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Optimization modeling of the district cooling system in Gothenburg

Master's Thesis in Sustainable Energy Systems

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Department of Architecture and Civil Engineering
Division of Building services engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Göteborg Energi is the sole provider of district cooling in the Gothenburg. The district cooling system (DCS) is currently expanding. The installed capacity in 2030 will be double the current capacity. Besides, a thermal energy storage (TES) in the form of a tank that stores cold water will be installed in the system by 2024. The impact of future investments on the operation of the system must be investigated. Further, the district cooling network is also modeled and an effective method to model the district cooling network into a numerical model is developed.

To evaluate the effect of the different investments and the interaction of the cooling system with the heating and electricity sectors, an optimization study through the software GAMS has been conducted in this thesis. The model has been formulated as a mixed integer optimization problem. Models and cases were created to examine different scenarios. Model 1 dealt with the optimization of the chilled water generation in the DCS. Further, three different cases are setup within model 1 to analyze different scenarios. Case 2018 compared the optimal operation of the district cooling system to a hypothetical best alternative case of having chillers in individual buildings. The impact of the thermal energy storage on the system was investigated in case 2024. In case 2030, different scenarios were considered to evaluate the impact of the developments in the heating and electricity systems on the operation of DCS. In model 2, the chilled water generation and distribution are optimized together. Like model 1, model 2 also consists of different cases to investigate different scenarios. Case 2018 compared different methods of effectively modeling the network in numerical models. The two methods considered in this case are the 'Fixed pumping parameter' method and the 'Linked cost functions' method. In case 2024, the impact of the tank was investigated when modeled along with the network. The optimization was performed on an hourly basis and the prices of heat were obtained from a corresponding model of the DHS. The electricity price profiles were obtained either from spot market prices or from modeled future prices.

It was found from model 1 that the district cooling system was more economical and environment friendly that the hypothetical best-case alternative of a conventional cooling system. The results from model 1 also showed that the installation of the TES in the system helps achieve significant savings in the system. The major result from 'model 1 - case 2030' was that future investments in the district cooling system depend largely on the developments in the electricity system. From model 2, it was concluded that the linked cost functions method has a more detailed representation of the network and is a more effective method to model the network. Lastly, in 'model 2 – case 2024', it was seen that the optimal operation of the TES depended on the control strategy of the TES and the location of the chillers.

Keywords: District cooling, optimization modeling, network modeling, thermal energy storage.

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Shravan Kumar, Gothenburg, June 2020

Contents

Abbreviations and Symbols

Abbreviations

DC	District cooling
DCS	District cooling system
CHP	Combined Heat and Power
COP	Coefficient of Performance
SES	Seasonal Thermal Energy Storage
DH	District Heating
DHS	DHS
GAMS	General Algebraic Modeling System
LP	Linear Programming
MILP	Mixed Integer Linear Programming
TES	Thermal Energy Storage

Symbols

T Temperature [°C]
ΔT Temperature difference [°C]
E Energy [MWh]
P Chilled water generation unit
α Power to Heat ratio [-]
V Volume [m3]
C Cost [MSEK]
q Chilled water generation [MWh]
Q Storage charge or discharge [MW]
η Efficiency [-]
C_p Specific heat capacity [kJ/kg]
ρ Density [kg/m^3]
ΔP Pressure drop [KPa]
v Velocity [ms^{-1}]
g Acceleration due to gravity [ms^{-2}]
$\dot{Q}$ Flow [m^3/h]
A Area [m^2]
l Length[m]
d Diameter[m]
f Friction coefficient [-]
K Loss coefficient [-]
k Roughness coefficient [m]
Re Reynolds number [-]
v Kinematic viscosity [m^2/s]
P_p Pumping power [KW]
El_t Electricity prices [SEK/MWh]

VC variable cost [SEK/MWh]
SC Startup cost [SEK]
D Cooling demand [MWh]
RU Ramp up [MW]
RD Ramp down [MW]
On binary variable to indicate the status of a unit [-]
t_{sh} Shut down time [hours]
t_{st} Start up time [hours]
chr Plant charge [MW]
dis Cluster discharge [MW]
char Total charge [MW]
disc Total discharge [MW]
t Time Variable [hour]

Chapter 1: Introduction

The greatest challenge faced by the world right now is global warming. To limit the rise of temperatures around the globe, it is crucial to reduce emissions arising from the use of fossil fuels across various sectors. Reducing energy consumption is an effective approach to reduce emissions. Energy use in buildings accounts for about 37 % of the total primary energy use. About half of the energy consumption in buildings is for space heating and cooling. Space cooling in buildings can be provided by installing chillers, air conditioners or heat pumps in each building or by district cooling (DC). The use of district cooling can reduce the total energy consumption compared to inbuilding installations, by increasing chilled water generation efficiency in centralized plants and make more use of renewable energy. [1]

The future of the District Cooling Systems (DCSs) can be described as a smart DCS with an optimal interaction with the electricity grid and the DHS (DHS). With the increasing share of variable renewable electricity in the energy system, there is a need for flexibility in the system. There are several methods to add flexibility, such as combining different systems, adding storage in the system and increasing supply and demand flexibility. [2]

In the city of Gothenburg, the utility company Göteborg Energi is the sole provider of district cooling. The chilled water for cooling is generated from three different methods: free cooling from the river, absorption chillers, and electric chillers. In the year 2018, the installed capacity of chillers is 54.5 MW. By the year 2030, Göteborg Energi plans to increase the installed capacity up to 132.5 MW. Also, Göteborg Energi plans to invest in a Thermal Energy Storage (TES) in the form of a tank that can store chilled water. [3]

In 2018, about 50% of the chilled water generation is from electric chillers. Electric chillers are the expensive peak load generation in the DC system. With an expansion of the system, the chilled water generation costs will also continue to increase. The DCS in Gothenburg continues to use electricity to run electric chillers to meet peak demand. The electricity consumption from the chillers leads to a large additional demand in the electricity system and can potentially stress the electricity grid. It is to be examined, whether the DCS relieves or burdens the electricity grid as compared to using individual chillers. Thus, the effectiveness of a DC system must be analyzed. This is done by comparing the optimal operation of the DC system with a hypothetical best alternative case of using individual chillers to meet the cooling demand.

The usage of TES in the system can replace the expensive peak load generation and hence reduce the chiller running costs [4]. Also, the thermal energy storage in the system can help reduce variations in the cooling demand and hence increase the efficiency of the chillers [5]. The performance of the thermal energy storage will depend on several factors in a DCS: temperature, demand for cooling, electricity prices, the constraints from the network, and prices of heat. Thus, the impact of having a TES in the DCS is to be examined.

Further, the performance of DCS in Gothenburg is dependent on the electricity system and the DHSs. The changes in the future electricity and DHS could thus have a significant impact on future investments in the DCS. Thus, the operation of future DCS must be examined. Besides, the impact of the changes in the electricity and the DHS on the operation of the DCS should also be analyzed.

A major problem in most models of the district cooling system is the representation of the DC network in the model. A physically-based model can indicate the effects of the district cooling network well, but it is computationally expensive to run optimization programs for large time periods in physical models [6]. Whereas, in a numerical model, the topology of the network is not represented accurately. Thus, for optimization modeling, an effective method must be devised to model the network accurately in numerical models.

1.1 Purpose

The purpose of this thesis is to evaluate the optimal operation of the DCS and the DC network in Gothenburg and investigate the impact of future investments in the system. Further, the thesis also explores different methods of modeling the network and integrating the network into numerical models of the DCS.

The evaluation will be performed by creating different optimization models of the DCS. These models will represent different scenarios where the effect of installing thermal energy storage is studied and various methods of including the network in the optimization model are examined and compared. The optimizations shall yield the total yearly chiller running costs as well as the hourly marginal price for generating chilled water and the hourly chilled water generation from the chillers. Also, the effects that differing electricity prices will have on the DCS are studied. The effect of the corresponding developments in the DHS is also examined.

1.2 Research questions

This thesis aims at answering the following questions.

- How effective is the DCS compared to a case of having individual chillers in buildings?
- What is the optimal functioning of the DCS and how different is it from the practical operation ?
- What impact does a TES have on the DCS and how does it affect the chilled water generation from different chillers?
- How is the performance of the DCS in 2030 and what are potential investments in the system?
- How will different development scenarios in the electricity and the DHS affect the performance of the DCS in 2030?
- How does the inclusion of the DC network affect the results of the model?
- What are the different possible methods to effectively model the network in a numerical model?

1.3 Scope

The scope of modeling in this thesis will include a model of the DCS in Gothenburg. The model consists of the various chiller units in the DCS, the TES, and the network of the DCS. The main aim of the model is to optimize the chilled water generation and the chiller water distribution. The thesis also covers the alternative case of having conventional cooling systems and provides a comparison between the DCS and the conventional cooling system. Further, in the framework of the thesis, different methods are devised for modeling the district cooling network in numerical models. Within the scope of this thesis, both current and future DCS systems are modeled. The current district cooling system is the DCS in 2018 and the future DCSs are the systems in 2024 and 2030.

1.4 Limitations and delimitations

The prices of heat and electricity must be input to the model as fuel price. The price of electricity is retrieved from an external source and is not modeled internally. The prices of heat are obtained by running a corresponding model of the DHS in Gothenburg.

The district heating network of Gothenburg is connected to several other neighboring district heating networks and district heat can be exported and imported between these networks. In this thesis, only the heat load in the Gothenburg network is modeled and no import or export is considered.

It will be assumed that there are no feedback effects between the DCS, the DHS, and the electricity system. In other words, the use of electricity and heat in the DCS (electric and absorption chillers) will not affect the price of electricity and heat. In reality, the demand for electricity in the DC system will have some effect on the price of electricity and heat, but since the studied system is relatively small, the effects can be neglected.

The constraints in model 1 are limited to those concerned with the running of the chillers. The constraints due to the network such as congestions are not included in the optimization in model 1. Model 1 only deals with the generation of chilled water to meet the cooling demand but does not include the distribution of the chilled water. Whereas, model 2 includes the constraints in the network and the pumping cost. Thus, the model 2 includes both the generation and distribution of chilled water.

No installation costs or fixed costs will be considered when performing the optimizations. The only costs that are considered are the running costs, pumping costs, and startup costs of the chillers. The running costs of the chillers are just the cost of electricity and heat required to run the chillers. The costs of operating the condenser pumps and cooling towers are also excluded from the model.

Chapter 2: Background

The main aim of this thesis is the optimization of the DCS in Gothenburg and analyzing the impact of investments in the future DCS. Therefore, it is important to provide some background about the system for a better understanding of the results. This chapter explains DCS in general, the current DCS in Gothenburg, and the district cooling network. Future investments in the system such as the TES are also presented.

2.1 District Cooling System

The DCS is a setup where cooling energy is centrally generated and is supplied to end-users using water or another secondary fluid as an energy carrier and thus increasing economy of scale. DCSs deliver chilled water or a secondary fluid to consumers in a more efficient, reliable, and environmentally friendly way than the inbuilding air conditioners. The DCS has higher energy efficiency and lower emissions as compared to chillers or air conditioners used individually. [7]

At the same time, the DCS involves large investment and operating costs. Also, there are significant energy losses when transporting water in the pipes in the district cooling network. Thus, a high load density is necessary to cover the large capital costs which are about 50 % of the total cost of the system. This makes DC systems more attractive in urban areas with a large population density and high-density buildings with large thermal loads. [8]

A DCS can consist of different chilled water generation units such as absorption chillers, electric chillers, and free cooling. Thus, the fuels used in the DCS are heat and electricity. District cooling is a relatively new technology and very few statistics have been collected on the subject. However, statistics show that there is a sharp increase in the use of district cooling due to its positive effects on both the environment and the economy. [1]

2.2 The DCS in Gothenburg

The DCS in Gothenburg supplies cold water through pipes for space cooling. The DC system in Gothenburg generates chilled water from absorption chillers, free cooling sources from the river, and electric chillers. In Gothenburg, the cooling demand during the winters is satisfied using the cooling from the river. The river water is used to cool the return water from the buildings in heat exchangers. The usage of the river for cooling is limited by a constraint on the cooling production corresponding to a withdrawal of 16 000 m^3/h (4.44 m^3/s) at a temperature rise of 10˚C [9]. This makes the DCS in Gothenburg quite different from other systems. The cooling obtained from the river is referred to as “Free Cooling” in this thesis.

In addition to the free cooling, Göteborg Energi operates electric and absorption chillers to meet the cooling demand during the warmer periods of the year. The electric chillers use electricity as fuel while the absorption chillers use both electricity and the heat from the DHS. The chilled water generation systems and their technical details are specified in Table 1 [3].

Table 1: Chilled water generation units in 2018

Type of unit	Unit	Capacity [MW]	Primary Fuel
Absorption chillers	Rosenlund	22	DH and electricity
	Svenska Massan	3.4	DH and electricity
	Gullbergsvass	3	DH and electricity
	Odin	2	DH and electricity
	Ceres	1	DH and electricity
	Arkaden	1.1	DH and electricity
Electric chiller	Rosenlund	10	Electricity
	Svenska Massan	1.2	Electricity
	Gullbergsvass	1.25	Electricity
	Odin	2.2	Electricity
	Ceres	0.6	Electricity
	Arkaden	4.25	Electricity
	Sahlgrenska	2.5	Electricity

2.3 The district cooling network

The district cooling network consists of pipes that are used to supply the chilled water from the district cooling plants to the demand sites. The network consists of pipes of varying diameters. The pipes are dimensioned based on the maximum flow through the pipes. The dimensioning of pipes is discussed later. The pipes in the network are mostly made of plastic i.e. SDR 11 and SDR17. Besides, in some parts of the network, stainless steel pipes are also used.

The DC network is shown in Figure 1. The red dots in Figure 1 indicate the location of the chiller units connected to the network. The blue dots indicate the chiller units which are cooling islands. The cooling islands are usually chillers that are installed on the building sites and are used to meet the cooling demand at these buildings. The network consists of a main pipe which has a diameter of 630 mm.

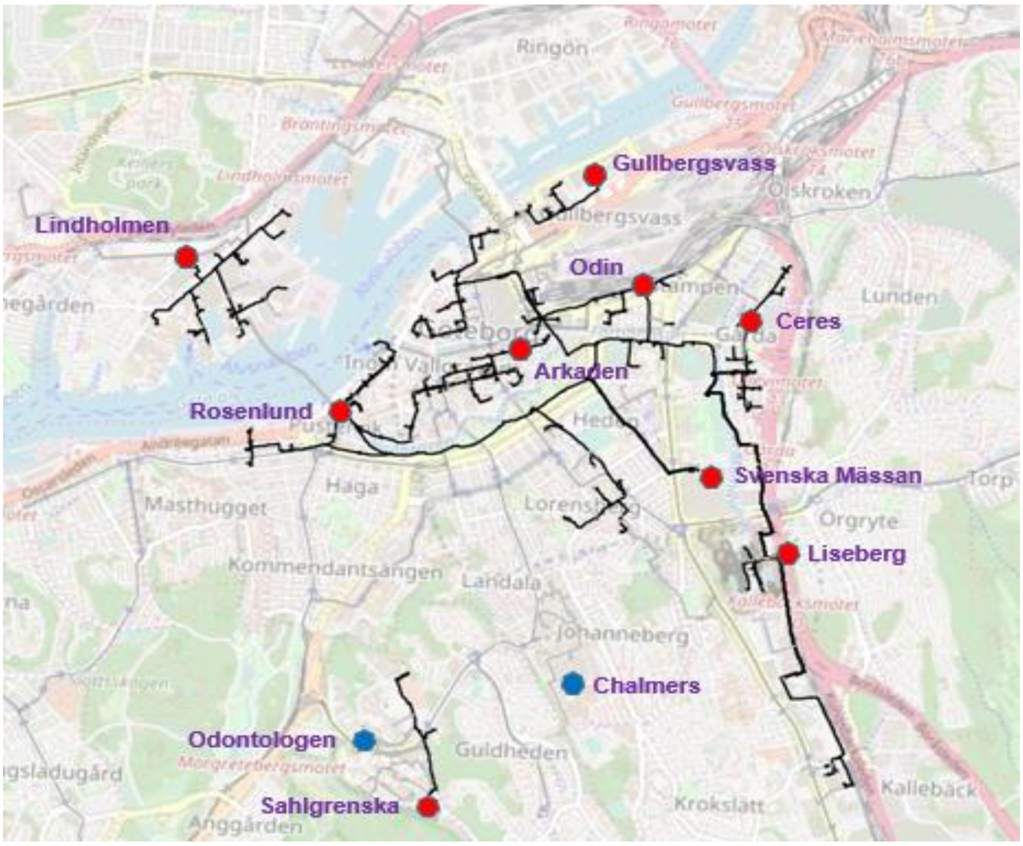


Figure 1: DC network [10]

2.3 Operation of the DCS in Gothenburg

The operation of the Gothenburg DCS is governed by a few different factors, namely the river temperature, the availability of excess heat in the DHS, and the cooling demand. The river water is used to provide cooling as long as the river temperature is below 6˚C. Therefore, the river water is used for cooling during the winter months i.e. from December to February. During spring and autumn, a combi operation between the chillers and free cooling exists. During this period, the river water temperature is greater than 6˚C but less than the return water temperature. The combi operation first uses the river water to cool the return water, as long as the temperature difference is less than the permissible value in the heat exchanger. The chillers are then used to further cool down the water to the supply temperature.

In summer, when there is a high demand for cooling, the absorption and electric chillers are run. The absorption chillers use heat as fuel. This heat is obtained from the DHS. In the summers, there is excess heat available in the DHS since the demand for heat is low. The excess heat arises from the industrial waste heat from the refineries and waste incineration. This excess heat is used in the absorption chillers. This excess heat is available to the DCS at zero cost. Hence, absorption chillers have very low running costs in the summer. The system is run based on merit order and the absorption chillers form the baseload. The electric chillers are used as peak load technology and are used to meet the peaks in the demand in summer. The operation of the system is shown in Figure 2.

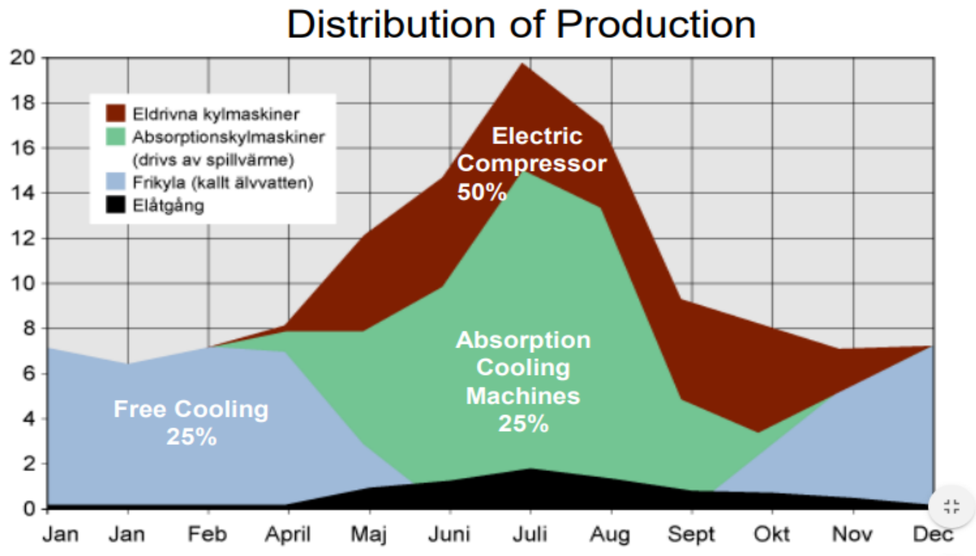


Figure 2: Distribution of district cooling production in Gothenburg [11]

2.4 Investment plans for Future DCS in Gothenburg

Since this thesis deals with modeling the future DCS in 2024 and 2030, it is important to state the reason for choosing these two years. As discussed earlier, Göteborg Energi plans to install thermal energy storage in the DCS in the form of a tank that stores cold water. It is planned to invest in the thermal energy storage by 2024. Hence, this year was chosen to analyze the immediate impact that the storage will have on the DCS. Also, the current investment plans for the DCS consist of the addition of capacity until the year 2030. There will be investments in the system after 2030. But it is not in the scope of this thesis to consider the investments after 2030. Hence it is important to analyze the optimal operation of the system in 2030. Also, the effectiveness of the thermal energy storage in 2030 is to be examined [3].

The plans for the DCS in Gothenburg mostly involve the expansion of the network for increasing the number of connected customers and hence investments in chilled water generation capacity. The existing absorption chillers have a functional issue described by Göteborg Energi as the "ΔT (temperature difference) problem". The change in temperature of the warm water in the absorption chiller is not high enough for it to be returned to the district heating network. However, to maintain the mass balance in the system, the water must be returned to the DHS. Hence, this leads to larger flows in the DHS causing increased costs. Thus, no plans to install new absorption chillers in the system exist as of now [3]. The installed capacity is thus increased by installing electric chillers and thermal energy storage. Installing heat pumps instead of electric chillers are also being considered, but this thesis does not consider heat pumps. Tables 2 and 3 show the list of chillers in the year 2024 and the year 2030 [12].

Table 2: Chilled water generation units in 2024

DCS in 2024			
Type of unit	Unit	Capacity [MW]	Primary Fuel
Absorption chillers	Rosenlund	22	Heat and electricity
	Svenska Massan	3.4	Heat and electricity
	Gullbergsvass	3	Heat and electricity
	Odin	2	Heat and electricity
	Ceres	1	Heat and electricity
	Arkaden	1.1	Heat and electricity
Electric chillers	Rosenlund	30	Electricity
	Svenska Massan	1.2	Electricity
	Gullbergsvass	8.25	Electricity
	Odin	2.2	Electricity
	Ceres	6.6	Electricity
	Arkaden	4.25	Electricity
	Sahlgrenska	2.5	Electricity
TES	Chilled water tank	30	n/a

Table 3: Chilled water generation units in 2030

DCS in 2030			
Type of unit	Unit	Capacity [MW]	Primary Fuel
Absorption chillers	Rosenlund	22	Heat and electricity
	Svenska Massan	3.4	Heat and electricity
	Gullbergsvass	3	Heat and electricity
	Odin	2	Heat and electricity
	Ceres	1	Heat and electricity
	Arkaden	1.1	Heat and electricity
Electric chillers	Rosenlund	60	Electricity
	Svenska Massan	11.2	Electricity
	Gullbergsvass	8.25	Electricity
	Odin	2.2	Electricity
	Ceres	6.6	Electricity
	Arkaden	4.25	Electricity
	Sahlgrenska	2.5	Electricity
	Almedal	5	Electricity
TES	Chilled water tank	30	n/a

The capacity of the thermal energy storage which has been specified as 30 MW indicates the discharging capacity of the tank. The storage capacity of the tank in terms of energy is 200 MWh. The charging capacity of the tank is not limited since the charging capacity depends on the network and the pumping capacity. [3]

2.5 DHS in Gothenburg

The DCS is linked with the DHS by the use of heat in the absorption chillers. The heat from the DHS is used as fuel in the absorption chillers and hence, the prices of heat must be input to the model of the DCS. Unlike electricity prices, the prices of heat for 2018 are not readily available. The prices of heat are determined from an optimization model of the DHS. Similarly, for the models which represent the future DCSs, the prices of heat are obtained from corresponding models of the DHS. Thus, it is important to describe the DHS in Gothenburg and how it is modeled.

The DHS is built and operated by Göteborg Energi. The basic concept of district heating is to make use of local fuel or heat source, that otherwise would be wasted, to satisfy the local heating demand. The DHS in Gothenburg has a large input of heat from the refineries and waste fired units. The heat from the refineries and incineration of waste constitutes a large part of the total heat in the system. The heat from these sources is referred to as industrial waste heat in this report. This industrial waste heat is available to Göteborg Energi at a very low cost and hence, it is optimal to maximize the use of industrial waste heat in the DHS. [13]

In addition to a supply of industrial waste heat, the system operates two large combined heat and power (CHP) plants, Sävenäsverket and Ryaverket. The CHP units are used to cover the baseload. These CHP units also produce electricity according to their respective power to heat ratios (α values). The generated electricity is sold to a spot market and hence additional income is generated. Also, two large heat pumps are operated. The heat pumps use cleaned sewage water as their cold sides. Göteborg Energi also operates a large number of small-scale heat generation plants as back-up and to cover peak loads. These plants are all boilers that are denoted as heat-only boilers (HOB), which simply means that they do not generate any electricity. All the heat generation facilities and their technical specifications in the current DHS are presented in Table 4. [13]

The DHS in Gothenburg is moving towards a cleaner production of heat. This means that the use of fossil fuels in the system is to be reduced. Göteborg Energi has plans to move to a fossil-free heat generation by the year 2030 [12]. The generation mix on the future models of the system is based on these plans. The major investments in the system are a thermal energy storage in the form of an accumulator tank and a new biofuel-powered combined heat and power plant. Also, plants that utilize biofuels are prioritized to a greater extent over plants based on fossil fuels. Thus, most plants that run on fossil fuels are either phased out or they are converted to biofuel-powered plants.

The generation mix considered for future models is presented in the appendix.

Table 4: Heat production units

Type of unit	Unit	Capacity [MW]	Primary Fuel
Excess heat	Renova	185	Municipal waste
	Preem	60	Industrial excess
	ST1	85	Industrial excess
CHPs and HPs	Sävenäs CHP	110	Wood chips/Natural gas
	Rya CHP	295	Natural gas
	Högsbo CHP	85	Natural gas
	Heat pumps Rya HP 1-2	60	Electricity
	Rya HP 3-4	100	Electricity
Heat only boilers	Rya HOB1	50	Wood pellets
	Rya HOB2	50	Wood pellets
	Sävenäs HOB1	90	Natural gas
	Sävenäs HOB2	60	Bio-oil
	Angered HOB1	35	Bio-oil
	Angered HOB2	35	Bio-oil
	Angered HOB3	35	Bio-oil
	Rosenlund HOB1	140	Bunker oil
	Rosenlund HOB2	140	Bunker oil
	Rosenlund HOB3	140	Bunker oil
	Rosenlund HOB4	140	Natural gas
	Tynnered HOB	20	Fuel oil

2.5.1 The heat demand

The heat demand is the most important input into the model. The heat demand for the year 2018 is determined by looking at heat generation data from various units. The hourly production data is summed up to calculate the demand in the year 2018.

For the models representing the future DHS, the demand in the corresponding years must be projected. The demand in a future DHS in the year 2030 is estimated using the method developed by Holm and Ottoson [13]. The demand for heat is reduced by the increased efficiency measures in the buildings, whereas, the demand will increase with an increase in the number of connections to the DHS. A study conducted to determine the future district heating demand in Gothenburg regions showed that the demand for heat will stay constant or increase by a very small level of about 2% [14]. This study claims that the increased demand from the new connections will balance out the reduction in demand due to the efficiency measures.

Despite the total annual demand remaining almost constant, the profile of the demand curve changes to a significant extent. This is because, the space heating demand in the winter is reduced to a large extent due to the increasing efficiency measures, whereas in the warmer periods where the hot water demand is greater than the space heating demand, the total demand is increased as the new connections to the system lead to an increase in the total demand. Hence, the demand profile of the future DHS is different from the present demand profile. This is a key aspect of demand projection [13].

2.6 Thermal energy storage

The future energy system, including electricity, heating, and cooling sectors is transforming into a system with more intermittencies than the current system. The intermittencies stem from an increased share of variable renewable energy in the system in the form of solar and wind energy. The DCS is directly affected by these developments in the electricity system as electricity is used in both electric and absorption chillers. During hours when the share of generation from the variable renewables is very low in the system, expensive peak power plants fired by fossil fuels must be operated to meet the electricity demand. This is neither economically nor environmentally optimal. During such hours, the electricity prices are at the highest. To prevent such large variations in the system, various measures are being discussed. Installing a thermal energy storage (TES) in the system in one such measure. The TES can be used to store energy during peak demand hours and hence reduce electricity consumption during high electricity price hours. Besides, the TES can help make use of the waste heat available in the summer to run the absorption chillers at peak capacity and store the generated chilled water. The stored energy can be discharged to meet peak demands in the system.

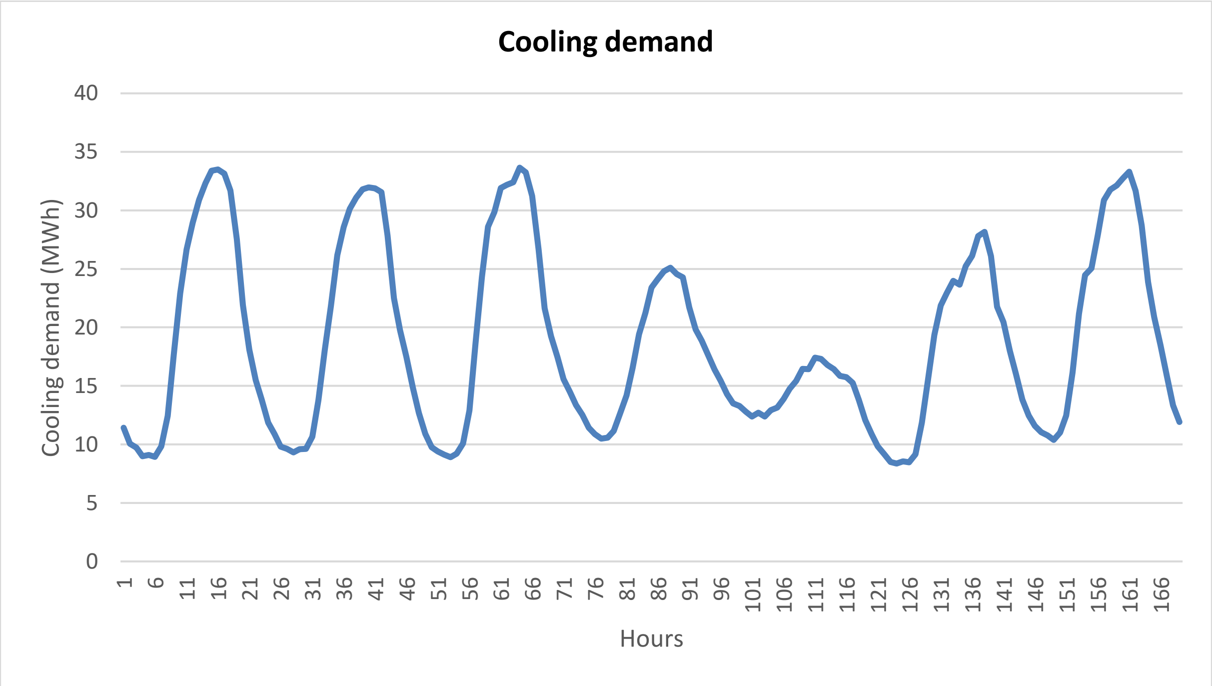


Figure 3: Cooling demand in the last week of July 2018

The cooling demand in a DCS can fluctuate heavily between different hours of the day. Figure 3 shows the cooling demand in DCS in Gothenburg in the last week of July 2018. The diurnal variation in the demand is as high as 25 MW. To meet the varying demand many starts, and stops are required which may reduce the lifetime of the chiller and reduce its efficiency. This problem can be solved by using a TES. The storage can then be charged during low demand hours and the discharge from the storage can be used to meet the peak demands. The high diurnal variation in cooling loads during warm summer days gives a high incentive for TES in DCSs. Also, the storage can help reduce the total installed capacity of chillers substantially. The storage will then reduce the investment cost and the operating cost for chillers installed for the total peak capacity [15].

TES can be classified into two broad categories, short-term storage, and long-term storage. Examples of short-term TES are rock and earth beds, cold water tanks, and phase changing materials. The short-term storages are most suited for handling diurnal variations. On the other hand, long term TES is suited to handle seasonal variations in the demand. Examples of long-term cold storages are aquifer thermal energy storage, borehole thermal energy storage, and cavern thermal energy storage [4].

2.6.1 Thermal energy storage in a chilled water storage tank

The most common type of short-term thermal energy storage in a DCS is a tank that stores chilled water. The supply and return lines of the network are directly connected to the tank. The chilled water from the chillers is pumped into the tank during low demand hours. The stored chilled water is then discharged during high demand hours to complement the chillers to meet the demand.

Tanks are typically constructed of steel or pre-stressed concrete. The ambient temperature is typically higher than the temperature of the water in the cold storage tanks and heat load from the environment can be a major cause of inefficient operation of the system. Thus, tank surfaces are properly insulated including a high-integrity exterior vapor barrier to prevent the chilled-water from unwanted warming and to minimize ingress of moisture and condensation into the insulation layer [16].

The loss of energy from a chilled water tank depends on the temperature of the stored water and the ambient temperature. The relationship between the two temperatures is defined in equation 2.1 [17]

$$Q_{loss} = \frac{T_{water} - T_{outdoor}}{h_{tank}} \qquad 2.1$$

Here, T_{water} is the temperature of the water inside the tank and $T_{outdoor}$ is the temperature of the surroundings. h_{tank} is the heat transfer coefficient of the tank wall. The calculation of the h_{tank} includes several uncertainties as h_{tank} is the total heat transfer coefficient of the tank wall material, the insulation, and the convection on the inside and the outside of the tank. Generally, the energy loss from a chilled water storage tank per day is between 2-5% of the stored energy.

The active volume in a water accumulator tank required for a given amount of energy to be stored can be calculated according to equation 2.2.

$$V_{Tank} = \frac{E_{Tank}}{C_{p,water} * \rho_{water} * \Delta T_{water}} \qquad 2.2$$

Where E_{Tank} is the amount of energy (in Joules), ρ_{water} is the density of water and $C_{p,water}$ is the heat capacity of water per kg. ΔT_{water} is the temperature difference between the supply and return water in the system. The lowest temperature in the tank would be equal to the district cooling supply. The active temperature difference in a DCS is between 10-12°C. The actual volume of the tank might be larger than the volume calculated from equation 2.2 due to increase in volume from construction and operational purposes [17].

The capital cost of a chilled water storage tank consists of the cost of construction the tank, installation costs, and the cost of connecting the tank to the network. Based on previously installed thermal energy storage tanks in Sweden, an expression for an estimation of the construction and installation costs of an accumulator tank is made [18].

The construction costs are calculated by

$$C_{tank} = 1.55 * 10^7 * \ln(V_{tank}) - 1.39 * 10^8 \qquad 2.3$$

Where C_{tank} is the cost of constructing the tank in SEK and V_{Tank} is the actual volume of the tank in m3.

The installation costs can be approximated as below

$$C_{installation} = 157 * V_{Tank} + 6\,000\,000 \qquad 2.4$$

Where $C_{installation}$ is the installation costs in SEK. The costs for connecting the tank to the network are hard to generalize as it varies in each case based on the network and the tank. The costs presented above can be used to approximate the investment costs of the tank. The tank has a technical lifetime of 25-30 years [19].

2.7 Literature review

Various previous studies focusing on the modeling of district cooling and DHSs have been conducted. These studies deal with the simulation of the system operation, the best design of generating plants, or on optimal capacity and utilization of a thermal storage.

The optimization models of the DHS are considered since they are quite similar to the DCS models. Romanchenko et al. [18] developed an optimization model that investigated the characteristics of interaction between DHSs and the electricity system, and how this interaction changed when moving from present to future electricity price curves. A mixed-integer linear programming model was developed in GAMS to study optimal operating strategies for DHSs. The model minimized the total cost of heat generation for a given DHS. Further developing this model, the impact of the implementation of thermal energy storage on the operation cost of the system, dispatch of various heat generation units, and environmental impact in a future DHS in Gothenburg were investigated by Holm et al [13]. This study made use of an optimization model in GAMS to determine the optimal functioning of a future DHS with and without thermal energy storage and hence evaluating the impact of the addition of storage into the system.

A few other models have analyzed the district energy system as a whole and looked at the dynamic optimization of the network. In contrast to the models above, Schweiger et al. [20] set up a thermo-hydraulic model of the district energy system to represent a framework for on-grid simulations, dynamic simulations, and optimization. The framework is based on the modeling language Modelica and the scripting language Python. This paper presented the continuous dynamic optimization of a DHS in a virtual city district. The network is first represented on a modeling tool and the optimizations conducted using a mixed-integer approach. An integrated energy model including electricity, district heating, and DCS was set up by Dominkovic et al. [21] to investigate the impact of District Energy Share in Cities on the Optimal Storage Sizing. A linear continuous optimization was built using the Matlab interface and Gurobi optimization solver. This paper also compared the socio-economic costs in the systems with and without storage. Also, the effectiveness of having storages in different systems was analyzed.

Söderman et al. [22] developed an investment model for optimization of the design and operation of a district cooling network. A Mixed Integer Linear Programming model was developed for the design optimization of a DC network in an urban region. The cooling demand profile from the year 2006 was used as input. A predicted future demand profile with an additional number of new potential consumers for the year 2020 was also used. The impact of a thermal energy storage in the system was also analyzed. This model optimizes both the structure of the DCS and its operation. Also, a thermo-hydraulic modeling approach is used for determining the optimal operation. This presents the most comprehensive model of a DCS and hence this model is chosen as a base for further modeling. But since this is an investment model, only the part which deals with the optimization of the operation is considered. The model is further presented in the next section.

Gang et al. [23] compared the operation of the DCS and the conventional cooling system. The DCS was designed, and the operation of the system was simulated using TRNSYS. The main aim of this study was to quantitatively assess the performance of the DCS in a new development area in Hong Kong. In this model the cooling demand in the buildings and installed capacity of the cooling systems is included. The performance of DCS is compared with the conventional cooling system i.e. individual in-building cooling systems with chillers installed at the demand site. The major conclusion from this study was that the district cooling system was more beneficial economically and used about 15 % less electricity than the conventional cooling system. Further, the DCS provided higher savings during the cold months when the operating load was less than 50 %. This was due to the higher efficiency of the chillers in the DCS

Jungbauer et al. [24] compared the operation of the conventional cooling systems and the district cooling systems in Europe. This paper uses a three-step method to create parameters for comparing DCS with the conventional cooling system. In the first step, practical measurements are made to compare the practical and theoretical energy efficiency ratios of the chillers. In the second step, a primary energy factor is calculated for the district cooling system. The primary energy factor is a measure of the efficiency of the DCS. In the third step, the PEF of the DCS is compared with the EER of the conventional cooling system. It was concluded that the district cooling system is better because of better utilization of locally available resources and a combination of different cooling sources.

Zhang et al. [25] analyzed the impact of the installation of the thermal energy storage in a DCS in hot summer and cold winter areas in China. The analysis method is based on measured data, which is obtained by long term monitoring and on-site measurements of the cooling season. The main aim was to investigate the operation modes of the DCS and determine the change in the energy efficiency of the system when the TES is installed. The chillers operate at partial load for a large proportion of the cooling time which reduces the energy efficiency of the system. Thus, the TES was installed in the system to increase energy efficiency.

Söderman et al. [26] developed a model for the structural and optimization of distributed energy systems. In this model, production, and consumption of electrical power and heat, power transmissions, transport of fuels to the production plants, transport of water, in the district heating pipelines and storage of heat are considered. This is similar to the model described in [22]. Additionally, in this model, the storage of heat in the pipelines is considered. A part of the model developed in this study is also used as a base for formulating models in this thesis.

Schwan et al. [27] illustrated a new approach to use Modelica to evaluate the dynamic behavior of district heating grids. The simulation approach presented can simulate thermo-hydraulics of a district heating grid. This approach simplifies the grid into a radial network and considers the pressure drops in the pipes to evaluate the dynamics of the system. Similar methods have been used in this thesis to compute the pumping costs.

Damien et al. [5] built a simulation model for DCS using the object-oriented language Modelica. The model consists of a cooling production plant, a network of pipes, and 6 substations. The approach is used to study interactions between substation cooling demand and cooling production plant efficiency. A simplified model of substations with ideal control and a performance-based model of electric chiller considering variable evaporator entering conditions were developed. These models are used to evaluate alternate control strategies for substations. This study describes the use of Modelica for building a physically-based model of a DCS.

Sandou et al. [28] developed an optimization model for DHSs. A global modeling approach has been described in this paper, where individual models of various components of the DHS such as boilers, pipes, heat exchangers, etc. were brought together into a single model of the system. The model has been simulated under different scenarios and was used to design new DHSs.

Oppelt et al. [29] presented a dynamic thermo-hydraulic model ISENA in their paper. ISENA can be applied for design and operational simulation of the district cooling network. The network-based model consists of a two-part model, a quasistatic hydraulic model, and a transient thermal model. The two-part model is based on tracking the transport of water through the whole network (Lagrangian method).

Sameti et al. [6] described different types of optimization problems, constraints, and techniques as well as the optimization tools used in district energy systems. This paper examines existing optimization models, the objective functions in these models, the tools used, and gives a review of these models and tools. Different software, solvers, and tools used for building and running the optimization algorithms are compared and their applicability to specific scenarios are defined. A major conclusion is that most models suffer from a very long computational time when large networks are considered and thus, a special tool is required for the model to be applicable in larger districts.

Khir et al. [30] investigated the optimal design and operation of a DCS so that the total investment and operational costs are minimized. The model optimizes chiller capacities, network layout and pipe diameters, storage tank capacity, and the district cooling production. The mixed-integer programming (MIP) models, developed in the study model the structural aspects and the pressure and temperature demands.

Schweiger et al. [31] presented a novel framework for representing and simplifying on-grid energy systems as well as for dynamic thermo-hydraulic simulation and optimization of district heating and cooling systems. The framework built consists of a physical model in Modelica coupled with a MIQCP based optimization algorithm.

Chapter 3: Method

This thesis deals with the modeling of the district cooling systems. The main aim of modeling is to determine the optimal functioning of the DCS and the impact of various future investments. To evaluate the different situations that could arise in the district cooling system in Gothenburg, an optimization model has been used. The optimization model uses hourly data regarding cooling demand, electricity prices, and heating prices and shows how the DC system is operated.

Different models and cases are set up to investigate different scenarios.

- Model 1: DCS model excluding the network.
  - Case 2018: DCS vs Individual chillers in 2018
  - Case 2024: DCS in 2024 with the inclusion of TES
  - Case 2030: DCS in 2030 with corresponding developments in electricity and DHS
- Model 2: DCS and DC network model.
  - Case 2018: Comparison of methods for modeling of network
  - Case 2024: DCS and network in 2024 with the inclusion of TES

These models can thus be a pre-study to investigate the operation of the DCS in the future and the impact of investments in the DCS.

The prices of heat must be input to the model of the DCS. The prices of heat are obtained for each case from a corresponding model of the DHS. The DHS is modeled similar to the DCS. Like the DCS, the DHS is operated based on merit order. Hence, the dispatch of power plants is based on their running costs. Since the only output expected from these models is the prices of heat, the model only provides a basic representation of the district heating, and a few technical details such as variable α values of the CHP plants are not included in the model.

3.1 Description of the DCS in Model 1

This DCS is modeled in the linear program solver software GAMS (General algebraic modeling software). A mixed-integer linear program is created, which solves an optimization problem. The objective of the optimization is to reduce the yearly total chiller running costs. The model has an hourly resolution, which means that data about the demand for heat, cost of electricity, and outdoor temperature is available for every hour of the year. Given this information, the model decides the heat generation dispatch in each hour that gives the lowest total system cost over the entire year. The various constraints and equations of the model are explained further [32].

GAMS (The General Algebraic Modeling System) is a modeling system that is constructed specifically for modeling linear, non-linear, and mixed-integer optimization problems. GAMS handles an optimization process from the stage of a defined mathematical model of a real-life problem to the stage of solution evaluation. Many solvers are connected to GAMS such as CPLEX, MINOS, CONOPT, and SCIP. In this thesis project, the CPLEX solver is used. For problems with integer variables as in this thesis, CPLEX uses a branch and cut algorithm which solves a series of Linear programming (LP) problems, subproblems. Because a single mixed-integer problem generates many subproblems, even small mixed-integer problems can be very computationally intensive and require significant amounts of physical memory [33].

3.1.1 Objective function

In an optimization model, the objective function can be described as the main goal of the model. To obtain an optimal result from the model, the objective function must be controlled. The models in this thesis deal with the economic optimization of the DCS. Therefore, in the models described in this thesis, the main aim of the optimization is to reduce the cost.

The objective of the optimization is to minimize the yearly chilled water generation cost which is calculated according to Equation 3.1. The cost function consists of several different terms i.e. fuel costs, start-up, and shut-down costs, fixed and variable running costs, and taxes. The startup and the shut-down costs are included as a constant value. The running cost in each hour is summed up over the total number of hours in a year to get the yearly chilled water generation cost.

$$Total\ cost\ = \sum_{1}^{t} \sum_{p} \left[q(p,t) \times VC_p \right] + SC_{p,t} \qquad 3.1$$

3.1.2 Demand-Supply balance constraint

A constraint is an equation that describes the various boundaries of the system in the model. The constraints can also be used to describe the operation of the system. The demand-supply balance constraint describes the basic operation of the district cooling system. This constraint is binding in the model. i.e. this constraint has a direct effect on the decision variable which is the chilled water generation from each chiller.

The major constraint of the model is the balance constraint. The demand for cooling must be satisfied in each hour of the year. This ensures that the sum of chilled water outputs from all the chillers is equal to or greater than the total demand. This constraint thus directly affects the dispatch of the chillers in each hour. This constraint is mathematically represented in equation 3.2.

$$\sum_{p} q[p,t] \geq D_t \qquad 3.2$$

3.1.3 Ramp up and Ramp down constraint

Ramp up and ramp down constraints limit the maximum increase and decrease in chilled water generation from a given chiller at any given hour. Equations 3.3 and 3.4 show how ramp-up and ramp-down rates affect the chilled water generation at the next hour to be within the limits.

$$q(p,t) \leq \ q(p,t-1) + RU(p) \qquad 3.3$$

$$q(p,t) \geq \ q(p,t-1) - RD(p) \qquad 3.4$$

The difference between the amount of chilled water generated at hour t and the hour (t-1) should be less than or equal to the ramp-up rate if the production level is increased, and the difference between the chilled water generated at the hour (t-1) and the hour t should be less than or equal to the ramp down rate if the production level is decreased. This has been described numerically in equations 3.3 and 3.4.

3.1.4 Minimum up and down time constraints

Minimum on time constraints are assigned to prevent a chiller to be turned off before it has been run at least as long as its “minimum on time”. Similarly, minimum off-time constraints are defined to prevent a chiller to be switched on before it has been off at least for the “minimum off-time”. Minimum on time constraints are defined by Equation 3.5 [34].

$$on(p,t-1) - on(p,t) \leq 1 - \sum_{t}^{t+t_{st}} on(p,t) \qquad 3.5$$

Minimum off time constraints are defined by Equations 3.6 [34].

$$on(p,t) - on(p,t-1) \leq \sum_{t}^{t+t_{sh}} 1 - on(p,t) \qquad 3.6$$

The above two constraints are based on the binary variable on(p,t). This variable describes whether a certain chiller is generating chilled water during an hour. The variable takes a value of 0 or 1. When on(p,t) is 0, then the chilled water generation is 0, i.e. the chiller is not turned on, whereas if it takes a value of 1, the chiller is turned on and there is some chilled water generation from the chillers.

3.2 Description of the District cooling network model: Model 2

The model which includes district cooling network is built on the previous model of the DCS. This model is hereafter referred to as the network model. This model consists of additional constraints that describe the network. The district cooling network is a complex network that consists of a large number of buildings and district cooling plants. The pipes in the network connect the plants to the demand. A method must be developed to include the network into the model both in terms of constraints and costs. The network is first simplified into a simpler form called the radial network. Based on their location, the buildings are grouped into demand clusters. These demand clusters are included in the radial network. The radial network and the demand clusters are then used to develop the ‘linked cot functions’ which are used to link each chiller to every demand. This is further explained below.

3.2.1 Radial network

A district cooling network can be constructed as a radial, ring, or mesh system. Radial networks are the simplest form of a district cooling network in which a large main pipeline feeds several distribution pipelines, forming individual branches. In these branches, the pressure of the main pipe is distributed homogeneously over all distribution pipes. The complex and big network must first be represented in the simplest possible form i.e. a radial network. However, due to restrictions in time, it was very difficult to model the entire DCS. Therefore, a part of the network was first chosen. While making this choice, a few major factors considered were

- An accurate representation of the whole network.
- Must consist of both electric and absorption chillers in equal capacities.
- Must cover a significant portion of the network and the demand.

Taking to account the above, it was decided to take the district cooling network in the center of the city as a representative network for modeling. This network consists of the chiller units in Table 5.

Table 5: Chilled water generation units in the chosen central network

Type of unit	Unit	Capacity [MW]	Primary Fuel
Absorption chillers	Rosenlund	22	DH and electricity
	Svenska Massan	3.4	DH and electricity
	Gullbergsvass	3	DH and electricity
	Odin	2	DH and electricity
	Arkaden	1.1	DH and electricity
Electric chiller	Rosenlund	10	Electricity
	Svenska Massan	1.2	Electricity
	Gullbergsvass	1.25	Electricity
	Odin	2.2	Electricity
	Arkaden	4.25	Electricity

The chosen central network is shown in Figure 4. This network accounts for a total of 65 % of the total demand (excluding cooling islands) in the system. However, the installed capacity in this network is about 92.4 % of the total installed capacity (excluding cooling islands). However, the main aim of this study is to investigate methods by which the network can be integrated into the model. Dimensioning of the system for the peak demand is not the most important aspect of this model. Hence, this mismatch in the share of the total demand and the share of total installed capacity can be overlooked.

Figure 4: Chosen central network [10]

The network shown in Figure 4 is then simplified into a radial network, by creating the different demand clusters. 7 demand clusters were created based on their location with respect to the different chiller units. The demand clusters are shown in Figure 5.

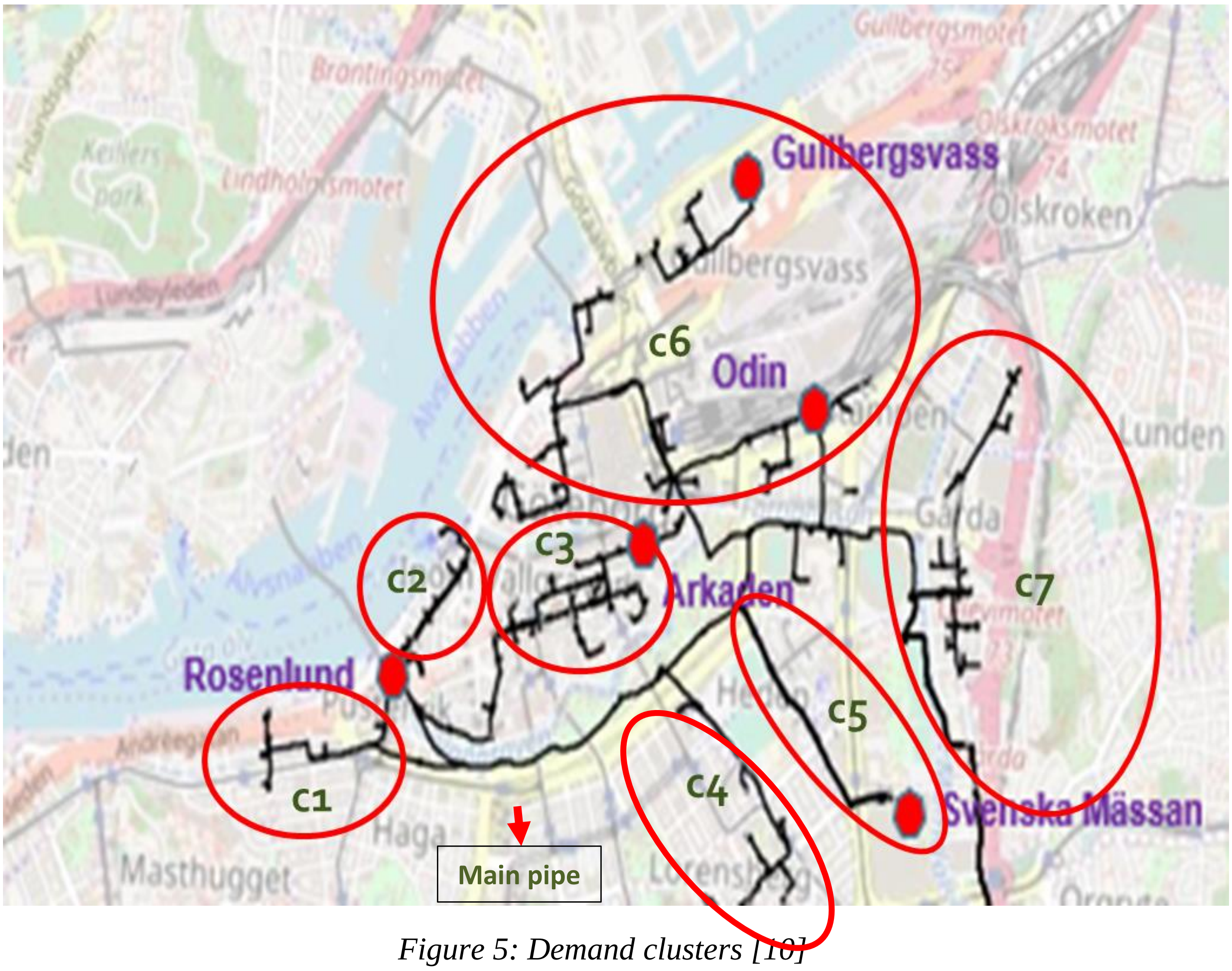


Figure 5: Demand clusters [10]

The demand clusters, along with the pipes and the chiller units are used to make the radial network as shown in Figure 6.

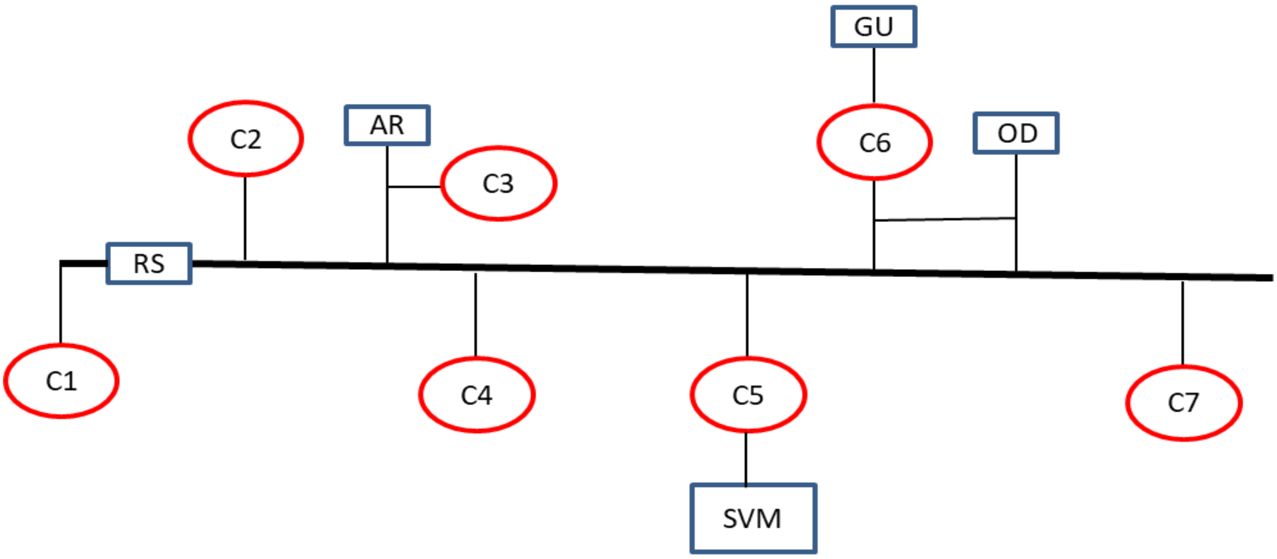
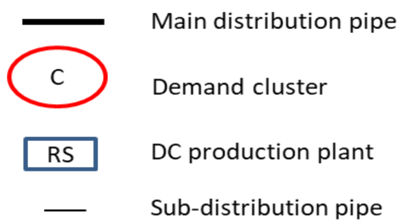


Figure 6: Radial network



In Figure 6, RS, AR, SVM, GU, and OD denote the chiller units in Rosenlund, Arkaden, Svenska Massan, Gullbergsvass, and Odinsplatsen, respectively. The developed radial network is used to develop the linked cost functions as explained below.

Flow and temperature difference

The data regarding the temperature difference is obtained from a physically-based model of the Gothenburg DCS. This model is built and run by Göteborg Energi. In this model, the average temperature difference between the supply and return temperatures at all the customers is 6.64˚C. The same value is used for temperature difference in the models in this thesis [35]. From this value, the flow is calculated using equation 3.12.

3.2.2 Linked cost functions

The linked cost functions as specified earlier are developed to link each chiller to every demand cluster. The linked cost function gives the pumping power needed in kW to pump water from chiller A to demand cluster B. This can then be used to calculate the pumping cost required to pump water from chiller A to demand cluster B. Since the pumping cost is dependent on flow, the linked cost functions are developed as a function of flow. The cost functions are developed based on the pressure drop in the pipes [36]. The pressure drops are obtained by using equations 3.6 to 3.12.

$$\Delta P = \frac{K * 9.81 * v^2}{2g} \qquad 3.6$$

$$v = \frac{Q}{A} \qquad 3.7$$

$$K = \frac{f * l}{D} \qquad 3.8$$

$$f = \frac{0.25}{[\log\left\{\frac{k}{3.7 * d} + \frac{5.74}{Re^{0.9}}\right\}]^2} \qquad 3.9$$

$$Re = \frac{v * d}{\nu} \qquad 3.10$$

3.11

$$P_p = \frac{Q * \Delta P}{\eta}$$

The flows for calculating the pressure drops are obtained from the demand as below.

$$\dot{Q} = \frac{Q_{heat}}{c_p * \rho * \Delta T} \quad 3.12$$

The maximum and minimum flow from a chiller to a demand cluster is determined by the demand and the capacity of the chiller. Thus, a set of data points within this range of flows is used to plot a function of the pumping power based on the above equations. The data points in the range of the flow are chosen linearly with the equal difference between each data point. Also, mean, median, mode, the maximum and minimum values are also included in the set of points used to calculate the pumping power. An example of the calculated linked cost function between Rosenlund and C1 is shown in Figure 7.

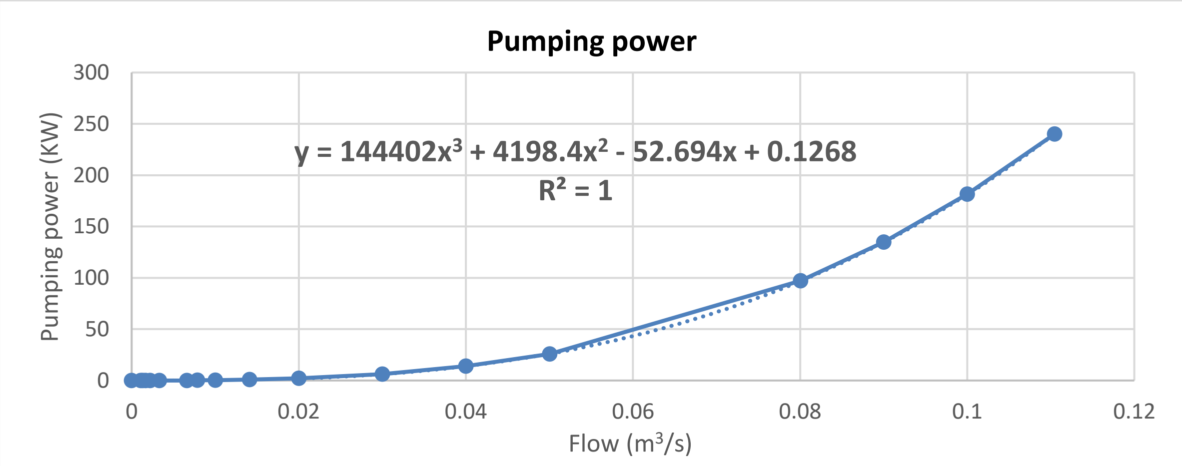


Figure 7: Linked cost function

The Figure 7 shows the linked cost function between Rosenlund and C1. As shown in the graph, here the function which defines the pumping power is non-linear and hence has to be linearized. When linearizing, the accuracy to which the function can represent the curve is lost. The linearized linked cost function is shown in Figure 8. The coefficient of determination (R^2) is 1 in this case, which means that there is a negligible variance when the cubic polynomial is used.

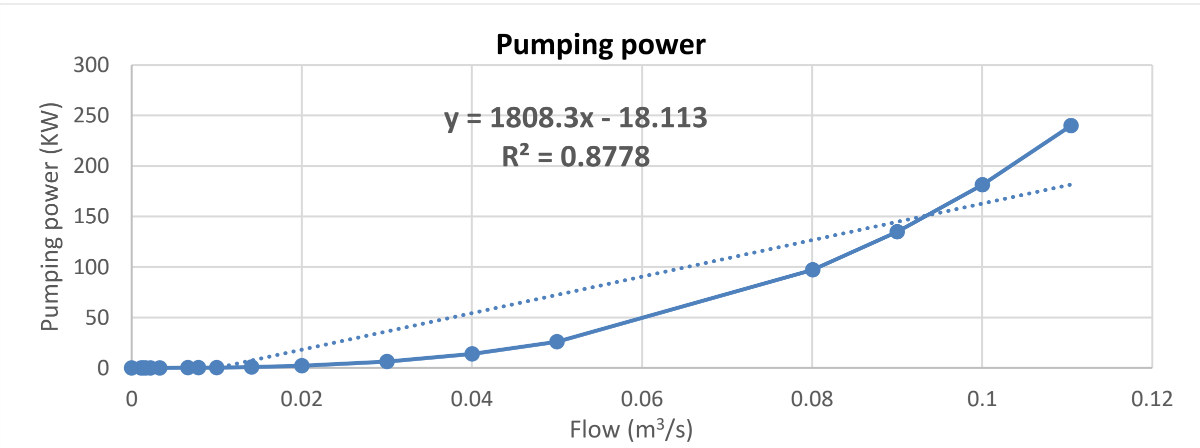


Figure 8: Linearized linked cost function

When using the linear polynomial to represent the function, the variance is much higher, and the R^2 is 0.88. There is an inaccuracy in the linked cost function when represented as a linear function. But most of the linked costs function used for modeling have an R^2 value of above 0.7 and thus, the cost linear cost function is able to represent the actual curve to an acceptable accuracy.

3.2.3 Objective function

The objective of the optimization is to minimize the yearly running cost of the district cooling network which is calculated according to Equation below. The cost function consists of several different terms i.e. fuel costs, start-up, and shut-down costs, fixed and variable running costs, and taxes. The startup and the shut-down cost are included as a constant value. The pumping costs are also included in the model as a representative of network operation costs.

$$Total\ cost\ = \sum_1^t \sum c \sum_p \{[q(p,c,t) \times VC_p] + [P_p(p,c,t) \times El_t]\ + SC_{p,t}\} \qquad 3.13$$

3.2.4 Demand-Supply balance constraint

The demand-supply constraint in this model includes an additional index in terms of the cluster. Since the demand is split into different clusters, it is required to provide separate constraints for each demand. Thus, the demand at each cluster must be met during every hour.

$$\sum_p q[p,c,t] \geq D_{c,t} \qquad 3.14$$

3.2.5 Capacity and ramping constraints

The chilled water generation from the chillers must be restricted in the model to their peak capacity. Since the chilled water generation is indexed over both the plant and the cluster, the capacity constraint for this model must be defined differently.

$$\sum_c q[p,c,t] \leq Cap_p \qquad 3.15$$

The ramping constraints are defined similarly

$$\sum_c q(p,c,t) \leq \ \sum_c q(p,c,t-1) + RU(p) \qquad 3.16$$

$$\sum_c q(p,c,t) \geq \sum_c q(p,c,t-1) - RD(p) \qquad 3.17$$

The minimum off-time and minimum on-time constraints are defined as done previously.

3.2.6 Pipe constraints

The constraints related to the pipes must also be included in the model in order to completely represent the network in the model. The main constraint in the pipes is the maximum possible flow in the pipes. This is defined by the dimensioning pressure drop in the pipes, which is 1.5 bar per km length of the pipe [35] The maximum flow is calculated for this value of pressure drop using Equations 3.6 to 3.10. The flow constraints in the pipes are defined by dividing the network into various pipe segments based on the diameters of the pipes. This is shown in the Appendix. The constraints are then defined based on the possible flows in these pipe segments. When the pipe segment connects the main pipe to the demand, then the flow through that pipe is equal to the demand flow. Whereas, when the pipe connects a demand cluster and a chiller unit to the main pipe, then the flow in the pipe is then equal to the sum of the demand flow and the generation flow from the chiller. Thus, the constraints for each pipe segment are defined similarly.

Another constraint included in the models is regarding the two chillers pumping the chilled water in opposite directions to each other. This is not possible in reality and hence must be defined in the model. This is defined by using binary variables. A binary variable called on(plant,t,cluster) is created to identify whether there is a flow of water from a plant to a cluster at a given hour. This variable has a value of 1 when there is flow and 0 when there is no flow. An obvious example of the above situation is pumping water from a chiller at one end of the network to another end i.e. Rosenlund to c7 and Odinsplatsen to c1. For this example, the constraint is defined as below

$$on(Rosenlund,t,c1) + on(odinsplatsen,t,c7) \leq 1 \tag{3.12}$$

This constraint ensures that only one of the binary variables can have a value of 1 during a given hour t, thus eliminating opposite flows in the model.

Chapter 4: Assumptions and Input data

To evaluate the developed optimization model, a large amount of data must be gathered and processed. Certain assumptions are made wherever necessary. This chapter explains the various assumptions and the simplifications made in the optimization model. Also, this chapter provides a description of the data used, how this data was obtained, processed, and transformed to reflect the actual system as closely as possible.

4.1 Assumptions

Appropriate assumptions and simplification are made in cases where there is a lack of proper data or when specific information is not available. The assumptions are made such that they can be reliable enough to represent reality as accurately as possible. Therefore, the model has various assumptions related to the DCS's functioning, the chillers, and the input data.

The first assumption is related to the heat gains along the pipes in the distribution network. The data concerning chilled water generation from each chiller was not available. This made it hard to calculate the heat losses directly despite the data from the demand side being available. For model 1, the losses in the network were assumed to be negligible. After looking at the results, this assumption did not seem reasonable and hence it was decided to modify this assumption for further modeling. Hence, in model 2, the heat gains in the network are considered to be 2% and are included as a percentage of the hourly demand. This assumption was made based on [37].

The objective function of all the optimization in model 1, is to minimize the annual running costs of the chillers. But the running costs here consist only of the costs of fuels i.e. heat and electricity costs for running the chillers. The objective function in model 1 does not include the pumping costs in the network. Also, the costs of electricity for running the condenser pumps are excluded from the objective function. Whereas, in model 2 when the network is modeled, the pumping costs are included as a representative of the network operation costs. But, as in model 1, the costs associated with the condenser pumps and the cooling towers are excluded in model 2.

The network-based models in model 2 do not consider the dynamics of the system. The model is built assuming that each chiller has a separate pipe connecting to each demand, which is not the case in reality. Although the constraints have been imposed on the maximum flows in the pipes, the dynamic effects of the network such as the fluid junctions, pressure drops in loops, etc. have been excluded while calculating the pumping costs. Besides, the pressure drops considered are only those due to the pipes. The pressure drops from the valves, substations, etc. have been excluded in this study. These are the major assumptions made in setting up the model. Other assumptions have also been made in processing the input data and while setting up the different scenarios. These are scenario specific assumptions and are explained further when each scenario is described in chapter 5.

4.2 Input Data

In this section, the technical and economic data of the various chillers is presented. Also, the method of obtaining and processing various input data such as demand and fuel prices is explained. The DCS in Gothenburg consists of absorption chillers, electric chillers, and free cooling from the river. The technical details of the various chillers are presented in Table 6.

Table 6: Technical details of units in DCS

Type of unit	Unit Name	Primary Fuel	$COP_{electricity}$	COP_{heat}	Minimum up time (Hours)	Minimum Output (MW)
Absorption chillers	Rosenlund	Heat and electricity	20	0.7	4	0
	Svenska Massan	Heat and electricity	20	0.7	4	0
	Gullbergsvass	Heat and electricity	20	0.7	4	0
	Odin	Heat and electricity	20	0.7	4	0
	Ceres	Heat and electricity	20	0.7	4	0
	Arkaden	Heat and electricity	20	0.7	4	0
Electric chillers	Rosenlund	Electricity	Variable	N/A	0	2
	Svenska Massan	Electricity	Variable	N/A	0	0.24
	Gullbergsvass	Electricity	Variable	N/A	0	0.25
	Odin	Electricity	Variable	N/A	0	0.44
	Ceres	Electricity	Variable	N/A	0	0.12
	Arkaden	Electricity	Variable	N/A	0	0.85
	Sahlgrenska	Electricity	Variable	N/A	0	0.5

4.2.1 Fuel prices

As seen in Table 6, there are two major fuels in the DCS, heat from the DHS, and electricity. The electricity prices from the spot market were considered in this thesis. The prices for electricity were taken from the nordpool website [38]. In reality, there are some taxes and grid connection fees that are added to the spot market prices. Since, here there is a comparison between two scenarios and two methods, the taxes and the grid connection fees have not been included. Therefore, it is assumed that the spot market prices are the electricity prices paid by Göteborg Energi to run the chillers.

The prices for heat are obtained by running an optimization model of the DHS. This model is based on a previous model of the DHS developed to study the impact of thermal energy storage in the system [13]. An assumption has been about the prices of heat from the DHS. The absorption chillers use both electricity and district heating as input fuels. The absorption chillers are run only during the periods when excess heat is present in the district heating network. The marginal cost of heat output from this model is used as heating price input. If the heat demand is lower than the total amount of waste heat coming from the industries, then there is said to be excess heat in the system. According to Göteborg Energi, this excess heat is available to the DCS at zero price. Hence, in hours when there is excess heat in the system, the price of heat is set to zero.

4.2.2 COP of electric chillers

The COP of electric chillers varies based on the load on the chiller. The COP varies based on the load as shown in Figure 9.

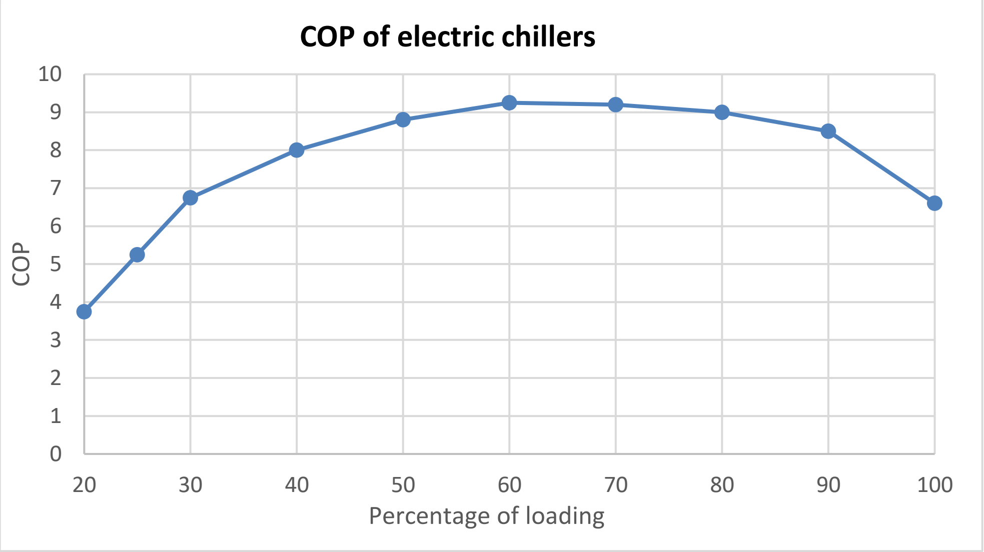


Figure 9: Variation of COP of electric chillers with load

The relationship between the COP and the load on the chillers is non-linear and hence, it cannot be represented in a linear program that is used to construct the model. In addition, since the COP will be used to calculate the running costs of the chillers, it must be a constant value. Therefore, a constant value must be assigned to the COP value, the ESEER (European seasonal energy efficiency ratio) is used. The ESEER value is calculated using the equation below [39].

$$ESEER = COP_A \times WC_A + COP_B \times WC_B + COP_C \times WC_C + COP_D \times WC_D$$

Here A, B, C, and D represent the various load condition of the chillers. WC is the weighting coefficient for that load condition.

Table 7: Loading conditions of the electric chiller

Condition	Load Ratio %	Weighting coefficient
A	100	0.03
B	75	0.33
C	50	0.41
D	25	0.23

Loss of accuracy of results obtained by the program runs with constant COP can be assumed to be insignificant, since the operation of the chillers is modeled over the entire year. Moreover, since the thesis aims to compare different modeled scenarios, efficiency can be assumed as a constant value without diminishing the accuracy of results. The issue of variable efficiencies occurs only in the case of electric chillers since the absorption chillers have a constant efficiency irrespective of the load on the chiller.

4.3 Demand data

The cooling demand is input exogenously to the model. This data must be obtained at an hourly resolution, which means that the demand in MWh for each hour of the year is to be determined. The cooling demand for each hour is obtained by measuring the hourly consumed cooling energy from the substations in each connected building. The total hourly cooling demand is obtained by summing up all the hourly consumed cooling energy from each building.

The cooling demand is the most vital parameter in the optimization model because the demand-supply balance constraint must be satisfied in each hour and hence decides the dispatch of the chillers. Also, the demand curve created here will be used to make a projection for future demand in further modeling. Hence, the demand considered here must be an accurate representation of the cooling demand in any year. Hence, the demand data from two years, 2017 and 2018 were considered.

The year 2017 was a cold year with a lesser than average cooling demand. Thus, this demand had more dense regions in the average cooling demand and lesser peaks. This is shown in Figure 10.

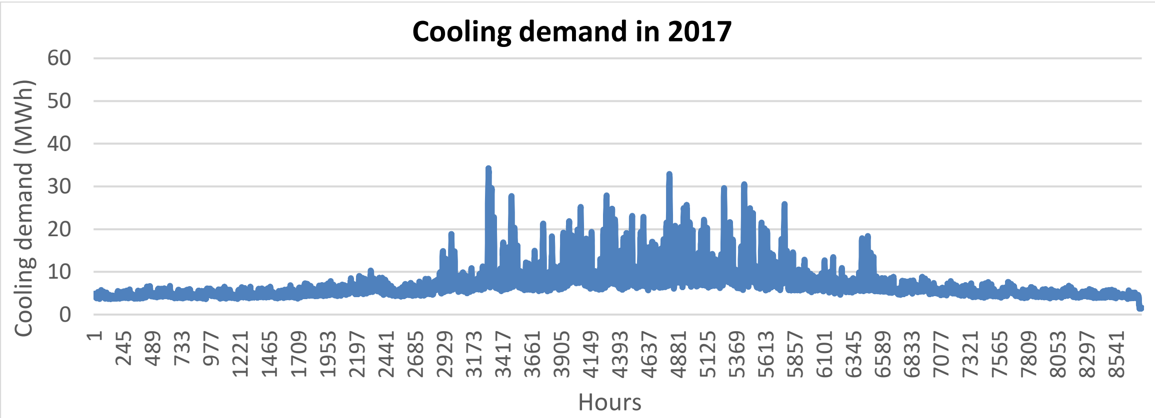


Figure 10: Cooling demand in 2017

The year 2018 was a warm year with a higher than average cooling demand. Thus, the demand curve in 2018 had more demand peaks as shown in Figure 11.

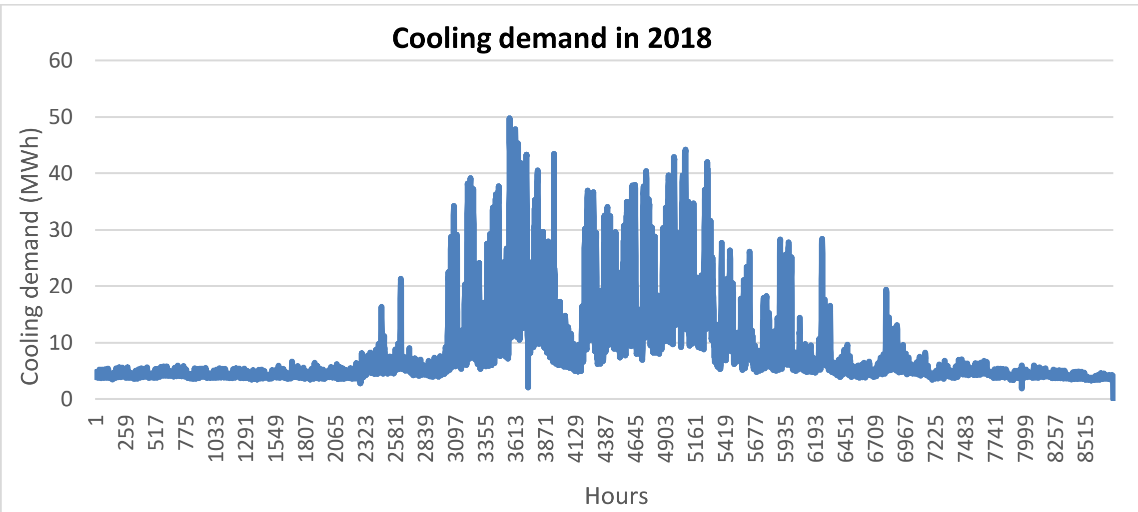


Figure 11: Cooling demand in 2018

Since, there were two demand profiles considered, these have to be further processed to create an average demand. The peaks in the demand are pivotal to design and dimension the capacity of the DCS. The main aim of the optimization model was to determine the optimal functioning of the DCS, hence the dense regions in the average demand is more important than the peaks. Thus, the peaks in the demand were not added to the average demand. Instead, an arithmetic average of the demands in 2017 and 2018 was calculated. This demand will be referred to as "Average Demand" from here on.

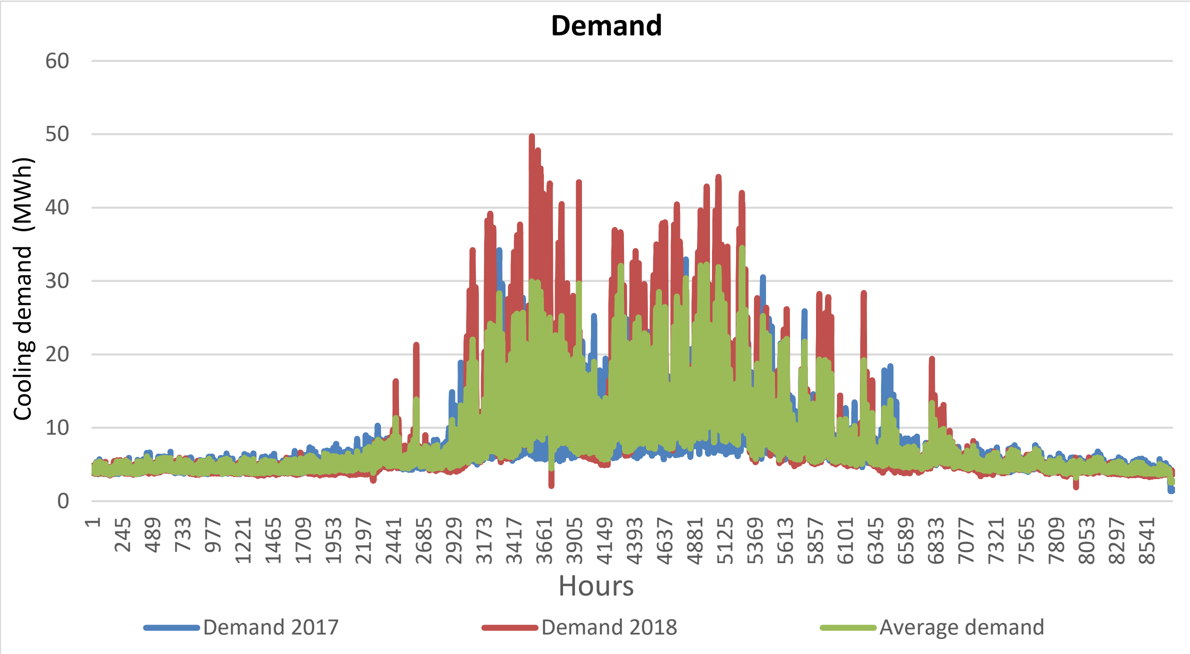


Figure 12: Comparison of the demands

Figure 12 shows the average demand with the demands in 2017 and 2018. The average demand profiles have points both above and below the other demands at different hours in the year.

Table 9 : Variation in demand

Variation		
Average Variation	2017	2018
Above Average	8,8%	14,6%
Below Average	19,4%	10,4%

Table 8 : Comparison of the demands

Maximum hourly Cooling production from Chillers (MW)		
2017	2018	Average
34,2	49,8	34,5
Total Cooling demand (GWh)		
2017	2018	Average
62,3	76,2	69,3

Table 8 shows the variation of the average demand. The total demand in 2018 was higher than that in average demand case and in 2017. The peak production from the chillers in 2018 is much higher than in the average demand case and in 2017. But, the peak production in the average case is very close to the peak in 2017. This shows that the peak demands in the two years do not occur at the same hours. Hence, this average demand is an accurate representation of the demand in the dense average regions in the profile and thus, the demand in an average year.

Chapter 5: Model Implementation

The modeling in this thesis is split into two models. The models are based on the scope of modeling and the main aim of the models. In model 1, the scope of modeling is limited to the DCS i.e. the network is not included in these models. Further, different scenarios are investigated in this case. In model 2, the main aim is to develop methods to accurately model the network in numerical optimization algorithms. Further, different scenarios are set-up to analyze different situations. This chapter explain in detail the models, cases and the scenarios.

5.1 Model 1

Figure 13 shows the different cases and scenarios in model 1.

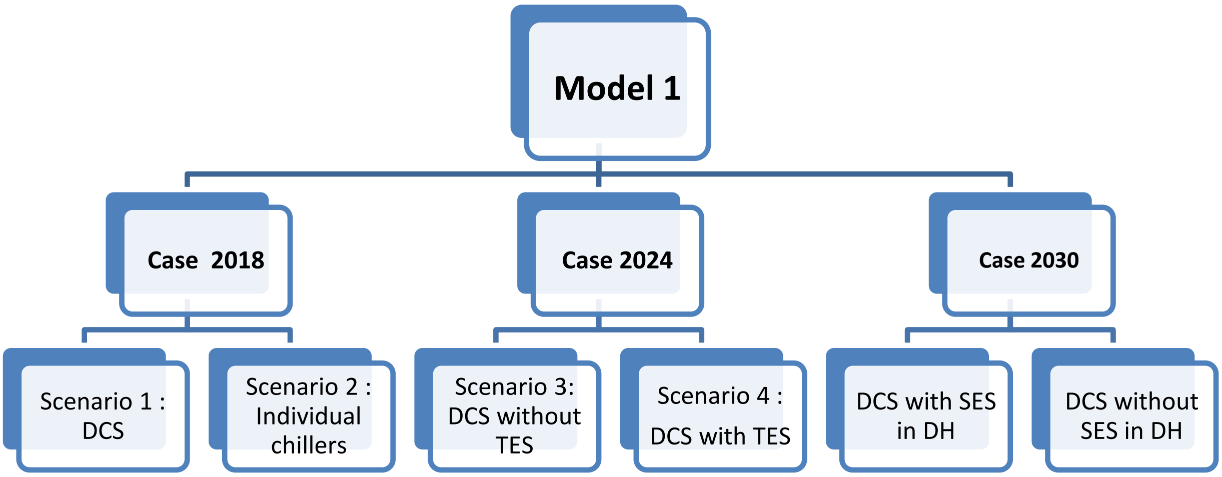


Figure 13: Cases and models

5.1.1 Case 2018

The first case in this thesis presents a comparison between the DCS and a hypothetical case in which individual chillers are used to meet the entire cooling demand. Two different models are set up for each scenario in this case. An optimization model of the DCS in 2018 is used to determine the optimal operation of the system.

Scenario 1

This is a model of the DCS in the year 2018. The main aim of this model is to determine the optimal functioning of the DCS in terms of the dispatch of the chillers. The system consists of electric chillers, absorption chillers, and free cooling from the river. The average demand which was described in the previous section is used as input to the model. The free cooling from the river is included in the system by revising the demand. The free cooling from the river is used to meet the cooling demand during the winter. Hence, it is assumed that the free cooling satisfies the cooling demand entirely from December to February. This assumption is made by looking at the chilled water generation from the chillers and the temperature of the river. To include this into the model, the hourly demand is made zero in hours between December and February. Also, the free cooling from the river is not included as a chilled water generation technology in the model. This ensures that chillers do not have to operate during the winter and the free cooling is not available during the months after the winter. During the combi-operation period, the chiller and free cooling are used together to meet the demand. During this period, a net demand is calculated. The net demand is given by the equation below.

Net demand = Actual demand – Free cooling from the river

This net demand is included in the model and hence, the chillers are run to satisfy this demand. Thus, the free cooling from the river is included in the optimization model through the demand profile which is input exogenously.

Scenario 2

A hypothetical case of using individual chillers to meet the entire cooling demand is represented in this model. This model is referred to as “Individual chillers” in this thesis. Since it is a hypothetical case, the model has many inherent assumptions which are explained in this section.

Firstly, the demand for each individual chiller is determined. There is a total of about 150 substations in the network. Since including each of those demands in the model can be very time consuming and make the model computationally complex, it was decided to group these demands into clusters. The main parameter that was used to make these clusters is the location of the buildings. It is assumed that the buildings which are located close to each other have a common chiller to meet the demand. The demand for this chiller is then determined by summing up the hourly cooling energy consumption from the substations. The chiller is dimensioned with an oversizing of 20% on the highest hourly demand. The buildings were grouped into 60 clusters [40].

It is assumed that only electric chillers are used in the buildings and no absorption chillers are considered. Another assumption is that there is no free cooling from the river. Although, it was decided that the river water could be used in water-cooled condensers in buildings that are located close to the river. Buildings that are located farther from the river have air-cooled condensers. Further, an additional assumption is made that the buildings do not have air-based free cooling in the winters i.e. cooling by using outdoor air in the ventilation system in the winter. Thus, in this scenario, it is assumed that the chillers must be run to meet the cooling demand even during the winter. The COP for the chillers was obtained from “Daikin Chiller catalogs” based on the installed capacity of the chiller and the type of condenser [41].

The demand of a cluster is coupled with the respective chiller by the equations in the model. Since each demand can be met only by the corresponding chiller, this is a simulation model where the main aim would be to calculate the total cost of running the chillers. The technical data of the chillers are presented in the appendix.

5.1.2 Case 2024

This case investigates the impact of the thermal energy storage in the DCS in Gothenburg. A tank that stores cold water is to be installed in the system. The main aim is to determine the impact of the thermal energy storage on the system. Hence, two models are set up, one with a thermal energy storage and one without. The prices of heat are obtained by running a model of the DHS in the year 2024.

The main reason for installing the thermal energy storage in the system is to reduce the usage of the electric chillers during the summer. Göteborg Energi wants to operate absorption chillers at peak capacity and store the generated cold water in the tank. This is because a large amount of waste heat is available from the DHS free of cost. Thus, when the absorption chillers are run at peak capacity, a large amount of chilled water can be generated at very low costs and hence reduce the running costs of the system significantly. The stored cold water can then be discharged from the tank to meet the peak demand. Hence, the absorption chillers and the discharge from the tank can be used to meet the demand, and therefore, the electric chillers need not be operated. The viability of operating the system as described above is investigated in this case.

According to the current plan, the tank will have a storage of size 200 MWh. A review of thermal energy storages in different DCSs has shown that the active temperature difference in the system is between 10-12˚C. Considering a ΔT of 10˚C, the volume of the tank can be determined by the equation 2.2.

$$V_{Tank} = \frac{E_{Tank}}{C_{p,water} * \rho_{water} * \Delta T_{water}} = \frac{200 * 10^6 * 3600}{995 * 4200 * 10} = 17230 \text{ m}^3$$

According to equations 2.3 and 2.4, this corresponds to an investment cost of 20.9 MSEK. But this cost is very uncertain as it does not include the connection costs. According to Göteborg Energi, the projected cost of installing the tank is about 100 MSEK [3].

Cooling demand in 2024

The demand data for the year 2024 was forecasted. It was assumed that with an increase in the installed capacity of the system, there will be a proportional increase in the number of connections to the DCS. Hence, the demand would increase proportionally to the installed capacity. To forecast the demand, a representative demand was needed. This demand profile could then be adapted for 2024 based on the installed capacity in the system. The average demand which was described in the previous chapter is considered to provide an accurate representation of the demand in an average year. Therefore, the average demand is used to project the demand in 2024. Since the average demand is used, all the assumptions made about free cooling, combi operation etcetera are applicable here.

The demand curves for the two years have a very similar shape as shown in Figure 14. An inherent assumption here is that the diurnal and seasonal variations in temperatures in the two years are similar to each other. The demand is hence only projected based on the installed capacity and the assumed corresponding increase in the number of connections.

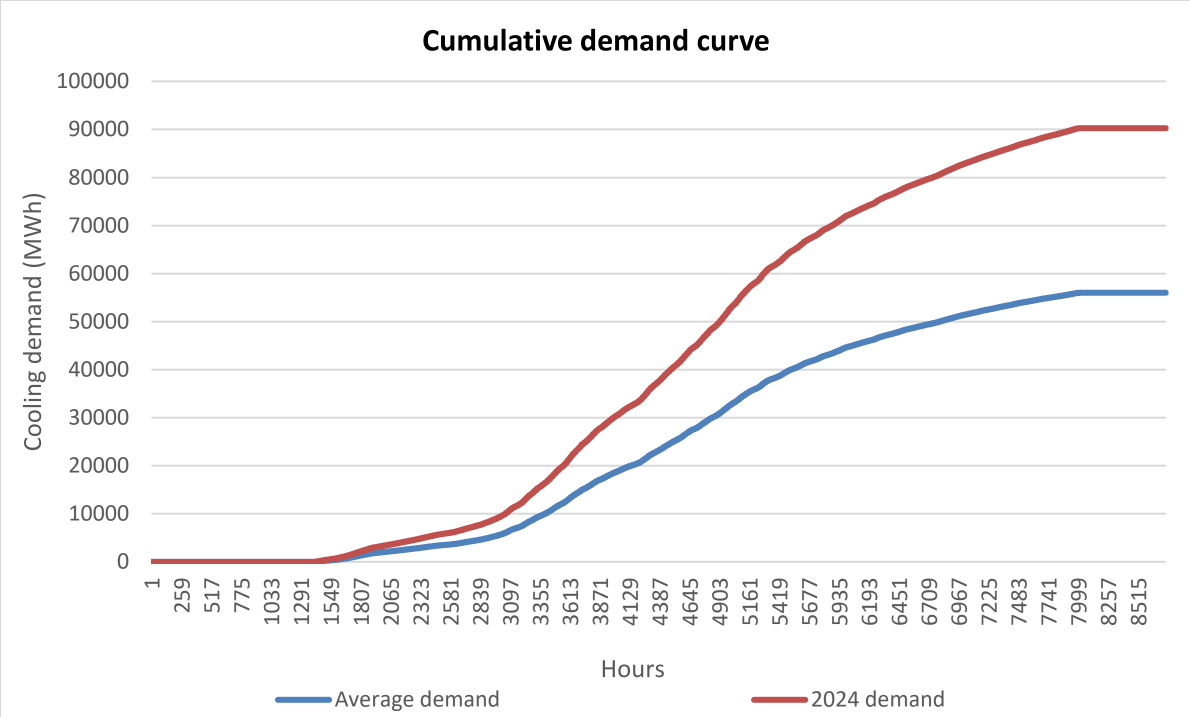


Figure 14: Cumulative demand curve in 2018 and 2024

Scenario 3

This model presents the DCS in 2024. The thermal energy storage is not added to the system in this model. The new investments made in the system between 2018 and 2024, which are shown in Table 2 are included in this model.

The projected prices of electricity for 2024 are not available. To include electricity prices in the model, it is assumed that there will not be any large-scale changes in the electricity system between 2018 and 2024 and so, the prices in 2018 can be used in 2024. The prices of heat are obtained from a corresponding model of the DHS in 2024.

Scenario 4

Model 4 is set up to analyze the impact of installing the thermal energy storage in the DCS. The only difference between this model and the previous one is the inclusion of the storage into the system. In GAMS, the storage is modeled in its most simple form as an energy capacity (MWh) and a power capacity (MW). The storage is represented in the model using the equation 5.1.

$$E_{storage}(t) = E_{storage}(t-1) * \eta_{storage} + Q_{storage}(t) \qquad 5.1$$

The above equation represents the operation of the storage. $E_{storage}$ is the energy that is stored in the tank. $\eta_{storage}$ is the efficiency of the storage. $Q_{storage}$ is the energy-charged into or discharged from the storage. It takes a negative value when the storage is discharged and takes a positive value when the storage is charged. The level of the storage in any given hour is determined based on the storage level in the previous hour and the energy charged into or discharged from the storage. The operation of the storage must also be linked with the demand equation. This is because, when the storage is charged, the total demand in the system increases, and when the storage is discharged the total demand in the system decreases. This is modeled using the equation below.

$$\sum_p q[p,t] \geq D_t - Q_{storage}(t) \quad 5.2$$

The starting value of $E_{storage}$ has a significant effect on the operation of the storage. In the DCS, since the cooling demand is very low at the start of the year, the chillers are not operated and the free cooling from the river is used to meet the demand. Therefore, the storage will not be used during the winters and hence the starting value of the $E_{storage}$ is set to zero.

5.1.3 Case 2030

A future model of the DCS in 2030 is setup. The year 2030 has been chosen because the current investment plans for the DCS are up to 2030. Therefore, this case analyzes the performance of the DCS in 2030 with the corresponding developments in the district heating and the electricity systems. Drastic changes in the electricity and the DHS are considered in these models. Various situations are considered with different combinations of these developments in the systems. The performance of the DCS in each of these scenarios is analyzed.

Cooling demand in 2030

The cooling demand for the year 2030 was projected. The method used for estimating the demand for 2024 was used. The demand was assumed to increase linearly with an increase in capacity. Figure 15 shows the cumulative demand curves for 2018 and 2030

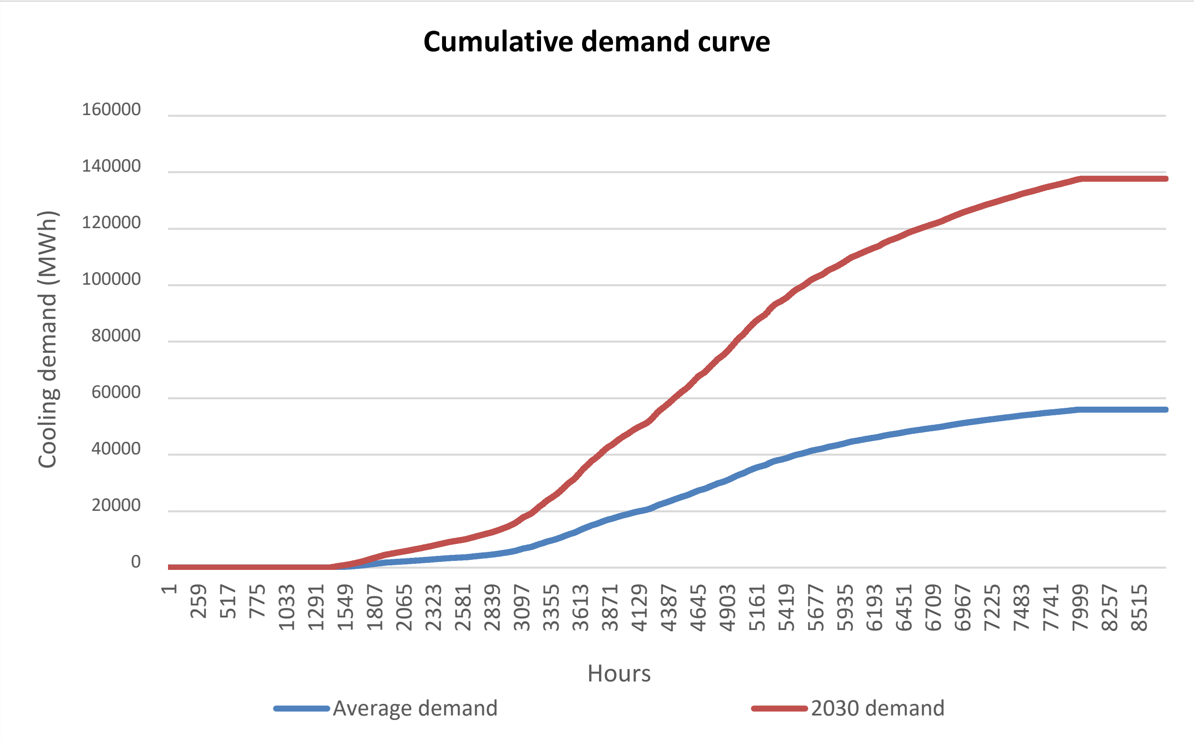


Figure 15: Cumulative cooling demand in 2018 and 2030

Developments in the DHS

The prices of heat must be input to the DCS model. The prices of heat are as usual obtained from a corresponding optimization model of the DHS. In this case, the developments in the DHS between 2024 and 2030 are added to the model which is used in the previous case. In addition to that, the inclusion of a seasonal energy storage in the DHS is also considered.

During the warmer periods of the year, the demand for heat in the heating system is lower than the total amount of the industrial waste heat available to the system. During these situations, there is excess heat in the system. A part of this excess heat is used in the DCS. The rest of the excess heat is cooled off in chimneys or using natural cooling sources such as the river. In some instances, additional coolers are installed to cool off this excess heat. Figure 16 shows the excess heat in the system in the month of July.

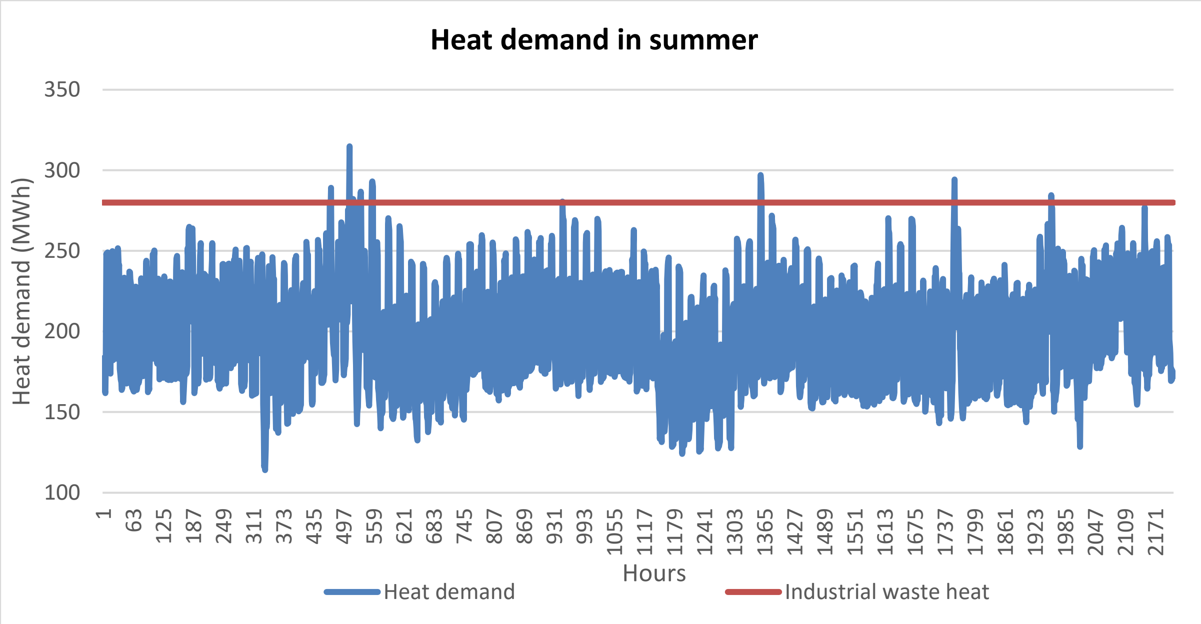


Figure 16: Heat demand in summer vs Industrial waste heat

The excess heat available in the system can be stored and used in the periods when the heating demand is very high. This can help reduce the use of peak load power plants which run on fossil fuel, thus making the system fossil-free. This storage will help shift a large amount of excess heat from the summer and use it in the winter when the heat demand is high. Since a large amount of energy is to be stored over a long time, the size of storage will have to be very large. Thus, the investment cost and the volume of the storage is also very large. There are several possible technologies for seasonal storage of heat such as aquifer TES and borehole TES. But according to Göteborg Energi, the most suited technology for constructing the seasonal thermal energy storage is cavern TES(CTES). CTES can store a large amount of water in large underground rock formations. These can either be natural or manmade. Water is used as a heat carrier along with the rock formation and thus CTES has low heat losses. The main advantage of CTES is that the charging and the discharging capacity can be very large. But, the cost of excavating a large underground cavern can be exorbitantly high. According to Göteborg Energi an approximate size of such a storage in the system can be 200 GWh with a peak charging or discharging capacity of about 300 MW. Thus, the inclusion of the seasonal thermal energy storage in the DHS in 2030 has been considered.

A study was conducted by Göteborg Energi in 2019, to investigate the possibility of using the cavern in Syrhåla as a seasonal thermal energy storage. The size of the storage proposed by Skanska is 200 GWh. The study concluded that the technical risks of using the storage can be significant and hence, it was decided not to invest in the cavern storage in Syrhåla. Thus, there are large uncertainties in investing in the CTES and an extremely large investment cost. Therefore, it is decided to investigate situations with and without CTES in the system [42].

The electricity system in 2030

The electricity system in the year 2030 has been modeled in various studies [43]. Two different situations are considered for modeling the electricity system. The prices of electricity are hence obtained for two different situations. The first situations is called the 'collaboration scenario'. The electricity prices from this model are referred to as 'coll' prices in this report. The collaboration scenario assumes perfect co-operation between electricity, heating, transportation, and the industrial sectors with the objective of reducing costs in the electricity system. This model consists of a large penetration of variable renewables in the system optimized EV charging, vehicle to grid, electrification of steel industries with a possibility to store hydrogen, district heating with CHP and heat pumps, and thermal storages in the form of tanks or pits. The resulting electricity price profile from this model is shown in Figure 17.

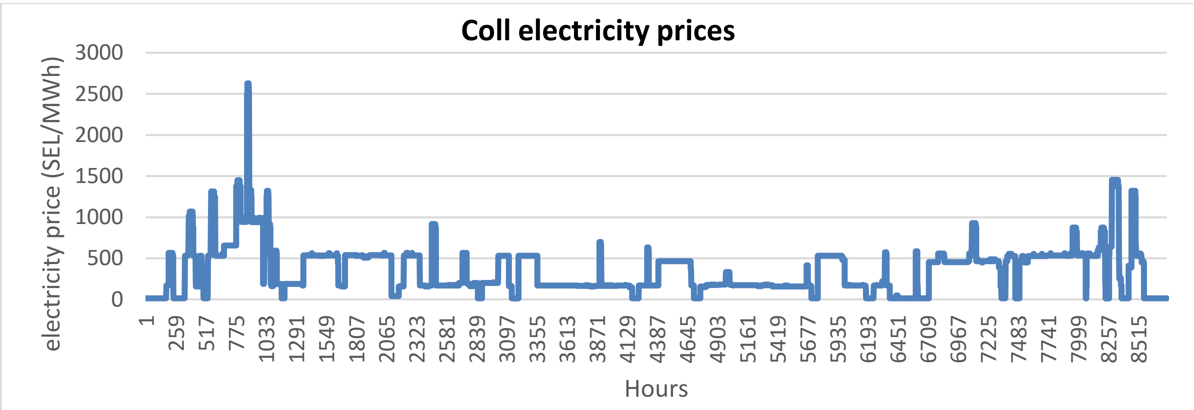


Figure 17: Collaboration electricity price profile 2030

The no collaboration scenario assumes that there is a large share of variable renewable energy in the system, but the variation management strategies that are included in the collaboration scenario are not included in this model. The resultant electricity prices are referred to as 'no coll' prices in this report. The scenario considers EVs to charge immediately after each trip, no hydrogen storages, no new district heating, and no heat storages. The price profile is shown in Figure 18.

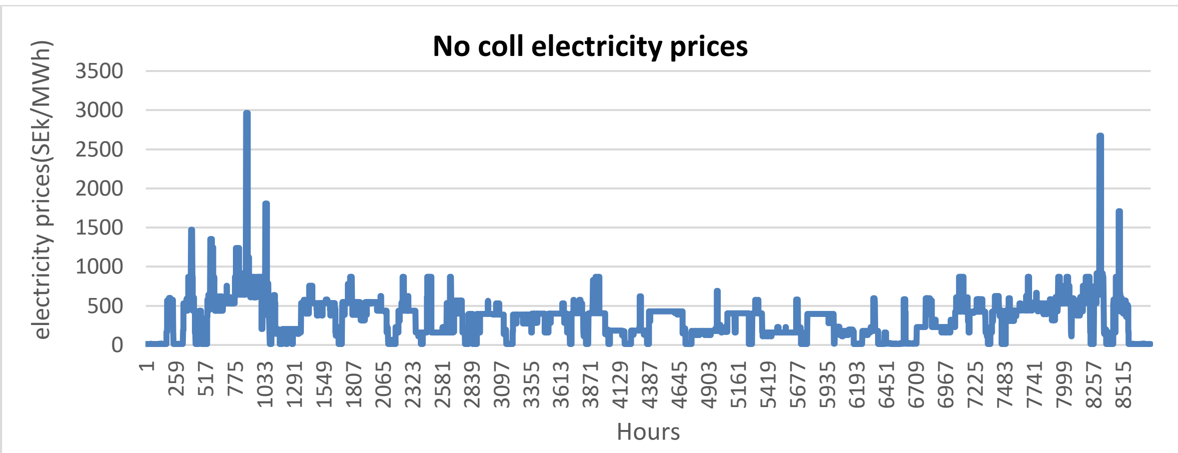


Figure 18: No collaboration electricity price profile for 2030

DCS in 2030

The model of the DCS in 2030 is based on model 4. In addition, the new investments in the system between 2024 and 2030 are also included in this model. Since there are several different situations in the heating and the electricity system, the operation of the district system in these different situations can be compared. Also, another aspect that must be investigated here is the operation of the TES. The impact of the TES on the system must be studied and hence, the system is modeled without the TES. It is assumed that the tank will be installed in the system before 2030, but the system is modeled without the tank just to look at the impact that the storage has on the system in 2030. In model 4, the viability of operating the system by using only the absorption chillers and the TES to meet the demand in the summer was examined. A similar study is made in this model too. With increased demand, the possibility of the scenario described above is to be examined once again.

Figure 19 shows the various scenarios that have been considered in case 2030.

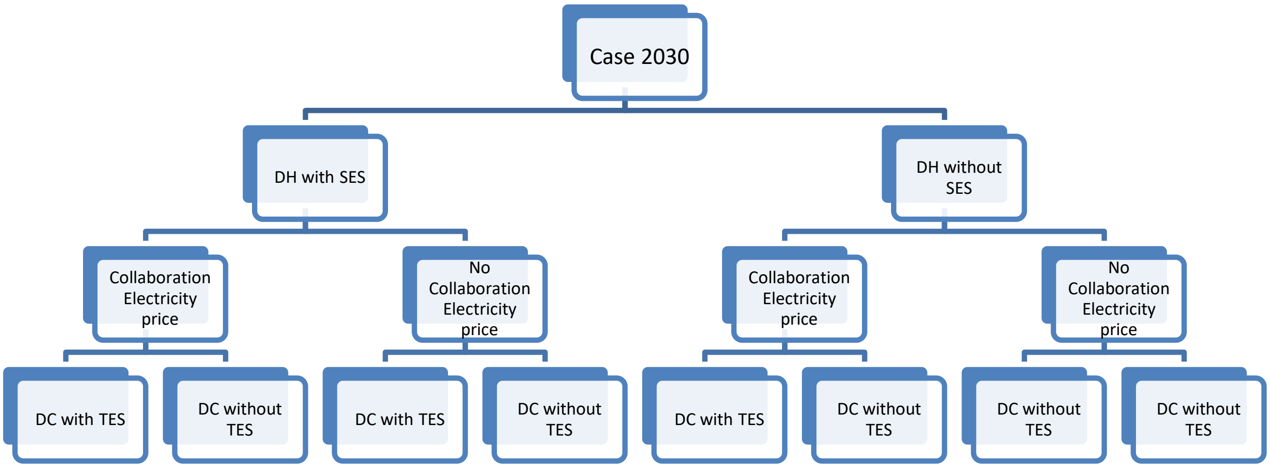


Figure 19: Case 2030

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5.2 Model 2

Figure 20 shows the cases and scenarios in model 2.

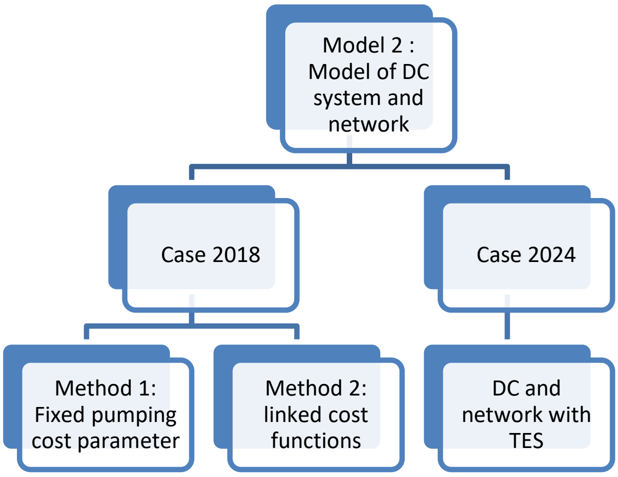


Figure 20: Cases in Model 2

5.2.1 Case 2018

Method 1: Model based on fixed pumping cost parameter

The main aim of this case is to examine the different approaches to represent the network in the numerical optimization program. The first method is based on having fixed pumping costs as additional operational and maintenance costs for each chiller. Since the main aim is to compare the results with the model with linked cost functions, this model also considers only the central district cooling network which was presented earlier. To calculate the pumping costs, a fixed input parameter is input exogenously to the model. This parameter defines the kW of pumping per MW of cooling for each chiller. The model then calculates the pumping costs from this parameter. Since it is associated with the cooling generated, it has a direct effect on the decision variable in the model. The input parameter for the chillers was obtained from the results of a physically-based model of the district cooling network. This is a simulation model of the district cooling network. The values for the pumping cost are obtained for the hour with the largest cooling demand. Due to time constraints, the pumping costs for other hours could not be included in the model. Thus, the pumping costs in the results of this model are overestimated. However, since the main goal of this case is to compare the accuracy to which the network is represented, the value for the pumping cost is not the most important. Also, since the pumping cost is from the highest demand scenario, the network-based constraints will be the most restrictive. This will help in the comparison between the two methods better in terms of the significance of the network-based constraints in the model. The pumping cost for the different chiller units is presented in Table 10. These are obtained from the physically-based model run by Göteborg Energi [35].

Table 10: KW Pumping power per MW cooling

Chilled water generation unit	KW pumping / MW cooling
Rosenlund	26.8
Svenska Massan	12.6
Odinsplatsen	8.3
Gullbergsvass	37.0
Arkaden	24.1

The demand for this model is input in MW and the net demand described in 'model 1- case 2018' is also used here. The demand profile from 2018 is used.

Method 2: Model based on linked cost functions

The models in this method are built based on the linked cost functions described earlier. To include the linked cost functions, the structure of the model needs to be changed. The linked cost functions are a function of the flow. Thus, the decision variable in the model must be as a flow rather than in terms of MWh of cooling. Thus, the cooling demand and cooling production are denoted in terms of the flow of chilled water. The flows are calculated using equation 3.11 using a temperature difference of 6.64°C [35]. Thus, the entire model is restructured in terms of the flow of chilled water. The linked cost functions are used to calculate the pumping power, which is in turn used to calculate the pumping cost. The pumping cost is a part of the total costs which is the objective function. The main difference between this model and the previous model is the representation of the pumping costs. In the previous model, each plant had a fixed pumping power parameter irrespective of which part of the network the water was being pumped. Whereas, in this model, the linked cost functions define the pumping power parameter based on which demand cluster the chilled water is being pumped to. Thus, each chiller has 7 different pumping cost parameters i.e. one for each demand cluster. In addition, unlike in the previous model, the pumping power parameter is not a constant value. The pumping power parameter is defined by the linked cost functions which are a function of the flow. Thus, based on the flow between a chiller and the demand, the pumping cost also tends to change. Thus, this model coupled each chiller to each demand cluster. This model contains a large number of binary variables that lead to memory constraints. Hence, it was not possible to run this model over a time period of 8760 hours. To overcome this, the simulation was divided into two segments of 4380 hours, corresponding to roughly six months. This is not necessarily a disadvantage, as it might resemble actual operation of the system, where the time horizon never is an entire year. The demand profile from 2018 is used. Figure 21 shows the total cooling demand in the clusters.

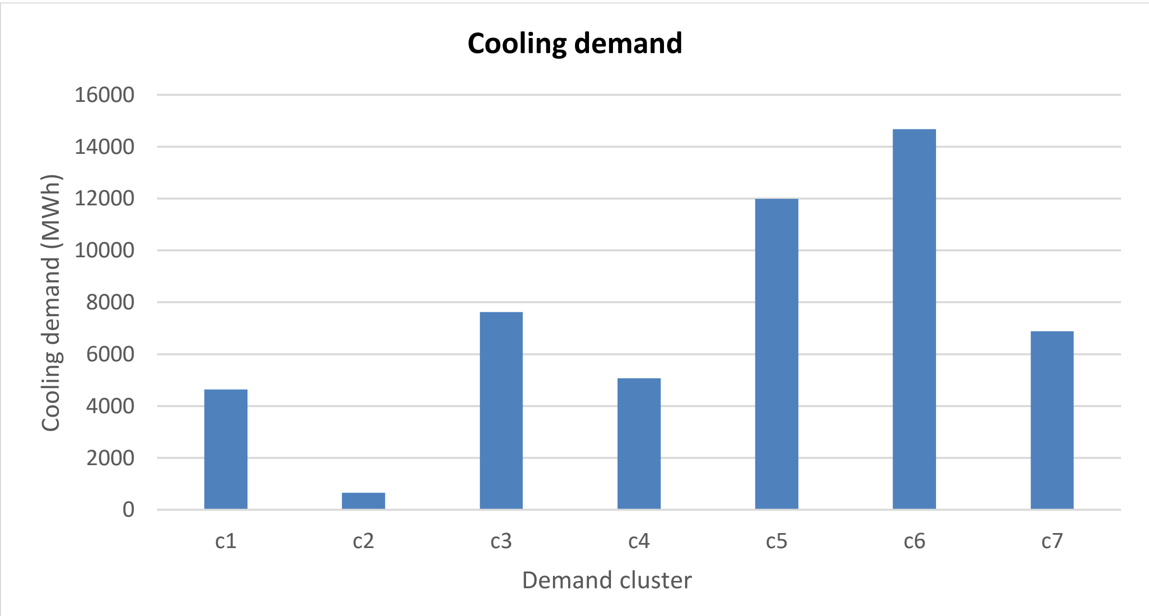


Figure 21: Cluster cooling demands

5.2.2 Case 2024

Model with DCS, network and thermal energy storage

This model is built based on the previous model with linked cost functions. Thus, in this model too, the decision variable is in terms of flow. The thermal energy storage is also added to this model. As discussed previously, Göteborg Energi plans to install a TES in the DCS. A tank that stores cold water will be installed by 2024. The location for the installation of the tank is known. However, the plans for the layout of pipes that connect the tank to the network are tentative. Hence, the length and diameter of these pipes are unknown. The pipe dimensions are required to develop the linked cost functions and hence assumptions must be made. The tentative plan for the pipes is shown in Figure 22. Based on this layout of the network, the pipe lengths can be calculated by superimposing this image onto google maps. The lengths measured are shown in Figures 23 and 24. The diameters of the pipes are assumed to be 630 mm. This assumption is based on the diameter of the main pipe in the network. Since the tank will have a large discharge, the pipe dimension must be the same as the largest in the network. At maximum discharge from the tank, the pressure drop in the pipe is lower than the permitted 1.5 bar per kilometer of the pipe. Thus, the pipe diameter of 630 mm is allowed.

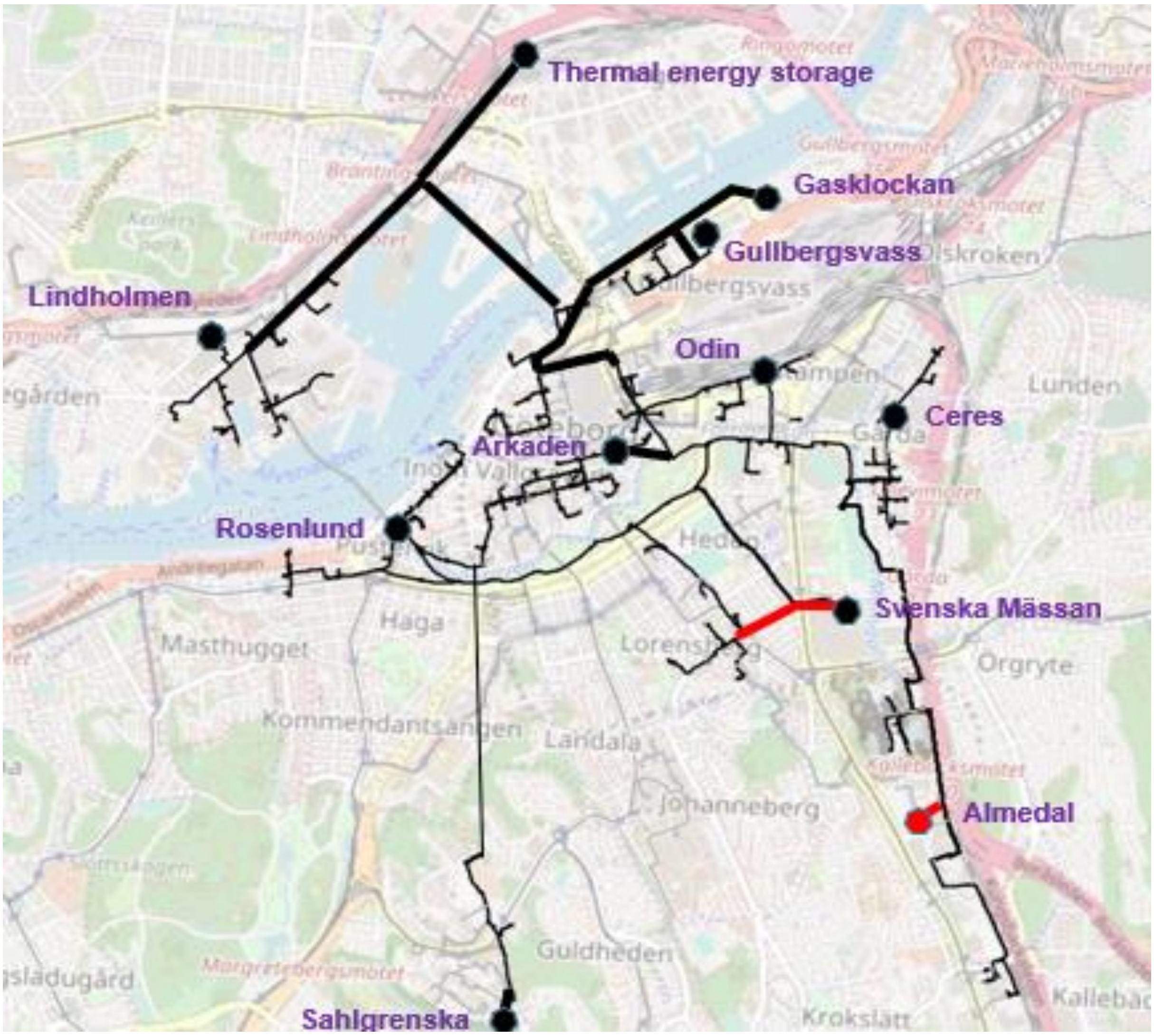


Figure 22: Tentative plan for network layout connecting the tank

Figure 23: Measured length of the pipes connecting to the tank

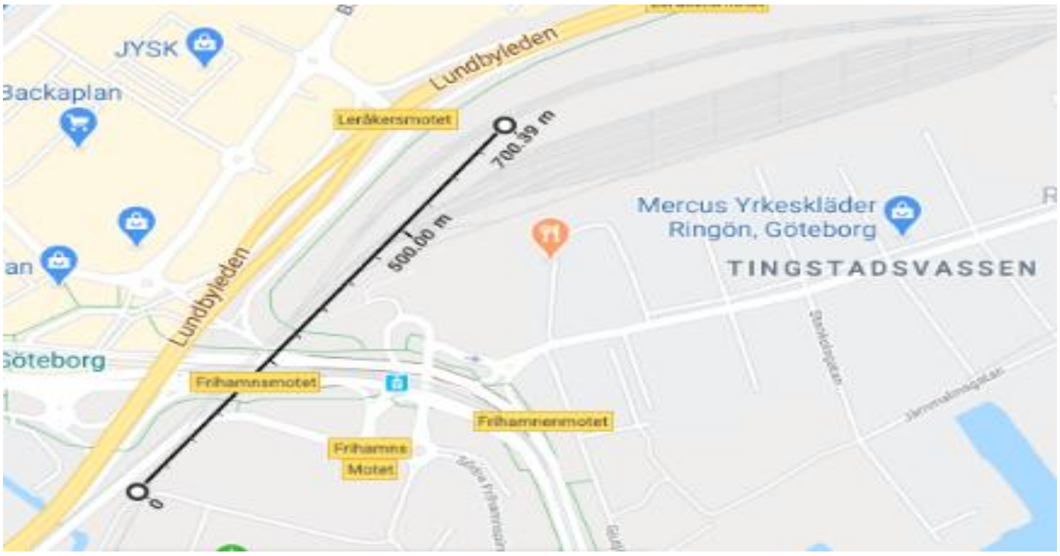


Figure 24: Measured length of the pipes connecting to the tank

Since the thermal energy storage is included as a part of this model, additional equations representing the tank must be inserted. The equations for the tank are quite similar to those used in scenario 4. However, in this case, since the demand is modeled as clusters, the storage variables must be indexed over the clusters too. Also, since the supply-demand constraint is defined for each cluster, the charging and discharging from the tank must be represented as two different variables.

$$E_{storage}\,(t) = \; E_{storage}\,(t-1) * \; \eta_{storage} + char_{storage}(t) - disc_{storage}(t) \quad 5.3$$

$$\sum\nolimits_p q[p,c,t] \geq D_{c,t} - dis_{storage}[tank,c,t] \quad 5.4$$

$$\sum\nolimits_c q[p,c,t] + chr_{storage}[p,t,tank] \leq Cap_p \quad 5.5$$

$$char_{storage}(t) = \; \sum\nolimits_p chr_{storage}[p,t,tank] \quad 5.6$$

$$disc_{storage}(t) = \; \sum\nolimits_c dis_{storage}[tank,t,c] \quad 5.7$$

The demand profile in the year 2024 is used. This demand profile is projected based on the demand in 2018. Also, the constraints are imposed such that the storage can be used only between the beginning of March and the end of November. This constraint is necessary to prevent the model from using the storage in the winter when it will be used by the DHS.

Chapter 6: Results

The results of all performed optimizations are presented in this chapter. The results are presented for each model and then the combined results of the model are presented for each case and each scenario.

6.1 Model 1 - Case 2018

This section presents the results of scenario 1 and scenario 2.

6.1.1 Scenario 1

The results of the optimization model are presented in this section. The main aim of scenario 1 was to determine the optimal dispatch of chillers in the DCS in 2018. So, the total cost of the system, and the dispatch of the chillers are the most important results from this scenario.

Table 11 shows the main results from scenario 1.

Table 11: Scenario 1 results

Parameter	Results
Chiller running cost (MSEK)	1.65
Total cooling produced (GWh)	56
Total electricity consumption for cooling (GWh)	3.48

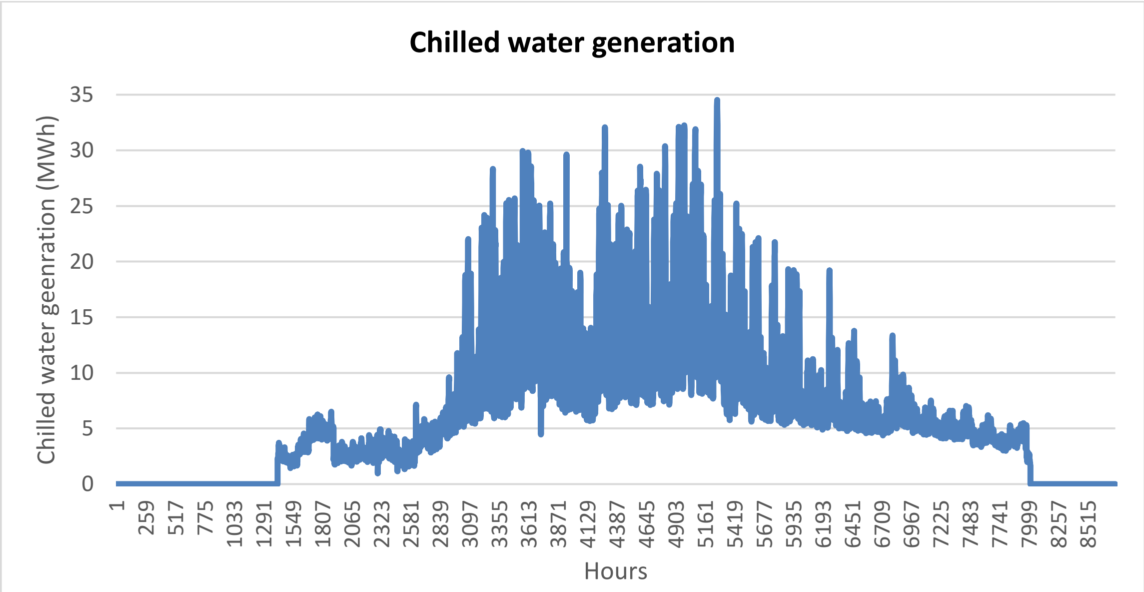


Figure 25: Chilled water generation – Scenario 1

Figure 25 shows the chilled water generation from the chillers. The chillers are not run during the winter and the peak generation occurs during the summer. The generation profile follows the demand profile with peaks in the summer and low generation during autumn and spring.

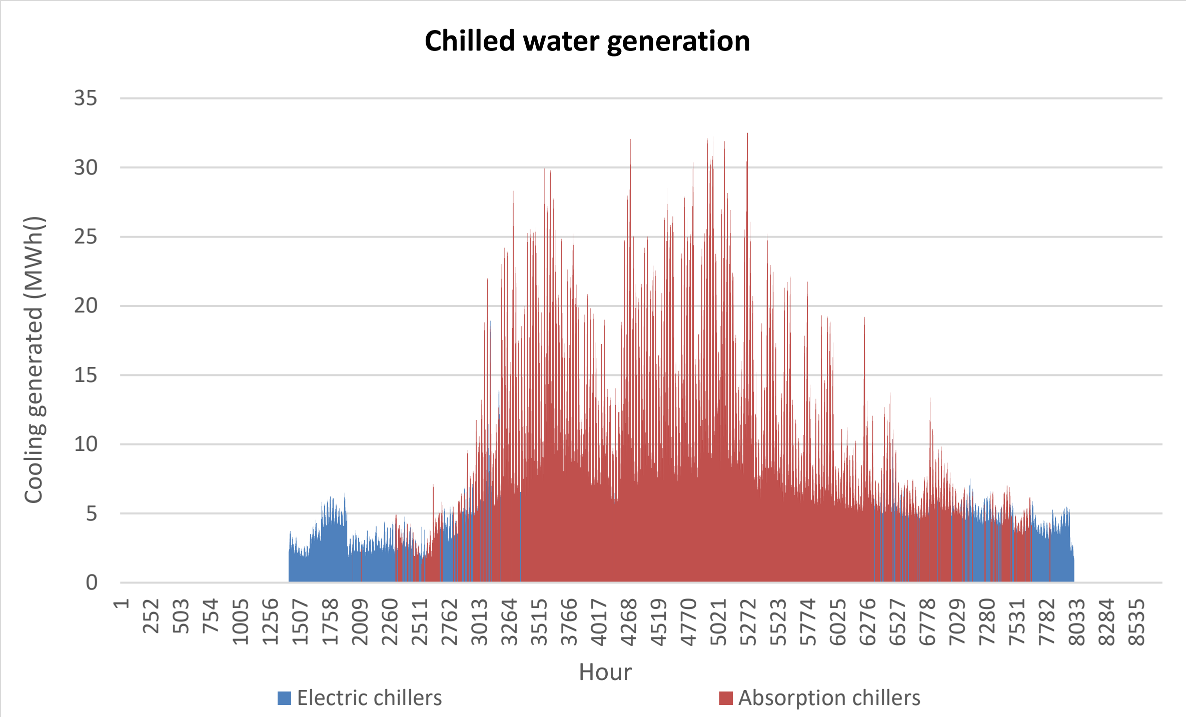


Figure 26: Chilled water generation - Absorption chillers vs Electric chillers

Figure 26 shows the chilled water generation from the absorption and electric chillers. The chillers are grouped into the electric and absorption chillers. This classification is done because the set of electric chillers have the same running costs and the same applies to the set of absorption chillers too. Thus, the dispatch can be analyzed by looking at how the absorption and electric chillers are run. Figure 26 shows the dispatch of the chillers. Figure 26 shows that the electric chillers are used mostly in the spring and the autumn months. The electric chillers are run very seldom in the summer because the absorption chillers can meet the demand by themselves. Since the optimization model tries to reduce the total chiller running costs, the dispatch is each hour is based on the merit order of the chiller running costs. In the summer, the absorption chillers are run to maximum because the price of heat is zero and hence, the running costs of the absorption chillers are much lower than that of the electric chillers. On the other hand, during the spring and autumn months, the heat demand in the DHS is significant and hence the prices of heat are higher than zero, and it is more economical to run the electric chillers during these hours. However, during the spring there are a few hours when the absorption chillers are also run. There a few hours in spring when the prices of heat are low enough to run the absorption chillers. This is further analyzed by looking at the variation of the chilled water generation from the absorption chiller with changes in the heating prices. Figure 27 shows the chilled water generation from absorption chillers and the heating prices.

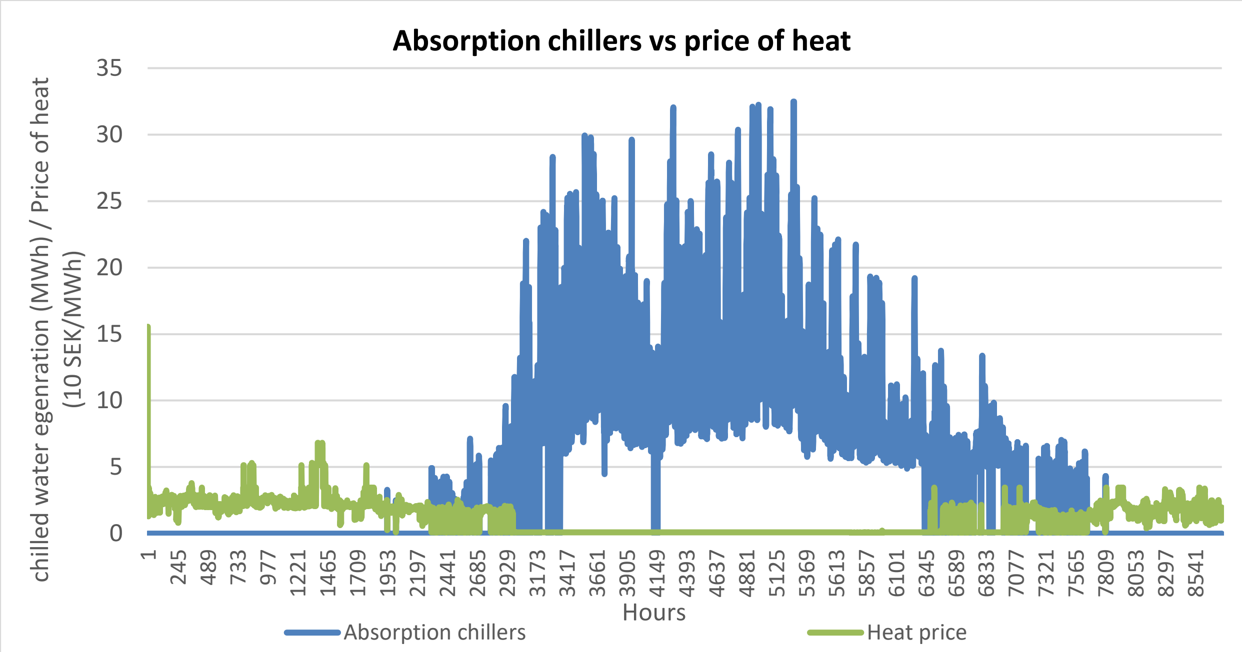


Figure 27: Variation of chilled water generation with prices of heat

It can be seen in Figure 27 that the chilled water generation has a direct correlation with the price of heat. The absorption chillers are run only when the prices of heat in the DHS is very low, which means that there is "excess heat" in the DHS. The absorption chillers are used mostly during the summers when the prices of heat are zero continuously for a very long period. Besides, the absorption chillers are also run during a few hours in the spring and the autumn. Since the model is based on economic optimization, the results prove that it is more economic to run the absorption chillers during some hours even in the spring and the autumn. This is quite different from the practical functioning of the system. The absorption chillers are not run until the prices of heat are zero for a continuously long period. Therefore, the absorption chillers are not run until the beginning of the summer when the prices of heat are zero. Thus, it can be of more interest to look closely at the dispatch of the chillers in the period just before summer when the absorption chiller and the electric chillers are run alternatively based on the prices of heat and electricity.

Figure 28 takes a closer look at the dispatch of the chillers in the period just before the summer when the absorption chillers are run for the first time. The absorption chillers are run to meet the cooling demand for a few hours. During these hours, the electric chillers are turned off and hence, the chilled water generation from the electric chillers is zero. Therefore, the economically optimal operation of the system is quite different from the actual operation. The reasons for this difference are explained in later sections.

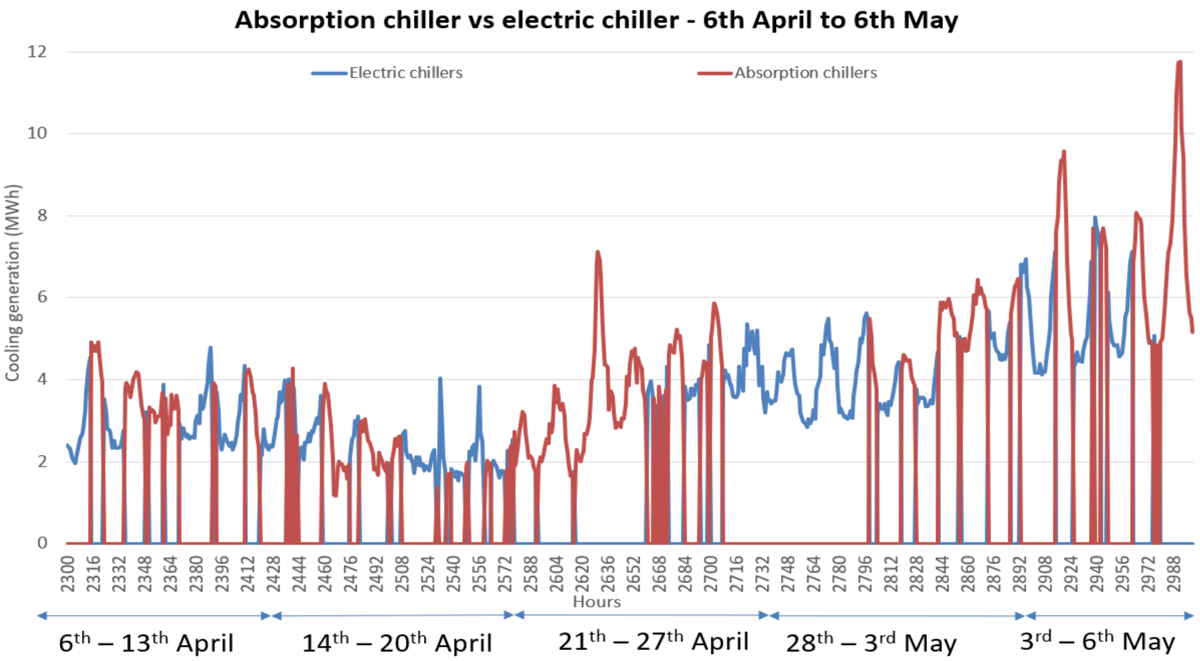


Figure 28: Chilled water generation from absorption chiller vs electric chillers in the spring

6.2.1 Scenario 2

Scenario 2 describes the case of having individual chillers. The results of this model are in Table 12.

Table 12: Scenario 2 results

Parameter	Results
Chiller running cost (MSEK)	6.96
Total cooling produced (GWh)	68.54
Total electricity consumption (GWh)	14.51

Since the scenario is a simulation model, there is no optimization. Thus, unlike the previous scenario, the results do not show the optimal way in which the system can operate, rather the results indicate how the chillers must be operated to meet the cooling demand.

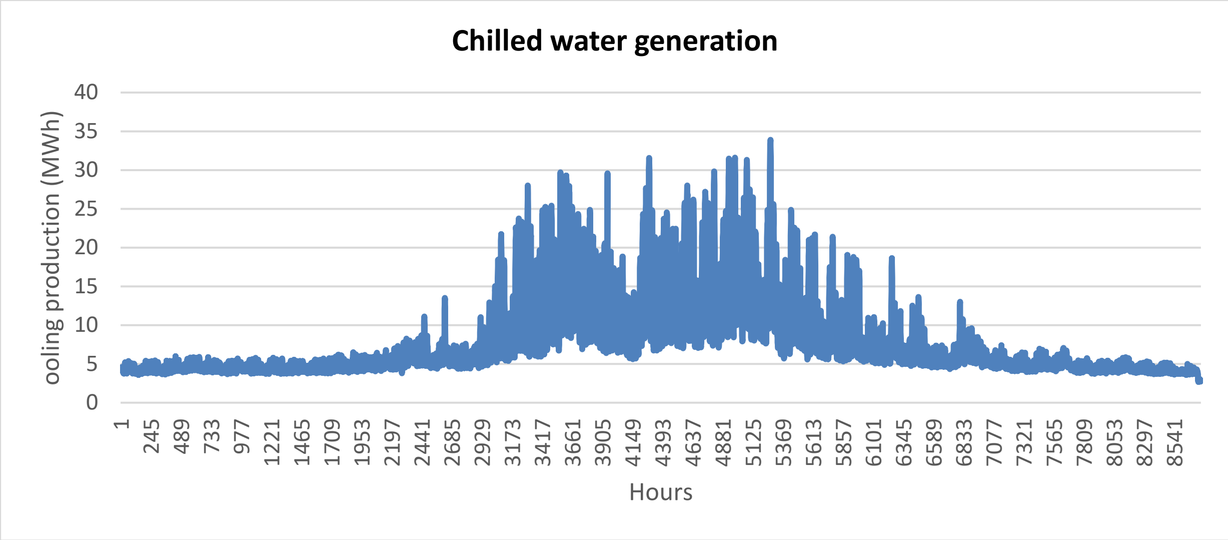


Figure 29: Chilled water generation in scenario 2

The chilled water generation profile shown in Figure 29 is similar to the previous scenario because in both the scenarios, the chilled water generation is based on the cooling demand. Since the cooling demand is similar, the generation profile is also quite similar. But the chilled water generation is not zero during the winter as in the previous results. This is due to the assumption that there is no free cooling either from the river or from outside air in this scenario

6.1.3 District cooling vs Individual Chillers

The main goal of the case 2018 was to compare the operation of the DCS with that of a hypothetical case of individual chillers. The comparative results are shown in Figure 30.

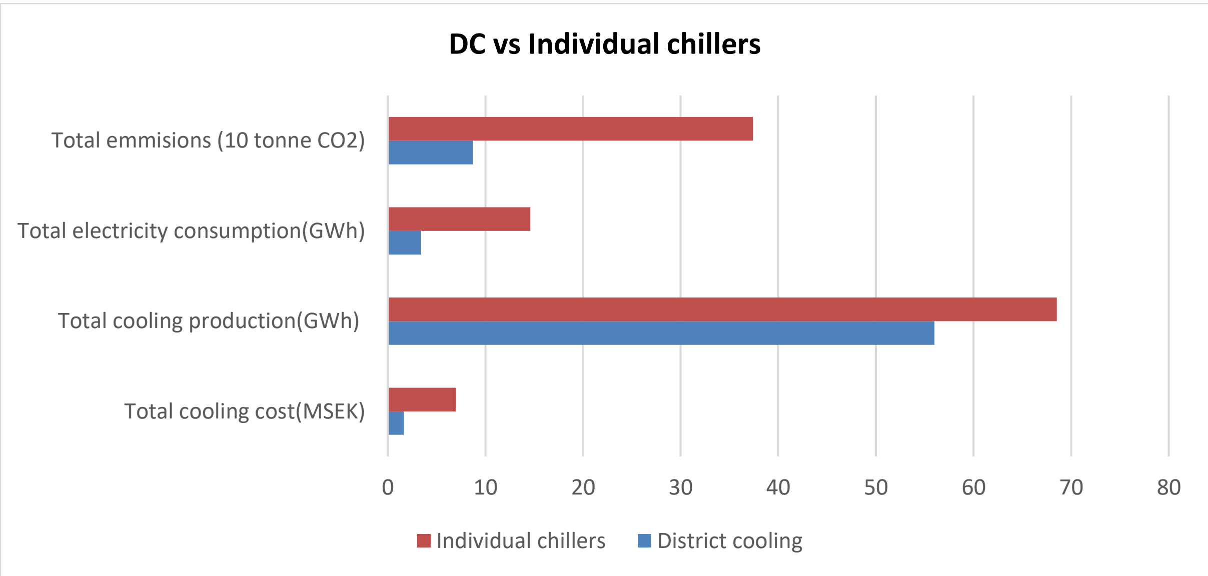


Figure 30: Comparison between results of scenario 1 and 2

From Figure 30, it is quite clear that the DCS is better than the individual chillers both economically and environmentally. The total chilled water generation in scenario 1 is lower by about 12.5 GWh. This is because the free cooling from the river accounts for this energy in the scenario 1. Also, the individual chillers use more than 4 times the electricity used in the district cooling case. This is because of the use of absorption chillers in the district cooling scenario.

The absorption chillers are the major chilled water generation technology in the district cooling scenario. Whereas in the individual chillers case, the entire cooling demand is handled by electric chillers and hence the use of electricity is also much higher. Therefore, according to this result, the DCS has the potential to relieve the electricity grid since it uses much less electricity as compared to the individual chillers case. In accordance with these two results, the chiller running costs in the individual chillers are about 4 times of that in the case of the DCS. This result is directly linked to electricity use. The operation of absorption chillers running on waste heat helps to reduce electricity use in the DCS. Another result directly linked to electricity consumption is emissions. In the individual chillers case, the emissions are higher than in the DCS case due to higher electricity use.

Thus, from the above results, it is quite clear that the DCS is better than the individual chillers economically. The lower consumption of electricity ensures that there is less stress on the electricity grid. Besides, there are lower emissions in the system since there is a lower electricity demand, and the peak units such as gas turbines which are responsible for the emissions are used to a lesser extent in the winters. An increase in emissions could occur in the system during the winters when the electricity demand is high due to the high consumption of electricity for heating. In such cases, additional demand for electricity created by the individual chillers could lead to emissions as the peak units will be used to meet the demand for electricity from the chillers. In the case of the DCS, this issue does not arise as the cooling demand in the winters is handled by the free cooling from the river and hence the peak electricity demand is lower.

Another advantage of the DCS is that it makes use of the waste heat from the refineries. The excess heat in the district heating in the summer must be cooled off. The DCS makes use of a part of this excess heat in the absorption chillers. Since cooling off this excess heat involves costs for the DHS, a part of this cost is avoided by making use of this heat in the DCS.

6.2 Model 1 - Case 2024

This section presents the results from scenarios 3 and 4. There are several uncertainties associated with the modeling of future DCS. Hence, it is not realistic to look at results such as chiller running costs in absolute terms. Rather, the results must be looked at relative to each other and the differences in the two results must be examined.

6.2.1 Scenario 3

The existing chillers in 2018 were kept in the model and the new investments made were also added to meet the increased demand. The functioning of the DCS in 2024 is very similar to that in 2018. The major results are presented in Table 13.

Table 13: Scenario 3 results

Parameter	Result
Chiller running cost (MSEK)	2.8
Total chilled water generation (GWh)	90.3
Total electricity consumption (GWh)	5.3

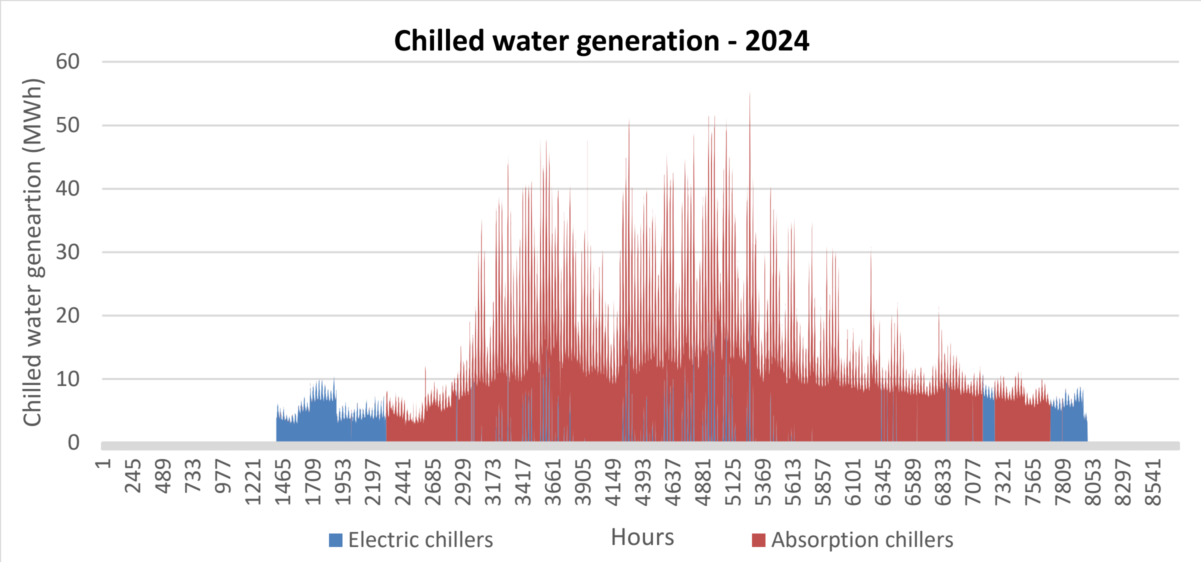


Figure 31: Chilled water generation in scenario 3

The dispatch of the chillers shown in Figure 31 is almost identical to that in scenario 1. The running costs, total chilled water generation, and electricity consumption are higher in this model and it is an expected result since the demand is higher. The major difference between the results of scenario 3 and scenario 1 is that the electric chillers are operated more often during the summer in 2024. This is because the demand peaks are higher than the installed capacity of the absorption chillers. The use of thermal energy storage to eliminate this increased operation of electric chiller is analyzed in the next section.

6.2.2 Scenario 4

This section presents the results of scenario 4. The inclusion of thermal energy storage changes the operation of the system significantly. In scenario 3 the dispatch of the chillers is based on the cooling demand. The hourly chilled water generation must be at least equal to the cooling demand in that hour. But, with the introduction of the storage into the system, energy can be shifted in time, and hence the dispatch does not have to follow the cooling demand anymore. Instead, now the dispatch of the chillers is based on how the storage is operated. Thus, the results of this scenario are quite different from the previous results. The major results are presented in Table 14.

Table 14: Scenario 4 results

Parameter	Result
Chiller running cost (MSEK)	2.4
Total cooling generation (GWh)	90.54
Total electricity consumption (GWh)	5.4
Total energy stored (GWh)	43
Break-even storage cost (SEK/MWh)	9.4

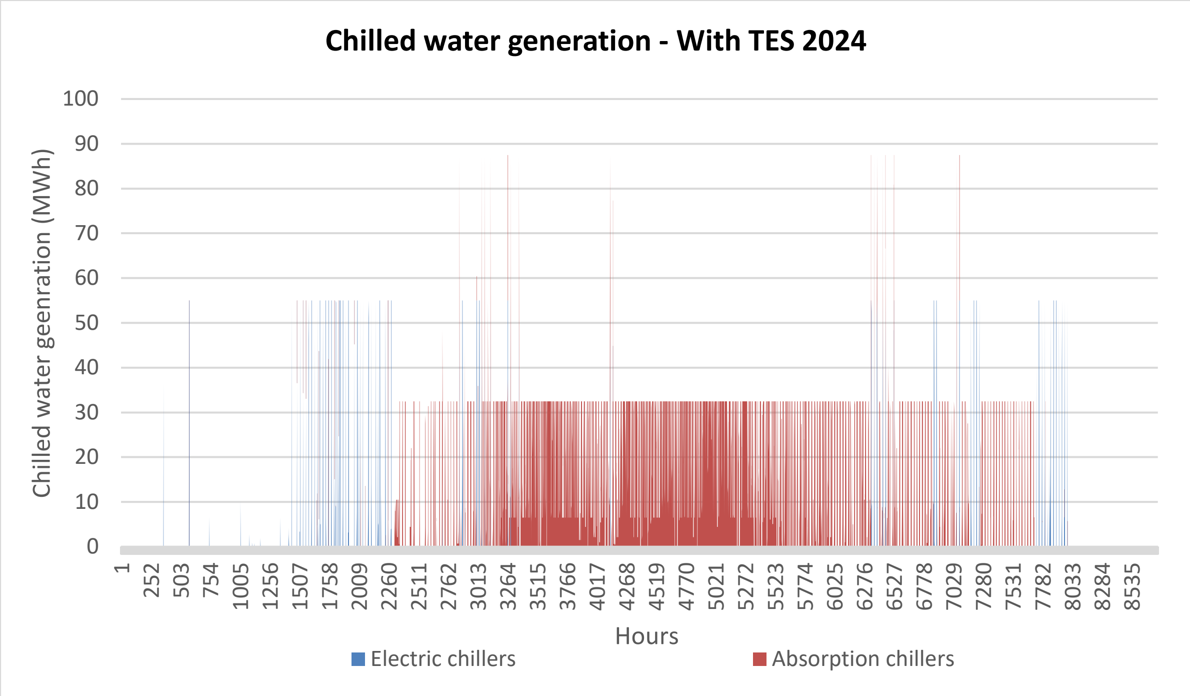


Figure 32: Chilled water generation in scenario 4

The chilled water generation shown in Figure 32 profile is much different from the previous scenario. There are more peaks in this generation profile. The chillers are run at peak load during the low electricity price hours and the chilled water hence generated is pumped into the tank and stored over time. The stored energy is discharged during high demand hours.

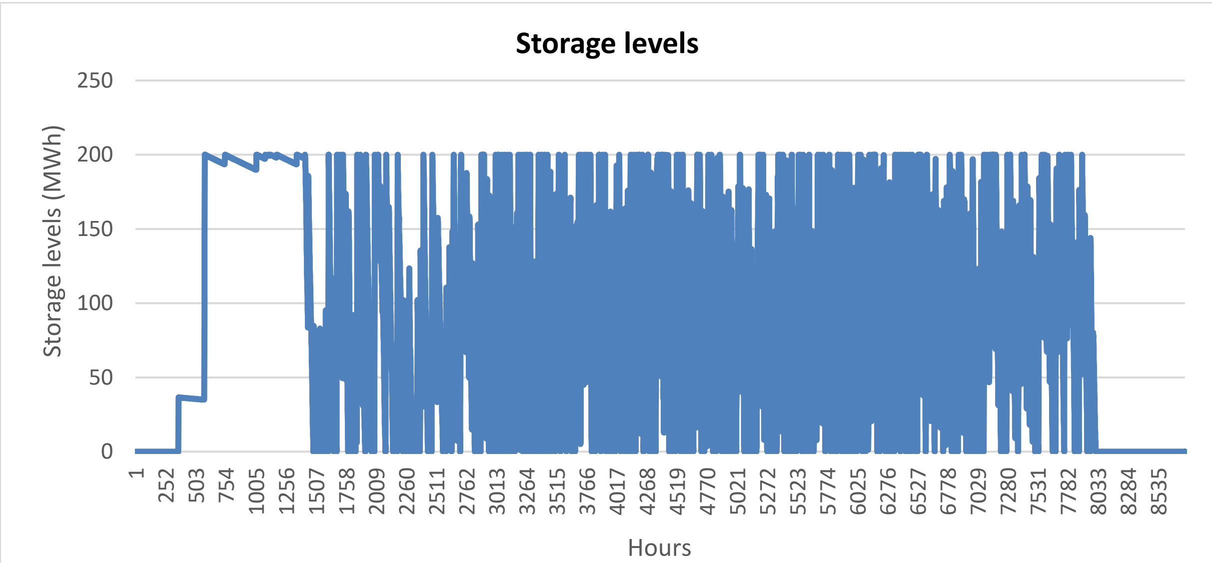


Figure 33: Energy levels in the storage

The energy levels in the storage are shown in Figure 33. The charging of the storage starts in the winter when the cooling demand is low. The electric chillers are run during low electricity price hours in the winter and the storage is charged with cold water. The decrease in the energy levels during the winter is due to the loss of energy from the storage. The cycling of the storage starts when the cooling demand is high. In summer, the storage is cycled continuously as shown in Figure 34.

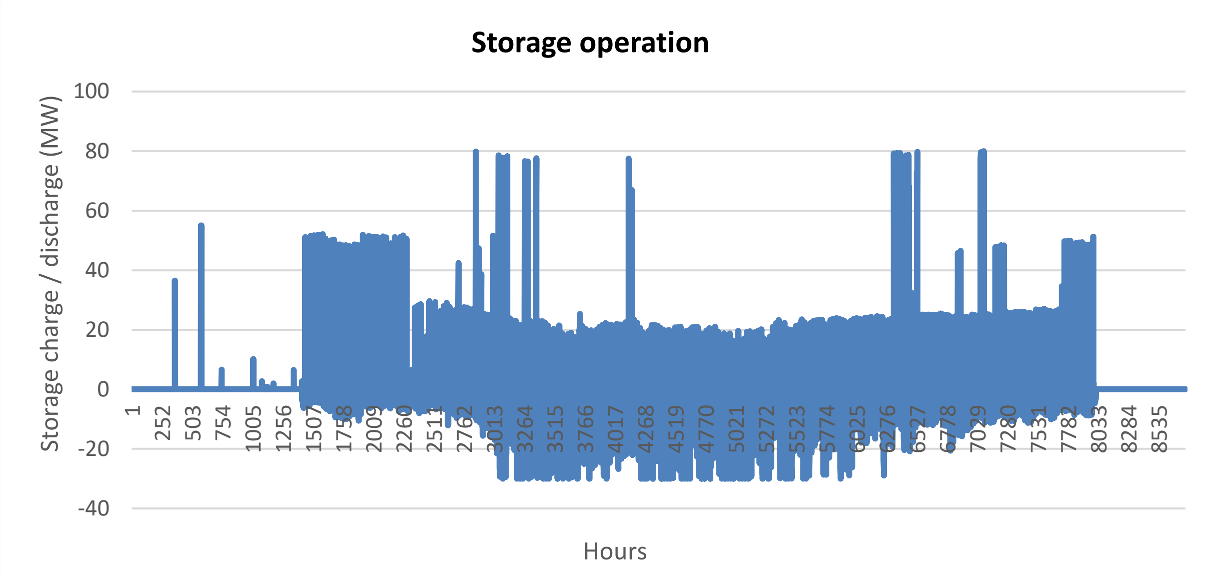


Figure 34: Charging and discharging of the storage

The charging of the storage is represented by the positive values and the discharging is shown by the negative numbers. Most discharge from the storage takes place in the summer when the demand is high. The results show that the absorption chiller and the storage are used extensively during the summer. To check if the electric chillers must be operated to meet the demand during the summer, the chilled water generation in the summer months was analyzed.

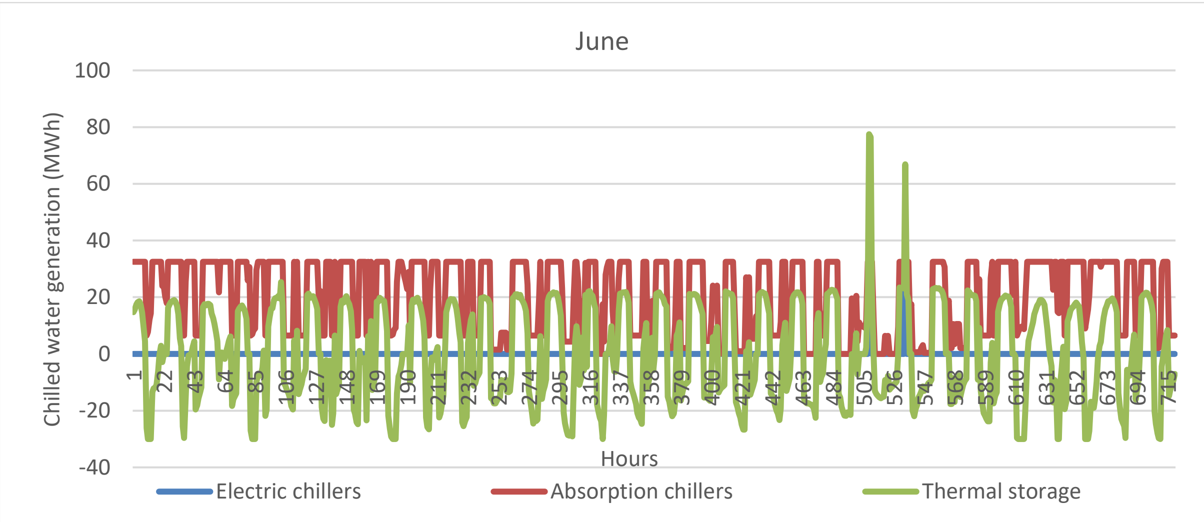


Figure 35: Chilled water generation in June

In June, the electric chillers are run for a few hours as shown in Figure 35. The electric chillers are not operated to meet the demand, rather the chilled water generated from the electric chillers is used to charge the tank. The electric chillers are run during these hours because of the low prices of electricity. Hence, the absorption chiller and the tank are enough to meet the demand in June.

In July, the electric chillers are not operated. The chilled water generation from the electric chillers remains zero throughout the month. The same is also observed in August as shown in Figure 37.

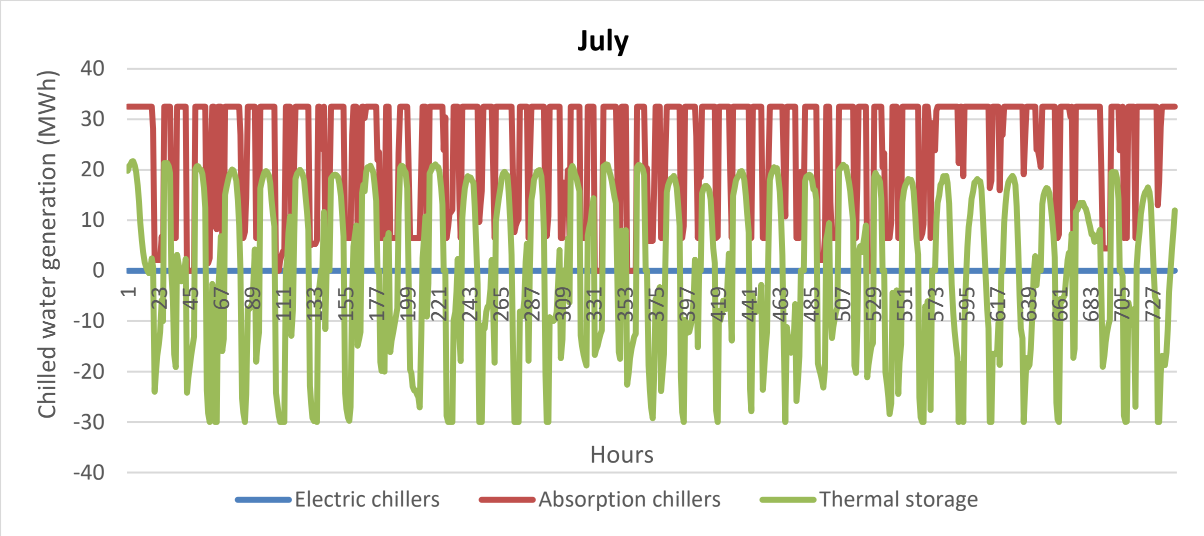


Figure 36: Chilled water generation in July

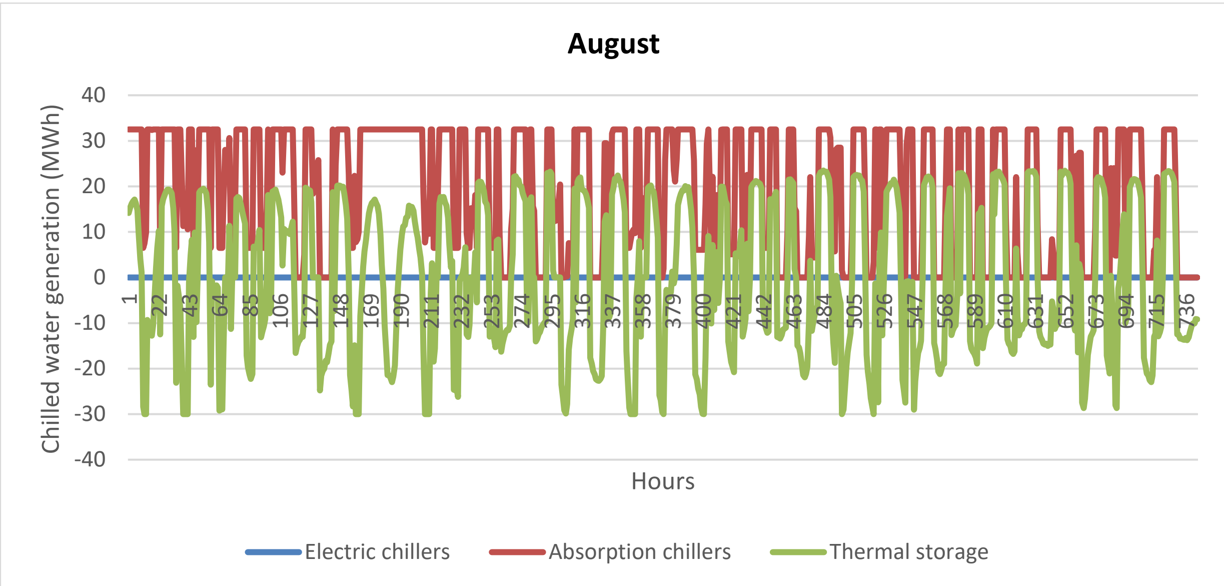


Figure 37: Chilled water generation in August

The results show that the electric chillers are not operated during the summer months of July and August when the demand is the highest. Thus, the optimal use of absorption chillers and thermal energy storage is enough to provide cooling during the summer months.

6.2.3 Impact of the thermal energy storage

The results from the previous section showed the difference seen in the dispatch of the chillers between the two scenarios. The changes in the operation of the system when the thermal energy storage is introduced is examined further in this section.

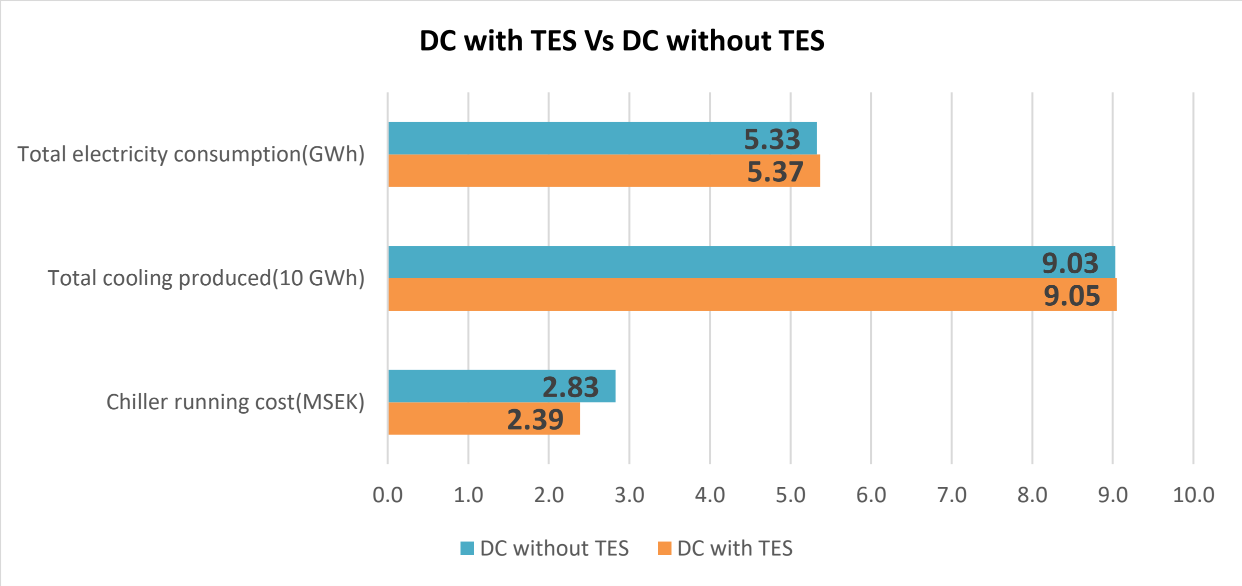


Figure 38: Impact of thermal energy storage on the system

The introduction of the thermal energy storage into the system reduces the chiller running costs by about 439 500 SEK. The most interesting trend in Figure 38 is that the cost reduces despite an increase in the total chilled water generation and the total electricity consumption.

The increase in the total chilled water generation is due to the losses from the thermal energy storage. To compensate for the energy loss from the tank, the chillers must generate more chilled water than before.

The increased electricity consumption is due to the increased use of electric chillers in the system. The electric chillers are run at peak capacity during some hours in the winter, spring, and autumn when the prices of heat are high. But the electric chillers are run only during those hours when the price of electricity is low. The presence of storage in the system ensures that the electric chillers can be run selectively and not based on the demand. The variation between the supply and the demand is handled by the storage. Hence, the total cost of the system is less despite the increased use of electric chillers.

6.3 Model 1 - Case 2030

This section presents the results of the case 2030. Since several different scenarios were considered, all the results are presented together in Figure 39.

The total chiller running cost from all the scenarios is shown in Figure 39. It is important to note that these results depend on several uncertainties such as future prices of fuels, development of future systems, etc. Hence, it is not sensible to look at these results in absolute terms. Rather, the relative difference between the results of each scenario must be analyzed. In the scenarios with no coll electricity prices, it is seen that the presence of a seasonal energy storage does not have a large impact on the costs. The results of the scenarios with and without the SES in the DHS are almost identical. As expected, the scenario with storage in the DCS has better results. Also, the impact of the storage in the DCS in 2030 is larger than the impact that it had in 2024 in terms of cost savings. In the scenarios with coll electricity prices, the presence of SES in the system makes a large difference in the running costs. Hence, the impact of SES on the DCS is dependent on the electricity prices.

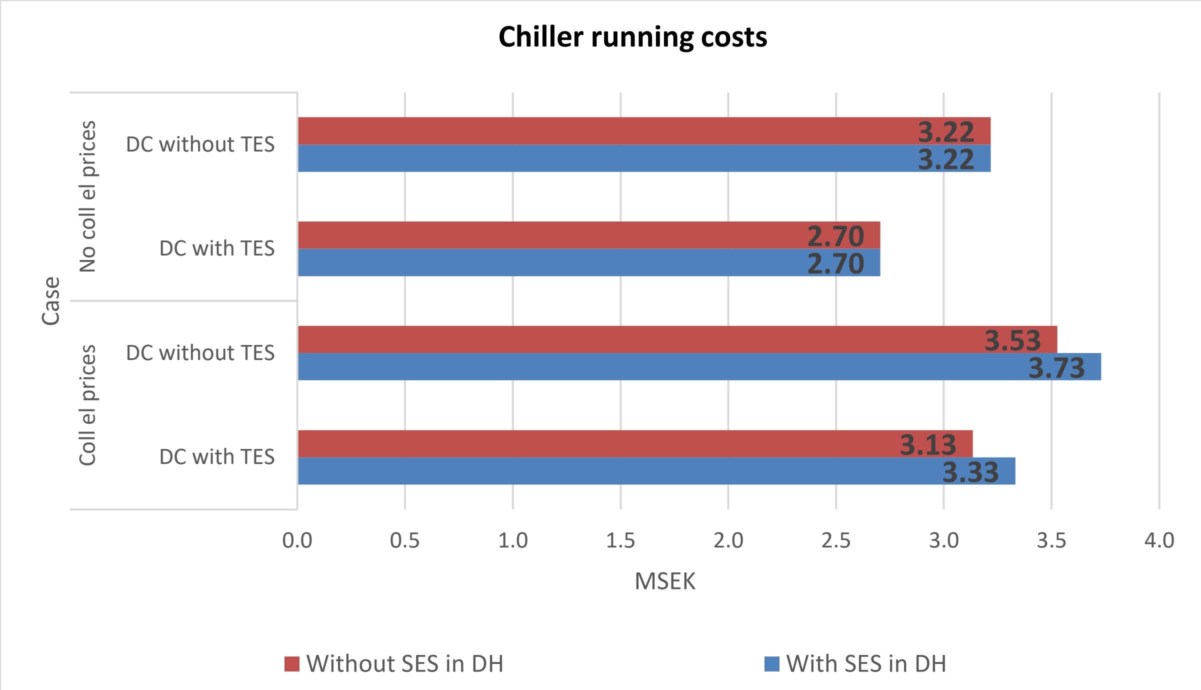


Figure 39: Comparison between results of all scenarios in case2030

Thus, it is important to analyze similar scenarios with different electricity prices. The difference in how the system operates in these two scenarios is examined further. The dispatch of the chillers from the different scenarios are analyzed. As it has been assumed that the installation of storage in the DCS is a certainty, the scenarios without TES in the cooling system are not considered. These scenarios were created only to examine the impact of the TES in the DCS in 2030

6.3.1 Results for scenarios with No coll electricity prices

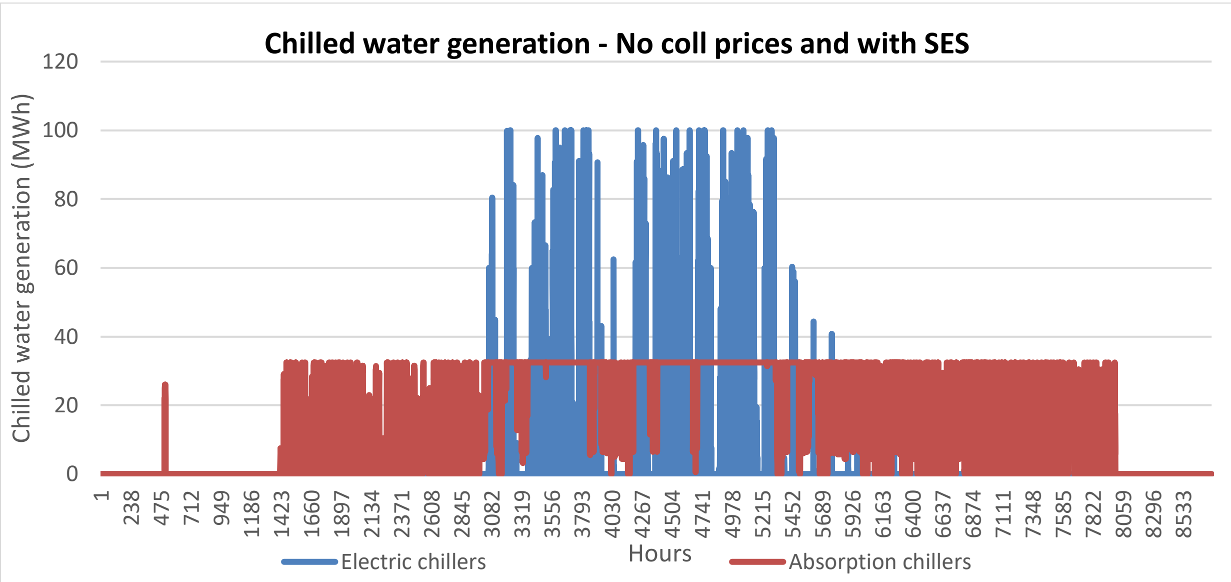


Figure 40: Chilled water generation - No coll electricity prices and SES in DH

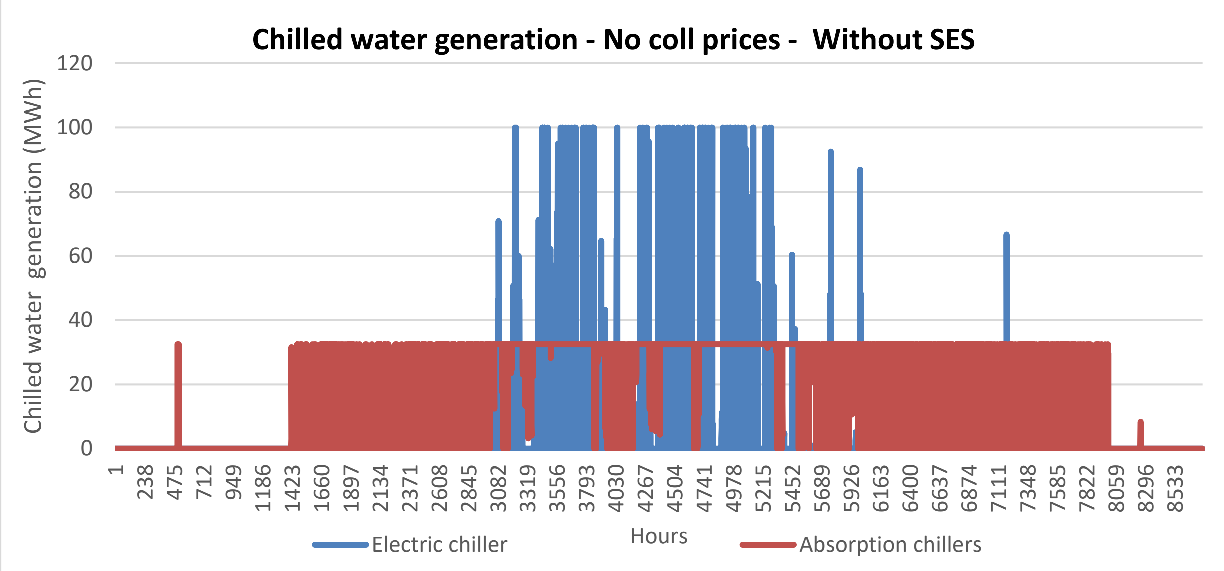


Figure 41: Chilled water generation - No coll electricity prices and without SES in DH

The chilled water generation profile in these two scenarios are identical to each other. Since the results are from an optimization model with an objective function of minimizing the total running costs, the dispatch is dependent on the prices of the fuel. Since both models have the same electricity prices, the prices of heat are further analyze as shown in Figure 42.

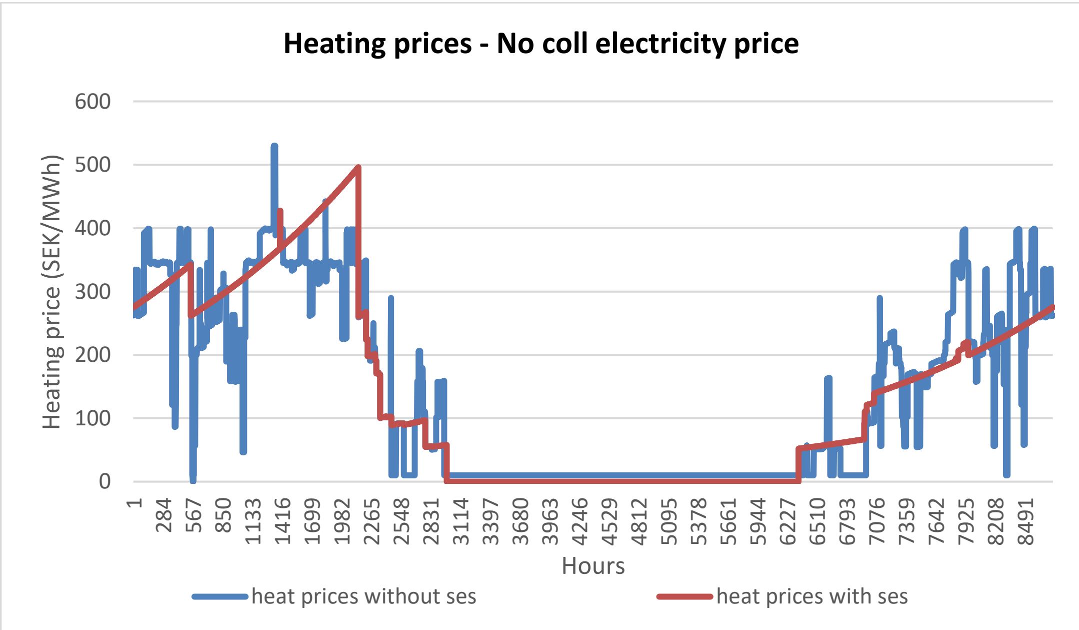


Figure 42: Comparison of prices of heat in scenarios with and without SES in DH

The prices of heat in the two scenarios are very similar. The prices of heat in the model without SES fluctuates continuously. This is because the dispatch follows the demand. whereas in the other scenario, the prices of heat are much more constant. Despite the storage of excess heat during the summer, the prices of heat are low during the entire summer. The prices of heat continue to be low even after the heat demand increases in the autumn. This is because the heat from the storage is discharged during this period. Since the prices of electricity and heat are similar to each other, the dispatch in both the models is identical.

6.3.2 Results for scenarios with Coll electricity prices

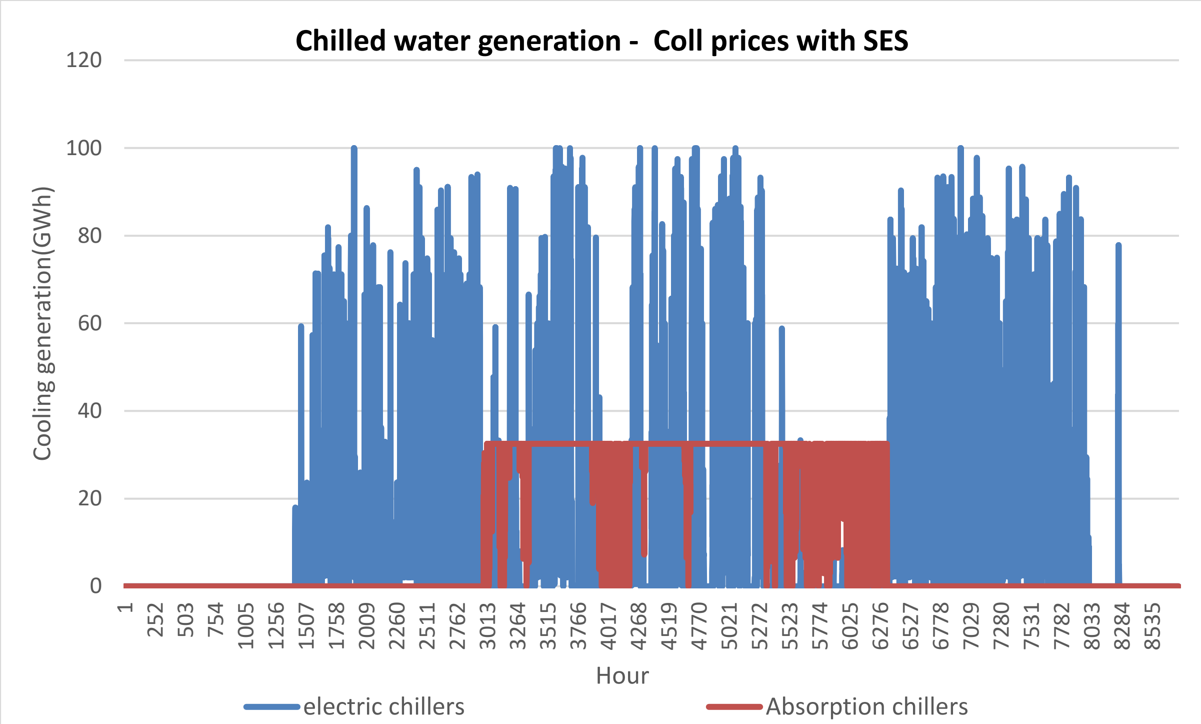


Figure 43: Chilled water generation - Coll electricity prices and SES in DH

The dispatch of the chillers in the scenario with collaboration electricity prices and the SES is shown in Figure 43. The chilled water generation in this scenario is very different from that in the previous results. The generation of chilled water from absorption chillers is low even in warmer periods of the year.

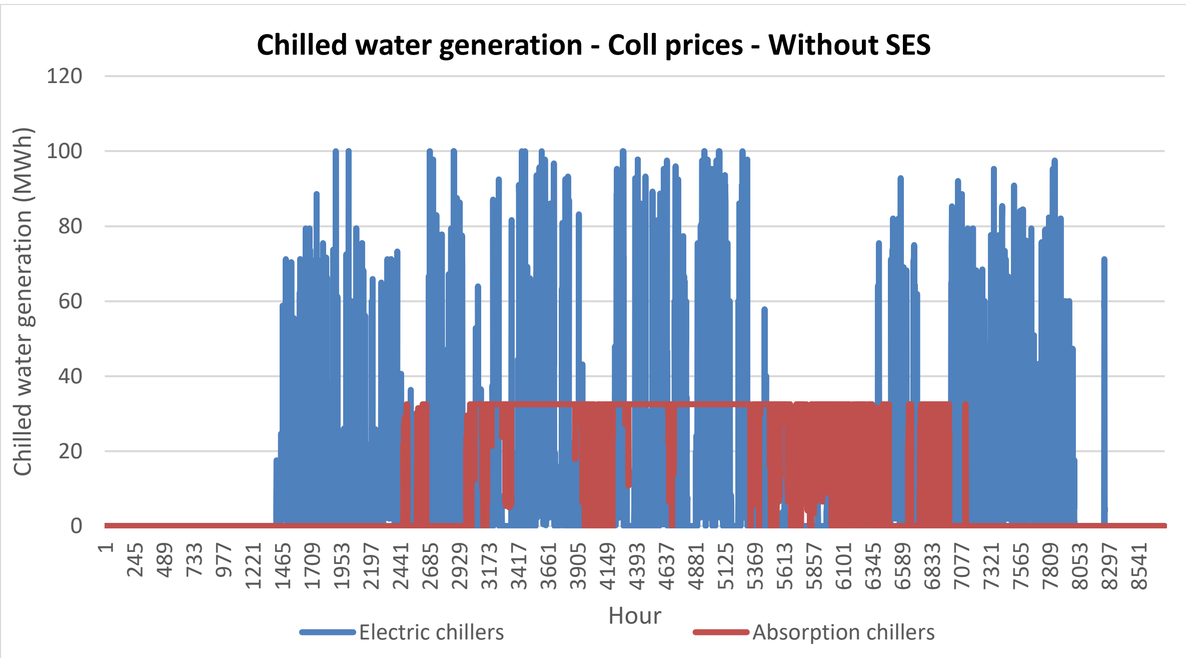


Figure 44: Chilled water generation - Coll electricity prices and without SES in DH

The chilled water generation in the scenario with coll electricity prices and without SES in the DHS is shown in Figure 44. The chilled water generation from the absorption chillers is higher in this scenario compared to the previous one. When there is no seasonal energy storage in the system, the absorption chillers are operated more. This implies that the prices of heat are lower in the system during the summer when there is no seasonal storage is the system. The variation of the heating prices in the two scenarios is shown in Figure 45.

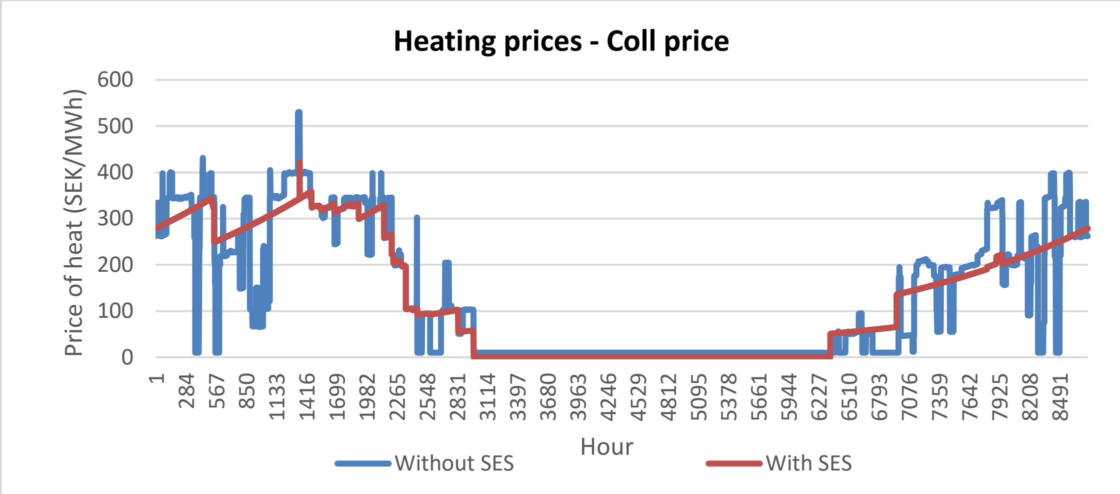


Figure 45: Comparison of prices of heat in scenarios with and without SES in DH

The prices of heat are similar in both scenarios. The difference in the prices of heat in the spring and the autumn creates a different dispatch of the chillers. Thus, in the scenarios without SES, absorption chillers are run even during the autumn and the spring, and hence the chiller running costs are lower in these scenarios.

6.3.3 Performance of the DCS

To analyze the performance of the DCS in 2030, the best scenario is chosen. The best scenario has the lowest running costs. Thus, the scenario with no coll electricity prices and without SES is chosen. The chilled water generation in the scenario is shown in Figure 41. The absorption chillers are used to meet the cooling demand throughout the year. The absorption chillers at peak capacity are run continuously during the summer. During the warmer periods of the year, the electric chillers are used to meet the demand. The operation of the DCS in the summer is based on the prices of heat and electricity. The prices of heat are low throughout the summer and hence the absorption chillers are run continuously, whereas the electric chillers are run at peak capacity during the low electricity price hours. The chilled water generated during these hours is pumped into the thermal energy storage and discharged during high electricity price hours. The operation of storage is shown in Figure 46.

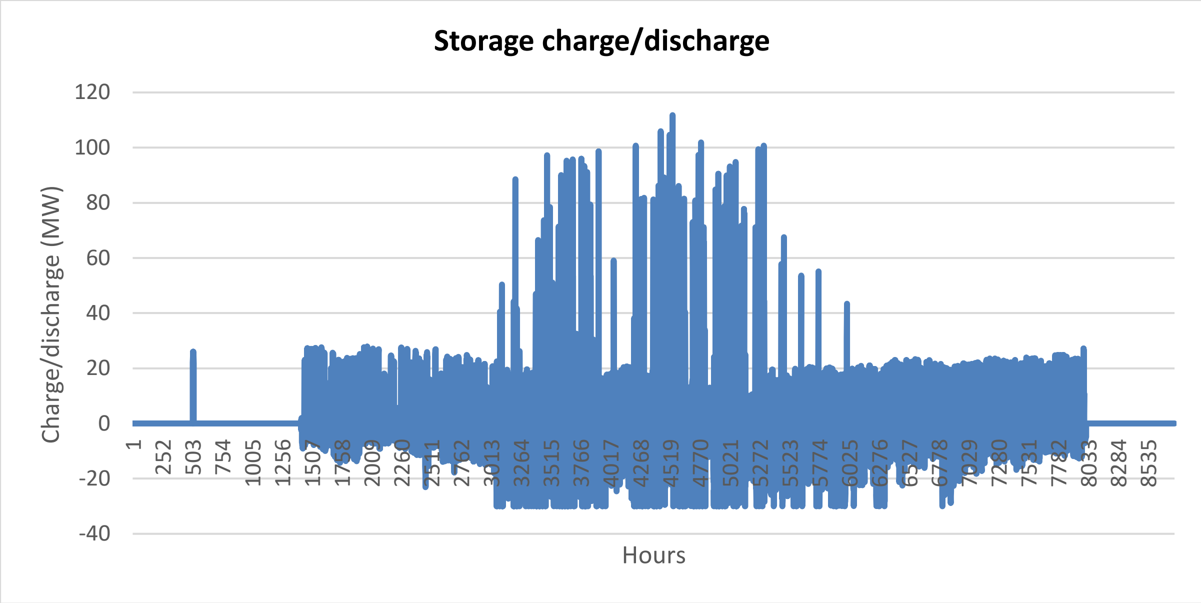


Figure 46: Charging and discharging from storage

There is a large discharge from the storage during the summer. The operation of the storage is similar to that in the previous case. The operation of the DCS in the summer months must be analyzed to determine whether the cooling demand can be met by operating only the absorption chillers and the thermal energy storage. The operation of the storage in the summer months is shown in Figures 47-49. The TES in the system in 2030 leads to a saving of about 513,300 SEK.

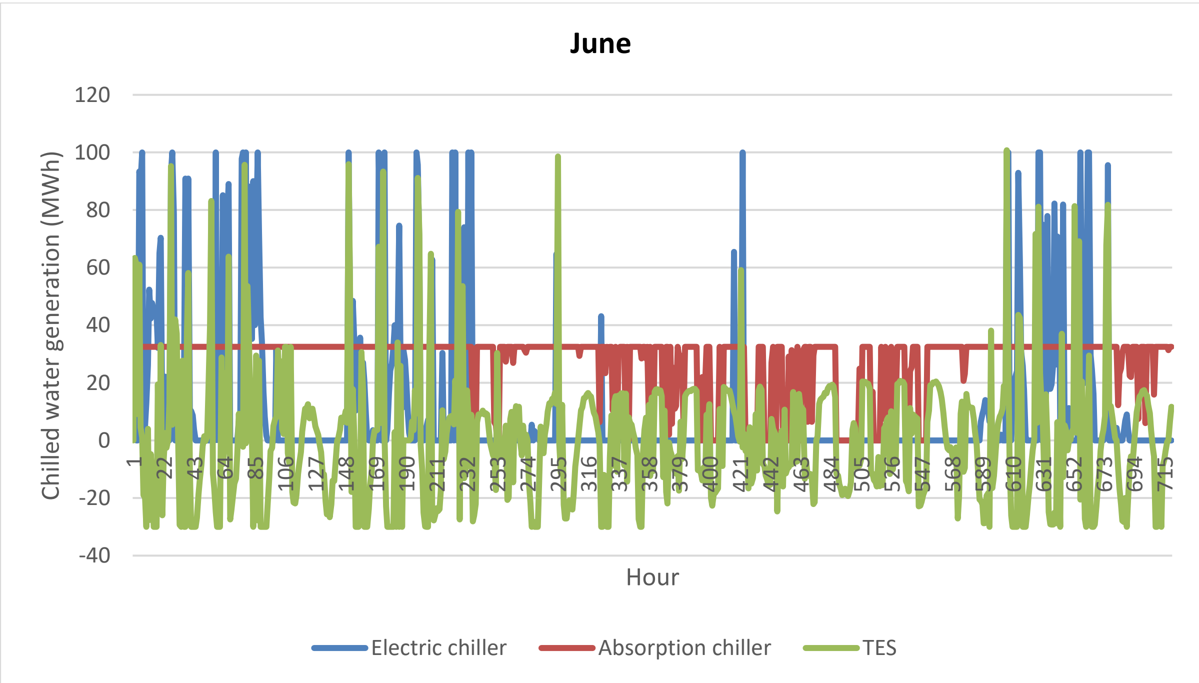


Figure 47:Chilled water generation in June

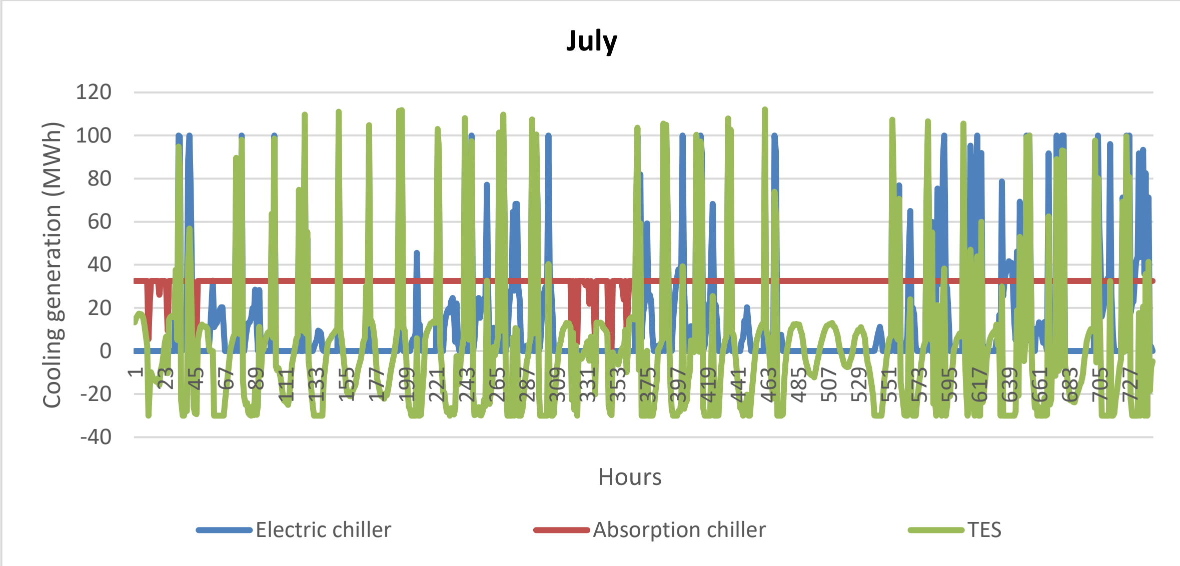


Figure 48: Chilled water generation in July

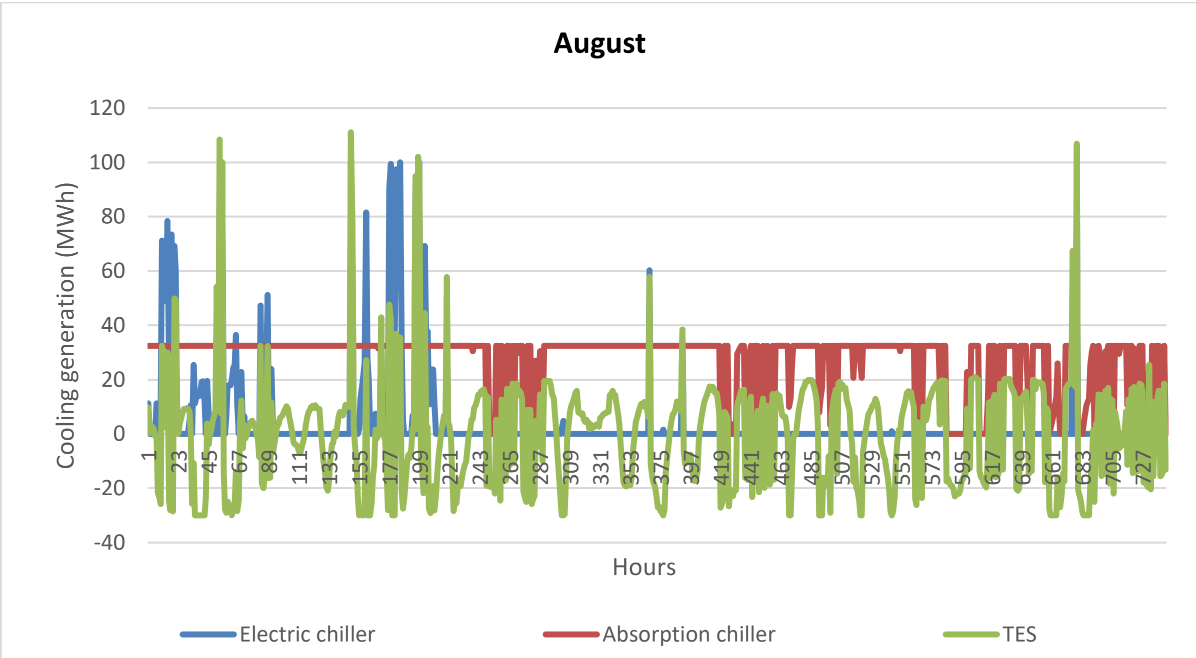


Figure 49: Chilled water generation in August

The peak demand in the district cooling is much higher in 2030 than in 2024. The peak demands in the system are higher than the sum of the installed capacity of the absorption chillers and the discharge capacity of the tank. Thus, the electric chillers are run for several hours to meet the demand. But the electric chillers are not run just to meet the demand, rather the electric chillers are run at peak capacity during the low electricity price hours, and the chilled water generated is stored in the tank. This can be seen in Figures 47, 48, and 49. The charging of the tank is high when the production from the electric chiller is at peak capacity. But, during these hours, the generation from the electric chillers is higher than the energy-charged into the tank. The remaining part of the chilled water generated from the electric chillers is used to meet the demand. Hence, with the current storage and discharge capacity of the tank, the electric chillers must be run to meet the demand during the summer.

6.4 Model 2 - Case 2018

6.4.1 Method based on fixed pumping cost parameter

The results of the optimization model are presented in this section. The main aim of this method was to include the pumping cost as a fixed cost parameter.

Table 15: Results of fixed pumping parameter method

Parameter	**Results**
Total cost (MSEK)	1.23
Pumping cost (MSEK)	0.44
Total cooling produced (GWh)	51.92

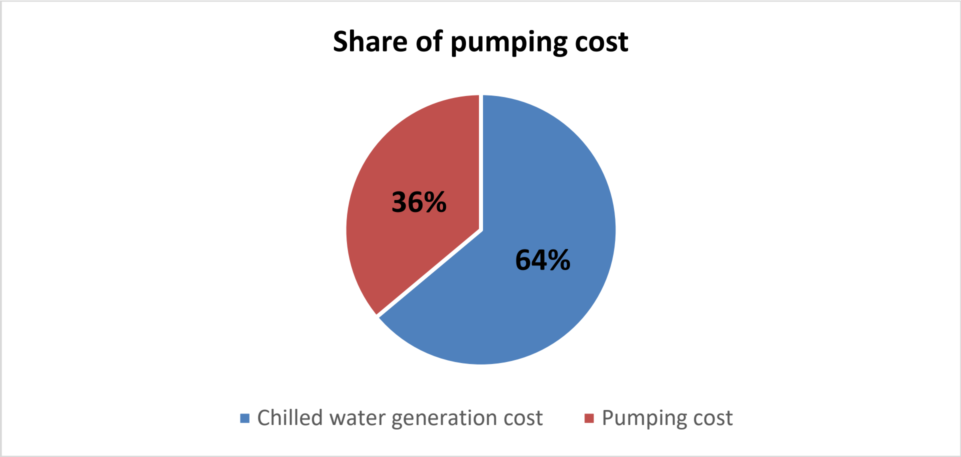


Figure 50: Share of pumping cost

The above results show that the pumping cost is about 36 % of the total cost. Hence, the costs related to the network can have a significant effect on the chilled water generation and thus the cost.

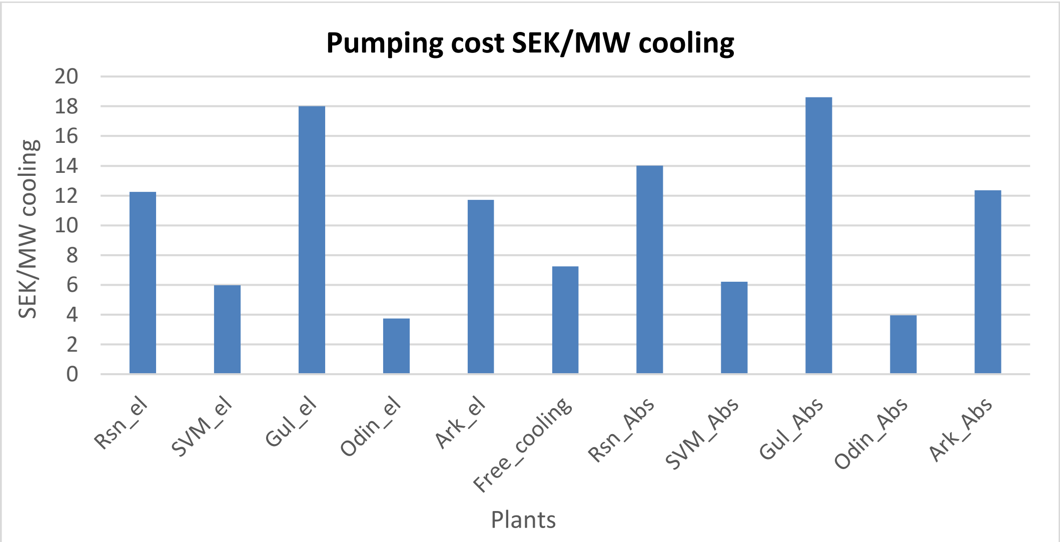


Figure 51: Specific pumping cost

In Figure 51 the specific pumping cost for each plant is shown. The graph shows the cost in SEK to pump one MW of cooling out of each district cooling plant. The results are calculated based on the total chilled water generation and the total pumping cost for each plant. The results are different for electric and absorption chillers installed on the same site because the total chilled water generation from each chiller is different.

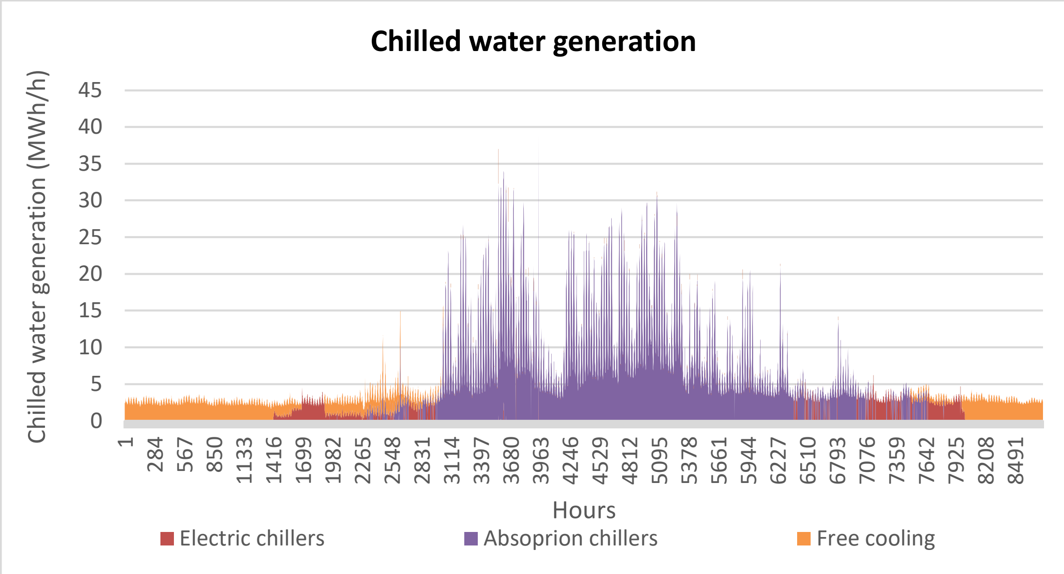


Figure 52: Chilled water generation from free cooling, electric and absorption chillers

The dispatch of the chillers is similar to that in the previous model where pumping costs were not included. The inclusion of free cooling in this model gives a better representation of the chilled water generation in the winters.

6.4.2 Method based on linked cost functions

The main aim of this method is to represent the pumping costs as linked cost functions and include the other network-based constraints. The results obtained from this method are cluster-specific and are quite different from the results obtained in the previous method.

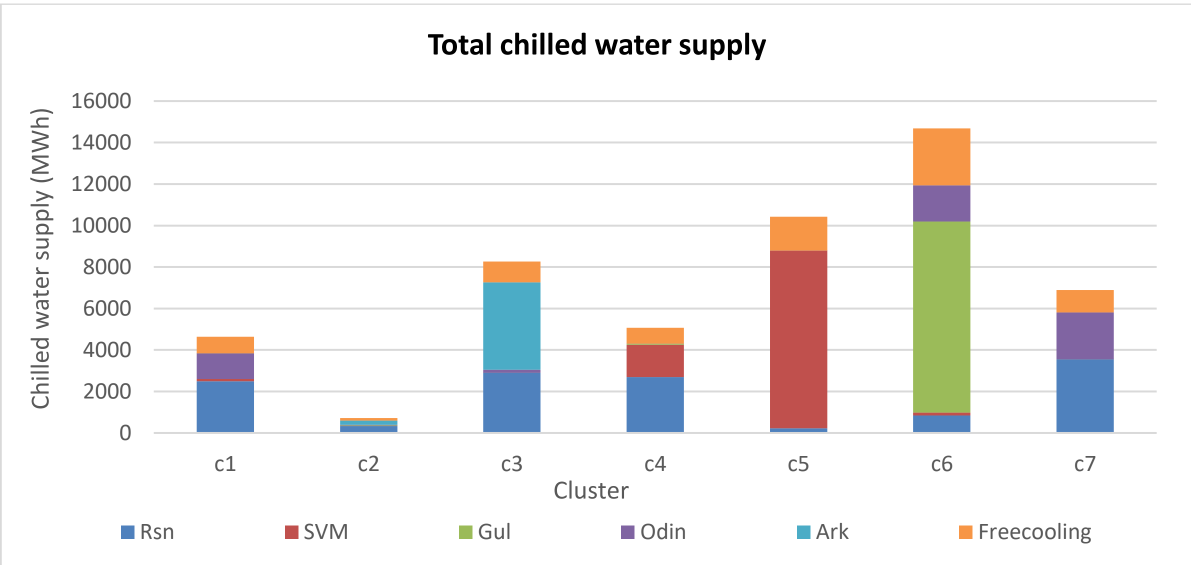


Figure 53: Total chilled water supply to clusters

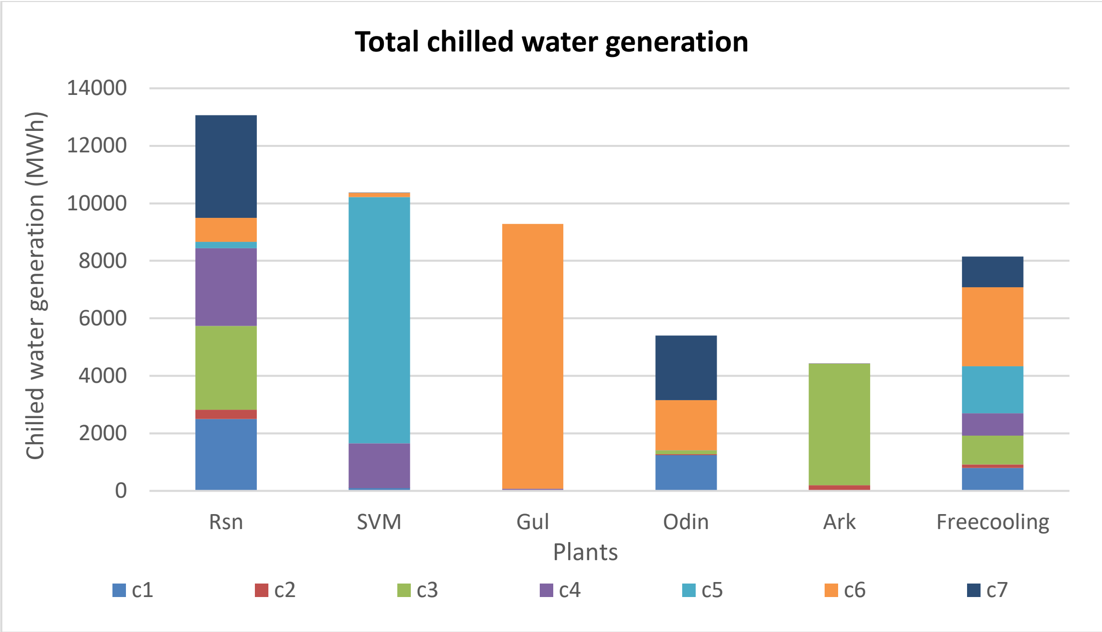


Figure 54: Total chilled water generation – Linked cost functions method

The total chilled water generation can be seen in Figures 53 and 54. Figure 53 shows how the demand in the clusters is met. The chilled water supply to the cluster is dependent on the location of the chiller plant. For example, most of the demand for the cluster c1 is met by the chiller at Rosenlund which is located closest to the demand. The same follows for the demand cluster c5 and the chiller at Svenska Massan and the demand cluster at c6 and the chiller plant at Gullbergsvass. Similarly, the results from Figure 54 also show chilled water generation from each plant and how it is supplied to each cluster. The electric and absorption chillers at Rosenlund have the maximum chilled water generation. Also, the chilled water from Rosenlund is supplied to all clusters. Another interesting result is the supply of chilled water to the extremes of the network i.e. supply of water from Rosenlund to the demand cluster at c7 and from Odinsplatsen to c1. The flow from Odinsplatsen to c1 is quite small with an average flow of 0.016 m3/s which corresponds to an average 0.45 MW of cooling. Thus, a small flow leads to low pumping costs. During these hours, the chilled water from Rosenlund is used to meet the demand from the other clusters. Besides, this is mostly during the hours when the demand from the clusters is less than the minimum possible production from Rosenlund. Therefore, it is not possible to have any chilled water generation at Rosenlund during these hours. Also, since the chiller at Odinsplatsen has a connection to the main pipe which has a large diameter, the pressure loss and pumping costs are low.

Table 16: Results of model with linked cost functions

Parameter	Result
Total cost (MSEK)	1.68
Pumping cost (MSEK)	0.48
Total cooling generation (GWh)	50.69

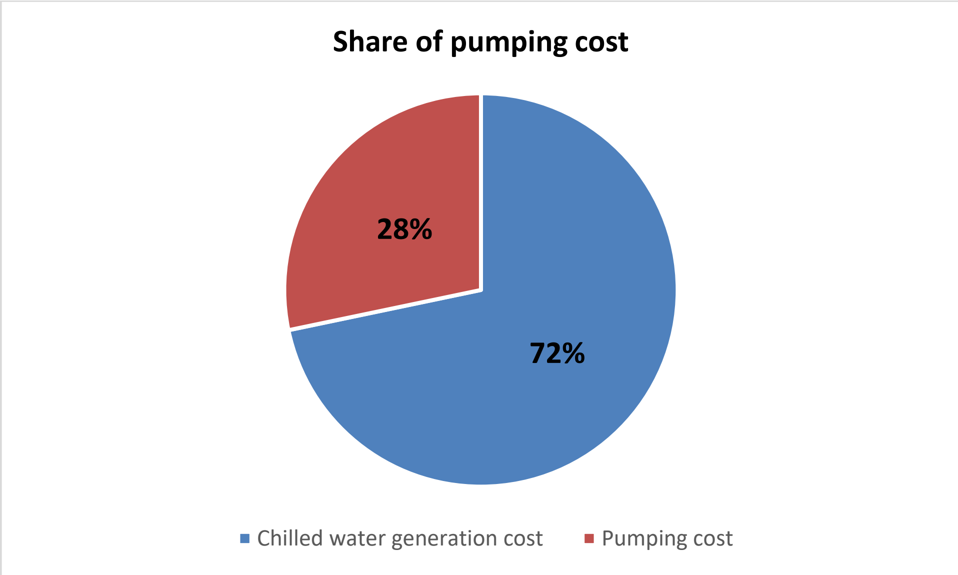


Figure 55: Share of pumping cost

The pumping cost in this model is higher than the previous model, at 0.48 MSEK. But, the share of pumping cost is lower than in the previous method at 28 %. Also, the total cost is higher than in the previous method. This is explained further in later sections.

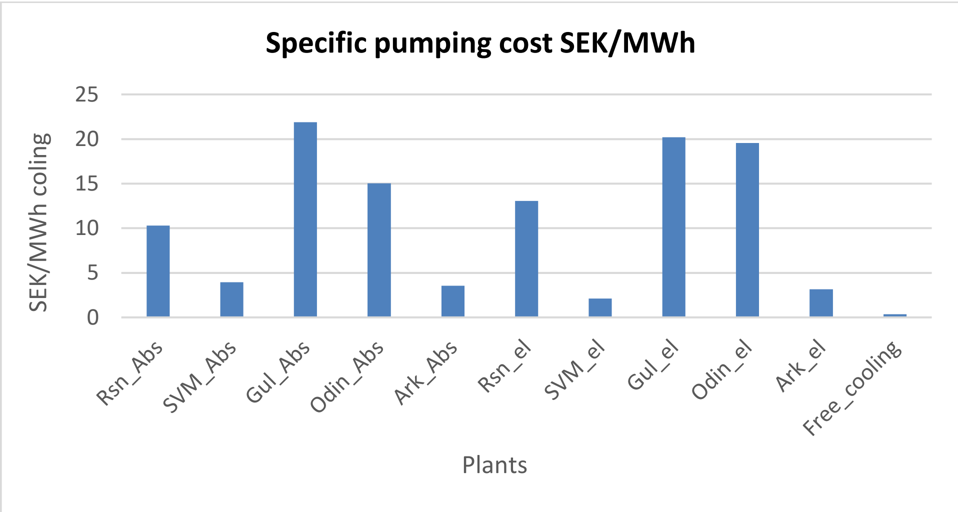


Figure 56: Specific pumping cost for plants:

The Figures 55 and 56 show the specific pumping cost in SEK/MWh$_{cooling}$ for all the district cooling plants and the clusters. Figure 55 shows the specific pumping costs for each district cooling plant. These results are calculated as a ratio of the total pumping costs of a plant to the total chilled water generation from the plant. Hence, the results are calculated separately for the electric and the absorption chillers which are located on the same sites. Figure 56 shows the pumping cost for supplying chilled water to each cluster. This is calculated as the ratio of the total pumping cost for each cluster and the total chilled water supply to each cluster. This result is also represented in SEK/MWh$_{cooling}$. From Figure 57, it is obvious that C6 has the highest specific pumping cost. The cluster c6 also has the largest total demand and the peak demand. Hence, with larger flows, the pumping costs to c6 is very high compared to the other clusters. From Figure 53, it is found that the demand at c6 is met by chilled water generation from Rosenlund, Odinsplatsen, and Gullbergvass. Thus, with the available data, the pumping cost to c6 can be split between these chillers to see which chiller contributes the most to the high specific pumping cost.

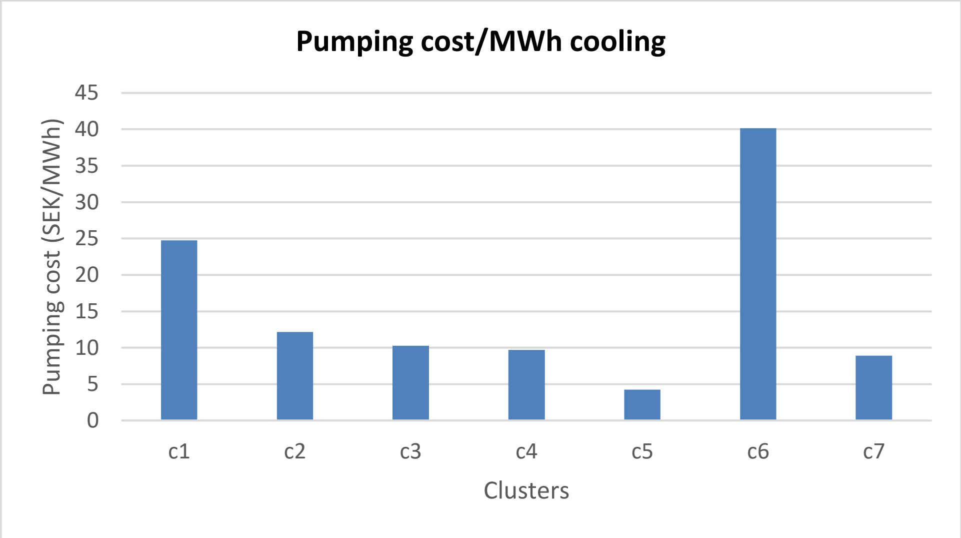


Figure 57: Specific pumping cost for clusters

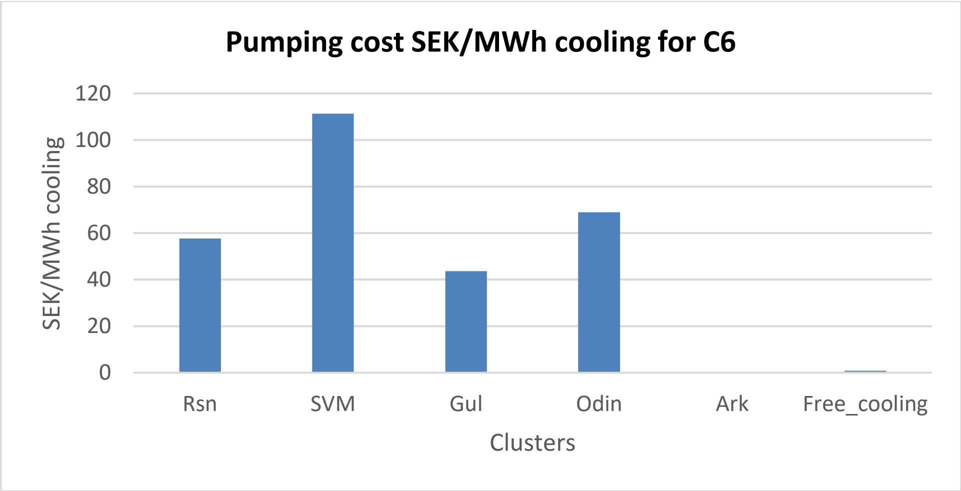


Figure 58: Split of specific pumping cost for c6

Figure 58 shows that the chiller at Svenska Massan is the largest specific pumping cost to the demand cluster at c6. Thus, in the linked cost function method, results like the one above can be studied for different chillers. This can give us a fair idea of the congestions in the network. Also, when additional demand is added to the network in terms of new customer connection, it is possible to analyze how the chilled water can be supplied to the new demand. Also, it helps examine the new investments in the system and how it will help supply the demand in the network.

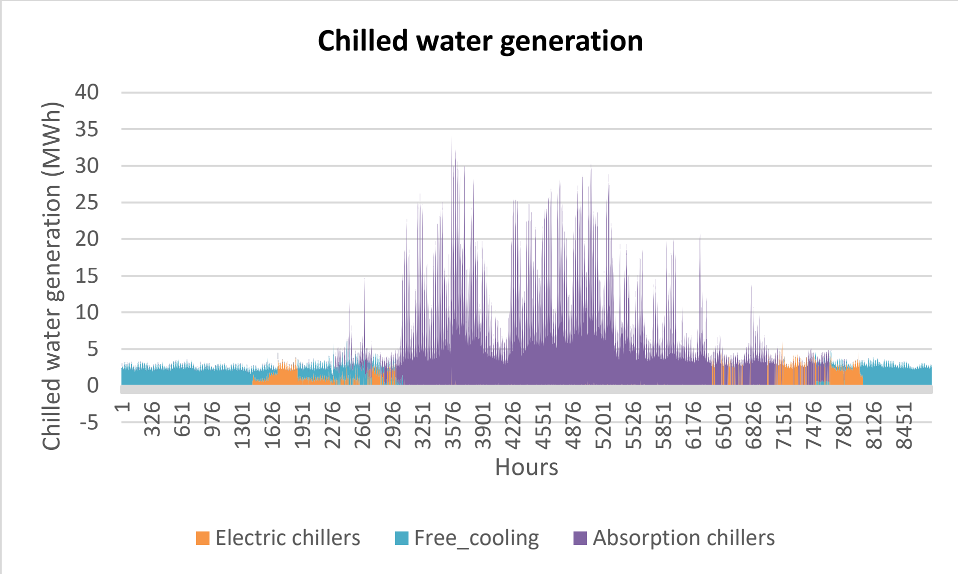


Figure 59: Chilled water generation

The chilled water generation profile is similar to the previous models. The linked cost function does not have a significant effect on the dispatch of electric and absorption chillers. This is because all the chiller sites in the network have both electric and absorption chillers. Also, the pumping costs are quite low compared to the chilled water generation cost and hence, during the summers, the additional pumping costs does not change the merit order of dispatch.

6.4.3 Comparison of the two models

The two methods explained previously are compared in this section. In the model with the fixed pumping power parameter, the main constraint that affects the decision variable is the additional pumping costs. The pumping costs are fixed and hence, they ensure that the absorption chillers in different chiller locations are also competing with each other. This is an addition to the constraints in model 1. Thus, this model can represent the network-based constraints in terms of cost. Whereas, in the method based on the linked cost functions, the pumping costs are represented as dynamic linear functions of the flow. Besides, the costs are separately defined for each chiller. Thus, there is a greater level of detail in the modeling of the network. In addition to the cost functions, additional constraints such as pipe flow constraints and constraints preventing opposite flow are included in the model which gives a more detailed representation of the network. Figure 60 shows a comparison of the results of the two methods. The greater detail of representation of the network is reflected in the increase in the total cost, while the pumping cost is very similar in the two models. The increase in the chiller running cost is because the chillers have to be run differently because of the additional constraints on the decision variable.

Thus, the model with the linked cost functions has a better and more accurate representation of the network. The additional constraints based on the network and the linking of each demand to each chiller help provide a more detailed description of the network in the model. This leads to more binding constraints on the decision variable in the model. Therefore, the network is represented better in this method. The linked cost functions method has been used to create another model of the DCS in 2024.

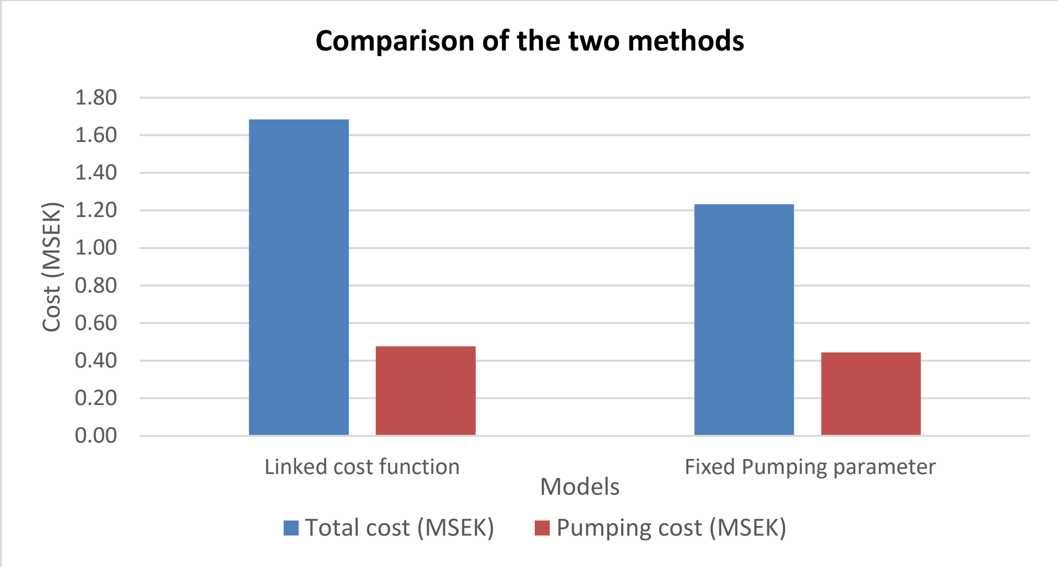


Figure 60: Comparison of the two modeling methods

6.5 Model 2 - Case 2024

Model with DCS, network and thermal energy storage

In this model, the DCS and network are modeled using the linked cost functions method. The main results from this model would be the charging and the discharging of the storage and how this is impacted by the addition of the pumping costs.

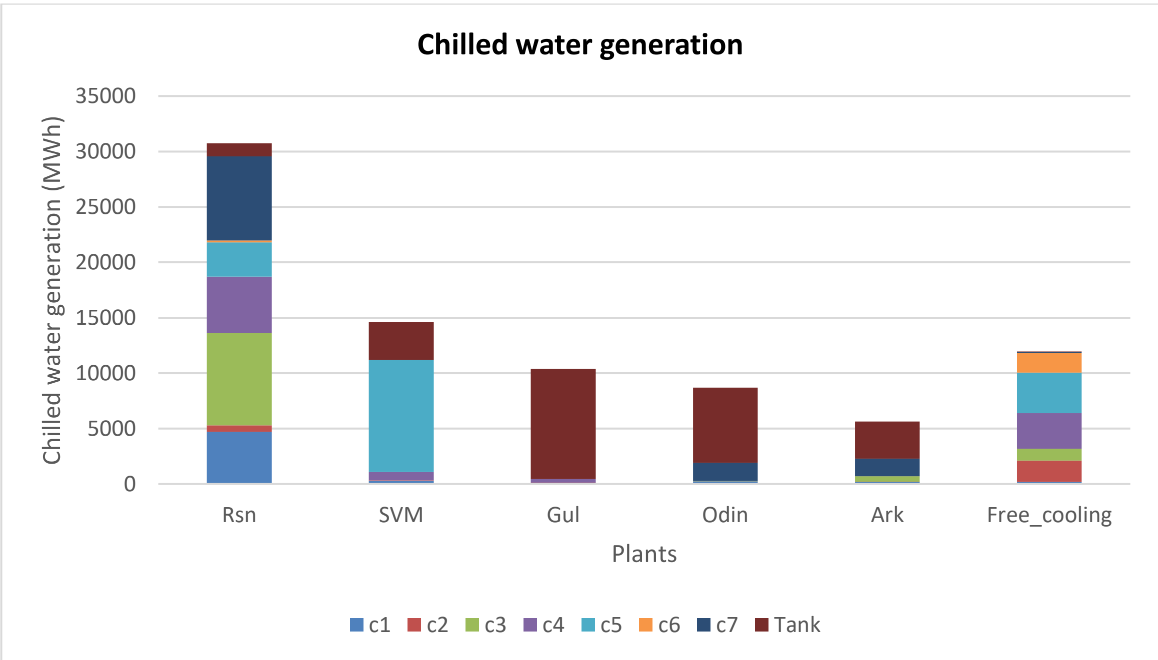


Figure 61: Chilled water generation

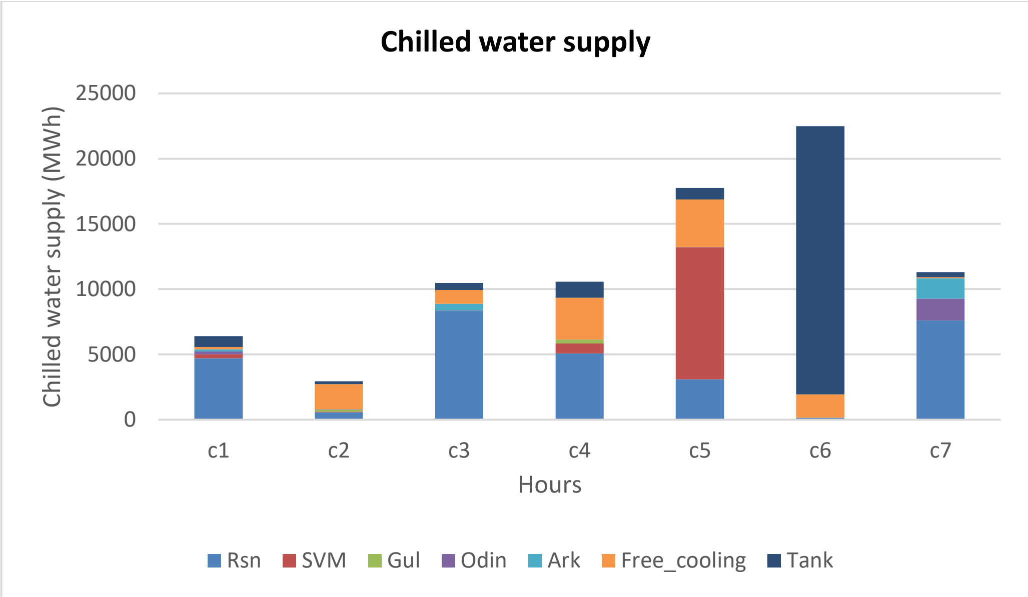


Figure 62: Chilled water supply

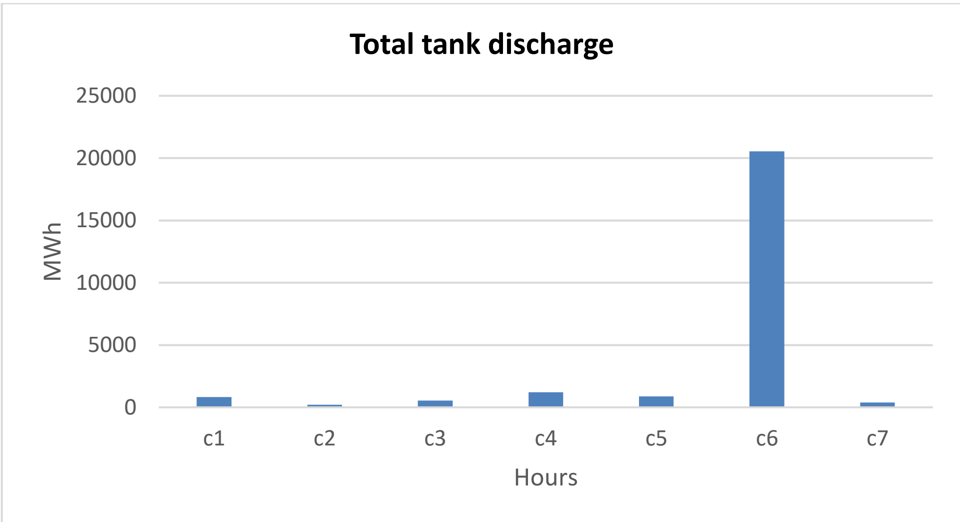


Figure 63: Discharge from the tank

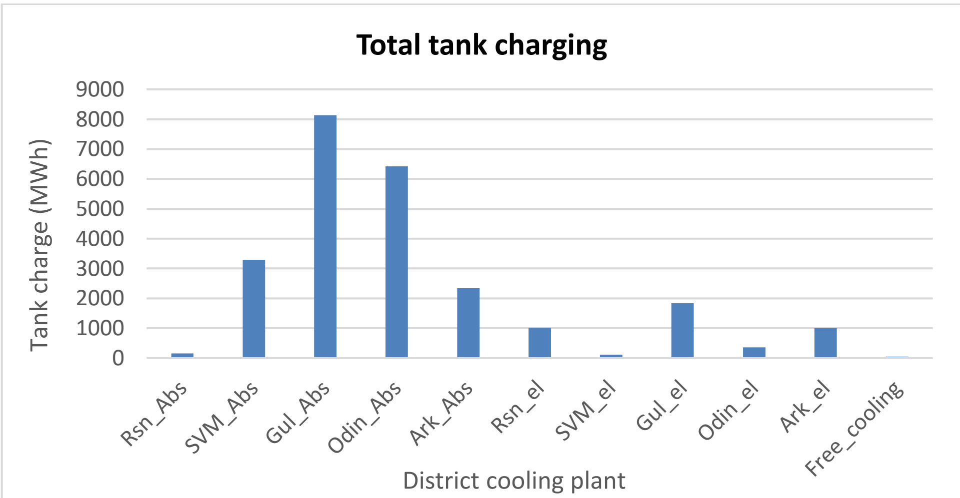


Figure 64: Charging of the tank

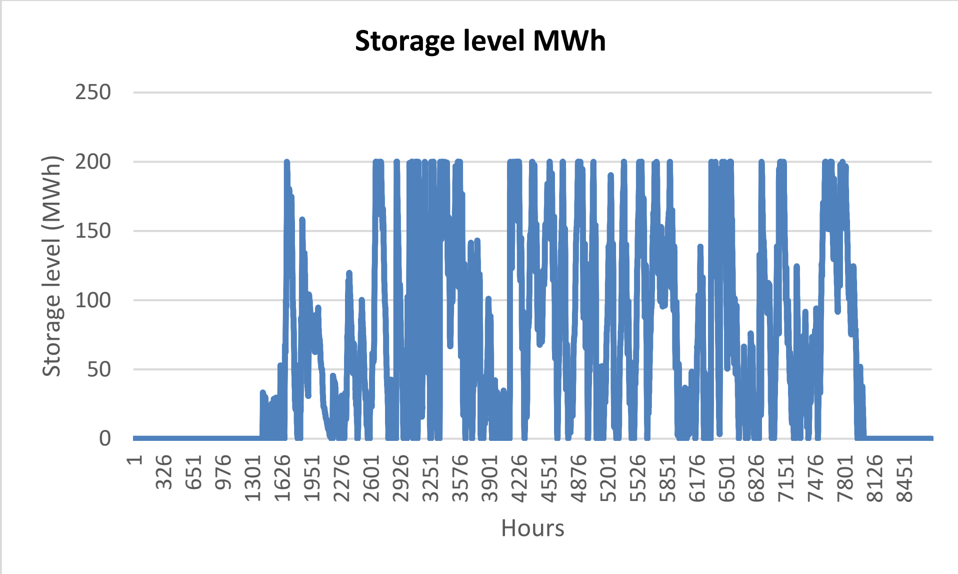


Figure 65: Storage level

The charging and discharging of the tank are shown in Figures 63 and 64. The charging of the tank is mostly from the absorption chiller at Gullbergsvass and Odinsplatsen. The chillers at Rosenlund have the maximum chilled water generation as shown in Figure 61. Since Rosenlund is located quite far away from the tank, the pumping costs are very high to charge the tank using the chilled water from Rosenlund. Instead, the model used the chillers which are closer to the tank such as Gullbergsvass and Odinsplatsen to charge the tank. The clusters that are close to these chillers are either supplied with chilled water from Rosenlund or a combination of chilled water from Rosenlund and discharge from the tank. This is valid for the demand cluster c7. Also, from Figures 63 and 64, it is seen that the largest charging to the tank is from the chillers at Gullbergsvass and the largest discharge from the tank is to the demand cluster c6. However, the demand cluster c6 is located very close to the chiller at Gullbergsvass and the pumping cost between the cluster and the chiller is low. Hence, according to the results, the water is pumped from Gullbergsvass through the tank to c6 in every hour. But this is not a realistic result. Hence, charging of tank by the chillers at Gullbergsvass and the discharge of the tank to the demand cluster c6 is examined closely.

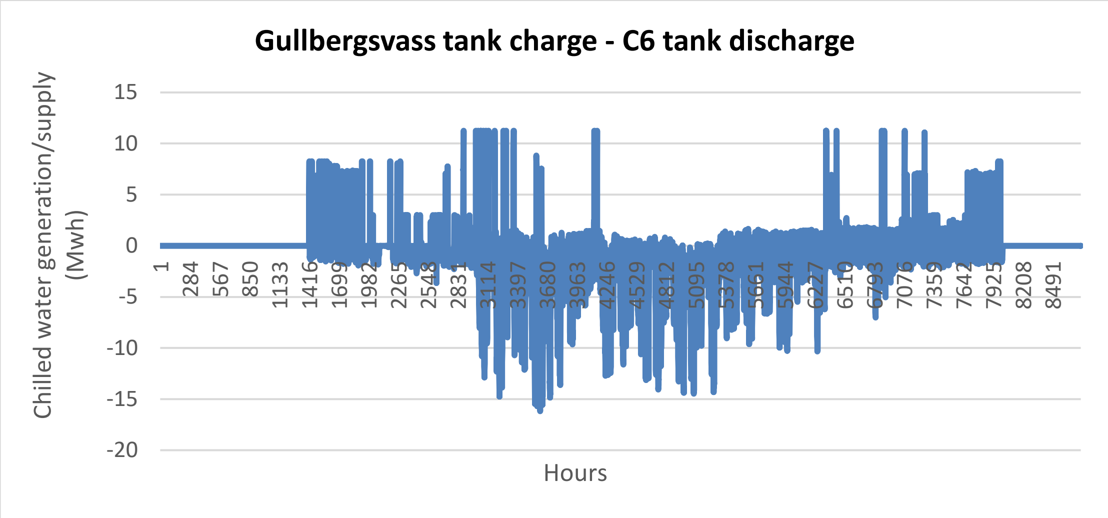


Figure 66: Charging from Gullbergsvass and discharging to c6

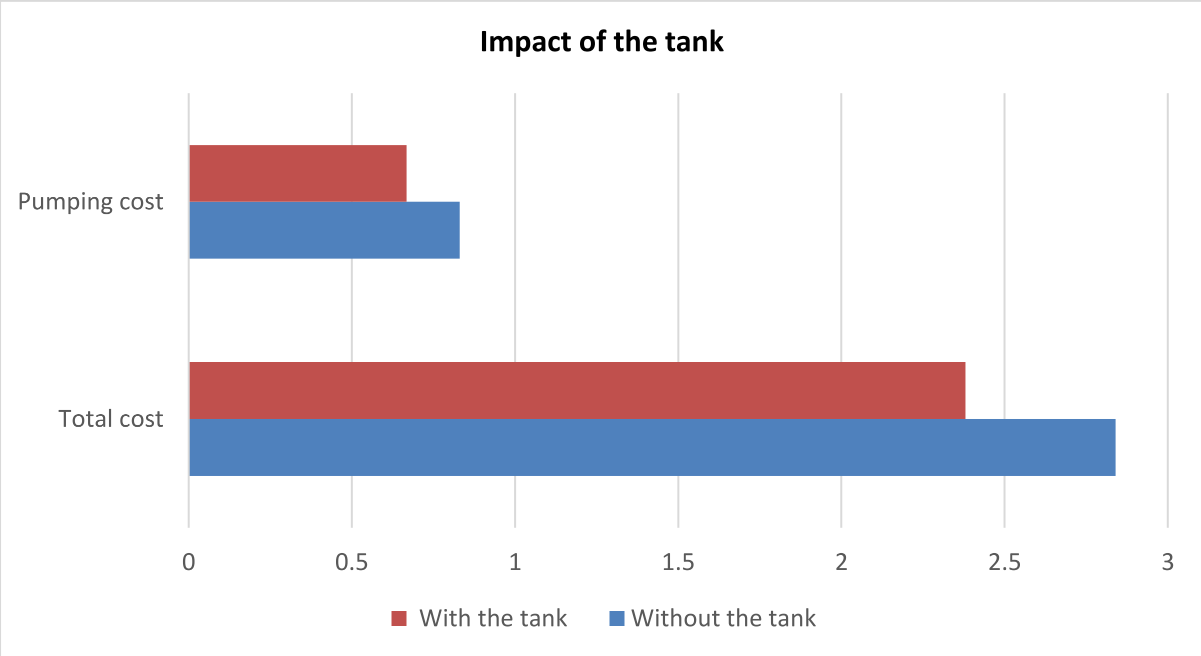
A parameter was calculated by subtracting he discharge from the tank to the demand cluster c6 from the charging of the tank from Gullbergsvass. This calculation was done for each hour. If the result for this calculation were to be zero for all the hours, then the conclusion previously made is valid and the model is producing unrealistic results. The calculated parameter is plotted for each hour and shown in Figure 66. This parameter is zero at very few hours. When the parameter is positive, then the model is making use of the low electricity price hours to pump water into the tank and when it is negative, the water from the tank is discharged. Thus, the water is not charged and discharged at the same hour. The energy is stored over time. Thus, the model is not producing unrealistic results.

The storage levels are shown in Figure 65. This result is similar to those in the 'model 1 - case 2024'. The storage is not used much during the autumn and spring periods, but it is cycled continously during the summer months.

The installation of the tank is also able to significantly reduce the share of the pumping costs in the system. This is because the model makes use of low electricity price hours to charge and discharge water from the tank and hence reduce the cost due to pumping. Also, to evaluate the savings from the tank, a model of the DCS without the tank was developed. The comparative results are shown in Table 17.

Table 17: Results case 2024

Parameter	Result
Total cost with the tank (MSEK)	2.38
Total cost without the tank (MSEK)	2.84
Pumping cost with the tank (MSEK)	0.58
Pumping cost without the tank (MSEK)	0.83
Tank savings (MSEK)	0.46
Tank discharge(GWh)	24.62



The share of the pumping cost in the instance without the tank is 29% of the total cost, whereas, in the scenario with the tank, it is 24.3% of the total cost. Also, the tank generates an annual saving of 463,457 SEK in the system operating cost.

6.6 Sensitivity analysis

The results presented above are dependent on several assumptions made. The uncertainty arising from these assumptions might have a significant effect on the results. This section will analyze the effect of the assumptions on the results. A sensitivity analysis based on these assumptions is conducted. The uncertainties of the results are also presented.

6.6.1 Model 1 - Case 2018

The major result from the case 2018 is the comparison between the DCS and the individual chillers scenario. The results showed that the district cooling was better than the individual chillers in terms of costs. A sensitivity analysis of this result is conducted. The demands from the years 2017 and 2018 are used separately in the two models. This analysis was done because the competition between the DCSs and individual chillers depends to a large extent on the demand. The DCS becomes more profitable than the individual chillers only if the demand density is higher than a threshold level. Hence, it is necessary to verify if the results are still valid in a low demand year like 2017.

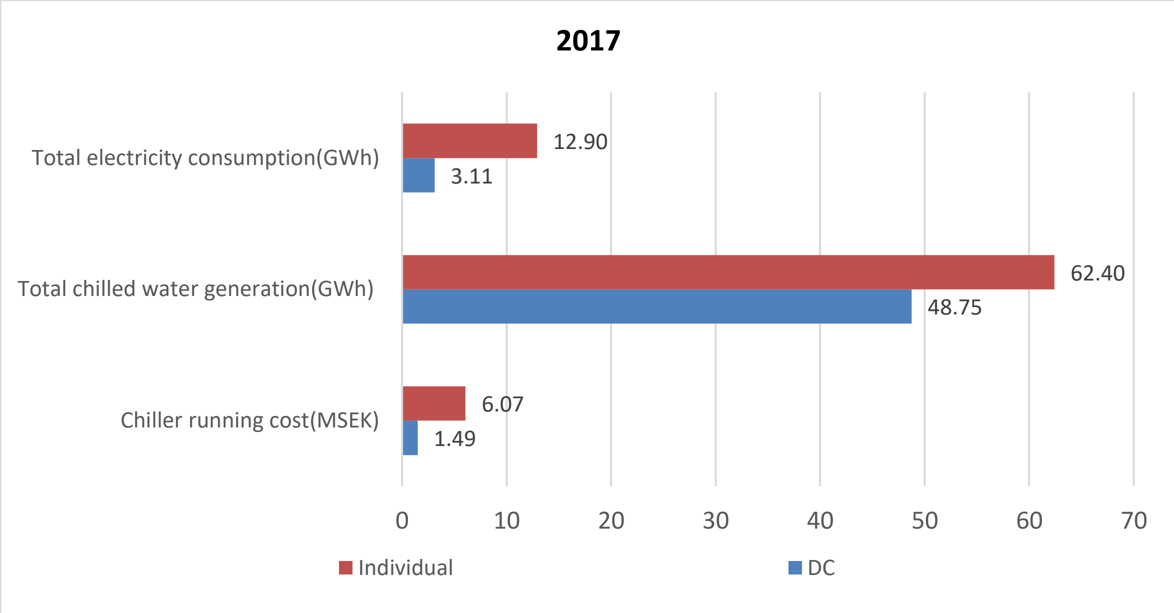


Figure 67: Individual chillers vs district cooling with 2017 demand profile

Figures 67 and 68 show the comparison between the results of the DCS model and the individual chillers scenario model when the demand data from 2017 and 2018 is used. The results vary between the demand cases in absolute terms. The chiller running cost is highest in 2018 because the demand is the highest in 2018 and hence the total chilled water generation. But the result of the comparison between the DCS and the individual chillers does not change with change in the cooling demand. Hence, the DCS is better than the individual chillers scenario in terms of cost, irrespective of the demand.

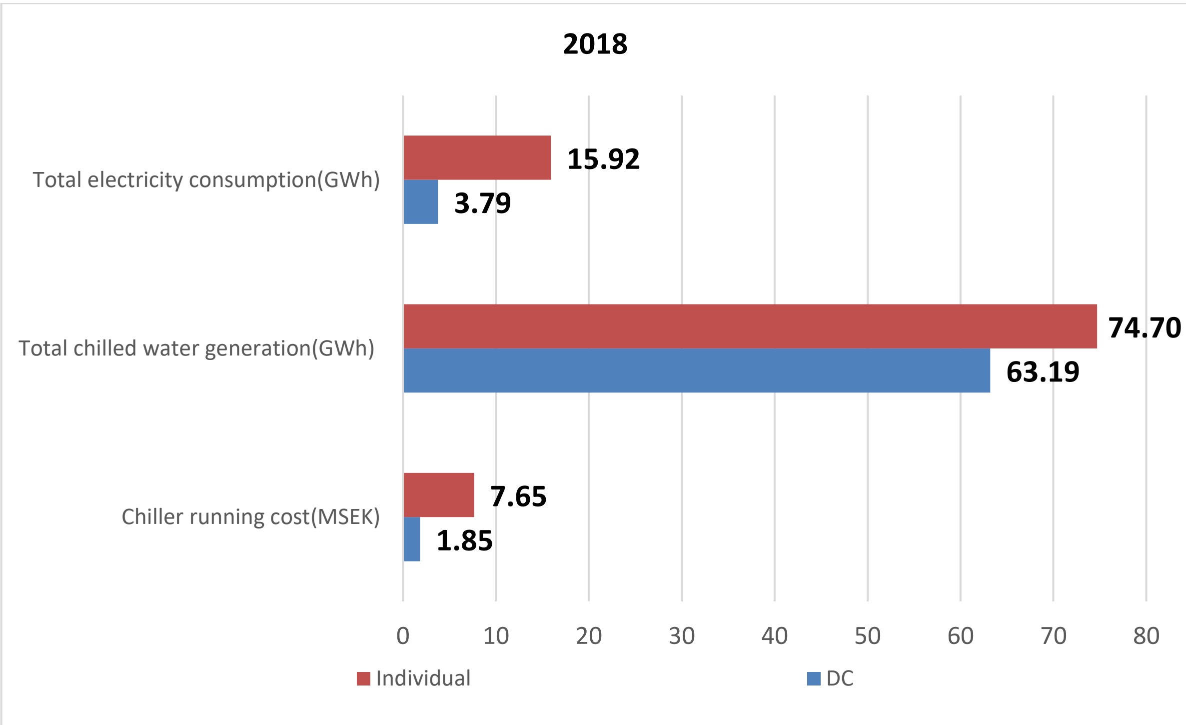


Figure 68: Individual chillers vs district cooling with 2018 demand profile

6.6.2 Model 1 – Case 2024

In this case, the impact of the TES on the DCS is analyzed. A major result from this case was the claim that the optimal use of the absorption chillers and the TES could meet the demand without operating electric chillers in the summer. This claim could vary with a change in demand. The operation of the system depends on the demand in the system. The demand must be met in each hour. When the peak demand is greater than the sum of installed capacity of the absorption chillers and the discharge capacity of the tank, then the electric chillers must be operated to meet the hourly demand. Hence, in a demand profile with more peaks, it might become necessary to operate the electric chillers in the summer. This is verified by running model 4 with the demand from 2018.

The Figures 69-71 show the chilled water generation in the summer. The results are from model 4 with the cooling demand from 2018. The cooling demand from 2018 has the highest peak demands in the summer. The results from this sensitivity analysis show that when the demand profile from 2018 is used, the optimal use of absorption chillers and TES is not enough to meet the demand in the summer. From Figures 69-71 can be seen that the electric chiller must be run during some hours to meet the demand. Hence, the result from scenario 4 is dependent on the input demand profile.

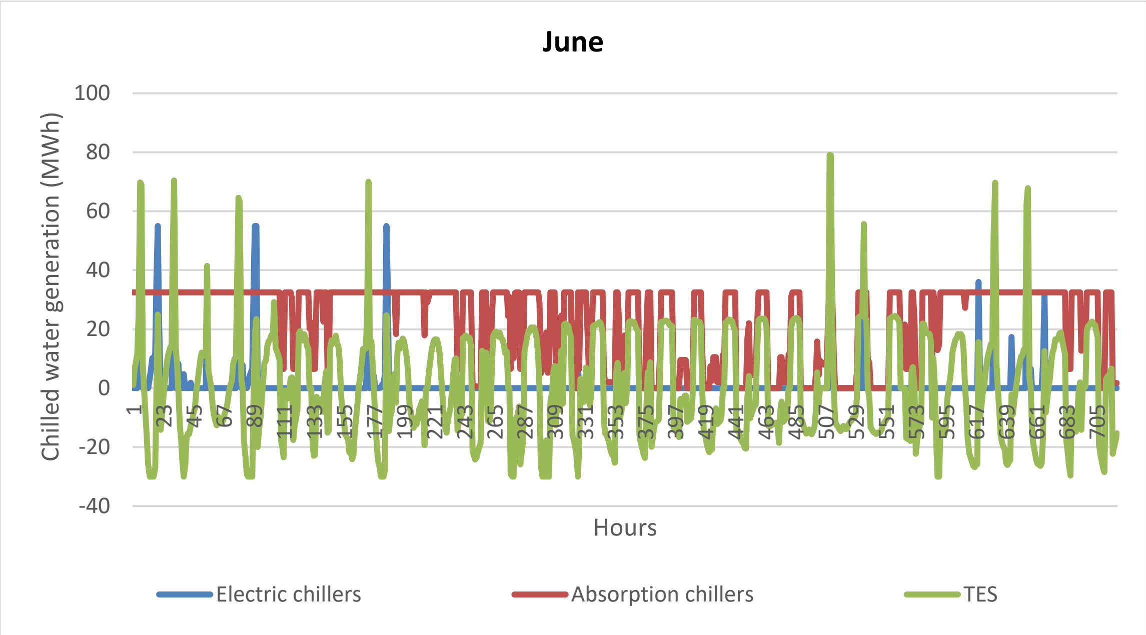


Figure 69:Chilled water generation in June

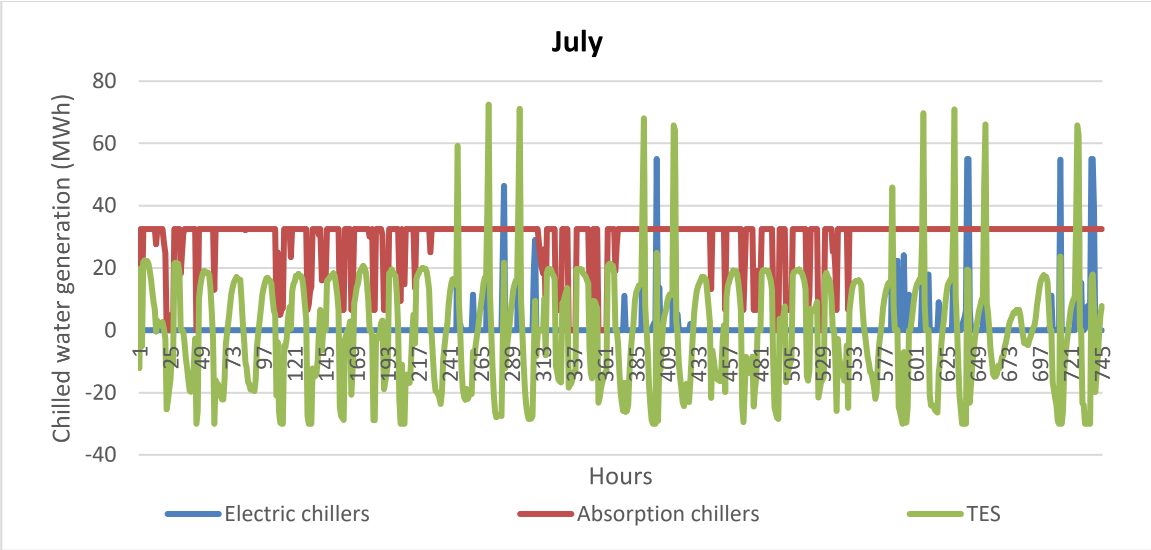


Figure 70:Chilled water generation in July

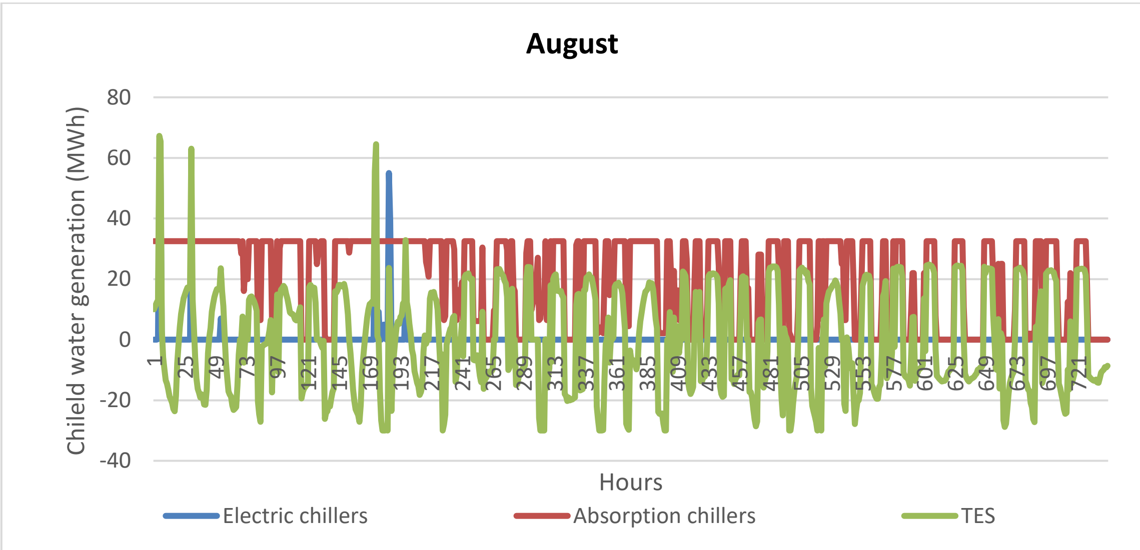


Figure 71: Chilled water generation in August

Another major uncertainty in the use of storage in the DCS is the availability of the TES throughout the year. According to the current plans that Göteborg Energi has, the TES must be shared with the DHS. Thus, there could be chances that the tank is available to the DCS only during the cooling period between March and November. Thus, a few Operation strategies are created to represent various operation strategies of the TES.

- Operation strategy 1: Storage used for the entire year, but free cooling is not stored. (Scenario 4)
- Operation strategy 2: Storage used only during the period when chillers are run.
- Operation strategy 3: Storage used during the entire year with the storage of free cooling from the river.

The results of the different operation strategies are shown in Figure 72.

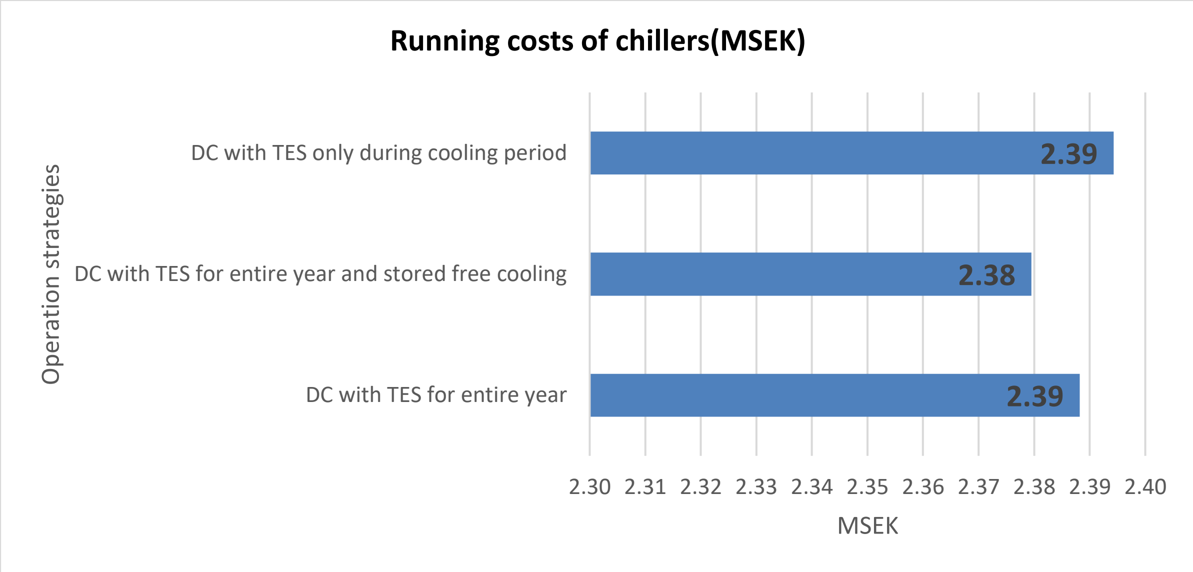


Figure 72: Comparison of results from different storage operation scenarios

The results from the three different scenarios are quite similar. But, when the chilled water cooled by the river is stored in the tank, an additional 200 MWh of free cooling is available in the system. Hence, the cost is the lowest in that scenario. The usage of TES during the entire year means that the electric chillers can be run during hours of low electricity price during the winter and the chilled water generated can be stored in the TES. This also reduces the costs as seen in Figure 72. The scenario with the highest cost is when the thermal energy storage is only available during the cooling period. The costs are high because the room for optimal usage of the storage is less here as the storage is not available for 3 months in the year. Hence, the usage of the tank starts only when the cooling demand is high. The cooling demand must be met during this period and simultaneously, the tank must also be charged. Thus, the costs in this scenario are the highest. But the difference in costs between the three scenarios is much less i.e. less than 0.5 % of the running cost. Thus, the operation strategy of the TES does not have a large impact on the costs.

6.6.3 Model 1- Case 2030

This case analyzed the operation of the DCS in the year 2030. Several scenarios were examined at where the changes in the DHS and the electricity system were considered to have a very different generation mix. A seasonal energy storage was also included in the DHS. When the best scenario was looked at, it was seen that the demand in 2030 was too high to not run the electric chillers during the summer. Despite the optimal use of the storage and the absorption chillers, it was necessary to operate the electric chillers in the summer months. Therefore, it was decided to vary the size of the storage to see how large the storage must be for the system to not operate electric chillers. The preliminary plan for the size of the storage is 200 MWh, but it could change depending on changes in the system. It could be interesting from a system perspective to see if a larger storage can help reduce the operation of the electric chillers. Hence, the size and the power capacity of the storage were doubled to 400 MWh and 60 MW, respectively. The chilled water generation in the summer from the model having a larger TES is shown in Figures 73 and 74.

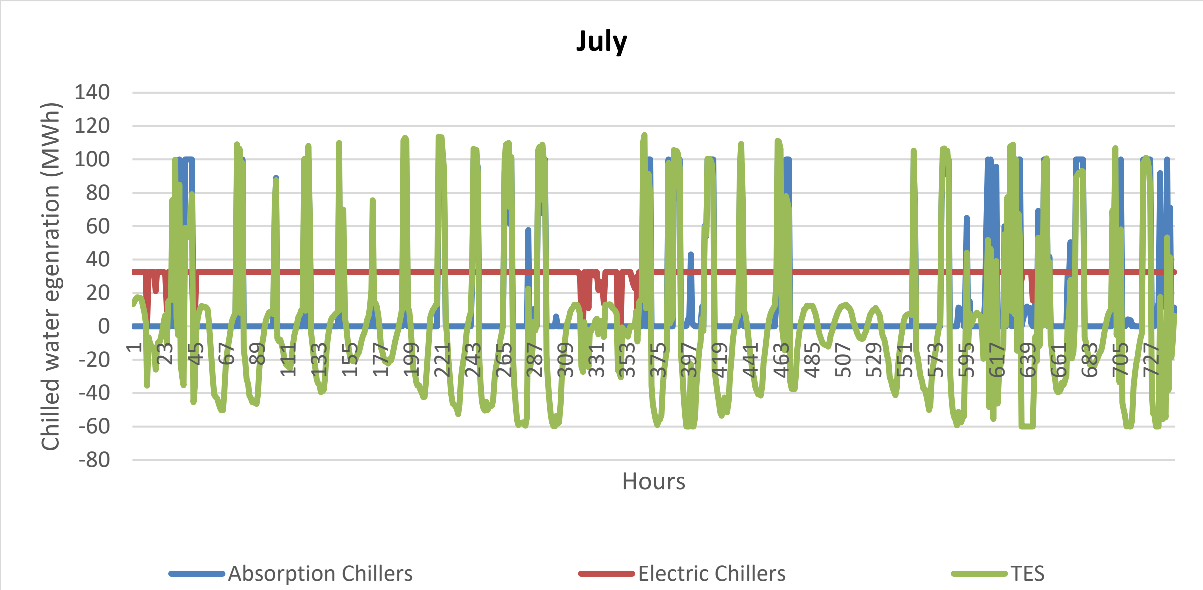


Figure 73: Chilled water generation in July

From the results of the model, it is seen that the electric chillers must be operated in the summer to meet the demand even when there is a larger thermal energy storage in the system. The tank is charged with chilled water every time the electric chillers are used, but the chilled water produced from the electric chiller exceeds the amount by which the TES is charged. This shows that the electric chillers are used to charge the TES and also meet the demand at the same time. During low electricity price hours, the electric chillers are used to charge the storage and are hence run at peak capacity.

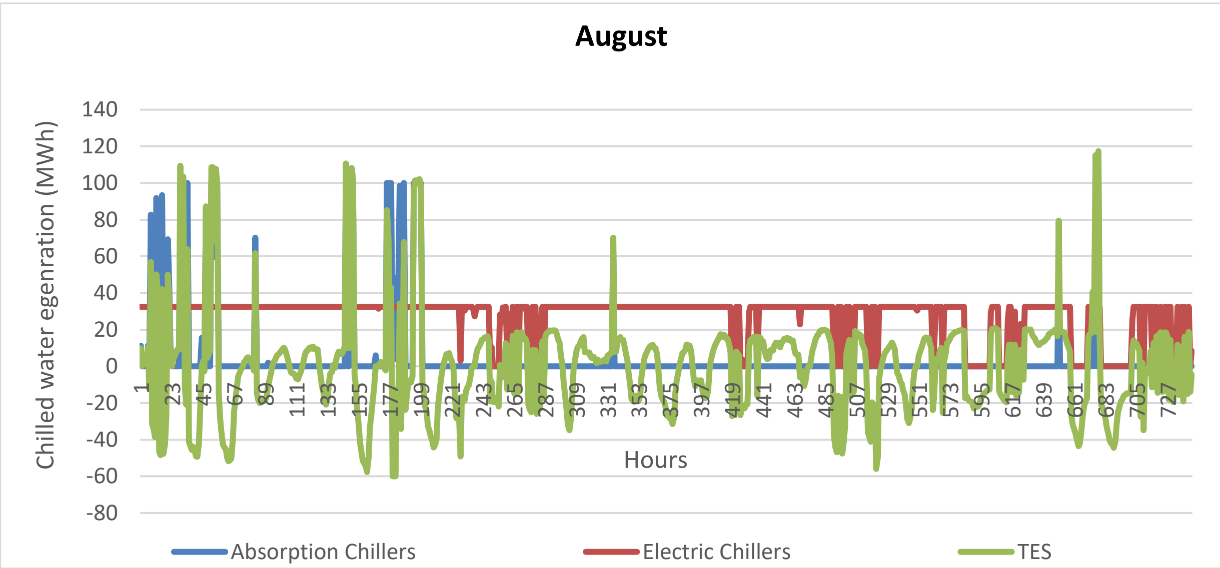


Figure 74: Chilled water generation in August

The volume of energy that is available from the absorption chillers is not enough to meet the demand even when the capacity of the TES in increased in case 2030. Therefore, the chilled water generation from the absorption chillers must be increased. Thus, to satisfy the demand in the summer without operating electric chillers, it is necessary to invest in the larger thermal energy storage and increase the installed capacity of the absorption chillers.

6.6.4 Model 2 - Case 2018

The major assumption made in this case was regarding the temperature difference. The demand flows are determined by the temperature difference. The demand flows are part of the supply-demand constraint which has a direct binding effect on the decision variable. Hence, a sensitivity analysis must be conducted on this assumption. The temperature difference of 6.64˚C is chosen based on the mean temperature difference in the current DC network. The other temperature difference that is of importance is the dimensioning temperature difference of the system which is 10˚C. Hence, the temperature difference of the model based on linked cost functions was changed to 10˚C and the demand flows were adjusted accordingly. The results are shown in Figure 75.

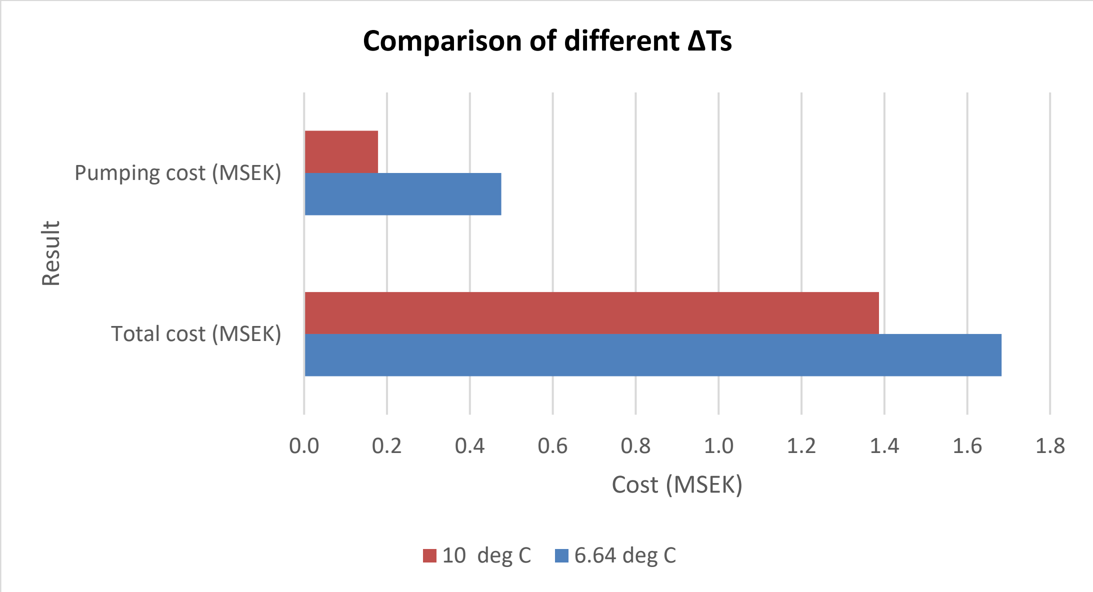


Figure 75: sensitivity analysis on temperature differences

The results indicate that the pumping costs are much lower in the case of the higher temperature difference of 10˚C. With a higher temperature difference, the chilled water flows are lesser and hence, the pumping costs are lesser. The share of the pumping costs in the system also reduces from 28 % of the total cost to about 12 % of total costs in the system. However, the change in the temperature difference does not have a very large impact on the dispatch of the chillers. Hence, despite a change in the pumping cost, there is an equivalent reduction in the share of pumping costs from each chiller. Thus, the shape of the cost curve remains the same while it is moved down due to reduced pumping costs.

6.6.5 Model 2- Case 2024

This case aims to investigate the impact of having the tank installed into the system, how the tank is charged and discharged, and the economic savings of having the tank. At present, Göteborg Energi has tentative plans of how the tank will be controlled. The main control strategy of the tank is to charge the tank using absorption chillers during the nights when the demand is low. The stored water is then discharged during the day when the demand is high to supplement the absorption chillers and meet the demand without using the electric chillers. This strategy depends on the location of the absorption chillers. If the absorption chillers are located far away from the tank, the high pumping costs could potentially make it unprofitable to charge the tank. In the current system, most of the absorption chiller capacity is located at the chiller plant in Rosenlund which is the farthest chiller from the tank. According to the utility's control strategy, most of the charging to the tank will happen through the chillers at Rosenlund. However, from the results of this case, it was seen that contribution of the chillers at Rosenlund to the charging of the tank was very low. Instead, the chillers at Rosenlund were being used to meet the demand, while the other chillers were being used to charge the tank. To see the effect of this control strategy on the system, a sensitivity analysis was conducted where the charging of the tank was restricted to absorption chillers at Rosenlund. The results are shown in Table 18.

Table 18: Results for sensitivity analysis with Rosenlund charging tank

Parameter	**Result**
Total cost with the tank (MSEK)	2.79
Total cost without the tank (MSEK)	2.84
Pumping cost with the tank (MSEK)	0.62
Pumping cost without the tank (MSEK)	0.83
Savings from the tank (MSEK)	0.05
Tank discharge (GWh)	8.16

The discharge from the tank is much lower in this sensitivity analysis. The savings from the tank is about 50,000 SEK per year which is very low. This makes it unprofitable to use the tank. Hence, either the chiller plant at Rosenlund must be moved to another location. The electric chillers can still be kept at the same location since they will not be used to charge the tank. The electric chillers can then be used to meet the demand from cluster c1, c2 and c3 which are located close to Rosenlund. The absorption chillers alone can be moved to a location close to the tank. Moving the absorption chillers close to the cluster c6 can also solve the congestion problem. Another possible solution is to have an alternate direct pipe connecting the chillers at Rosenlund to the tank.

Chapter 7: Discussions

This chapter contains some discussions around the relevance and the accuracy of the results. The uncertainties arising from the input data, the assumptions made and the accuracy of the computer model itself are discussed in this chapter.

Focusing on the main results from the modeling, in 'model 1 - case 2018', it was seen that the DCS is more economical than the hypothetical case of individual chillers and hence confirming the finding by Gang et al. [23]. The main difference between the two models is the climatic condition of the region. Gang et al. modeled the DCS in the subtropical area like Hong Kong, where the cooling is required throughout the year and the building density is very high. Also, the modeled DCS did not consist of absorption chillers and free cooling. Hence, there was not a large difference between the operation of conventional cooling systems (Individual chillers) and the DCS in the summer. Whereas, the model in this thesis includes free cooling and absorption chillers, and hence the operation of the system is much different in the two scenarios considered. A sensitivity analysis was carried out on the results from scenario 1 by varying the cooling demand input to the model. The cooling demands from the years 2017 and 2018 were used instead of the average demand. The sensitivity analysis showed that the general results remained the same irrespective of the demand i.e. the DCS continued to be more economical than the individual chillers irrespective of the demand. The saving in cost obtained by using a DCS instead of individual chillers increases in a higher demand case and decreases in a lower demand case.

Another important result from 'model 1 – case 2018' was the lower energy consumption in a DCS when compared to the individual chillers scenario. A similar result was shown by Jungbauer et al. [24] by comparing the electricity consumption measurements from the chillers. Jungbauer et al. concluded that the DCS is more efficient than the individual chillers because of efficient utilization of locally available fuels and combination of cooling sources in the network, namely free cooling, cooling by making use of surplus heat i.e. absorption chillers and high-efficiency chillers which consumes less energy due to economy of scale. A very similar result was seen from 'model 1 – case 2018'. The use of free cooling helped reduce electricity consumption in the winter, while the absorption chillers were used to meet the cooling demand in the summer instead of the electric chiller.

The results from 'model 1 - case 2024' showed the impact that the TES had on the system. The installation of the TES reduces the chiller running costs and also make better use of the absorption chillers during the summer. The results obtained are very similar to Zhang et al. [25] where the impact of the TES on the system was analyzed using long term measurements. Zhang et al. showed that the addition of TES in the system increases the energy efficiency of the system. Also, the chillers were able to use off-peak electricity for half the price of peak electricity. A similar result was seen from scenario 4 where the chiller running cost reduced with the installation of TES in the system.

In model 2, the main aim of the modeling is to include the network into the model. To achieve this, pumping costs and network-based constraints are included in the model. The results obtained in case 2018 show that the model based on the linked cost functions have a better representation of the network in the system. A previous study with a similar analysis was not found but there are a few research papers that have examined different ways to represent the network in numerical and physically-based models. The results obtained from the linked cost functions model are very similar to the results obtained in Söderman et al [22] in which, the optimization model is built for the operational and structure analysis of the DCS. The results obtained from this paper, show the discharge from the different district cooling plants into the various pipe segments of the network which is similar to the results from ‘model 2 - case 2018’ which shows the discharge from each plant to each cluster.

The results that show the share of the total pumping costs can also be seen in Damien et al. [5] where a physically-based model of a part of the DCS in Paris is developed. The simulation model is run for various short time periods and the electricity consumption from the DCS operation can be calculated. The electricity consumption for pumping is about 28% of the total electricity consumption. The result obtained from the linked cost functions model is almost the same.

7.1 Advantages and disadvantages of the model

The development of a new optimization model helped in understanding better the pros and cons of GAMS as a modeling software and the challenges faced by optimization model developers. This might not have been possible if an existing model of the DCS was chosen for analysis. Besides, since GAMS is a coding software, the optimization model developed has a high level of flexibility. Any changes can be made to the model by changing the equations in the program. This is an advantage of the software. The same flexibility does not exist in some existent visualized programs.

The objective function in the code of this model is to reduce the total costs. Minimizing the costs is, of course, one of the most important objectives for any utility, but at the same time, it is also important to decrease the use of fossil fuels to reduce emissions from an energy system. In the DCS, there is no direct use of fossil fuels. Hence, it is hard to include costs on emissions in the model of the DCS. But the DCS does lead to some indirect emissions due to the usage of heat and electricity. A tax on carbon dioxide emissions is included in the model of the DHS. But, since the prices of electricity from the spot market are used for the model in 2018, it is uncertain whether the emissions in the electricity system have been accounted for. Also, in the models of the electricity system in 2030, the objective function was to minimize the total costs, and hence the effect on the emissions cannot be accurately defined. Therefore, the models presented in this thesis do not handle the objective of reducing emissions from the energy system.

It was decided to create a mixed-integer linear program to represent the system as accurately as possible. The models have been fairly successful in representing the system accurately. This can be seen in the results of the dispatch of the chillers. The chilled water generation from the chillers is varying to meet the demand in each hour. This is exactly how the system operates in reality and this operation has been accurately represented by the model.

At the same time, there are a few technical details of the chillers which have not been represented in the model accurately. The COP of the electric chillers varies with the cooling load. But in the models, the COP is a constant value. Since the COP varies non-linearly with the load, a nonlinear program (NLP) would be needed to represent the COP. The main disadvantage of the NLP is the loss of accuracy in the model due to many simplifications. The loss of accuracy from the NLP was significantly higher than using a constant COP and hence, it was chosen to use a constant COP. But it is not an exact representation of the system.

7.2 Perfect foresight

All the optimization models have been built with perfect foresight given to the optimization model. Perfect foresight means the demand in any particular hour was known to the system at the start of the year. Thus, the operation of the system is optimized over the entire year. For example, the model can decide how to meet the demand in April based on what will happen in August. Also, the cooling demand and the electricity prices for each hour are known at the start of the year. With a perfect demand forecast, there is no need for backup generations and hence the operation of the system in the models is much cheaper than in reality. Also, certain practical scenarios such as a breakdown of units etcetera have not been considered here. In reality, such a breakdown might occur, and the operation of the system will then be different. The problem of perfect foresight occurs in most optimization models. It is very difficult to the problem with perfect foresight as the optimization problem cannot be built without demand and fuel prices.

7.3 Cooling demand and weather

The average cooling demand chosen in the first model was taken as an average between a cold year and a warm year. This annual cooling demand might be an accurate representation of the demand in the average year, but the hourly cooling demand depends to a large extent on the weather patterns. As seen before, the peaks in the cooling demands were not synchronous in 2017 and 2018. Thus, the hourly demand tends to vary a lot from year to year. Also, when making future cooling demand projections, it is assumed that the weather patterns of the average year would be prevalent in the future years. This is a very optimistic assumption. With rapid changes in weather due to climate change and increased occurrences of extreme weather instances, it becomes very hard to predict the cooling demand, and hence it is an uncertainty in the models of a future system.

7.4 Input data and assumptions

The fuel prices of the DCS present several uncertainties in the model. The electricity prices from the spot market have been used in the models. These prices do not include any taxes on the electricity prices. In reality, the prices of electricity may include a few taxes and this assumption leads to a few inaccuracies if the results of the model are looked at in absolute terms.

The prices of heat are obtained from a model of the DHS. The prices of fuels for generating heat in the DHS have been set at 2012 levels. This assumption also creates a few inaccuracies in the models. In reality, it is expected that the prices of fuels will change in the future. But here the prices are kept unchanged in the model. This is justified by the fact that the main goal is to analyze the operation of the DCS and hence it is not required to model the DHS to great detail.

Another major uncertainty is the availability of excess heat in the system in the future. Göteborg Energi plans to move towards a fossil-free production in 2030. Since most of the industrial waste heat comes from sources that lead to emissions, the availability of industrial waste heat, and thus excess heat is questionable. Also, refineries supply a significant part of the industrial waste heat into the system. With a growing market for electric vehicles, the extent to which the refineries will operate in 2030 is vague. Therefore, the availability of excess heat in the system in 2030 is unpredictable. This, in turn, affects the prices of fuel in the DCS. If there is no excess heat in the system, the heat is not available to the absorption chillers at zero cost any more. Hence, it becomes harder to operate the absorption chillers.

7.5 Network related uncertainties

The main disadvantage of the models described in model 1 is the exclusion of the network from these models. The costs from the network, i.e. the costs of pumping the chilled water are almost equal to a third of the cost of running the chillers. In addition, many constraints in the network such as congestion effect the operation of the chillers. To overcome these uncertainties, it was required to include the network in the model. Various methods to include the network have examined in model 2. Using these methods, it is possible to overcome a few of the uncertainties from model 1. This section analyzed how the results presented in model 1 are affected by the network, and how this effect is nullified by including the network into the optimization models in model 2.

In model 1, the optimal operation of the DCS is presented as a result of the modeling. In this case, the cost of pumping chilled water is not included. When the pumping costs are included, the constraints in the network will have a large effect on the result. This is because the pumping costs will lead to competition between different electric chillers and absorption chillers based on their location. Whereas, in model 1 competition exists only between the set of electric chillers and the set of absorption chillers. Thus, there is no internal competition between the absorption chillers and the electric chillers. Also, congestion in the network will lead to larger pumping costs and might change the result. This problem is solved in model 2, either by introducing fixed pumping power parameters or by using linked cost functions. In 'model 1 - case 2024' with TES, during low price electricity hours, the electric chillers are run at peak capacity, and chilled water is charged into the tank. To achieve this, a large amount of chilled water has to be pumped into the tank and thus, there is large stress on the network and hence, the cost of pumping the water becomes very high. This might not be the optimal operation of the system when the pumping costs are included. In 'model 2 – case 2024', it is found that the chillers that are quite far away from the tank are hardly used to charge the tank. This is due to the high pumping costs for the chillers that are far away. Thus, the inclusion of pumping costs in the model is able to provide a more comprehensive optimization. In addition, the inclusion of pipe-based constraints such as the maximum flow in the pipe ensures that impossible flows are not allowed on the model. Hence, it is important to consider these effects that the network will have on these results.

7.6 Future work

This thesis has a large scope and every case that is investigated in this thesis can be modeled further with a higher level of detail by including more parameters. The future work on the cases presented in this thesis can focus on the impact of varying the size of the thermal energy storage in the system. An investment model could be set up to determine the optimal size of the storage in the system.

In model 2, where the network is also included in the model, the main inaccuracy of the model is due to the dynamics of the network. The numerical model of the network does not consider the dynamic nature of the thermo-hydraulics, i.e. the pumping cost functions tend to change during each hour depending on the dispatch of the chiller and the consequent flow in the pipes. Thus, a method that includes these dynamic effects of the system must also be included. Further, the pipes can be modeled more comprehensively, to represent the flow through the pipes and associate an operation cost for the pipe based on the flow. In addition, the possibility of using the pipes for the storage of chilled water can also be explored. For the network-based model with the tank, several scenarios such as moving the absorption chillers at Rosenlund to a location closer to the tank, installation of a new pipeline to give a direct connection between Rosenlund and the tank, etc. can be further analyzed with an investment based economic optimization model.

Chapter 8: Conclusion

In this thesis, a computer-based model with the goal of determining the optimal operation of the units present in a DCS was successfully developed and applied to the existing DCS in Gothenburg. The model is a techno-economic model with an objective to minimize the annual running costs of the chillers in model 1 and the total operating costs of the DCS in model 2. The developed model includes overall and unit specific chilled water generation balances, minimum on and off-times, start-up and shut-down conditions, thermal storage describing constraints, and the network-based constraints. Various scenarios were created to examine the operation of the current and future DCSs in Gothenburg.

The results from 'model 1- case 2018' showed that the DCS in Gothenburg is economically better than the individual chillers scenario. The sensitivity analysis conducted on this result proves the same result prevails irrespective of the cooling demand.

One of the major conclusions drawn from the modeling is that the installation of thermal energy storage in the system reduces the running cost of the chillers. With the inclusion of storage in the system, the system will be able to meet the cooling demand in the summer without operating the electric chillers. Optimal use of absorption chillers and the storage tank can help meet the demand without using the electric chillers. A sensitivity analysis was carried out on this result by varying the demand. When a demand with higher peaks was used as input, the results changed. In this case, the electric chillers are operated to meet the demand. Thus, the results obtained in 'model 1 - case 2024' are dependent on the input demand. The operation of the DCS in 2030 was analyzed in model 1 – case 2030. Based on the changes in the heating and the electricity systems, different scenarios were set up. Two different development scenarios were considered for the electricity system, while the DHS was modeled as two different scenarios, i.e. with and without seasonal energy storage in the system. The results from these scenarios indicated that the developments in the electricity system had the largest effect on the operation of the DCS. This is because the electricity prices also affect the heating system and hence the prices of heat. Therefore, the electricity prices have a larger effect on the operation of the DCS. Another major observation from the results of 'model 1 -case 2030' is the operation of the system in the summer. Unlike in case 2024, the operation of electric chillers is necessary for the summer months even in the average demand situation. How a storage with a larger storage capacity would impact the results was investigated with the help of a sensitivity analysis. The sensitivity analysis showed that both a larger TES and increase in installed capacity of absorption chillers is required to meet the demand in summer without using the electric chillers.

Model 2 was developed based on the results from model 1. In model 1 results, it was seen that the assumption made regarding the network could have a significant effect on the results. But there was no means of conducting a sensitivity analysis on these assumptions. One possible solution was to create a model that included the network in it too. This has been done in model 2. Two methods for doing the above was examined in 'model 2 – case 2018'. Based on the results from these two methods, namely the fixed pumping costs parameter method and the linked cost functions method, the accuracy to which the network is represented in each method is compared. The degree of closeness to which the real network is represented in these models was evaluated and it was concluded that the model based on linked cost functions has a better representation of the network due to the more detailed modeling of the network by using demand clusters and network-based constraints. Hence, this method was used to create a model of the DCS with thermal energy storage in case 2024. The results obtained were significantly different from the TES based models in ‘model 1 - case 2024’. The charging of the tank was much more restricted due to the addition of pumping costs. The initial control strategy that Göteborg Energi has for the tank was also tested as a sensitivity analysis and it was concluded that it is either required to move the absorption chillers at Rosenlund to a location closer to the tank or to install a new pipe connecting Rosenlund directly to the tank.

Thus, it was concluded from the results that the DCS in Gothenburg is better than having individual chillers. The implementation of TES helps reduce costs and the use of electric chillers during the summer, but the results depend on the demand. Also, the control strategy for the TES must be examined again and the future investment in the system must be investigated from the point of view of having a TES in the system. Also, to facilitate the current control strategy a few changes might have to be made to the structure of the network and the system. For a favorable operation of the system in 2030, investment in a larger TES or absorption chiller capacity is necessary.

Bibliography

[1] UNEP, District energy report book, 2018.

[2] Lund et al., "4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems.," *Energy,* vol. 68, pp. 1-11, 2014.

[3] *Communications with Anders strand at Göteborg Energi.*

[4] I. Dincer, "“On thermal energy storage systems and applications in buildings”," *Energy and Buildings,* vol. 34.4, 2002.

[5] D. Casetta, C. Nerbollier, B. Guillaume, S. Pascal and M. Dominique, "Dynamic modeling of a district cooling system wth modelica," in *14th Conference of International Building Performance Simulation Association*, Hyderabad, 2015.

[6] M. Sameti and F. Haghighat, "Optimization approaches in district heating and cooling thermal network," *Energy and buildings,* no. 140, pp. 121-130, 2017.

[7] A. A. Olama, District Cooling : Theory and Practice.

[8] ASHRAE, District cooling guide, Atlanta: ASHRAE, 2013.

[9] S. C-G Göransson, "Kylvattenspridning från Rosenlundsverket," 2018.

[10] A. Strand, *District cooling in Gothenbrug,* Gothenburg, 2020.

[11] M. Jangsten, *Lecture slides - Energy supply systems,* 2018.

[12] Göteborg Energi , *”Resan mot en fossilfri produktion 2030”,* 2019.

[13] J. Holm and J. Ottosson, "Future developements of district heating system in Gothenburg," 2016.

[14] A. Göransson, J. Johnsson, H. Sköldberg, D. Stridsman, T. Unger and E. and Westholm, ""Fjärrvärmen i framtiden - behovet"," 2009.

[15] H. Werner and S. Gadd, "Thermal energy storage systems for district heating and cooling systems," in *Advances in Thermal Energy Storage Systems*, 2015.

[16] J.-F. Olivier, "Numerical Study of a Stratified Cold water tank storage," 2016.

[17] F. Incropera, A. Lavine, T. Bergman and D. DeWitt, Principles of heat and mass transfer, Wiley.

[18] M. Skogfält, "Dimensionering av ackumulatortank vid LKABs förädlingsverkDimensionering av ackumulatortank vid LKABs förädlingsverk i Kiruna – för uppvärmning av processvatten och minskad oljeanvändning - Masters thesis," Umeå universitet. , 2009.

[19] IRENA and IEA-ETSAP, *IEA-ETSAP and IRENA Technology-Policy Brief E17 : Thermal Energy Storage,* IEA and IRENA, 2013.

[20] G. Schewiger, P.-O. Larsson, F. Magnusson and P. Lauenberg, "District heating and cooling systems e Framework for Modelica-based simulation and dynamic optimization," *Elsevier,* 2017.

[21] D. F. Dominkovic and G. Krajacic, "District Cooling Versus Individual Cooling in Urban Energy Systems: The Impact of District Energy Share," *MDPI,* 2019.

[22] J. Soderman, "Optimisation of structure and operation of district cooling," *Elsevier,* 2007.

[23] W. Gang, S. Wang, D. Gao and F. Xiao, "Performance assessment of district cooling systems for a new developement area," *Applied energy,* vol. 140, no. 2015, pp. 33-43, 2014.

[24] J. Jungbauer, S. Garcia, A. Wallisch, P. Dalin, D. Terouanne and N. Wirgentius, "Measurements of individual chiller systems compared to district cooling solutions," *Energy efficiency first : The foundation of a low-carbon society,* pp. 1423-1430, 2011.

[25] L. Zhang, J. Jing, M. Duan, M. Qian, D. Yan and X. Zhang, "Analysis of district cooling system with chilled water thermal storage," *Building simulation, https://doi.org/10.1007/s12273-019-0581-x,* 2019.

[26] J. Soderman and F. Pettersson, "Structural and operational optimisation of distributed energy systems," *Applied thermal engineering,* no. 26, pp. 1400-1408, 2005.

[27] T. Schwan, O. Ziessler, T. Eckhardt and R. Unger, "A Modelica-Based Framework for District Heating Grid Simulation," in *13th International Modelica Conference*, Regensburg, 2019.

[28] G. Sandou, S. Font, S. Tebbani, A. Hiret and C. Mondon, "Global modelling and simulation of a district heating network".

[29] T. Oppelt, T. Urbaneck, U. Gross and B. Platzer, "Dynamic thermo-hydraulic model of district cooling networks," *Applied thermal engineering,* no. 102, pp. 336-346, 2016.

[30] R. Khir and M. Haouari, "Optimization models for a single -plant District Cooling System," *European Journal of Operational Research,* no. 247, pp. 648-658, 2015.

[31] G. Schweiger, P.-O. Larsson, F. Magnusson and P. Lauenburg, "District heating and cooling systems e Framework for Modelica-based simulation and dynamic optimization," *Energy,* no. 137, pp. 566-578, 2017.

[32] GAMS Development Corp., "GAMS," [Online]. Available: https://www.gams.com/products/introduction/.

[33] GAMS Development Corp., "GAMS - CPLEX," [Online]. Available: https://www.gams.com/latest/docs/S_CPLEX.html.

[34] J. Abrell, F. Kunz and H. Weigt, "Start Me Up Modeling of Power Plant Start-Up Conditions and their Impact on Prices," *MPRA,* 2008.

[35] M. Thevenot, *Personal communication with Marc Thevenot at Göteborg energi.*

[36] AECOM Design Build, *The Mathematics of Pumping Water,* The royal academy of engineering.

[37] A. M. Calance, "Energy Losses Study on District Cooling Pipes - master's thesis," University of Gävle, Gävle, 2014.

[38] Nordpool, "Nordpool," [Online]. Available: https://www.nordpoolgroup.com/historical-market-data/.

[39] S. Marinhas, "Eurovent chiller certification key stones and future challenges," *REHVA,* 2013.

[40] B. t. systems, "How to size a chiller," BV thermal systems, [Online]. Available: https://www.bvthermal.com/how-to-size-a-chiller/.

[41] Daikin, *Applied catalogue Chillers and air side equipment,* Daikin.

[42] Göteborg Energi, *VO produktions nyhetsbrev,* 2019.

[43] L. Göransson, M. Lehtveer, E. Nyholm, M. Taljegard and V. Walter, "The Benefit of Collaboration in the North European Electricity System Transition—System and Sector Perspectives," *Energies,* vol. 12, no. 4648, 2019.

[44] D. Romanchenko, M. Odenberger, M. Goransson and F. Johnsson, "Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden," *Elsevier,* 2017.

Appendix

Table A 1: Individual chillers

Number	capacity	Installed capacity	ESEER air	ESEER water
1	0.386	0.5	5.18	-
2	0.355	0.5	5.18	-
3	1.207	1.5	4.15	-
4	2.114	2.6	4.51	-
5	1.105	1.4	4.73	-
6	0.207	0.25	5.1	-
7	0.111	0.15	5.02	-
8	5.92	7.2	3.71	-
9	0.8	1	4.71	8.84
10	1.124	1.4	3.86	-
11	1.21	1.5	3.73	-
12	1.855	2.3	3.63	-
13	0.398	0.5	5.18	-
14	0.25	0.3	5.22	-
15	28.126	34	-	4.75
16	11.408	13.7	4.83	-
17	0.642	0.8	4.89	8.52
18	0.323	0.4	5.1	-
19	0.74	0.9	-	8.52
20	0.5	0.6	5.12	-
21	0.507	0.7	5.07	-
22	0.85	1.1	4.7	-
23	0.55	0.7	-	8.52
24	0.77	1	4.71	-
25	0.567	0.7	5.07	-
26	1.006	1.3	4.51	-
27	2.048	2.5	4.71	-
28	1.595	2	4.91	-
29	1.127	1.4	4.73	-
30	0.753	1	4.91	-
31	0.903	1.1	4.9	-
32	1.094	1.4	4.73	-
33	0.993	1.2	4.7	-
34	0.31	0.4	5.1	-
35	0.6	0.8	4.89	-
36	1.185	1.5	-	5.38
37	1.934	2.4	4.7	-
38	0.608	0.8	-	8.52

39	8.583	10.3	4.83	-
40	5.386	6.5	4.73	-
41	0.5	0.6	5.12	-
42	0.5	0.6	-	8.88
43	0.222	0.3	-	8.11
44	0.659	0.8	4.89	-
45	0.23	0.3	-	8.11
46	1.041	1.3	4.51	-
47	0.477	0.6	-	8.83
48	4.346	5.3	4.7	-
49	0.95534	1.2	4.7	-
50	0.764	1	4.71	-
51	1.942	2.4	4.7	-
52	0.304	0.4	5.1	-
53	1.126	1.4	4.73	-
54	0.26	0.4	5.1	-
55	0.618	0.8	-	8.52
56	1.947	2.4	4.7	-
57	0.795	1	4.71	-
58	2.689	3.3	4.62	-
59	0.07	0.1	5.02	-
60	0.31	0	5.1	-

Table A 2: DHS in 2024

Type of unit	Unit	Capacity [MW/MWh]	Primary Fuel
Excess heat	Renova	185	Municipal waste
	Preem	60	Industrial excess
	ST1	85	Industrial excess
CHPs and HPs	Sävenäs CHP	110	Wood chips/Natural gas
	Rya CHP	295	Natural gas
	Högsbo CHP	85	Natural gas
	Heat pumps Rya HP 1-2	60	Electricity
	Musikvagen	12	Electricity
	Rya HP 3-4	100	Electricity
Heat only boilers	Rya HOB1	50	Wood pellets
	Rya HOB2	50	Wood pellets
	Sävenäs HOB1	90	Natural gas
	Sävenäs HOB2	75	Bio-oil
	Angered HOB1	35	Bio-oil
	Angered HOB2	35	Bio-oil
	Angered HOB3	35	Bio-oil
	Rosenlund HOB1	140	Bunker oil
	Rosenlund HOB2	140	Bunker oil
	Rosenlund HOB3	140	Bunker oil
	Rosenlund HOB4	140	Natural gas
	Sodra natet Container boiler	16	Bio-oil
	Tynnered HOB	20	Fuel oil
Storage	Accumulator tank	130/1000	N/A

Table A 3: DHS in 2030

Type of unit	Unit	Capacity [MW/MWh]	Primary Fuel
Excess heat	Renova	185	Municipal waste
	Preem	60	Industrial excess
	ST1	85	Industrial excess
CHPs	Sävenäs CHP	110	Wood chips/Natural gas
	Rya CHP	295	biogas
	Högsbo CHP	85	Natural gas
	Heat pumps Rya HP 1-2	60	Electricity
	Rya HP 3-4	100	Electricity
Heat only boilers	Rya HOB1	50	Wood pellets
	Rya HOB2	50	Wood pellets
	Sävenäs HOB1	90	Natural gas
	Sävenäs HOB2	60	Natural gas
	Angered HOB1	35	Bio-oil
	Angered HOB2	35	Bio-oil
	Angered HOB3	35	Bio-oil
	Rosenlund HOB1	140	Bunker oil
	Rosenlund HOB2	140	Bunker oil
	Rosenlund HOB6	140	Bunker oil
	Rosenlund HOB7	140	Natural gas
	Tynnered HOB	20	Fuel oil
Storage	Accumulator tank	130/1000	N/A
	Cavern thermal energy storage	300/200000	N/A

Table A 4: Sub pipes in the district cooling network

Distribution pipes			
Sub Pipes	Segment	Diameter(mm)	Length(m)
P1	a	355	617
	b	300	317
	c	200	302
P2	a	315	396
	b	160	230
P3-P4	a	560	548
	b	450	255
	c	350	56
	d	500	208
	e	315	320
	f	250	162
	g(Ark)	355	88
	h	400	174
P5	a	450	504
	b	355	298
	c	300	80
	d	250	230
	e	200	36
	f	225	200
P6	a	500	381
	b	400	457
	c	450	211
	d (SVM)	400	212
P7	a	630	906
	b	500	470
	c	315	254
	d	225	288
P8	a	400	330
P9	a	400	310
	b	315	352

P10	a	500	339
	b	400	885
	c	500	409
P11	a	630	494
	b	560	166
	c	500	341
	d	400	118
	e	450	54
	f(CE)	355	249
	g	250	380
P12	a	630	1782.06

Table A 5: Main pipe in the district cooling network

Main pipe			
Main Pipe	Segment	Diameter(mm)	Length(m)
M1	a	600	114
	b	630	382
M2	a	600	126
	b	630	118
M3	a	630	988.224
M4	a	630	448.269
M5	a	630	272.603
M6	a	630	399.272