation for why such costly plants would run when there is so much installed heat generation all over Gothenburg. It can also be seen in Figure 4.4 that Rosenlund HP5 is running less when an accumulator tank is installed, which is a sign that the plant at the margin is less often Rosenlund HOB5 and more often the cheaper units at the district Rya which will lower the total cost of generation.

Section 4.1.1 showed that with an accumulator tank, the expensive units at Askim have lowered their peak generation during a specific time period. This is the accu-

mulator tank that decreases the bottlenecks and thereby reduces the total cost of the system. The other units at Angered, which are also expensive in the same size as the units in Askim, do not change their generation because the accumulator tank cannot help the bottleneck in the pipe between node 5 and node 6. Which then leads to a more expensive district heating system.

4.2 2030

The investments made in the new system are shown in Figure 4.8. The nodes where an investment is made are node 5 and node 6, with approximately 206 and 270 MWh, respectively. The annual generation cost is 29.40 M€ with additional accumulator tank investments and 29.95 M€ without added accumulator tank investments. Which results in annual savings of 0.55 M€.

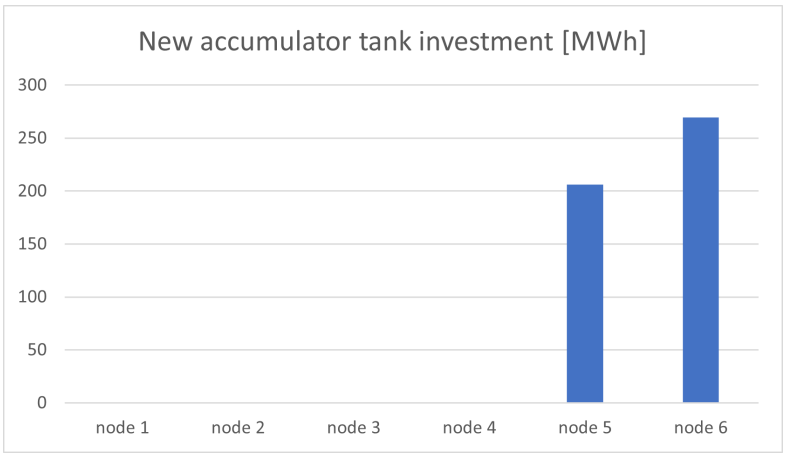


Figure 4.8: New accumulator tank investment for base case

Table 4.2 is the merit order, and if this is compared to Figure 4.9, there are some irregulars, such as Angered 1-3 is running when no new investment is made even though units as Sörred HOB2 and 4 is cheaper. This is due to bottlenecks in the system and the pipe from node 5 to node 6. Can also be seen when investments in accumulator tanks are made. These anomalies disappear except Rya CHP, and that is because the electricity price fluctuates, and there are some high points where Rya CHP is higher up the merit order. So the investments reduce the number of bottlenecks.

Production unit	Accumulative installed capacity [MW]	Order
Waste heat	387	1
HP1-4,6	597	2
Save CHP3	704	3
Rya bio-CHP	814	4
Sor HOB	854	5
Ris HOB/Save HOB4/Ang HOB	1004	6-8
Rya HOB8	1124	9
Sor HP2,4	1194	10
Rya CHP	1488	11
Ask HOB1-2	1508	12
Ang HOB1-3	1609	13

Table 4.2: Merit order *2030* assuming average electricity price of 33.3 €/MWh and excluding startup cost. Including installed heat capacity.

In Figure 4.9, it can be observed that the biofuel HOB:s decreases in their full load hours with the possibility of investing in more accumulator tanks. At the same time, there is an increase in Sävenäs CHP3, which can be referenced to the installment of 476 MWh accumulator tanks total in node 5 and node 6. Another mention is the Sörred HOB also increases in production.

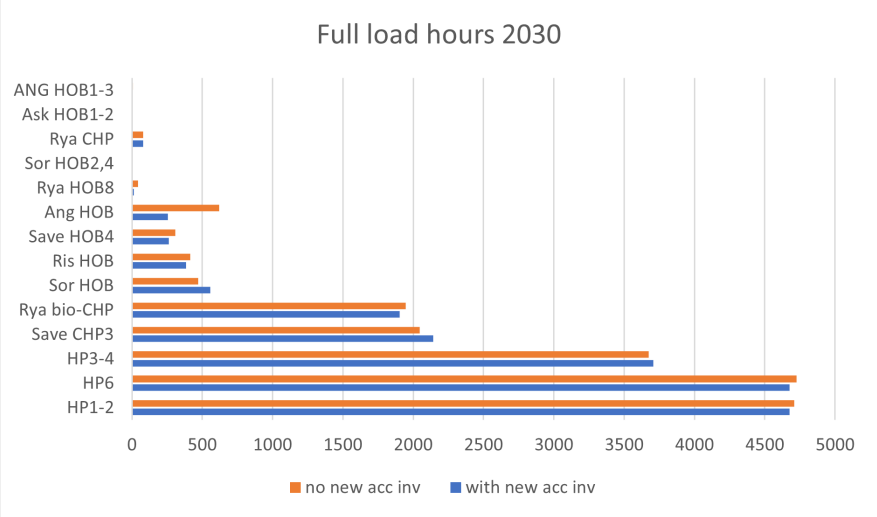


Figure 4.9: Full load hours for each generational unit *2030*, a comparison between with new accumulator tank investment and without new accumulator tank investment. Ranked in merit order.

The *2030* case has similar trends as the *2019* case, which is seen in Figure 4.10 with higher usage of the transfer pipes when more accumulator tanks are installed. The reason is that the one above waste heat and cheaper heat is prioritized and sent to the closest accumulator tank.

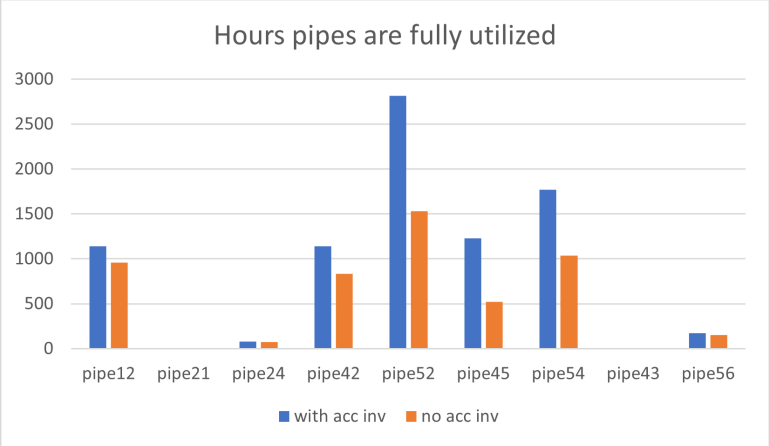
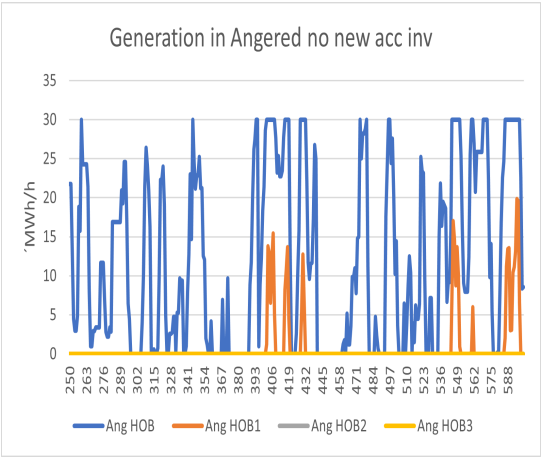


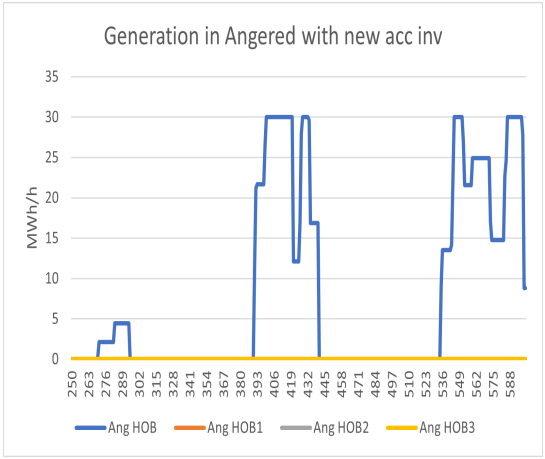
Figure 4.10: Amount of hours during the year that the export pipes are fully utilized. With a new accumulator tank compared to no new investments. The name indicates how the pipes are connected. For example, pipe12 export heat from node 1 to node 2.

4.2.1 2030 Trends

Section 4.1.1 mentioned that the Angered HOB:s was not decreasing in generation depending on the availability of the installed accumulator tank. In Figure 4.11a, the generation of the units at node 6 (Northern district) when no accumulator tank investments are allowed is shown. Figure 4.11b represents the same node with the same units but with an investment of accumulator tanks available. The difference between these two is that the generation when an accumulator tank is placed in node 6 is much less than when no new accumulator tank investments are allowed.



(a) Without new accumulator tank investment.



(b) With new accumulator tank investment.

Figure 4.11: Comparison of generation in Angered between without new accumulator tank investment and with new accumulator tank investment.

4.2.2 Discussion 2030

In *2030* Section 4.2, investing in more accumulator tanks is cost-efficient. This is due to the bottlenecks managed, which decreases the system's total cost. One of these fixes is shown in Section 4.2.1 where a plant that is high in the merit order is generating even if plants at a lower merit order are not, which can be seen in Table 4.2 and Figure 4.9, by looking at the Angered units (HOB1-3 and HOB). These accumulator tanks then erase a lot of these generations because of bottlenecks. The nodes chosen to invest in accumulator tanks are represented in Figure 4.8 and why node 6 and node 5 were shown due to the bottleneck in the pipe between these two nodes, which decreases with a storage opportunity in node 6. The other reason is waste heat usage, as argued in Section 4.1.2. This time the accumulator tank is in the same node, which makes the waste heat storage even easier, and it is independent of the pipe sizes to node 2, where the current accumulator tank is located. Another generation that the accumulator tank can make bigger use of is the Sävenäs CHP3, which according to Figure 4.9, is increasing. The reason is the accumulator tank, which will decrease the total system cost since the CHP will cover for more expensive units. In the *2019* case, node 3 was a big part of the discussion surrounding bottlenecks and prioritizing generation from cheaper units. In node 3, an extra generation unit called Riskulla is installed, so the investments in new accumulator tanks are zero. This unit will be the cheapest in the area where node 3 is directly interconnected since, according to Figure 3.1, the only connection is node 4, which has no generation in *2030*. So, the bottleneck in *2019* at node 3 is decreased by using a less expensive unit at the location. As explained in the introduction, according to [16], there is a good collaboration between CHP and tank storage, which could be one reason for CHP usage at Sävenäs. This also makes a presence in this thesis, where the generation of CHP increases when there is an accumulator tank at the same node both in the *2030* case and *2019*. This is to make larger use of the hours the CHP is lower in the merit order, and the electricity price is high. This eventually means cheaper heat for the system and a lower total generation cost.

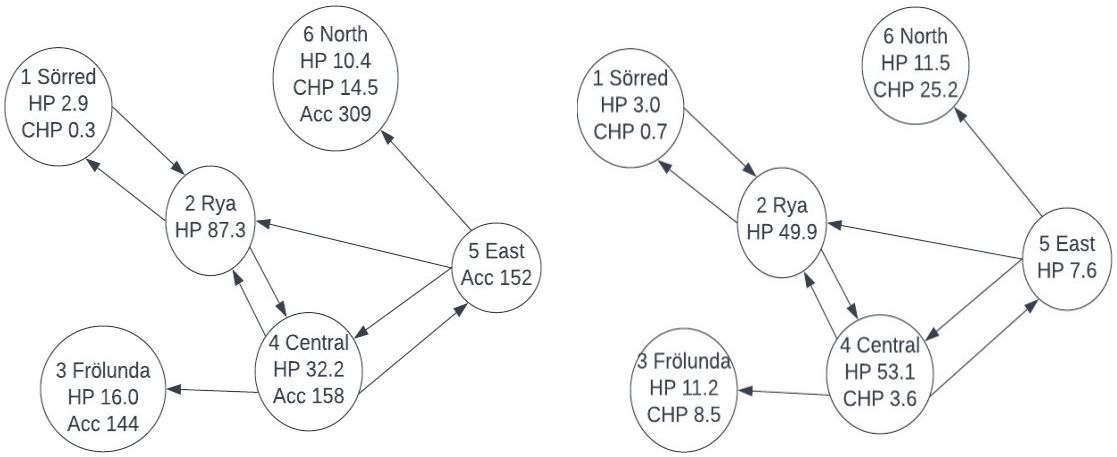
The same behavior of the pipes is present in *2030* as well. The increase in accumulator tanks increases the use of the pipes, which then comes back to cost-efficiency where the system finds rest heat from nodes and, via these pipes, uses the cheapest overproducing plant and lets it charge the accumulator tank.

4.3 2030 new investment plants

This section includes the results from another addition of investment possibilities. These are plants such as Heat only boilers, heat pumps, and combined heat and power plants at every node.

In Figures 4.12a and 4.12b and the investments with and without the possibility of accumulator tank investment included are shown. Where heat-only boilers are not invested in regarding of case, but the CHP and heat pumps are invested in. It can also be seen that the number of heat pumps installed increases from a total of 136.6

MW to 148.8 MW if the system is allowed to invest in new accumulator tanks, but CHP decreases from a total of 38 MW to 14.8 MW. The accumulator investments now occur at node 3, node 4, node 5, and node 6, with approximately 150 for the three first mentioned and 300 for node 6.



(a) New investment of plants in MW_{heat} with the possibility to invest in new accumulator tanks in MWh

(b) New investment of plants in MW_{heat} without the possibility of investing in new accumulator tanks.

Figure 4.12: Comparisons of new investment of HP, HOB, and CHP [MW_{heat}] with and without the possibility of new accumulator tank investment [MWh]. Total new investment with new accumulator tank investment, 218.8 MW HP and 14.8 CHP. Total investment without new accumulator tank investment, 136.3 MW HP and 37.9 MW CHP.

The annual generation cost for the no new investment in accumulator tank case is 33.52 M€and 32.97 M€with the allowance to invest in new accumulator tanks. Investments in more accumulator tanks can thereby save 0.56 M€annually.

Figure 4.13 presents the full load hours for the units remaining from *2019*. Where the largest generating units are heat pumps 1 and 2. There is a slight decrease in generation for every unit when new accumulator tanks are invested in, except for Sävenäs CHP3. Heat pumps 3 and 4 have lower full load hours in this case than in the other cases, *2019* and *2030*. The new investments of plants also have full load hours not presented in this figure, but for further reading, it is located in Appendix A.13 where the newly invested plants for the two cases all have full load hours around 4000 h.

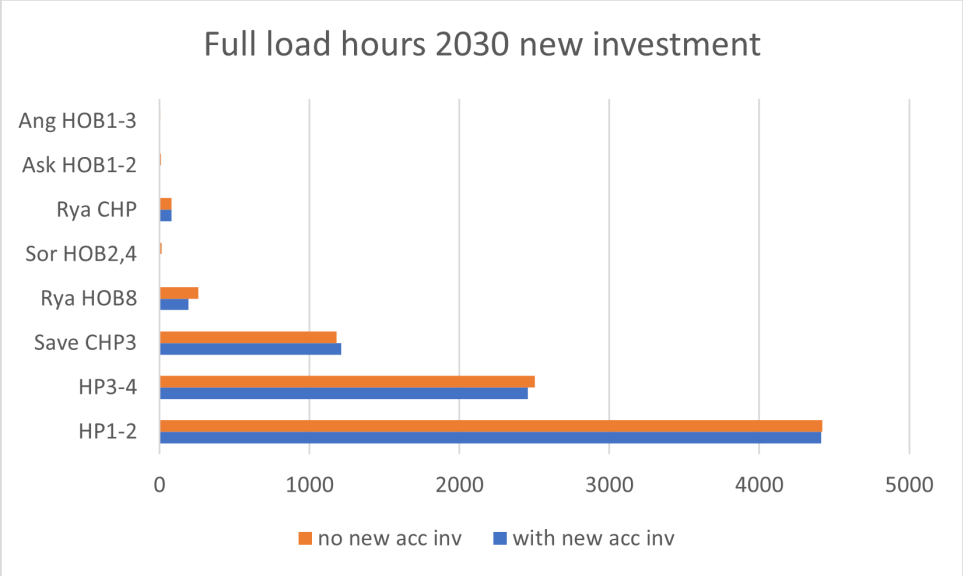
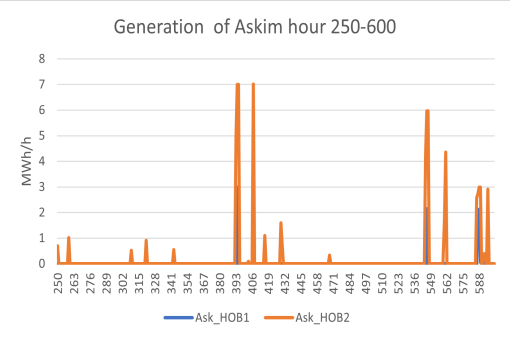


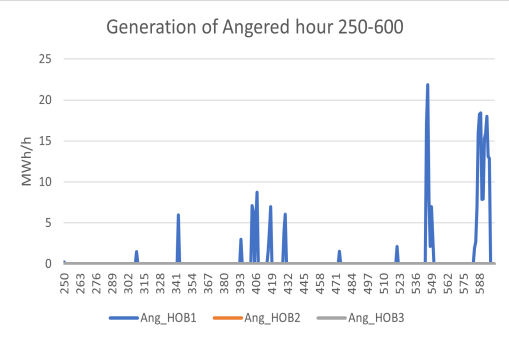
Figure 4.13: Full load hours for existing generation units, excluding new investments. All new investments have FLH of around 4000 and compete with some of the existing plants.

4.3.1 2030 new investment trends

In Figure 4.14a, the generation from the Askim HOB1 and 2 are shown, and in Figure 4.14b, the same but for Angered HOB1-3 and during these hours these are generating heat when there is no accumulator investment allowed. If the model is allowed to invest in accumulator tanks, the generation for the whole year for all of the units in Angered and Askim is 0.



(a) Askim generation without accumulator tank.



(b) Angered generation without accumulator tank.

Figure 4.14: Generation of Ask HOB1-2 and Ang HOB1-3 without new accumulator tank investment. Ask HOB1-2 and Ang HOB1-3 is not used when the model can invest in accumulator tanks.

4.3.2 Discussion 2030 new investment

An interesting comparison can be made between the *2030* new investment case and the *2030* case, which is how similar these are. Especially similarities in how units and plants are spread out in the different nodes. One of these similarities is the investment of more heat pumps in node 2 (Rya). In the *2030* case, heat pump 6 is installed with a capacity of 50 MW in node 2, and for the *2030* new investment case, either 87.3 MW or 49.9 MW is invested, which is similar. Other things are not similar such as the amount of HOB invested. In the *2030* case, the investment of HOB is massive, with 4 new such units. There are none in the *2030* new investment case. This is because HOB does not have a flexible fuel cost/revenue compared to HP and CHP, which means that the advantage with the accumulator tank combination decreases, while HP and CHP can take advantage of low/high electricity prices and charge the accumulator tank and thereby have a lower cost of generation. Because of this, HOB, together with accumulator tank storage, is not an effective way to erase bottlenecks since the HOB cannot, together with storage, apply load shifting. Also, in the 2030 the electricity price is more fluctuating, creating an increase in low-cost units generations since heat pumps take advantage of low electricity prices and CHP:s of high electricity prices.

There is also mentioned in the introduction by [16] that integration between CHP and storage is favorable, which also can be seen in Figure 4.12 where the biggest investment in CHP is located at the same node as the biggest invested storage unit. Even though it is argued that the integration of CHP and thermal storage is beneficial in these results, it seems that heat pumps have better integration with the accumulator tank because the increase in installed capacity for HP:s is substantial when the accumulator investment opportunity exists. At the same time, the CHP:s total generation capacity decreases. So, this thesis sees a more lucrative solution when the integration of heat pumps and storage units is applied.

The result in Figure 4.12 also shows a more even distribution of plant investments compared to the investment of both accumulator tanks and plants. This is due to the placement of accumulator tanks in the system where the addition of accumulator tanks in Central (Node 4) and East (Node 5) decreases the plants invested in. Where the HP in Central is reduced by 20 MW installed capacity and the CHP need is erased, and in East, the HP need is erased.

In this case, the bottlenecks are not as easy to show because the model adapts, and because of the minimized annual cost, the bottlenecks will be smaller because these are expensive, and the system would not allow it. Some bottlenecks can still be seen where the expensive plants Angered HOB1-3, and Askim HOB1-2 run at a low rate when no accumulator tank is allowed to be invested in. This is because more generation capacity is installed in the system for the no-accumulator investment case, which is less expensive. There are still some restrictions for transmission in the district heating system. Which then is erased when accumulator tanks are allowed. This is a sign of a decrease in bottlenecks in the system, and the system's total cost has decreased.

The need for a new generation also decreases from the *2030* and *2030* new investment cases. It is due to a more optimized system that has managed more bottlenecks than the expected 2030 system implemented with more than enough heat.

For the *2030* new investment case, were the available technologies possible to invest in HOB, CHP, and HP fueled by pellets, wood chips, and electricity/heat from the air, respectively. These technologies are the same as Göteborg Energi plans to construct, except for the heat pump, where they plan to use waste heat from Northvolt. However, heat pumps with air as a heat source were chosen due to the limited availability of waste heat. The investment cost for these technologies was not provided by Göteborg Energi but the Danish energy agency. The investment cost for accumulator tanks differed significantly between Göteborg Energi and the Danish energy agency estimate. The estimated investment cost will probably vary from the Danish energy agency and the actual investment cost. The results from the *2030* new investment case are thereby not an investment plan for new heat generation plants but more an investigation of how the district heating system interacts with other generation technologies with added heat storage and if the significant investments in HOB that Göteborg Energi plans compares to HPs and CHPs.

5
Sensitivity analysis

In the sensitivity analysis, changes in fuel cost and other parameters will be made as introduced in Section 3.6.1 to create a wider variety of how cost-efficient accumulator tank investments or those invested in are.

5.1 2019

As seen in Figure 5.1, there is a decrease in the total cost of generation when an accumulator tank is used at Rya, which is approximately 1.5-2 M€ for the *2019* case. The least savings occur when the biomass price is halved, and the most significant savings are when the fossil fuel prices are increased by 1.5 or 2 times the original value.

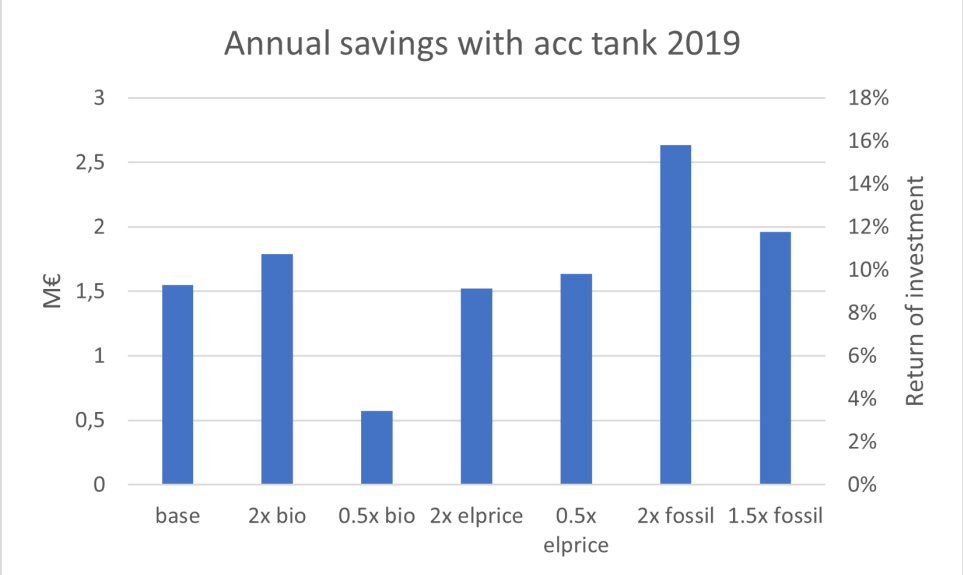


Figure 5.1: Results from sensitivity analysis. Savings with accumulator tank compared to no accumulator tank. Savings are in M€ and annual return of investment.

In Appendix A.14, there are some expected results where the plants are affected by the changes made to the fuel price. In Figure 5.2, the effect on the accumulator tank is presented where a doubling in electricity price increases the total energy use for the accumulator tank. According to the number of full load hours, it is when the CHP usage at node 2 is high. The least used case, except with no accumulator tank, is a doubling in bio-fuel costs.

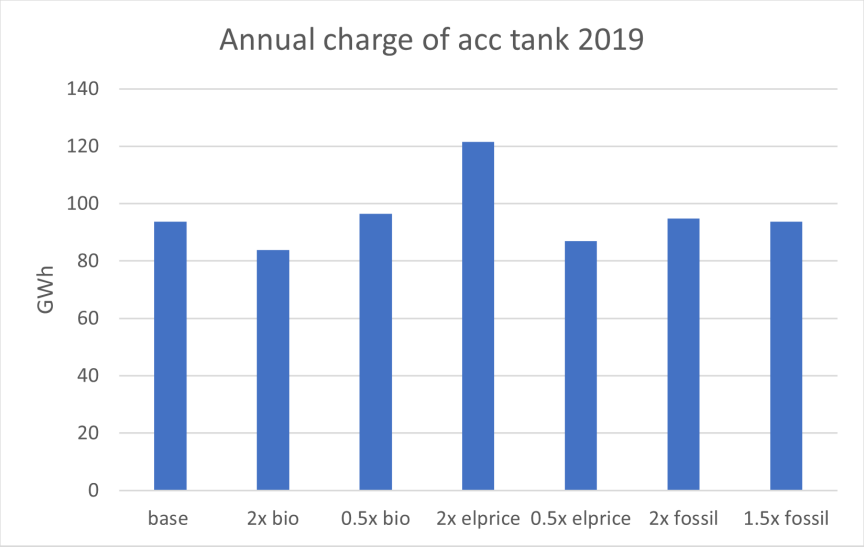


Figure 5.2: Total annual energy cycled through the accumulator tank at Rya in GWh for each sensitivity analysis case.

5.2 2030

In Figure 5.3 in the sensitivity analysis, it can be seen that another parameter has changed, and as explained in section 3.6.1, the waste heat coming from Preem is an uncertainty. Here it is seen that depending on the future system and different scenarios, the total cost of generation differs. If the solid biofuels decrease in price or the electricity increases, the system is less costly.

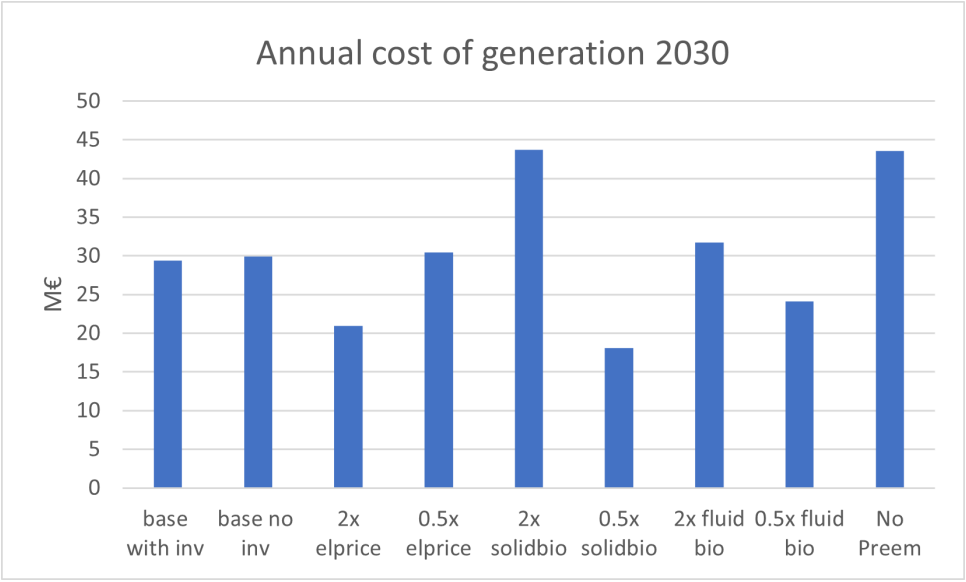


Figure 5.3: Annual cost of generation for each sensitivity case.

Looking at Figure 5.4, the degree of new accumulator investment depending on the sensitivity case can also be seen. An increase in solid biofuels would create a bigger

need for accumulator tanks. It is also clear that independent of which case the investment of accumulator tanks in node 6 the northern district, is made. Also, the least investments occur when the solid biomass price is halved, where it is only needed in node 6.

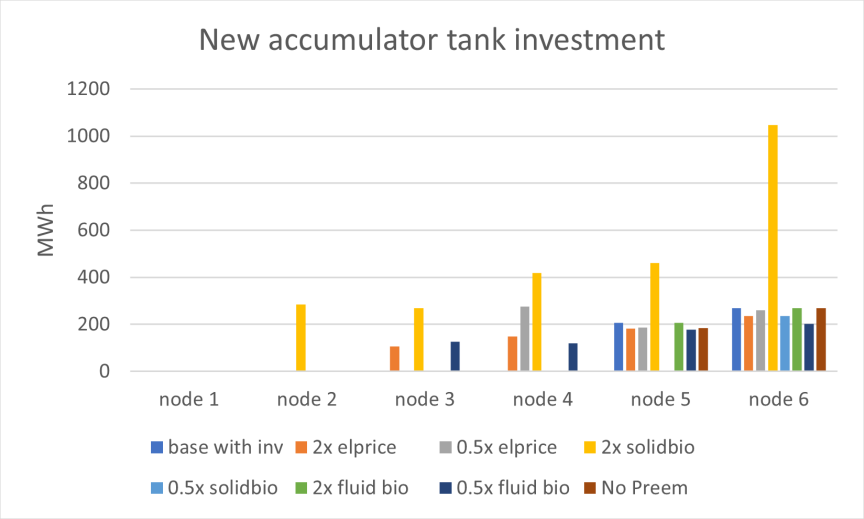


Figure 5.4: New accumulator tank investment for each node and sensitivity analysis case for *2030*. Excluding cases no new accumulator tank investment.

5.2.1 2030 new investment plants

Figure 5.5 presents the annual generation cost for each sensitivity analysis case. The cheapest one is the doubling of electricity price, and the doubling of solid bio-fuel cost becomes the most expensive.

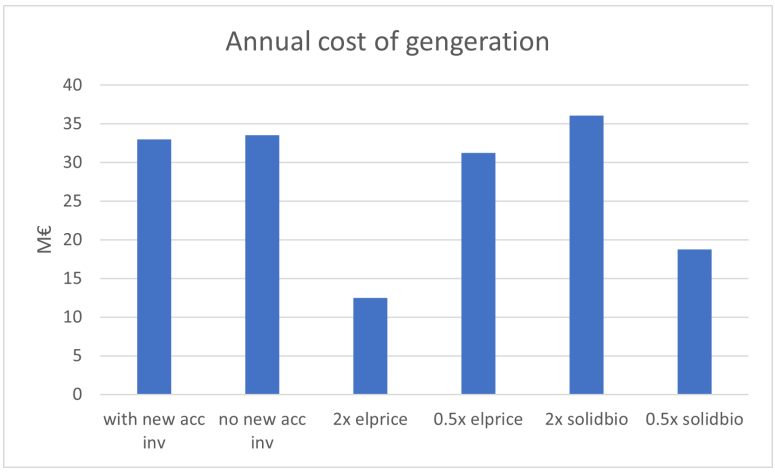


Figure 5.5: Annual generation cost for all sensitivity cases for *2030* new investment.

Figure 5.6 shows that varying accumulator tank investments are made depending on the fuel cost, where a doubling in solid biomass price creates the biggest accumulator tank need.

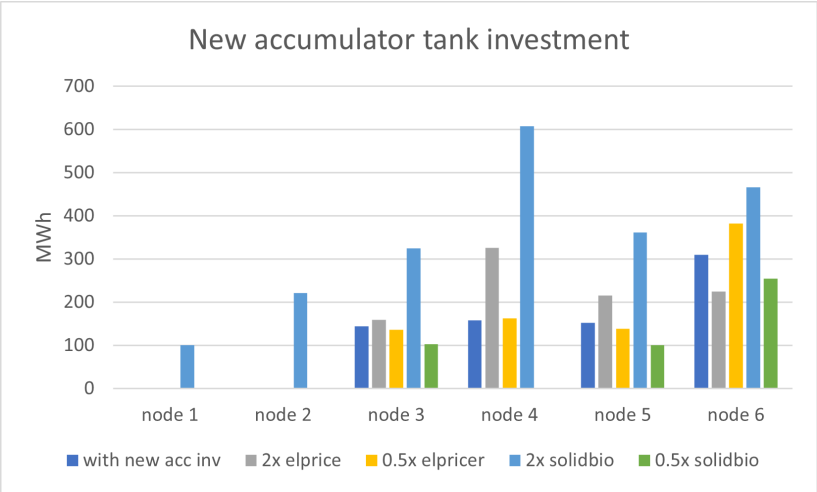


Figure 5.6: New accumulator tank investment for all cases for *2030* new investment.

One note from both Figure 5.5 and 5.6 is that when the annual cost at the double electricity price is at its lowest, there is still a total larger investment in accumulator tanks than the base case.

Figure 5.7 shows the investments of HP:s where an increase in solid bio-fuel prices and a decrease in electricity prices creates the most considerable need for HP:s

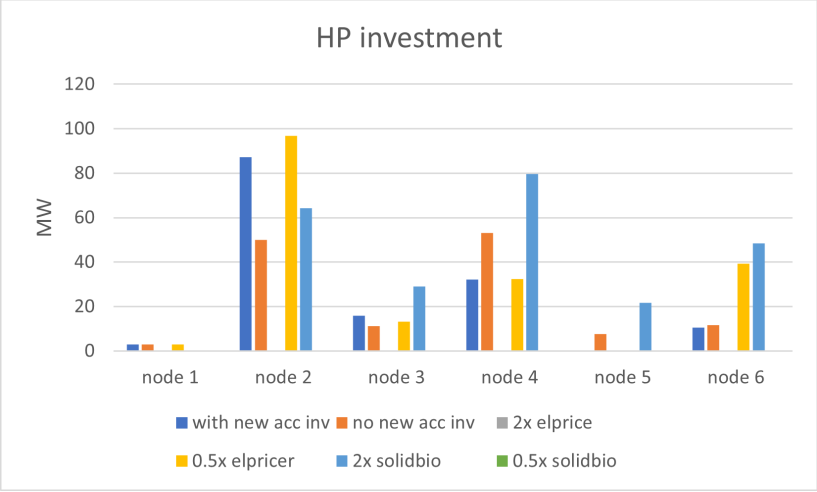


Figure 5.7: Investment of HP for each sensitivity analysis case for new investment *2030* in MW_{heat}.

It is shown in Figure 5.8 that the biggest influence on that investment is an increase in electricity price, and another note is that no new CHP plants are invested in if the electricity price is halved.

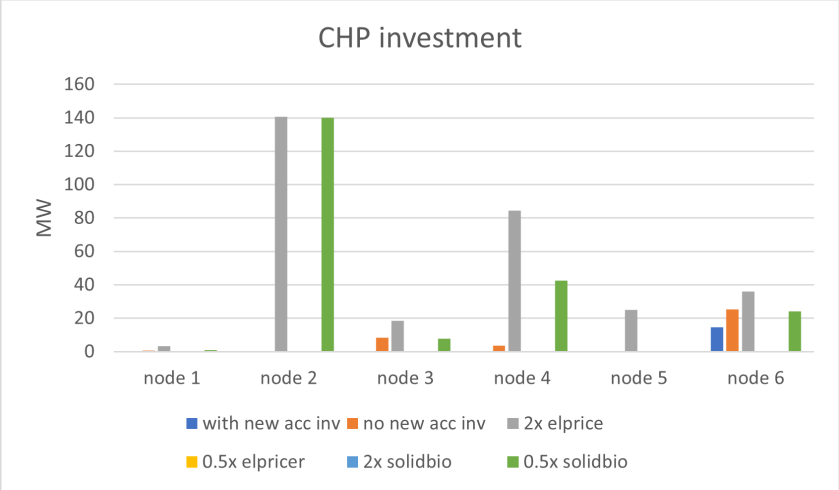


Figure 5.8: Investment of CHP for each sensitivity analysis case for new investment *2030* in MW_{heat}.

5.3 Discussion Sensitivity analysis

In the sensitivity analysis, a change in fuel cost is the most telling case. Where the different changes increase and decrease generation from specific units. The higher the cost is for a certain fuel, the higher up in the merit order a unit ends up. This was an important part of the thesis since fuel cost is especially a big uncertainty in the future. Even the sensitivity analysis for current conditions is relevant because of sudden changes such as war, pandemics, and new laws. This directly affects the district heating system, as the sensitivity analysis shows. Of the fuels, the two most interesting are electricity and biomass. As Section 5.1 states, when the bio-fuel costs are doubled, the usage in the accumulator tank decreases. This is because the marginal cost for more units will be the same for the bio-fuels but a larger gap to electricity. The accumulator tank cannot use price differences in the system at the same frequency. Still, the profit is greater when it is used because of these cost differences between bio-fuels and electricity in the system. Therefore the savings have increased from the base case, presented in Figure 5.1. For the other option, which is a halved electricity price, the usage of the accumulator tank decreases because the heat pump generation increases, which is the second lowest in the merit order. The electricity price increase generates extensive usage of the accumulator tank due to the increased use of CHP, where it can even be profitable to run the unit and become the lowest in the merit order. Then the accumulator tank stores the waste heat. These periods where the electricity price is remarkably high make full use of the tank, but these hours are fewer, and therefore the savings are approximately the same as the base case.

For *2030* the same tendencies are seen where a decrease in bio-fuel price (solid & fluid) decreases the investments of accumulator tanks as seen in Figure 5.4. It also decreases the annual cost of generation due to the lower fuel cost for heat-only boilers and, thereby, smaller fuel cost differences in the merit order. If the merit order is

not followed, the consequences are not large. This is due to the steady fuel price of the HOB and not as fluctuating as electricity cost. So, accumulator tanks become less profitable since price changes are less cost-beneficial to the system. The other way around, if biofuels increase in cost, the accumulator tanks are used more because of larger price differences in the merit order. This fuel price change also costs more because of a high dependency on HOB in the *2030* system. If then a further look into *2030* new investment some changes have occurred in the system depending on the fuel prices where the decrease in bio-fuels is no longer the cheapest because the district heating system no longer has a bio-fuel dependency and chooses not to have it either because of the fore mentioned steady HOB fuel costs which make load-shifting useless. Which is not cost-efficient for accumulator tank investments. On the other hand, the increase in biofuels does not affect the annual cost of generation to the same degree as for *2030* because of more use of heat pumps and accumulator tanks integration. Another interesting result mentioned is the doubling in electricity price which has the lowest annual generation cost. This is due to the combination of CHP and accumulator tanks. When the CHP is generating heat for a less high price and even on profit at times, it charges the accumulator tanks with large differences in costs in the merit order. So, the accumulator tanks can discharge at other times when the electricity price is lower and CHP higher in the merit order. This is seen in Figure 5.8 and 5.6, where the investments increase compared to the base case.

In the *2019* case, the fossil fuels are still in the system, and as can be seen in 5.1, the fossil fuels increase the annual savings the most and are because the differences in the merit order increase, and then the accumulator tank is used at bigger price differences and has larger savings per GWh. Therefore the usage in Figure 5.2 is approximately the same as the base case.

The sensitivity analysis affects the accumulator tanks both in the *2019* cases and future cases. Where the current accumulator tank helps the system's robustness, and if changes in the fuel market happen, the accumulator tank helps to make the system more profitable by using less expensive heat at other times when either the demand for heat is higher or the generation too expensive. Also, when the option of investment in accumulator tanks is added, most sensitivity analysis cases choose to invest in helping the system become less expensive.

Biomass, as explained in Section 1, is a tricky fuel since no one knows how it will be used in the future with industries, airplanes, public transport, personal vehicles, and electricity generation plants shown in the Sensitivity analysis. This will lead to the one who can pay the most will create the price for it. In this case, the district heating system will have certain limitations on how much it will be willing to pay for the fuel. If fuel costs increase, biomass-based units/plants will increase in the merit order, as shown in the sensitivity analysis. If this happens, a more suitable approach would be new-generation investments in heat pumps and accumulator tanks independent of the biomass price.

6
Discussion

The discussion for the different cases will be found in the result and, more specifically, Section 4.1.2, 4.2.2, and 4.3.2, respectively.

6.1 Assumptions

Thermal storage has certain aspects that cannot be evaluated in this study. Which both create added value or decrease profitability. For example, the model does not have a minimum load for certain plants, which is not the reality. But to generate a reasonable simulation time, this was needed. If all plants had a minimum load, the accumulator tank would have a greater value since if the system needs an amount lower than the lowest minimum load, the thermal storage would be used instead. Some things lower the value of thermal storage. When the system is running, storage in the pipes is possible. If you raise the temperature or energy level beyond what is needed, there will be a higher return temperature. This return temperature then creates the stored energy in the pipes. Of course, there will be losses along the way, but still will be stored energy. This possibility creates an accumulator tank in the system itself that is not included in this study and will lower the value of the actual accumulator tank. Since there is a possibility to store energy elsewhere and the usage of the tank is decreasing, thereby the cost-efficiency. There are also other factors outside this study's scope which are district cooling during summer. Then the thermal storage tank is used to pressurize the system instead of starting a plant which was done before the accumulator tank was installed. This is yet another advantage of the accumulator tank that is not investigated and again increases the usage of the accumulator tank. But was excluded since the pressure in the system is not included in the method.

The demand in the model is known, which means the model knows the temperature in hour 8700 when calculating the energy balances in hour 300, which it will take advantage of. For Göteborg Energi, it is not the same where a prognosis of the next ten days is almost a maximum where it also can differ a few ° C within hours. This means the system must be prepared for lower temperatures than the prognosis. For an accumulator tank, some storage must be left at times for safety measures to not run out of heat. For plants, it could be more reasonable to prepare a start (because of start-up times) of a unit limited by a minimum load to have that safety net if the plant on the margin is used fully. If the temperature ends up as the prognosis, the overproduced heat can be stored in the accumulator, creating a safety net for

having an accumulator tank ready. This means that the accumulator tank makes the process for the system easier than without one.

Some assumptions exist regarding adding new generation plants, especially the CHP:s. The CHP:s are non-binary, which then affects the results. The minimum load of the plant is neglected, and therefore, small CHP:s will be an asset for the system. A regular CHP will be limited, and small generating amounts will not happen due to a minimum cap. So, in the system, a newly installed CHP generates and can profit from high electricity prices at a minimal generation, leading to a bit higher rated power investment. While in a more realistic case, the rated power of the new investments in CHP:s would be a little lower.

6.2 Economics

The accumulator tank at Rya, with a storage capacity of 1000 MWh, had a construction cost of around 16 M€, more than Göteborg Energi estimated because of some problems during construction. Göteborg Energi estimates that a new accumulator tank of the size would cost closer to 10 M€. According to the [36], the investment cost of an accumulator tank is 3 M€/GWh with an uncertainty range from 2.2 to 8 M€. In future cases, an investment cost of 8 M€/GWh was chosen, between what Göteborg Energi and the Danish energy agency predict. Even if an accumulator tank is a mature technology, it should have a lower range of investment costs. Lager accumulator tanks have not been used in the past, so the range is because of the uncertainty of the economics of scale. Whereby is an investment cost of 8000 €/MWh a reasonable assumption? According to the results, accumulator tanks are a cost-efficient investment, and a change in investment cost would change the storage capacity and payback time. However, the accumulator tanks will still be beneficial for the system.
The discount rate chosen was 5 % which is in the lower category, and this is because this is seen from a social cost perspective and is used since it is academic and the municipality in Gothenburg owns Goteborg Energi and has then some responsibility for the social perspective as well. With a higher annuity factor, the investment in accumulator tanks would react similarly to changing the investment cost.

7
Conclusion

The current accumulator tank is a profitable investment, shown in the results with a return on investment of 9.7 % annually. Which will then generate a payback time of approximately 11 years.

In *2030* it will be profitable to install more accumulator tanks, but not in every node but node 6 and node 5, which are the eastern and northern parts of Gothenburg.

In the three cases, bottlenecks are occurring in the system. In *2019* there are bottlenecks both with and without the accumulator tank at Rya, and in both future cases, the bottlenecks decrease when accumulator tanks are invested in. The accumulator tank provides security against price fluctuations, both small-term electrical price changes and longer-term fuel price changes, by shifting load and avoiding operating more expensive units. The model does not include an added value since the demand is determined: if the demand suddenly increases, can the accumulator tank rapidly discharge heat and reduce the risk of not meeting the demand.

The sensitivity analysis concluded that disregarding changes in fuel prices, the current accumulator tank is more profitable than a system without one.

The sensitivity analysis was also made for future cases where for the *2030* case, Solid biofuels made the most significant differences in the annual cost of generation, while for the 2030 new investment, the electricity price made the most considerable impact because of a higher share of heat pumps and CHP:s in the system.

The *2030* new investment case showed that a higher share of heat pumps and CHP:s is more profitable than the heat-only boilers that are mostly planned for in the *2030* case. Also, the biomass price impacts the investments of both plants and accumulator tanks where an accumulator tank investment decreases with halved solid biomass price and increases with doubled solid biomass price.

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A

Appendix 1

A.1 Fuel costs

Fuel	Price [€/MWh] [37]
Natural gas	52
Fuel oil Eo1	89
Fuel oil Eo2-6	72
Wood chips 2019	25
Wood chips 2030	30
Pellets 2019	35
Pellets 2030	40
Bio-oil	120 [19]
Electricity	Spot price +Electricity tax [38]
Waste heat	0.5 [19]
Biogas 2030	55 [19]

Table A.1: Every fuel used in the study with its corresponding price.

A.2 Demand curves

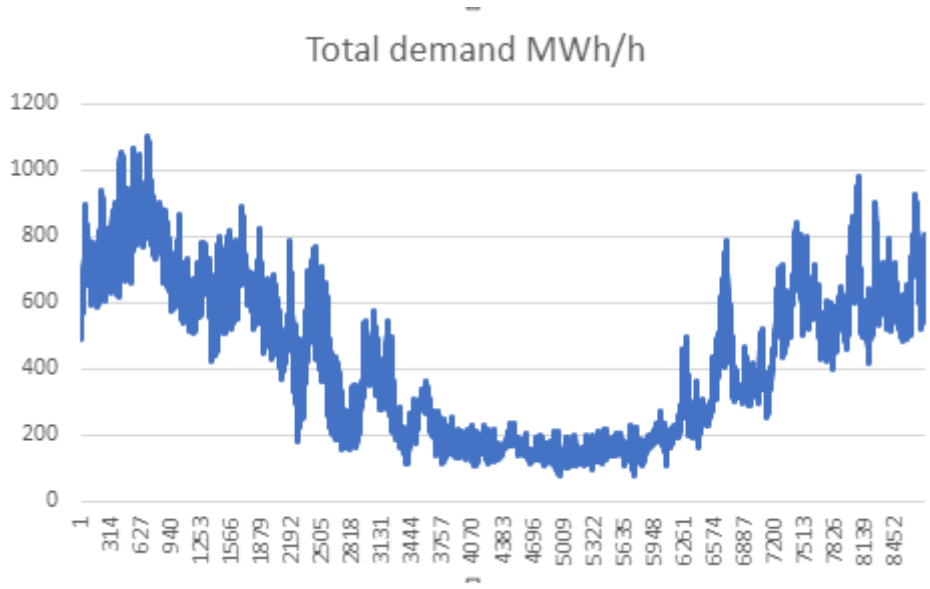

Figure A.1: Total demand.

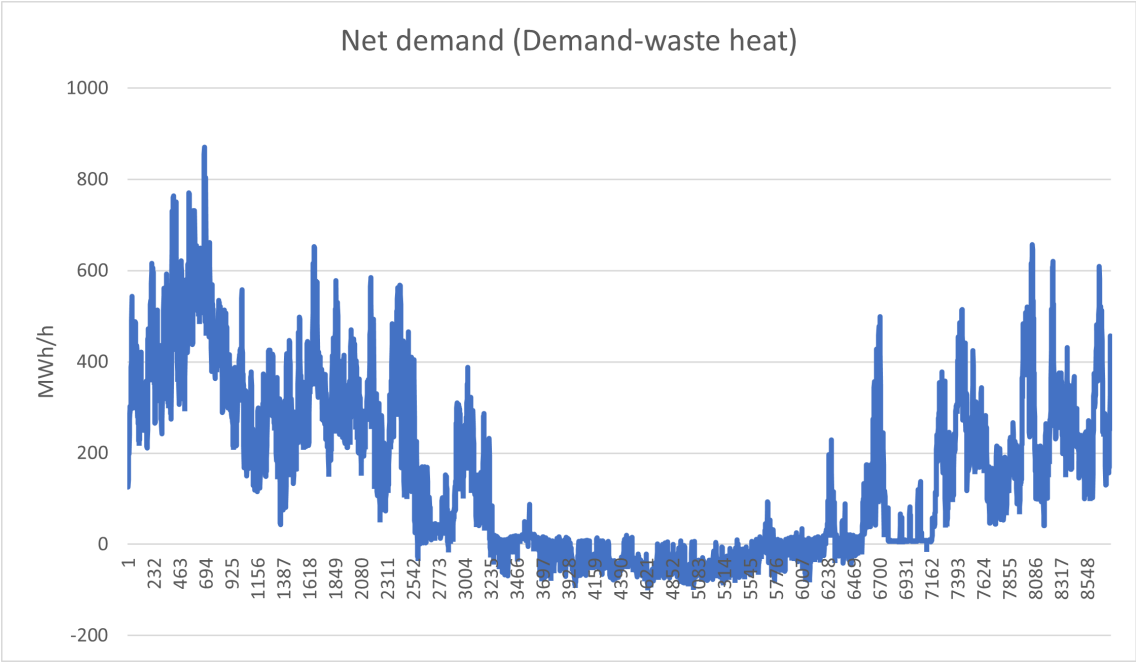

Figure A.2: Net demand, Demand subtracted with waste heat and import/export to other municipalities.

A.3 Input heat files

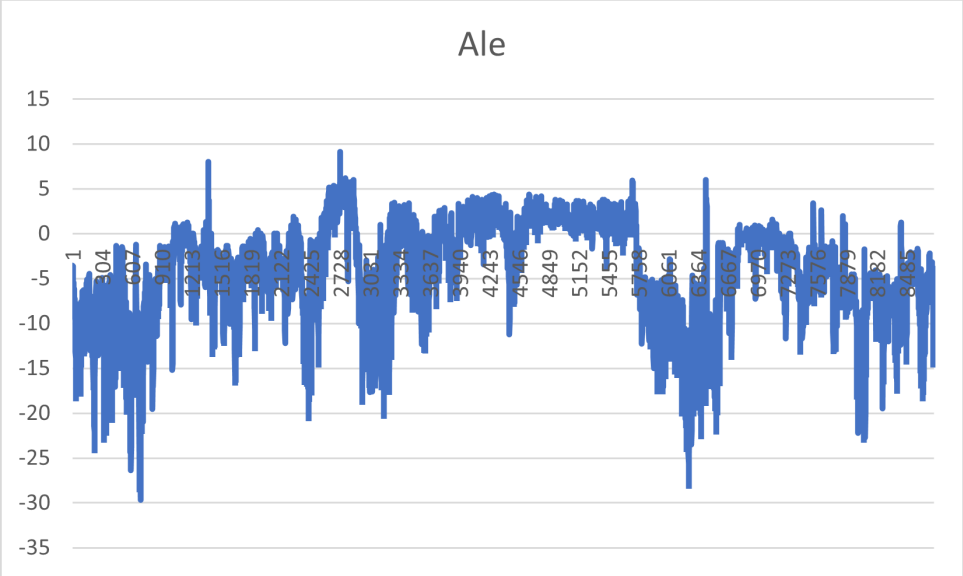

Figure A.3: Ale import and export heat profile for 2019.

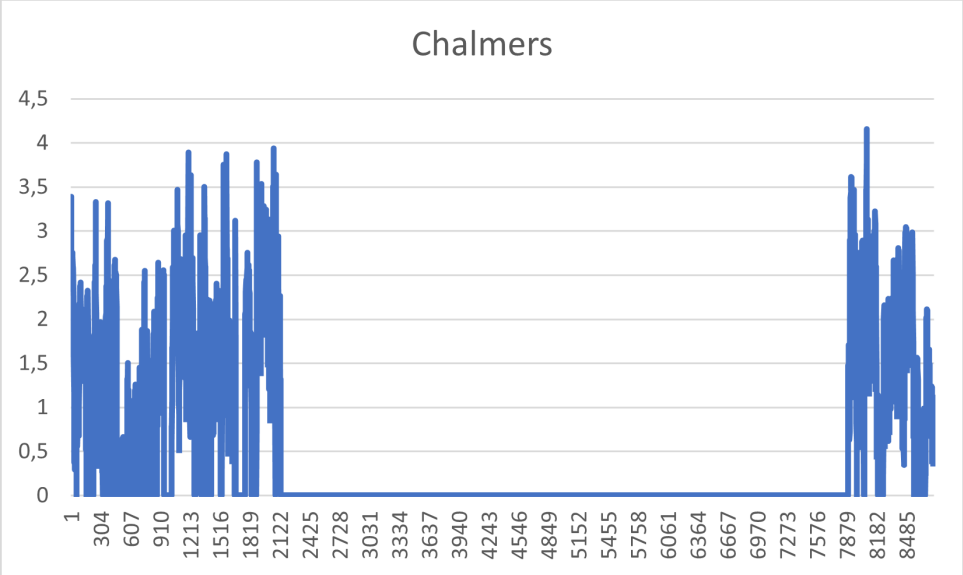

Figure A.4: Chalmers heat profile for 2019

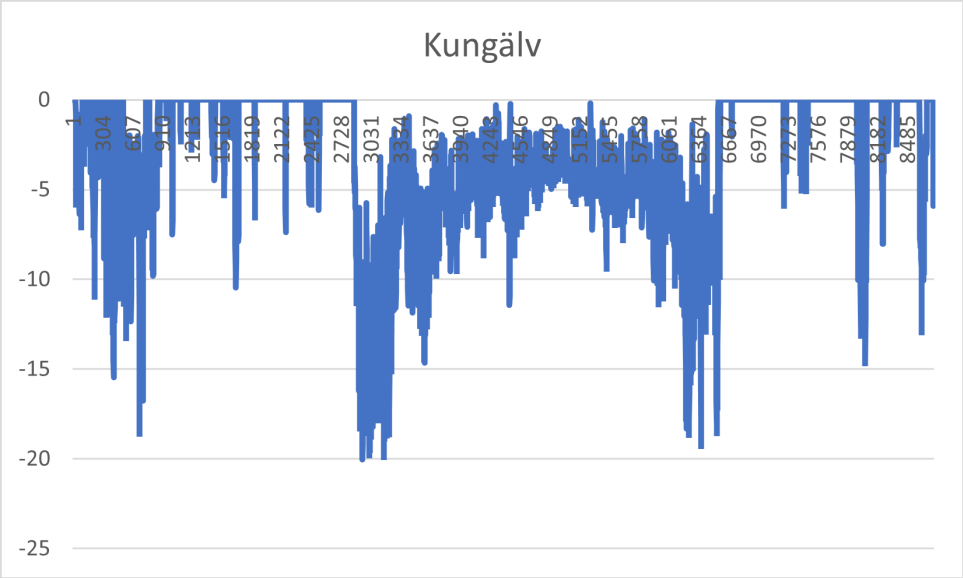

Figure A.5: Kungälv import and export heat profile for 2019.

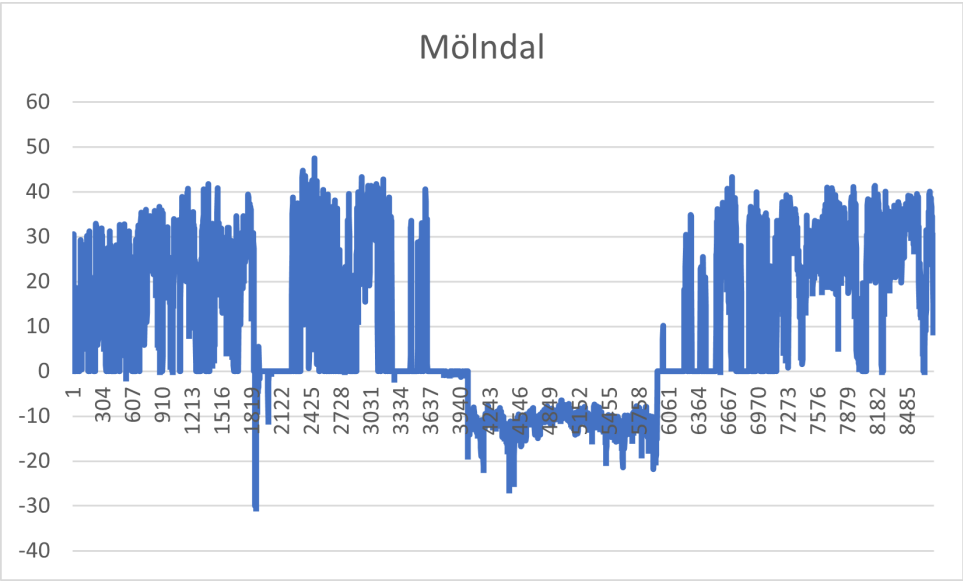

Figure A.6: Mölndal import and export heat profile for 2019.

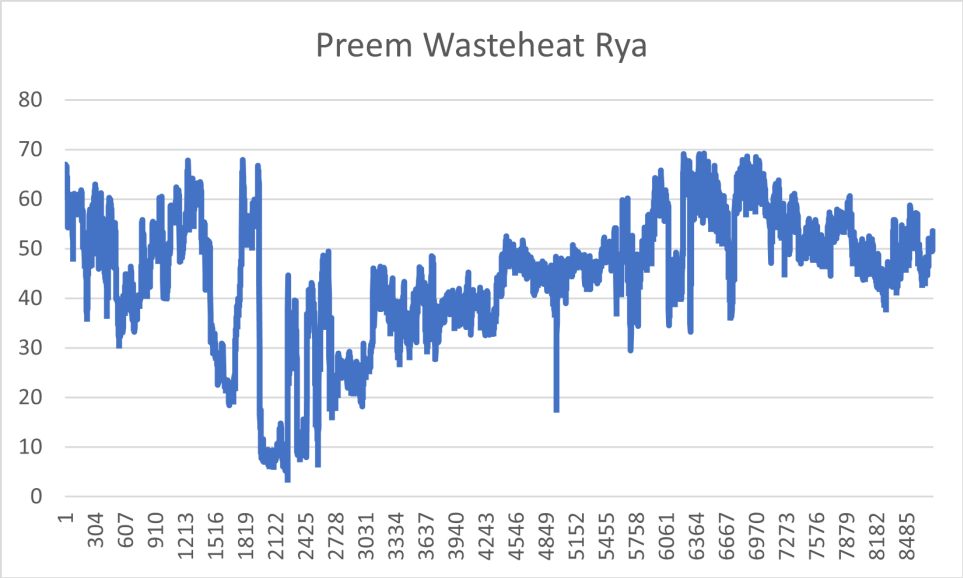

Figure A.7: Preem waste heat to Rya district heat profile for 2019.

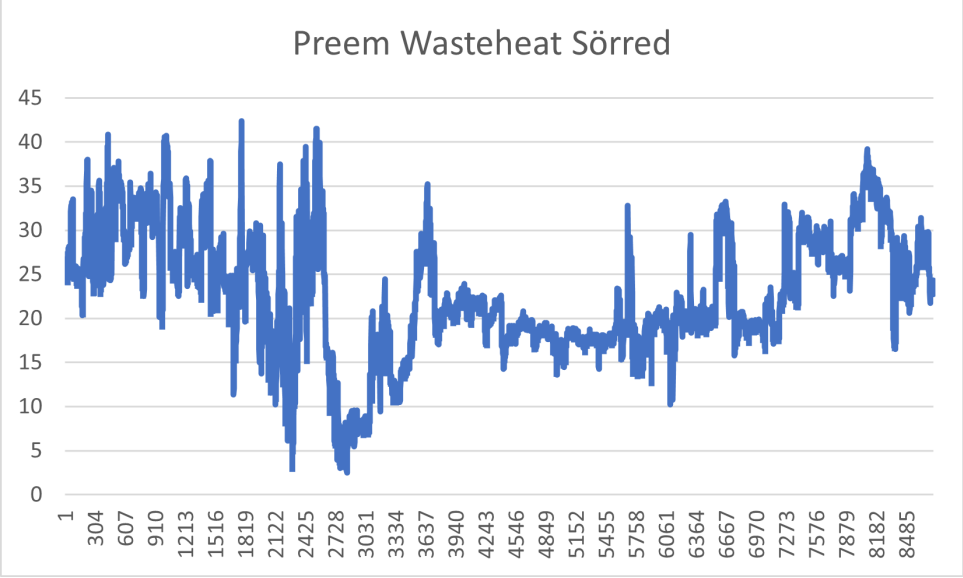

Figure A.8: Preem waste heat to Sörred district heat profile for 2019.

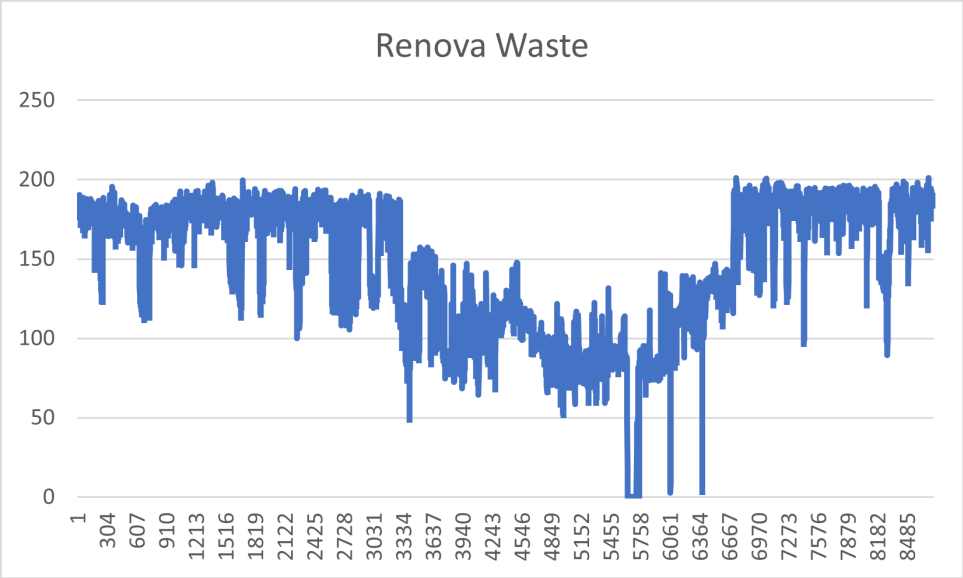

Figure A.9: Renova waste CHP generated heat to eastern district heat profile for 2019.

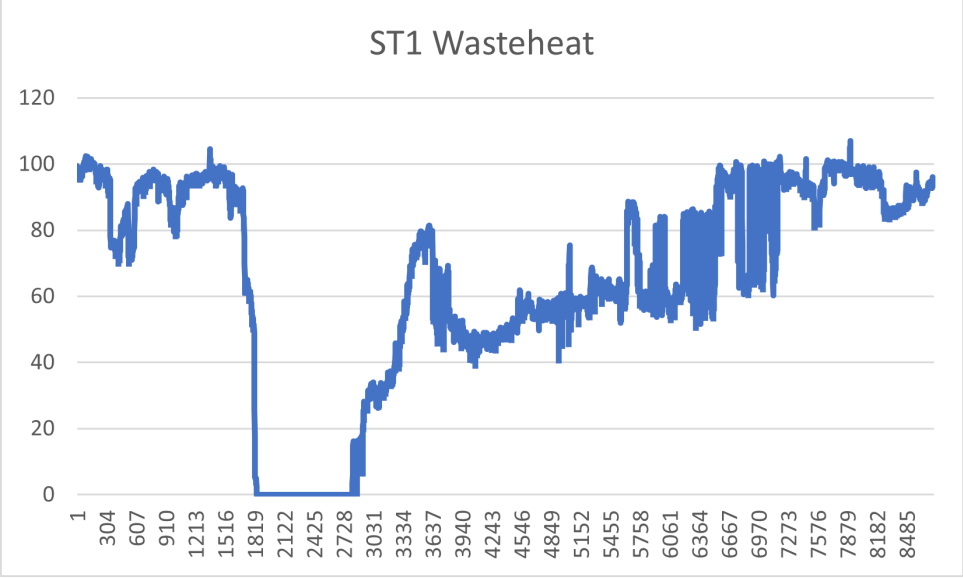

Figure A.10: ST1 waste heat to Rya district heat profile for 2019.

A.4 Spotprice

max	min	average
109.45	0.12	38.36

Table A.2: max, min, and average spot price in SE3 2019

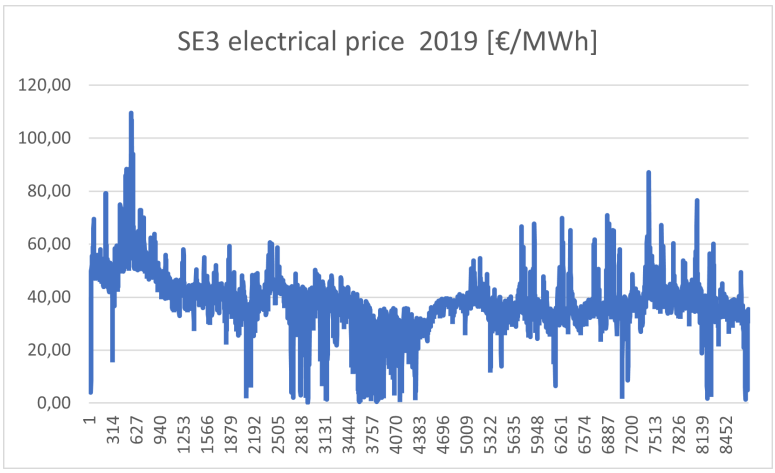

Figure A.11: Spot price in SE3 for 2019.

max	min	average
500	13.69	32.97

Table A.3: max, min and average projected spot price in SE3 2030, with peaks over 500 €/MWh reduced to 500 €/MWh

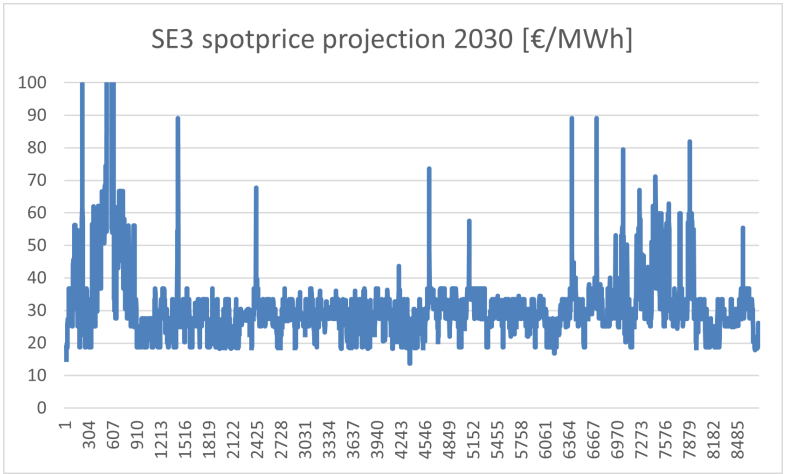

Figure A.12: Projected spotprice in SE3 2030.

A.5 Energy balance 2019

$$Q_{demand,node1(t)} \leq Q_{pipe21,node1(t)} - Q_{pipe12,node1(t+1)} + \sum_{u=1}^{U} Q_{node1(u,t)}$$

$$Q_{demand,node2(t)} \leq Q_{pipe12,node2(t)} - Q_{pipe21,node2(t+1)} - Q_{pipe24,node2(t+1)}$$
$$+Q_{pipe42,node2(t)} + Q_{pipe52,node2(t)} + Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} + \sum_{u=1}^{U} Q_{node2(u,t)}$$

$$Q_{demand,node3(t)} \leq Q_{pipe43,node3(t)} + \sum_{u=1}^{U} Q_{node3(u,t)}$$

$$Q_{demand,node4(t)} \leq Q_{pipe54,node4(t)} + Q_{pipe24,node4(t)} - Q_{pipe42,node4(t+1)}$$
$$-Q_{pipe43,node4(t+1)} - Q_{pipe45,node4(t+1)} + \sum_{u=1}^{U} Q_{node4(u,t)}$$

$$Q_{demand,node5(t)} \leq Q_{pipe45,node5(t)} - Q_{pipe54,node5(t+1)} - Q_{pipe52,node5(t)}$$
$$-Q_{pipe56,node5(t+1)} + \sum_{u=1}^{U} Q_{node5(u,t)}$$

$$Q_{demand,node6(t)} \leq Q_{pipe56,node6(t)} + \sum_{u=1}^{U} Q_{node6(u,t)}$$

A.6 Limitations plants

$$\sum_{t=1}^{T} Q_{RosHOB4(t)} \leq Maxload_{RosHOB4} * Roslim$$

$$\sum_{t=1}^{T} Q_{RosHOB5(t)} \leq Maxload_{RosHOB5} * Roslim$$

$$\sum_{t=1}^{T} Q_{AngHOB1(t)} \leq Maxload_{AngHOB1} * Anglim$$

$$\sum_{t=1}^{T} Q_{AngHOB2(t)} \leq Maxload_{AngHOB2} * Anglim$$

$$\sum_{t=1}^{T} Q_{AngHOB3(t)} \leq Maxload_{AngHOB3} * Anglim$$

$$\sum_{t=1}^{t_{save}} Spin_{(SaveHP3(t_{save})} = 0$$

A.7 Limitations Rya

Efficiency	Value
A	0,28
B	0,51
C	0,21
D	0,23
Waterlim	220

Table A.4: The constants calculated based on a percentage of rated power a single plant is compared to the total rated power in the area.

$$A * \sum_{u=HP}^{U} Q_{Rya,HP(t)} + B * \sum_{u=Rya,CHP}^{U} Q_{Rya,CHP(t)} + C * Q_{Rya,HOB8}$$
$$+D * Q_{ack,cha(t)} \leq Waterlimit$$

A.8 Sewage temperature

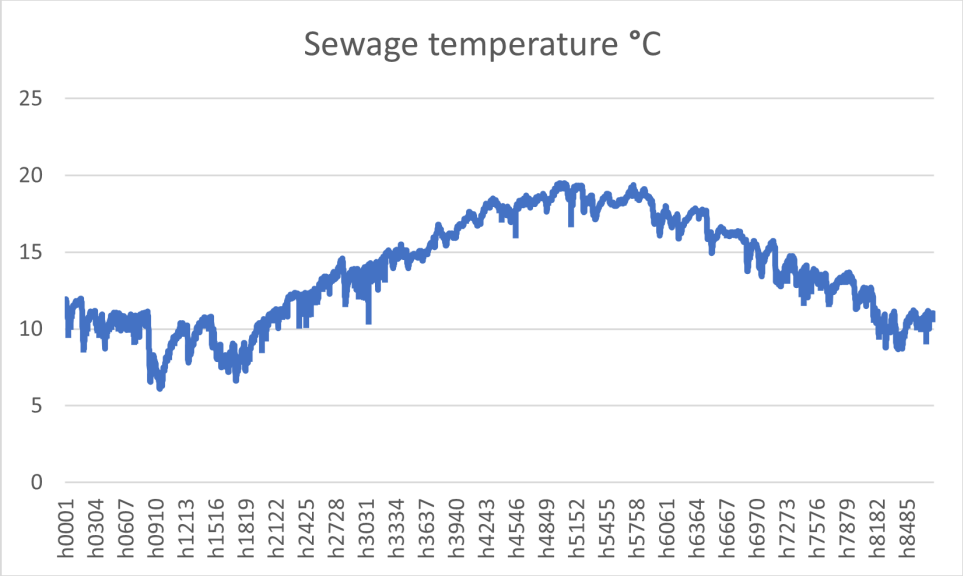

Figure A.13: Temperature of sewage during 2019.

A.9 Fineplant

Parameter	Value
OM_{var}	5
$starttime$	0
$Maxload$	10000
$Minload$	0
$\eta_{fineplant}$	1
$Fuel_{Fineplant}$	200
$Cost_{start}$	100

Table A.5: The set parameters for the Fine plant.

A.10 Energy balance equation for new accumulator tank investment

$$Q_{demand,node1(t)} \leq Q_{pipe21,node1(t)} - Q_{pipe12,node1(t+1)} + \sum_{u=1}^{U} Q_{node1(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

$$Q_{demand,node2(t)} \leq Q_{pipe12,node2(t)} - Q_{pipe21,node2(t+1)} - Q_{pipe24,node2(t+1)} + Q_{pipe42,node2(t)} + Q_{pipe52,node2(t)} + Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} + \sum_{u=1}^{U} Q_{node2(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

$$Q_{demand,node3(t)} \leq Q_{pipe43,node3(t)} + \sum_{u=1}^{U} Q_{node3(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

$$Q_{demand,node4(t)} \leq Q_{pipe54,node4(t)} + Q_{pipe24,node4(t)} - Q_{pipe42,node4(t+1)} - Q_{pipe43,node4(t+1)} - Q_{pipe45,node4(t+1)} + \sum_{u=1}^{U} Q_{node4(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

$$Q_{demand,node5(t)} \leq Q_{pipe45,node5(t)} - Q_{pipe54,node5(t+1)} - Q_{pipe52,node5(t)} - Q_{pipe56,node5(t+1)} + \sum_{u=1}^{U} Q_{node5(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

$$Q_{demand,node6(t)} \leq Q_{pipe56,node6(t)} + \sum_{u=1}^{U} Q_{node6(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx}$$

A.11 Energy balance equation for new investment plants

$$Q_{demand,node1(t)} \leq Q_{pipe21,node1(t)} - Q_{pipe12,node1(t+1)}$$
$$+ \sum_{u=1}^{U} Q_{node1(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node1(u,t)}$$

$$Q_{demand,node2(t)} \leq Q_{pipe12,node2(t)} - Q_{pipe21,node2(t+1)} - Q_{pipe24,node2(t+1)} + Q_{pipe42,node2(t)}$$
$$+Q_{pipe52,node2(t)} + Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} + \sum_{u=1}^{U} Q_{node2(u,t)}$$
$$-Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node2(u,t)}$$

$$Q_{demand,node3(t)} \leq Q_{pipe43,node3(t)} + \sum_{u=1}^{U} Q_{node3(u,t)}$$
$$-Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node3(u,t)}$$

$$Q_{demand,node4(t)} \leq Q_{pipe54,node4(t)} + Q_{pipe24,node4(t)} - Q_{pipe42,node4(t+1)}$$
$$-Q_{pipe43,node4(t+1)} - Q_{pipe45,node4(t+1)} + \sum_{u=1}^{U} Q_{node4(u,t)} - Q_{newacc,cha(t)}$$
$$+Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node4(u,t)}$$

$$Q_{demand,node5(t)} \leq Q_{pipe45,node5(t)} - Q_{pipe54,node5(t+1)} - Q_{pipe52,node5(t)}$$
$$-Q_{pipe56,node5(t+1)} + \sum_{u=1}^{U} Q_{node5(u,t)} - Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node5(u,t)}$$

$$Q_{demand,node6(t)} \leq Q_{pipe56,node6(t)} + \sum_{u=1}^{U} Q_{node6(u,t)}$$
$$-Q_{newacc,cha(t)} + Q_{newacc,dis(t)} * \eta_{hx} + Q_{new,node6(u,t)}$$

A.12 Total energy balance 2030 with new generation

$$Q_{demand,tot(t)} \leq Q_{acc,dis(t)} * \eta_{hx} - Q_{acc,cha(t)} - \sum_{node=1}^{6} Q_{newacc,cha(node,t)}$$
$$+ \sum_{node=1}^{6} Q_{newacc,dis(node,t)} * \eta_{hx} + \sum_{u=1}^{U} \sum_{node=1}^{6} Q_{(node,u,t)} + \sum_{u=1}^{U} \sum_{node=1}^{6} Q_{new(node,u,t)}$$

A.13 Full Load hours 2030 New investment

	with acc sum GWh	with acc FLH	no acc sum GWh	no acc FLH	diff FLH
Rya CHP	23.3	79.2	23.3	79.2	0.0
Save CHP3	129.5	1210.4	126.4	1181.2	29.2
HP1-2	264.7	4410.9	265.3	4421.1	-10.2
HP3-4	245.7	2457.0	250.4	2503.8	-46.8
Rya HOB8	22.9	190.6	31.2	260.2	-69.6
Ang 1-3	0.0	0.0	0.5	4.8	-4.8
Ask 1-2	0.0	0.0	0.2	8.0	-8.0
Sor 2,4	0.1	0.9	0.8	12.1	-11.2
HP node1	12.0	4080.1	11.9	3981.2	98.9
HP node2	365.8	4190.6	207.7	4161.3	29.3
HP node3	67.2	4209.4	42.8	3819.6	389.8
HP node4	134.1	4168.5	215.4	4057.7	110.8
HP node5	0.0	0	29.0	3834.3	-3834.3
HP node6	43.1	4139.7	43.5	3770.4	369.3
CHP node1	1.1	3987.2	2.5	3744.7	242.4
CHP node3	0.0	0	30.4	3585.5	-3585.5
CHP node4	0.0	0	13.9	3878.3	-3878.3
CHP node6	59.1	4075.5	90.1	3582.3	493.3

Table A.6: Diff is the case with new acc tank investment subtracted with no new acc investment.

A.14 2019 Sensitivity Analysis

	base		2x bio		0.5x bio		2x elprice		0.5x elprice		2x fossil		1.5x fossil	
With acc or not	with	no	with	no	with	no	with	no	with	no	with	no	with	no
Rya CHP	66	64	161	203	55	59	2075	1972	0	0	0	0	3	3
Rya HOB8	1939	1796	0	0	3099	3070	220	289	1981	1854	2063	2059	2048	2037
Save HOB3	3522	3496	3081	2961	3917	4161	3974	4008	3162	3132	3504	3693	3507	3653
HP1-2	4813	4808	4817	4833	4631	4465	2923	3089	4859	4835	4827	4792	4824	4790
HP3-4	3997	3765	4348	4144	2438	2203	1267	1234	4344	4137	4029	3747	4021	3744
Ros HOB4	0	4	4	51	0	1	0	3	0	18	0	5	1	18
Ros HOB5	461	716	1500	1500	423	545	233	360	545	766	498	594	496	617
Save HOB1	495	633	1143	1259	475	525	365	381	538	668	510	572	514	559
Save HOB2	0	1	1	3	0	0	0	0	1	1	0	25	0	1
Ang HOH1-3	64	63	67	0	63	71	63	62	64	63	69	69	65	65
Ask HOB1-2	79	75	110	99	60	57	74	70	77	72	52	47	59	57
Sor HOB2,4	8	39	152	317	5	23	10	27	21	72	16	61	19	61

Table A.7: FLH 2019, for each sensitivity case, with and without accumulator tank.

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