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Resilient cooling technologies

Simulation study to determine the cooling capacity in old residential
buildings located in mid-Sweden

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Preface

This study was done as the graduation project for my master's degree in energy systems. Many people provided me both technical and emotional aid throughout this thesis and my education period.

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Abstract

The Long-term changes in the climate conditions have increased the need for adequate thermal comfort systems. These alternations influence extreme events, which their intensity and frequency have increased over the past years. Moreover, this study focuses on space cooling and parameters that the system should have to be considered as resilient. Literature study was done to present the concept of resilience as well as the different methods used to provide space cooling. In addition, the cooling systems suggested in this study, which are district cooling and absorption cooling, were presented and explained. Furthermore, the study focuses on cooling demand in a group of residential buildings based on different thermal characteristics, which were implemented based on building regulations from late 1960s to early 1980s. The building thermal properties were used as input to obtain their cooling demand by using building energy simulation tool. Based on the acquired results, an evaluation has been made for the cooling demand of those buildings. Further analysis presented a correlation between the cooling demand and thermal properties of the buildings and aided in the determination of the required cooling capacity. The selection of the capacities was based on the resilience criterion as the system has to be able to provide adequate performance and safety for the occupants during extreme events. Furthermore, an assessment was done to compare the suggested system based on their capacities and the primary energy use.

Keywords: cooling, cooling demand, absorption chiller, absorption refrigeration, district cooling, primary energy, resilience, residential buildings, old buildings, cooling capacity.

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1. Introduction

1.1. Background

Global warming has affected the global climate, causing alternations in the general weather condition throughout the year. The alternation comes in the form of extreme climate events, whose intensity and frequency are highly influenced by climate change. According to the IPCC (Intergovernmental Panel on Climate Change), any climate event that has a value higher or lower than its regular range considered as an extreme weather event [1]. In the context of this study, heatwaves are the main concern, which need to be faced, in order to provide an adequate indoor climate for the occupants during such events.

The term resilience is a wide concept, which can be used to describe buildings, systems installed within buildings, environments, and energy systems. This term can be simplified to the ability of the system to withstand severe surrounding conditions and its ability to recover promptly if any damage to the system is done. Moreover, resilience should be a major parameter during the early stages of designing a building. However, in recent design procedures of buildings, resilience is considered one of the important parameters alongside energy efficiency and sustainability [1].

The majority of individual cooling systems that are used nowadays are vapor compressions systems (VCSs), which are based on the reverse-Rankine compression cycle. These systems are characterized by low efficiency and great use of electricity by their compressor. In addition, these systems have a great environmental impact due to the greenhouse gases (GHG) emissions associated with the electricity generation process, and the refrigerants (such as chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), and hydrofluorocarbons(HFC)) used in the systems which are considered the main source of ozone depletion [2,3]

At the present time, many systems were developed as an alternative to the conventional Vapor Compressions Systems (VCSs), such as evaporative cooling systems (direct and indirect), absorption systems, and cooling with chilled Surfaces. In compression, the developed systems use less electricity than VCSs, hence less CO₂ emissions. In addition, the lack of refrigerants will characterize the system as ozone-friendly alternatives [2,3].

Furthermore, absorption refrigeration systems are a very interesting alternative to traditional VCSs, since they use less electricity, due to the lack of a compressor unit, and deal less damage to the ozone layer and the environment. Moreover, an absorption chiller from the company Yazaki is used in this thesis. This device produces chilled water, which delivers cooling for indoor air conditioning demand. The required operational energy can be delivered from various sources, such as waste heat from industrial processes, cogeneration systems, solar thermal energy, etc., in the form of a heat medium (hot water) with a temperature ranging from 70 °C to 95 °C [4,5].

Other options include district cooling systems, which can be linked to a group of buildings to meet cooling demand. A coolant (water) is chilled at a central chiller station and sent to a group of buildings via a distribution network in the district cooling system. Free cooling is a procedure that uses natural cold sources (lake, sea, or river) to cool the water, which in turn is used to provide cooling for the buildings. However, a combination of cooling devices and free cooling is used when the natural source temperature is not low enough [6].

District energy systems are widely used in Nordic countries. These systems are well known for being environmentally friendly, as well as their flexibility in energy use. The energy used in these systems can be provided from renewable/non-renewable energy sources. These systems can provide heating or cooling to the building via a distribution network. Using this method, a reduction in resource usage can be achieved resulting in a decrease in CO₂ emissions [7].

1.2. Literature review

The term resilience has made its way into energy systems, due to the extreme events which are influenced by global climate change [1]. Zhang et al [1] proposed some criteria to define and describe resilience. These criteria have focused on the ability of the system to absorb, adapt, and restore, as well as the recovery speed of the system to get back to its initial condition before the interaction with such events. As a critical review, some resilient cooling strategies, which were utilized by the reviewed papers, have been presented. The cooling strategies have been categorized into four categories depending on the system approach to resilient cooling, as followed:

- 1) Reduction of heat gains to the indoor environment and the occupants.
- 2) Removal of sensible heat from the indoor environment.
- 3) Enhance personal comfort apart from space cooling
- 4) Removal of latent heat from the indoor environment.

The strategies fall into different categories that focus on several aspects of the building. That can be approached in the initial stages of the building design, which can be done by installing technologies that reduce the internal heat gains of the building, such as solar shading, window glazing, ventilated envelope surfaces, etc. Moreover, cooling is not limited to the reduction of the internal gains, other strategies focus on the enhancement of the thermal condition of the building in general and the occupants as individuals. The removal of heat from the building is done with two different approaches, which depend on the type of heat (sensible or latent) that needs to be removed. Sensible heat can be removed in different methods all of which focus on lowering the temperature of the air without affecting the humidity ratio or the dew point, which can be done by different technologies such as ventilation cooling, adiabatic/evaporative cooling, compression refrigeration, absorption refrigeration, etc. Meanwhile, the latent heat removal approach is done by reducing the humidity ratio of the indoor air hence decreasing the temperature and increasing the thermal comfort of the indoor environment. Another strategy is providing thermal comfort on the individual level, which is done by personalized comfort systems (PCSs), apart from the general cooling system installed in the building [1].

Moreover, further assessment has been conducted for the cooling strategies based on the proposed criteria and the type of the occurring extreme event (Heatwave or Power outage), which was later used to conduct a comparison between the different technologies, which in turn pointed out the findings and the limitations of the study. According to Zhang et al [1], one major limitation was the approach of the study, which was based only on a qualitative approach and mentions the need for conducting a quantitative assessment of the cooling strategies[1].

Meanwhile, Attia et al [8] introduced a more detailed approach to the concept of resilience in buildings in the study, where the most critical issues have been pointed out, and resilience definitions presented accordingly. Resilience has been defined as the “Ability of a system to resist perturbations outside of its equilibrium state and its speed to come back to it” [8], and according to this definition, resilience has been divided into four stages (Vulnerability, Resistance, Robustness, and Recovery).

Moreover, Attia et al. [8] has tried to answer some research questions based on the approach that has been taken in this study. One of those questions was “resilience against what?”, which has been answered by identifying the possible threats that the system or the building environment might face. Also, some of these threats have been pointed out and described briefly to give a better understanding of what might the system face during disruption periods. Furthermore, the parameters of scale and time were introduced, where resilience can be assessed based on the scale and duration of the disruption, to assess the resilience of the system. Nevertheless, a definition of resilient cooling for buildings has been presented which states that resilient cooling systems should increase the ability of the system to withstand and prevent any thermal damage to the occupants due to the increase in the outdoor temperatures and the increase in the frequency and the severity of extreme events such as heatwaves. In addition, resilience stages have been connected to the resilience cooling term, this connection has given a more detailed overview of resilience in cooling systems and pointed out the risk factors, which the system might face during each of these stages [8].

In general, resilience is not the only parameter that should be concerned when designing the system. Primary energy use and carbon dioxide emissions are other important parameters that should be concerned, such parameters have great economic and environmental impacts globally. The study is influenced by the Swedish National Board of Housing implementation for nearly Zero-Energy Buildings (nZEBs), which the board has set limits for designing and operational factors [9].

The numerical indicator of primary energy use has been considered in this assessment, which in Sweden is called the primary energy number (PE), which changes according to the source of energy delivered. Moreover, Gustafsson *et al* [9] utilized a numerical approach with the assistance of the transient simulation program Trnsys to analyze the models, which are all based on a reference building with specific thermal properties. The simulations have shown a proportional relationship between the primary energy number of a building and the primary energy factor of electricity. Another assessment is done for the global carbon dioxide emissions changes depending on the electricity production sources and the combination of the sources used to produce the electricity, all these combinations had an impact on the global carbon dioxide emissions. The lowest emissions level was obtained by combining the district heating with a Photovoltaic installation. According to Gustafsson *et al* [9], in order to decrease the carbon dioxide emissions, the Swedish board needs to increase the ratio between the primary energy factors for electricity and heat to a value larger than the value used at the time of the study [9].

Space cooling has turned into an essential demand in the buildings sector, and it is considered the fastest-growing end-use within this sector. According to the International Energy Agency (IEA) [10], an annual increase of 4% has been noticed in space cooling demand since 1990, which makes space cooling the fastest-growing end-use, accounting for 5% of the total energy end-use today. In addition, it is expected to increase by almost 150% globally by the end of 2050 [11].

According to Sayadi *et al.* [7], significant growth in the cooling demand can be predicted in Europe, due to the rising ambient temperature, heat island effects, the increase in thermal insulation in buildings, and the increase in the required indoor thermal comfort levels. This growth in the demand can be fulfilled by using individual cooling systems, or district cooling systems [12]. In this paper, Sayadi *et al* [7] performed a literature review, using different databases, to provide a summary of the available district cooling systems and to assess their performance for different applications in different climate conditions. Moreover, three classification systems are proposed based on the different parameters, the first being categorized according to the system: Centralized, which is more suitable for large scale regions, and decentralized, which is suitable for smaller capacities. The second category is based type of the central plant, which is based on the cooling methods used (free cooling systems or using chillers and heat pumps). Nevertheless, the third categorizing system is based on the building typology and the behavior of the occupants, which affects the energy use inside the building hence, affecting the cooling demand [7].

Moreover, the study points out the benefits and the limitations of the district cooling system, which falls into three perspectives: operational, economical, and environmental. In addition, the available district cooling technologies are introduced as well as their energy sources, operational aspects, and their applications, all of which were taken from the literature reviewed in this study. Nevertheless, Sayadi et al. [7] presents three factors that are used to quantify the energy efficiency in the district cooling systems, and suggested the implementation of life cycle cost analysis (LCCA) to obtain an evaluation of the system and the cost-effectiveness of the available alternatives.

Absorption cooling systems provide cooling by utilizing heat as the operational energy. The used heat can come from various sources such as district heating, solar thermal energy, CHP plants, and waste heat from the industrial processes, all of which are considered “low-grade heat”. Despite the lower efficiency of the absorption cycle compare with the traditional compression cycle, the energy required to run the absorption cycle is considered cheap since most of the heat is a by-product of other processes such as electricity production. In most absorption cooling systems, an electricity-driven internal solution pump is needed. However, the pump uses less electricity compared to motor-driven compression cooling systems. The utilization of waste heat and the low electricity usage make the absorption cooling systems very interesting from the energy-saving point of view [5].

Moreover, the properties of the working fluid solution are important thing in absorption cooling systems, as they affect the system’s construction as well as its effectiveness and cost [13]. Commercially, H_2O -LiBr and NH_3 - H_2O are considered the most common working fluids in absorption chillers [14].

1.3. Aim

This study aims to perform energy - analysis of a group of residential buildings within the city of Gävle, which will include:

- Description of the buildings, their components, and their building materials.
- Perform a quantitative approach to determine the cooling demand of each of these buildings via IDA-ICE and determined the required capacities to be installed.
- Primary energy analysis of different cooling technologies will be performed based on the cooling demand of the buildings.

2. Theory

2.1. Resilience concept and characteristics

This section will focus on reviewing the definition of resilience and resilience systems characteristics. Resilience is described as the ability of the object to return to its initial state after being exposed to a disruption. This concept is used in various disciplines, where it can be defined and interpreted according to the discipline of interest.

Identifying the threats is one of the most critical prerequisites to obtaining a comprehensive definition of the concept, which can be summarized in the question “resilience to what?” [8]. Moreover, extreme heat events (heatwaves) and the power outages, that occur as a result of the high demand from the cooling systems during these events, are the main threats facing the cooling systems.

As mentioned before, there is difficulty in generalizing the definition and characteristics of the resilience concept, due to its contribution to various disciplines. However, Zhang et al. [1] summarizes the characteristics of resilience cooling systems by four criteria based on the ability of the system to absorb (absorptive capacity), adapt (adaptive capacity), restore (restorative capacity), and recover (recovery speed) from the disruption.

- **Absorptive capacity** is the ability of the system to absorb the impact of the disruption and minimize the consequences of the disruption with little effort.
- **Adaptive capacity** is the ability of the system to adjust to the disruption by undergoing some changes. The system can analyze and evaluate the disruption and the system performance during the disruption and change the system configuration accordingly. This will make the system more flexible in the case of future disruptions.
- **Restorative capacity** can be defined as the ability of the system to return to its initial state after facing a disruption.
- **Recovery speed** is the time required of the system to perform the recovery process.

Moreover, according to Annex80 [15], resilient cooling is the ability of the cooling system integrated within the building to withstand and recover from the disturbance caused by the disruptions and also to adopt post-failure strategies to avoid degradation of building performance.

2.2. Absorption refrigeration cycle

In general, absorption refrigeration systems are considered thermally driven refrigeration systems, which use low-grade heat for cooling processes. There are four main components in the basic absorption chillers, these components are the generator, the condenser, the evaporator, and the absorber. Compared to the traditional vapor compression system, this system does not have a compressor unit, instead, it has an absorber, which carries the absorbent through a pump when the generator is supplied with heat [16].

The cooling device used in the thesis is an absorption chiller made by the Japanese company Yazaki. This device provides the cooling effect by chilling water. Yazaki absorption chiller uses lithium bromide-water ($\text{LiBr-H}_2\text{O}$) solution as the working fluid, where water (H_2O) is the refrigerant, and lithium bromide (LiBr), a nontoxic salt, is the absorbent. The device is designed based on the single effect absorption refrigeration cycle and it has only one generator as well as a condenser, an evaporator, and an absorber (Figure 1). The device is energized by a heating medium (Hot water), which its temperature ranges from 70°C to 95°C .

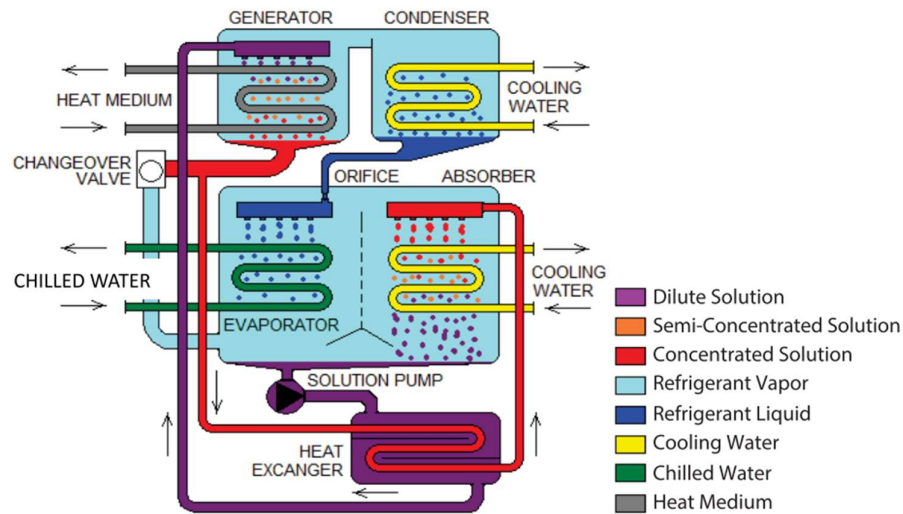


Figure 1 Cooling cycle of Yazaki absorption chiller [4]

The main components that the absorption cooling system consists of are the evaporator, absorber, generator, and condenser. The evaporator and the absorber, fall on the low-pressure side of the system, meanwhile, the generator and the condenser fall on the high-pressure side of the system. As mentioned before, the working fluid is a solution of a refrigerant and an absorbent, each of which follows a different cycle. The absorbent follows the cycle of absorber-generator-absorber, meanwhile, the refrigerant follows the condenser-evaporator-absorber-generator-condenser cycle.

2.2.1. Sequence of operation

As the liquid refrigerant leaves the high-pressure condenser, it passes through an expansion valve, which reduces its pressure before entering the low-pressure evaporator. In the evaporator, the refrigerant vaporizes as a result of absorbing the latent heat from the water that needs to be chilled for cooling purposes. The vaporized refrigerant then flows to the absorber, where it is mixed with the absorbent forming the refrigerant-absorbent solution.

The main driving force of the vaporized refrigerant from the evaporator to the absorber is vapor pressure since the vapor pressure of refrigerant-absorbent solution in the absorber is lower than the refrigerant vapor pressure in the evaporator. In addition, vapor pressure does not only work as a driving force for the flow but also determines the pressure of the low-pressure side of the system, which in turn determines the evaporating temperature of the refrigerant. Moreover, the solution's vapor pressure depends on the characteristics of the absorbent as well as its temperature and concentration.

As the vaporized refrigerant from the evaporator dissolves in the solution, the volume of the refrigerant decreases, which causes the compression effect, and heat is rejected. In addition, it is important to keep the solution more concentrated in order to keep the vapor pressure of the solution low enough, as is required by the evaporator. This is done by pumping the high concentrated solution from the absorber to the generator, where the solution evaporates by the air of the supplied heat, and then the low concentrated solution is sent back to the absorber. In the absorber, the weak solution receives more refrigerant from the evaporator forming a high concentrated solution again. Moreover, a pump is needed to deliver the highly concentrated solution from the absorber (the low-pressure side) to the generator (the high-pressure side). In order to deliver the low concentrated solution to the absorber, an expansion valve is needed to decrease its pressure as low as the absorber requires.

In the generator unit, the solution is heated by the supplied heat and as a result of that, the refrigerant evaporates and separates from the absorbent. More, the high-pressure refrigerant flows to the condenser, where it loses its latent heat and condenses to be sent back to cycle again. As for the remaining low concentration solution, it flows back to the absorber through a returning pipe.

The maximum efficiency of the system can be attained by maintaining the pressure difference between both sides of the system as small as possible (keeping the pressure of the high-pressure side as low as possible and the pressure of the low-pressure side as high as possible). Nevertheless, the pressure of the low-pressure side depends on the vapor pressure of the absorbing solution, which in turn depends on the solution's concentration and temperature. However, controlling the temperature of the solution is limited by the temperature of the refrigerant. To overcome this limitation, controlling the pressure of the low-pressure side is done via varying the concentration of the solution.

The efficiency of the system can be increased furthermore by introducing a heat exchanger between the generator and the absorber. This heat exchanger can be installed between the line that delivers the highly concentrated solution to the generator and the line that brings the low concentrated solution back from the generator to the absorber. By installing this heat exchanger, the highly concentrated solution is preheated before entering the generator and the temperature of the low concentrated solution is decreased before entering the absorber, which will result in less heat to be delivered to the generator as well as less cooling in the absorber.

2.2.2. Working fluid

The design and performance of the absorption cooling system are dependent on the properties of the working fluid. According to Sun *et al.* [17], there are some characteristics and requirements that the working fluid should have to be considered as a valid working fluid:

- Both refrigerant and absorbent should be chemically stable, non-toxic, non-corrosive, environmentally friendly, and cost-effective.
- The difference in boiling point between the pure refrigerant and the mixture should be as large as possible under the same pressure.
- The refrigerant should have high latent heat and high concentration within the solution to minimize the flow rate between the generator and the absorber.
- Properties that influence mass and heat transfer, such as viscosity, thermal conductivity, and diffusion coefficient are desired.

The most commercially used working fluids are water-lithium bromide (H_2O -LiBr) mixture, where water is the refrigerant and lithium bromide is the absorbent, and ammonia-water (NH_3 - H_2O) mixture, where ammonia is the refrigerant and water is the absorbent [18].

As for our case, a water-lithium bromide mixture is used in the studied system. Moreover, lithium bromide as an absorbent has a characteristic of non-volatility, which means that there is no need to purify the desorbed refrigerant vapor, due to the hygroscopic nature of the salt. However, it tends to crystalize easily. In addition, the freezing point of the water is another limitation of the system, as it can only operate above 0°C.

2.3. District cooling

A district cooling system is a cooling alternative that uses a coolant, usually chilled water, generated in a central refrigeration unit and delivered to the buildings via a distribution network. The chilled water is delivered to the cooling unit inside the building to provide adequate cooling for the occupants [7].

District cooling systems consist of mainly three units: refrigeration plant, distribution network, and end-use (Figure 2).

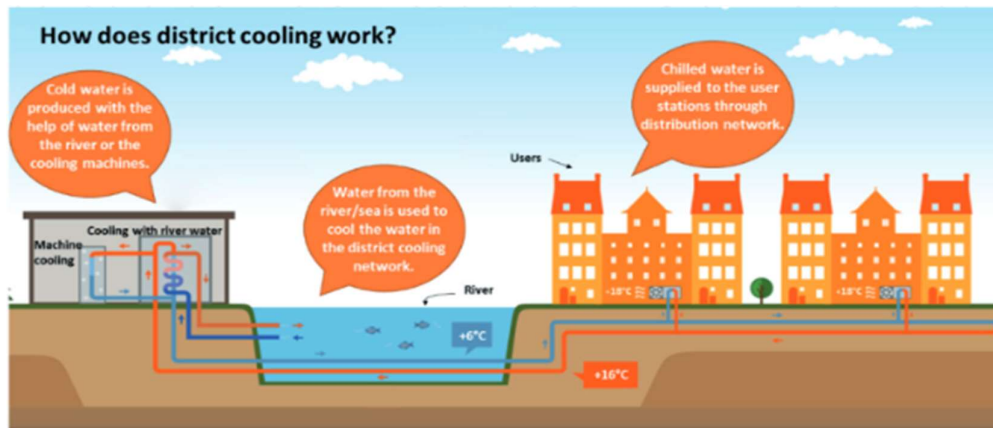


Figure 2 District cooling network [7]

District cooling systems provide a more efficient way to handle energy and also have the potential of reducing greenhouse gases emission since the production is centralized and can terminate the use of individual cooling devices that are relatively less efficient and produce emissions either directly or indirectly (from the energy required for operation).

Generally, the chilling of water can be provided by an adjacent lake or sea, which can provide relatively low temperatures. However, if the natural sources are not cold enough, the chilled water can be supplied by other cooling devices within the central station. Swedish guidelines suggest designing the system with temperatures of 4-10 °C for the supply and 14-20 °C for the return, where 6°C is considered as the supply temperature benchmark and 16 °C is the temperature benchmark for the return [19].

The flow of the coolant in the distribution network varies with the load, hence the flow is regulated by a two-way control valve in each substation. The purpose of the installation of the two-way valve is to lower the cost of pumping and increase the temperature difference between the supply and return. A higher temperature difference between the supply and the return will decrease the power used by the pump, but it will also increase the heat losses on pipe surfaces.

2.4. IDA-ICE

IDA ICE is a simulation program that allows the user to design a building, define the zones, simulate the performance of the heating and cooling system, as well as determine the cooling and heating demand as well as other energy parameters of the building [20].

For this study, IDA-ICE is used to determine the cooling demand of the designed model during the demand period (usually summer).

Several steps should be considered during the process of designing and simulating the models, the steps will be explained in this section, which are:

1. Location and Climate
2. Walls, roofs, floors, doors, and windows
3. Air change rate (ACH)
4. Internal gains
5. Setpoints

In order to get adequate simulation results, sufficient input data must be provided in each of these steps. The input data will be determining the building condition during the simulation period, which in turn will provide the building's thermal and energy requirement.

2.5. Cooling Capacity

The cooling capacity is an important in designing cooling systems as it determines the maximum cooling that can be provided by the system. The determination of the cooling capacity can be done by two different approaches, which are average cooling capacity and peak load cooling capacity. The average cooling capacity can be determined by dividing the cooling demand by the operation hours when cooling is needed (Equation 1).

$$\text{Average cooling capacity} = \frac{\text{Demand}}{\text{operation hours}}$$

Equation 1 Average cooling capacity

However, this approach would fail in cases when high cooling demand is required for short periods of time due to the building envelope being subjected to higher outdoor temperatures, where in this case the peak load capacity approach can be implied. The peak load capacity is based on the peak load of the systems, which falls in the periods with highest cooling demand. Using the later approach will ensure that the system can deliver enough cooling during the peak load periods. Moreover, in most cases a safety factor (safety margin) is implied to ensure the stability of the cooling system performance during extreme events. The safety factors can range from 5% to 20 % according the expected conditions that the system might face. [22]

2.6. Primary energy number

The primary energy number can be used to define the real primary energy efficiency of various energy-related activities. The Primary energy factors (PEF) allow for a comparison of the system's principal energy input and the energy delivered to the consumer. Its evaluation includes the energy required for extracting, processing, storing, and transporting to a power plant, as well as energy conversion, transmission, and distribution losses. Moreover, it can also be an indication of the impact that the used energy subject on the environment. The primary energy factor can be calculated by using the equation below (Equation 1):

$$EP_{pet} = \frac{\left(\frac{E_{heat,el}}{F_{geo}} + E_{cooling,el} + E_{DHW,el} + E_{op,el} \right) * PE_{el} + \left(\frac{E_{heat}}{F_{geo}} + E_{cooling} + E_{DHW} \right) * PE_{rem}}{A_{temp}}$$

Equation 2 primary energy number

Where:

PE number = Primary energy number (kWh_{primary energy}/m², year)

E_{heat,el} = Electricity used for space heating (kWh/year)

E_{cool,el} = Electricity used for cooling (kWh/year)

E_{DHW,el} = Electricity used for domestic hot water (kWh/year)

E_{op,el} = Electricity used for operation of the building (kWh/year)

E_{heat} = Space heating from other energy carriers (kWh/year)

E_{cool} = Space cooling from other energy carriers (kWh/year)

E_{DHW} = Space heating from other energy carriers (kWh/year)

F_{geo} = Geographic correction factor (between 0.9 and 1.8)¹

PE_{el} = Primary energy factor for electricity

¹ According to Boverket [23]

PE_{rem} = Primary energy factor for other energy carriers

A_{temp} = Heated floor area of the building

The primary energy factors (PEFs) used in the calculations are taken from Boverket as they provide the PEF of each energy carrier in the table below (Table 1).

Table 1 Primary energy factors for different energy carriers [23]

Energy carrier	Primary energy factor (PE_i)
Electricity (PE_{el})	1.8
District Heating (PE_{DH})	0.7
District Cooling (PE_{DC})	0.6
Biofuel (PE_{bio})	0.6
Oil (PE_{oil})	1.8
Gas (PE_{gas})	1.8

3. Case Study

This Chapter provides information about the data used for the simulation as well as the models used. All of which are required to perform an adequate simulation according to the predetermined indoor and outdoor conditions.

3.1. Location and Climate

The simulations will take place within Gävleborg county. Gävle is located at the latitude of 60.67 North and the longitude of 17.14 East. Moreover, the elevation is set to 16 m, hence the elevation of the buildings will be considered 18m above the sea level. In addition, the time zone is also assigned according to the time zone of the area, which is +1:00 hours as to the Greenwich meridian.

The climate conditions are considered one of the critical parameters in the simulations performed by IDA-ICE, hence it needs to be defined. The utilization of the climate conditions allows the program to perform more realistic simulations according to the surrounding conditions.

Moreover, the climate file used is provided by The Swedish Meteorological and Hydrological Institute and it is projected for 30 years. The climate file contains information about Dry-bulb temperature, relative humidity of the air, direct and diffuse solar radiation, wind speed, and cloudiness. In Figure 3, the dry bulb temperature during 2019 in Gävle can be seen, which is obtained by the climate file used.

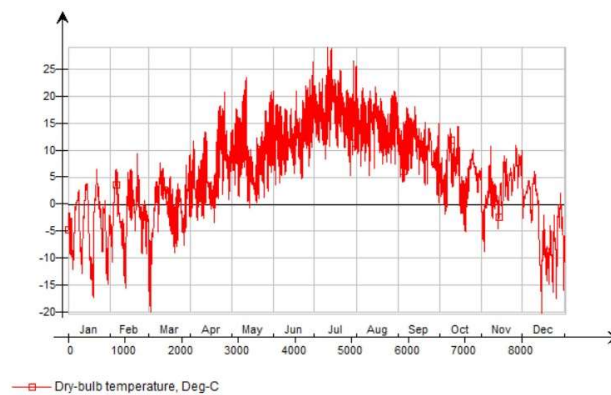


Figure 3 Dry-bulb temperature of Gävle[24]

Moreover, Table 2 is a report of climate variables, where the mean values of the climate variables, which is taken from the climate file used, are presented on a monthly basis. In addition, the dry-bulb temperature is an indication of the seasons, and summertime and wintertime can be differentiated depending on the mean value of the dry-bulb temperature.

Table 2 Mean values of the climate conditions during the year[24]

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	-4.1	86.2	24.8	7.8	0.8	0.6	72.3
February	-1.8	81.2	60.7	22.9	0.9	-0.5	64.2
March	-0.7	77.6	90.8	60.8	1.0	1.2	64.6
April	5.6	72.7	158.6	80.5	-0.1	0.4	56.2
May	9.9	67.8	228.0	99.7	-0.7	-1.0	49.7
June	13.3	70.4	234.3	102.9	-0.1	-0.3	53.6
July	17.7	65.2	191.1	127.7	1.2	1.0	55.9
August	14.4	77.4	105.0	99.3	1.0	0.6	70.3
September	10.2	81.0	113.9	55.2	-0.1	-0.1	62.8
October	5.4	81.5	67.0	30.9	1.6	0.6	61.3
November	3.0	86.8	48.4	8.3	1.1	1.6	68.5
December	-4.2	87.8	20.0	4.6	1.4	-0.2	73.8
mean	5.8	78.0	112.0	58.6	0.7	0.3	62.8
mean*8760.0 h	50532.7	682887.4	981139.1	513575.1	5960.4	3010.0	549900.0
min	-4.2	65.2	20.0	4.6	-0.7	-1.0	49.7
max	17.7	87.8	234.3	127.7	1.6	1.6	73.8

3.2. Walls, roofs, floors, doors, and windows

As mentioned before the simulations are done in the city of Gävle, which falls in older building regulation's zone II of Sweden (Figure 4), hence the U-values were implemented to match the maximum allowable values, which are set to be equal to those in the building regulations of BABS67 [20], SBN 75 [21] and SBN 80 [22] (applicable from the late 1960s to the 1970s and early 1980s), which will allow the evaluation of the cooling demand of buildings built in those periods. Moreover, this system has been replaced with a more detailed version called the geographical factor, which defines the building requirement in that location and is used to calculate the primary energy factor[25].

The evaluation is done based on the cases; each follows the maximum allowable U-values from the mentioned periods (except the doors, which have been changed for security requirements and aging). Moreover, during the simulation the windows are set to closed to prevent any heat exchange caused by wind entering the envelope, All the U-values and the materials as well as the windows properties are listed in the tables below (Table 3 and 4).

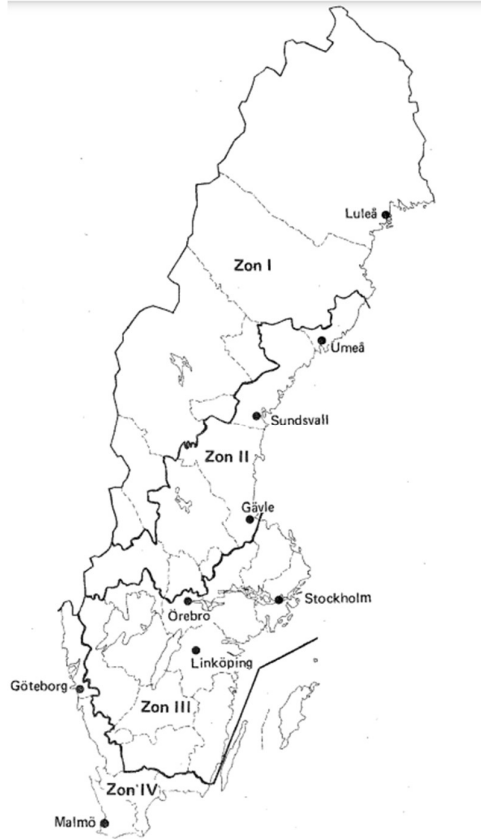


Figure 4 Sweden climate zones [26]

Table 3 Building components Properties

Case number	component	Average U-value (W/m ² *K)	Materials		
			Material	Thickness m ²	Thermal conductivity W/m*K
CASE I ²	Walls	0.53	Render layer	0.02	0.8
			L/W Concrete	0.25	0.15
			Render layer	0.02	0.8
	Roof	0.3	Wood	0.022	0.14
			Mineral Wool	0.1	0.036
			Wood	0.022	0.14
	Floor	0.37	Wood	0.015	0.014
			L/W concrete	0.15	0.15
			Mineral Wool	0.05	0.036
	External doors	1.1	Wood	0.025	0.14
Styrofoam			0.015	0.04	
Wood			0.025	0.14	
Case II ³	External Walls	0.3	Gypsum	0.02	0.04
			Extruded polystyrene	0.1	0.036

² Based on the data provided by Boverket [27]

³ Based on the data provided by Boverket [28]

	Roof	0.19	L/W concrete	0.2	0.15
			Gypsum	0.02	0.04
			Wood	0.022	0.14
			Mineral wool	0.17	0.036
			Wood	0.022	0.14
	Floor	0.37	Wood	0.015	0.14
			L/W concrete	0.15	0.15
			Mineral Wool	0.05	0.036
	Doors	1.1	Wood	0.025	0.14
			Styrofoam	0.015	0.04
			Wood	0.025	0.14
Case III ⁴	External Walls	0.47	Render	0.02	0.8
			Extruded polystyrene	0.02	0.036
			L/W concrete	0.2	0.15
	Roof	0.3	Render	0.02	0.8
			Wood	0.022	0.14
			Mineral Wool	0.1	0.036
			Wood	0.022	0.014
	Floor	0.5	Wood	0.015	0.14
			L/W concrete	0.15	0.15
			Mineral Wool	0.025	0.036
	Door	1.1	Wood	0.025	0.14
			Styrofoam	0.015	0.04
			Wood	0.025	0.14

Table 4 Windows properties

Case nr.	U-value Glazing (W/m ² *K)	Solar heat gain coefficient	Type of window
Case I	2.9	0.76	Double Pane Window
Case II	2	0.66	Triple Pane Window
Case III	2	0.76	Triple Pane Window

3.3. Air change rate (ACH)

The air change rate (ACH) for specific urban airspace is defined as the amount of air exchanged between this volume and its surroundings in one hour, as estimated by volumetric ventilation rates and the volume of this airspace 38. The ACH will vary depending on the intensity of activity and the equipment in the room. As a result, an ACH must be set that provides occupant comfort through heat or cold supply while simultaneously cleaning the environment of contaminants.

For the simulation, the air change rate was set to 0.35 l/s*m² for the supply air and 0.37 l/s*m² for the return air, which are the default values set by IDA-ICE.

⁴ Based on the data provided by Boverket [29]

3.4. Internal heat gains

The heat gain caused by humans, lighting, and equipment is considered by IDA ICE in its models. As a result, it incorporates these characteristics into its model to predict the building's total heat gain more correctly. As a result, identifying all these variables for each room of the building is a critical stage in the modeling process. As a result, the facility needed to be inspected to compile a list of personnel, lighting, and equipment.

3.4.1. People

Heat is discharged within the envelope in proportion to the number of individuals in the room. Because of the varying distributions of occupants in the building, the number of persons per zone is an important aspect to be considered. Furthermore, a person's activity levels determine how much heat (latent and sensible) and carbon dioxide they emit. The activity level of the occupants has been set to be 1 met (metabolism), which is the amount of energy emitted by a single sitting, inactive human. This amount is equal to 58.2 W per m² of the body surface. The body surface area in IDA ICE has been set to 1.8 m², which corresponds to an average adult. Furthermore, the occupants schedule must be considered, as people will gain heat only during their exitance within the buildings.

3.4.2. Equipment

Household equipment is another source of internal gains. Depending on their type and operation time, they can emit a significant amount of heat to the envelope. For these models, equipment is set in each apartment with a power of 120 W and average yearly power of 1051 kWh/year*apartment (87.6 kWh/month*apartment).

3.5. Setpoints

Setpoint temperatures are very important parameters in the design and operation of thermal comfort systems. The setpoints determine the temperature range for the indoor climate and triggers the operation of the cooling and heating devices within the rooms. The lower setpoint is minimum allowable temperature of the rooms, where if the temperature falls below this value the heating devices will start operating. Similarly, the higher setpoint is the maximum allowable indoor temperature, which if exceeded the cooling devices will start operating. Moreover, for our simulations values of 25 °C and 21 °C were used as setpoints for the maximum and minimum allowable indoor temperatures.

3.6. Models Description

The models used are designed as apartment residential buildings. These buildings are characterized by having different ground areas, floor areas, number of floors, and number of apartments, each of which can affect the average U-value of the building hence, its thermal properties.

3.6.1. Model-1: Row house

This model consists of 8 apartments divided into 2 floors (4 apartments per floor), each of which has its independent entrance. The model is built on an area of 200 m², giving a total floor area of 400 m². Moreover, the envelope area of this model is 889 m², this area includes the wall area, windows area, roof area, as well as the area of the windows, which covers (9.4%) of the total envelope area. The figures below (Figure 5 and 6) illustrate the building plane and the 3-dimensional (3D) view of the building.

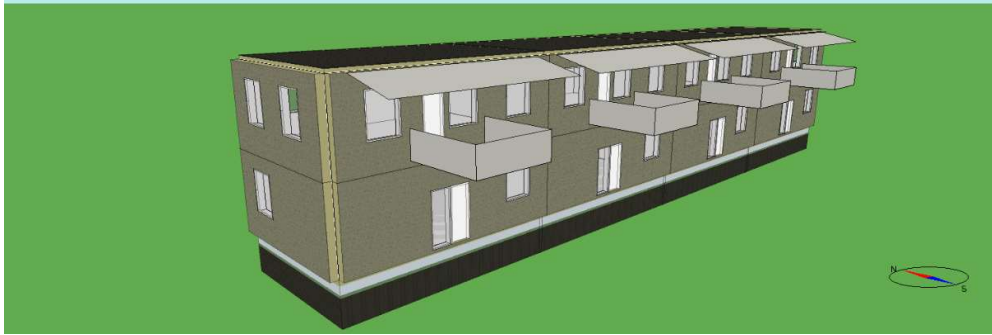


Figure 5 Model-1: Rowhouse 3D view

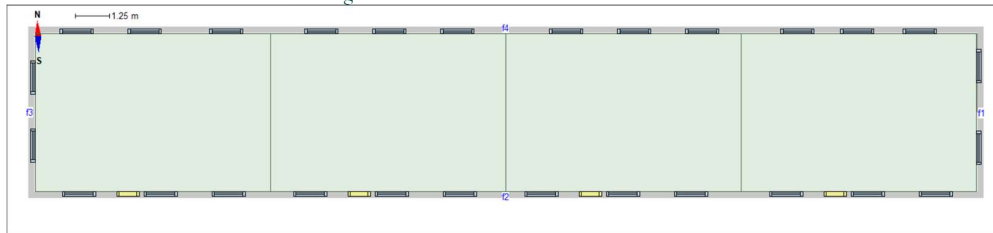


Figure 6 Model-1: Rowhouse 2D plane

3.6.2. Model-2: Apartment building

This model is for a building with 8 floors, which have 5 apartments on each floor (except the first floor) giving a total number of apartments of 39. The building has a main entrance that leads to an open space, where you can find the entrance for each apartment. The building is built on an area of 290 m² and has a floor area of 2144 m². The envelope area for this model is 2242 m² with an envelope/window ratio of (10.2%). Figures 7, 8, and 9 show the 2-Dimensional building plane for the floors as well as a 3D model of the building.

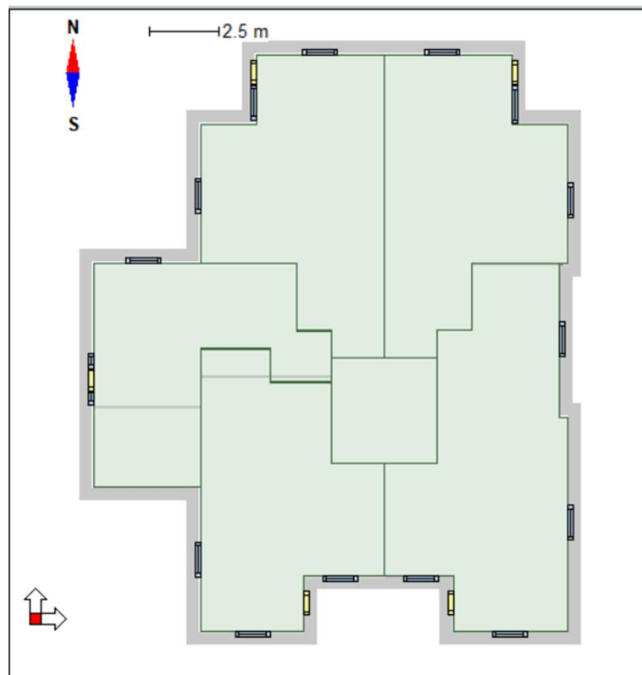


Figure 7 Model-2: Apartment building 2D plane of the first floor

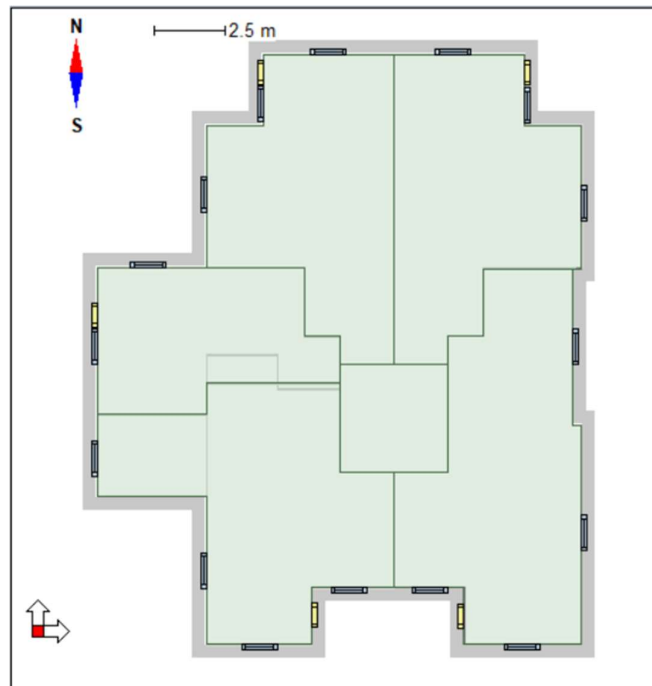


Figure 8 Model-2: Apartment building 2D plane of the 2-8 floors

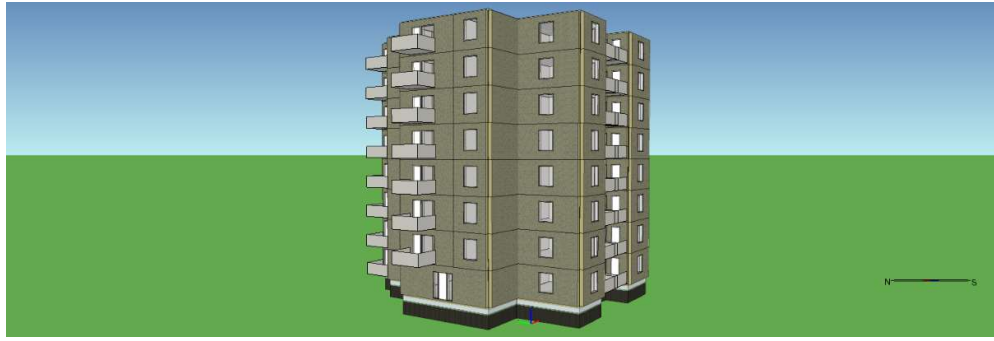


Figure 9 Model-2: Apartment building 3D view

3.6.3. Model-3: Terraced apartment house

This building consists of 18 apartments divided into 4 floors, each of which has its entrance. The ground area of the building is 450 m² and it has a floor area of 1500 m². The envelope area of the building is 1818.5 m² with an envelope to windows ratio of (8.2%). The figures below (Figure 10 and 11) illustrate the building plane as well as the 3D view of the model.



Figure 10 Model-3: Terraced apartment house 3D view

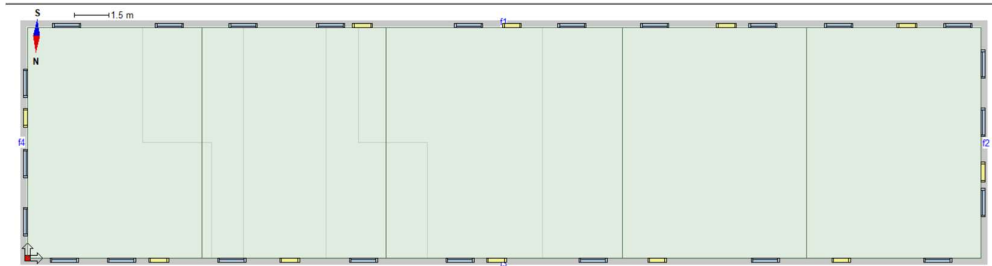


Figure 11 Model-2: Terraced apartment house 2D-plane

Table 5 provides a summary of the characteristics of each of the models.

Table 5 Summary of buildings characteristics

Model No.	Nr. of apartments	Nr. of floors	Nr. of open spaces	Ground Area (m ²)	Floor Area (m ²)	Envelope Area (m ²)	Envelope/windows
Row house	8	2	-	200	400	889	9.4%
Apartment building	39	8	8	290	2144	2242	10.2%
terraced apartment house	18	4	-	450	1500	1818.5	8.2%

The thermal properties of the building's components are based on the values mentioned in the previous section (Section 3.2). Using the provided values, the average U-value of each building was calculated and shown in the table below (Table 6). The cases are based on building regulations from the late 1960s, mid-1970s, and early 1980s.

Table 6 Average U-values of the buildings

Model No.	Average U-Value (W/m ² K)		
	Case I	Case II	Case III
Row house	0.6282	0.4026	0.5278
Apartment building	0.7078	0.4301	0.5909
terraced apartment house	0.6076	0.3881	0.5174

4. Results

IDA-ICE has been used to estimate the cooling demand for the group of buildings. The simulations were done for the summertime by using three models of residential buildings, and the properties of their components are based on the cases presented in chapter 3.

4.1. Cooling Demand

The models were simulated for the whole year, where the cooling equipment was set as the IDA-ICE ideal cooler. In the next subsections, detailed results will be presented.

4.1.1. Model-1: Row house

The results of the simulations can be seen in the Figure below (Figure 12), noticing that only the months with cooling demand were mentioned. It can be noticed that the highest demand is during July with the demand of all cases on the 13th of July, due to the high dry-bulb temperatures. Moreover, the amount of internal heat gains, due to equipment and occupants, in this model was 32.42 kWh/m². The high U-value in Case I will allow the envelope to transmit the surplus heat generated inside the building to its surroundings, which will aid the removal of the internal heat gains. Moreover, the difference in the demand between Case II and III is due to difference in the windows properties. The windows in Case II have lower Solar heat gain coefficient which will reduce the number of internal gains caused by solar radiation.

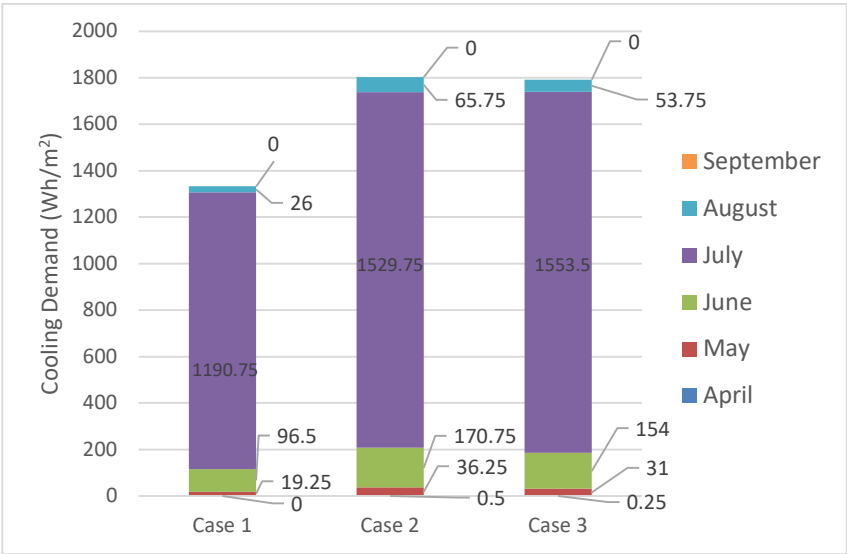


Figure 12 Model-1 Rowhouse cooling demand on monthly basis

Moreover, from the data shown in the table below (Table 7), a relationship between the cooling demand and U-value can be noticed, as the cooling demand increases with the decrease of the Average U-value. The trendline can be seen more clearly in the figure below (Figure 13), as the result takes a linear shape between case II and III and tends to be constant between Case I and III. This reaction is related to both temperatures inside and outside the building, as the heat transfer always takes the direction from high to low.

Table 7 Cooling demand and average U-value of model-1

	Cooling demand (kWh)	Demand per unit area (kWh/m ²)	Peak Demand (kW)	Average U-value Building (W/m ² ·K)
Case I	533.1	1.333	5.973	0.6282
Case II	721.2	1.803	5.701	0.4026
Case III	717	1.792	6.291	0.5278

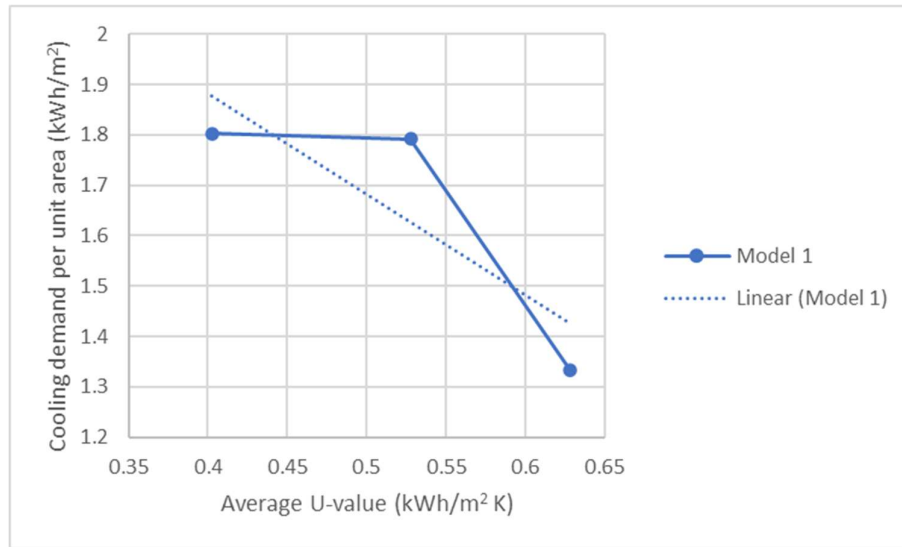


Figure 13 Model-1: Relationship between cooling demand and average U-value

4.1.2. Model-2: apartment building

The simulation results are summarized in the figure below (Figure 14). Similarly, to model-1 the highest demand was recorded during July, with the peak value being on the 13th of July. The internal heat gains for this model were estimated at 31.42 kWh/m². Moreover, the cooling demand for Case II and III during July have very similar value, which is due to the difference in the windows properties. However, in contrast with the other cases, the cooling demand of Case II is still the highest.

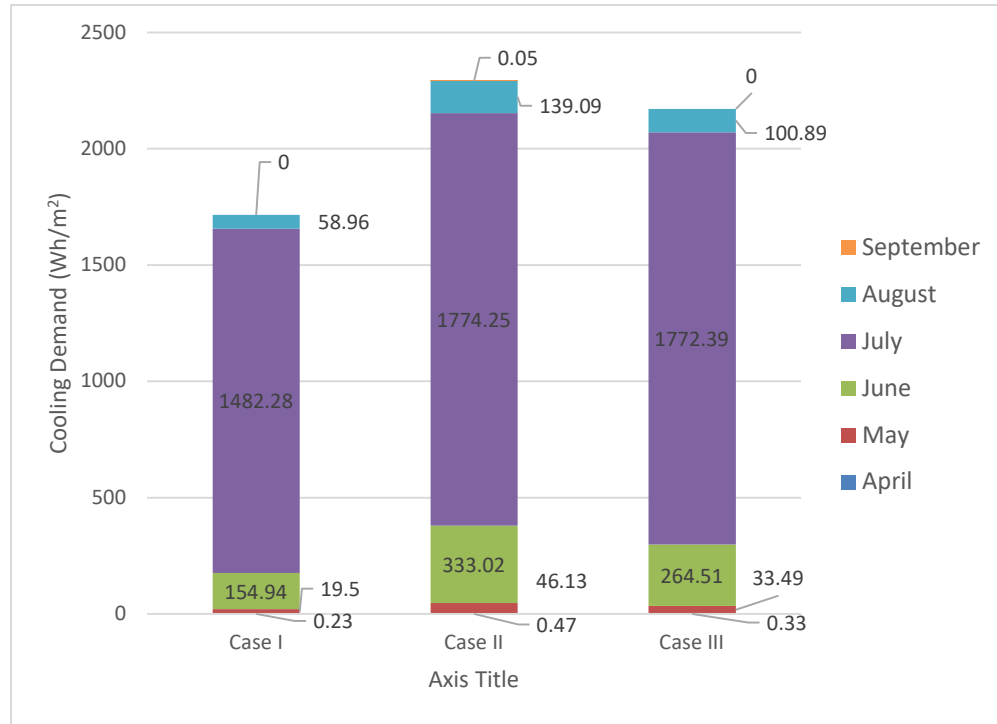


Figure 14 Model-2; Apartment building cooling demand on a Monthly basis

From the data provided in Table 8, we can provide a graph that shows the relationship between the Average U-value and the cooling demand. Similar to model-1, the cooling demand decreases as the U-value increases (Figure 15).

Table 8 Cooling demand and average U-value of model-2

	Cooling demand (kWh)	Demand per unit area (kWh/m ²)	Peak Demand (kW)	Average U-value Building (W/m ² ·K)
Case I	3678.8	1.716	28.86	0.7078
Case II	4916.3	2.293	26.11	0.5909
Case III	4655.9	2.172	28.6	0.4301

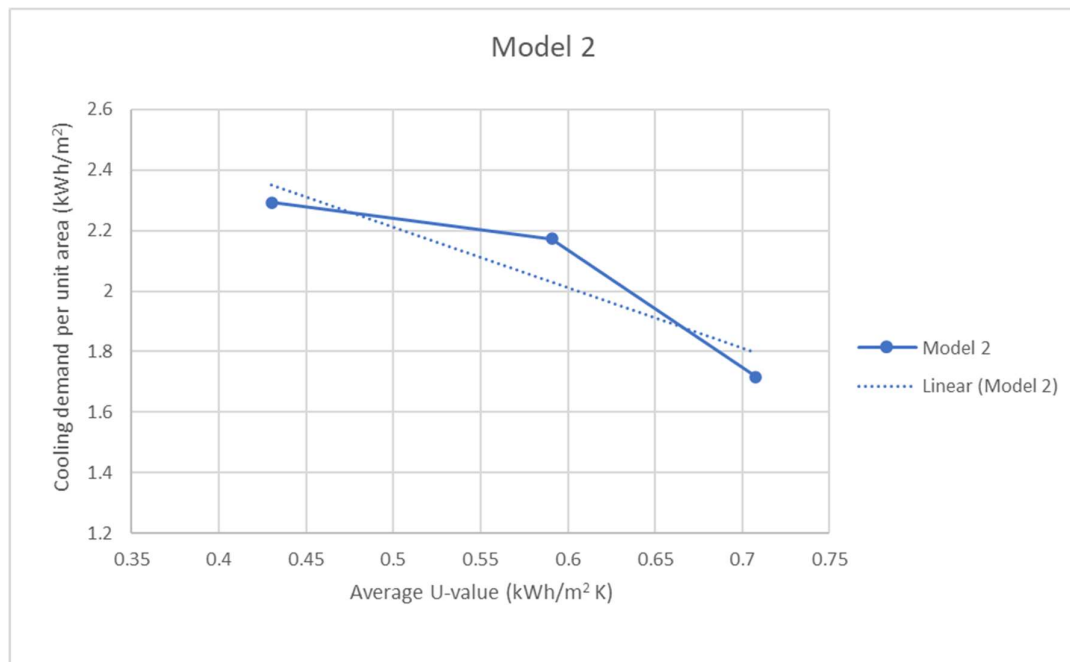


Figure 15 Model-2: Relationship between cooling demand and average U-value

4.1.3. Model-3: Terraced apartment house

The results of this model can be seen in the figure below (Figure 16). Similarly, to the previous models, the highest demand is recorded during July with peak demand being on the 13th of the month. The amount of internal heat gains due to occupants' activity and equipment was 29.59 kWh/m². Similar to the previous models, impact of the different windows properties can be noticed in Cases II and III, where the cooling demand of Case III during July is the highest.

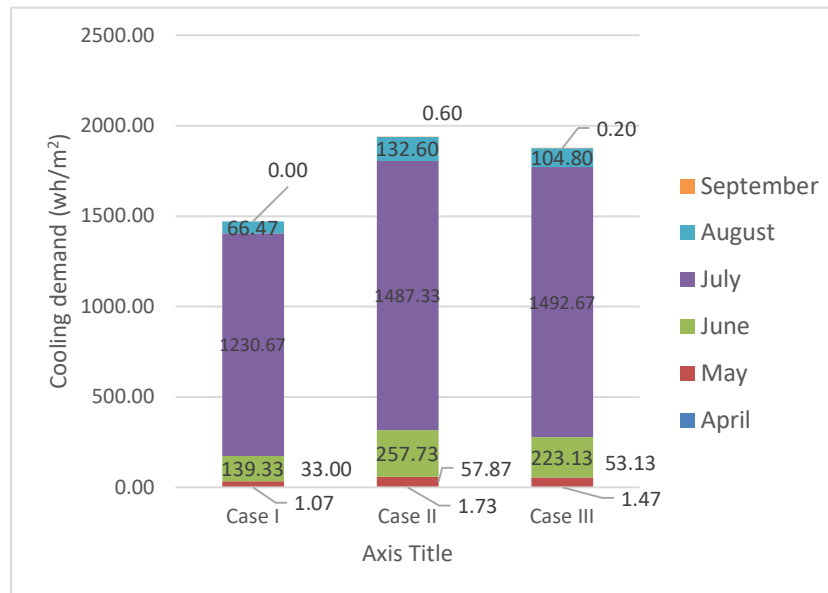


Figure 16 Model 3- Terraced apartment house cooling demand on monthly basis

In addition, a similar relationship between cooling demand and the U-Value can be noticed also in this model.

Table 9 Cooling demand and average U-value for Model-3

	Cooling demand (kWh)	Demand per unit area (kWh/m ²)	Peak Demand (kW)	Average U-value Building (W/m ² ·K)
Case I	2206.9	1.471	18.27	0.6076
Case II	2906.8	1.938	16.67	0.3881
Case III	2813.1	1.875	18.3	0.5174

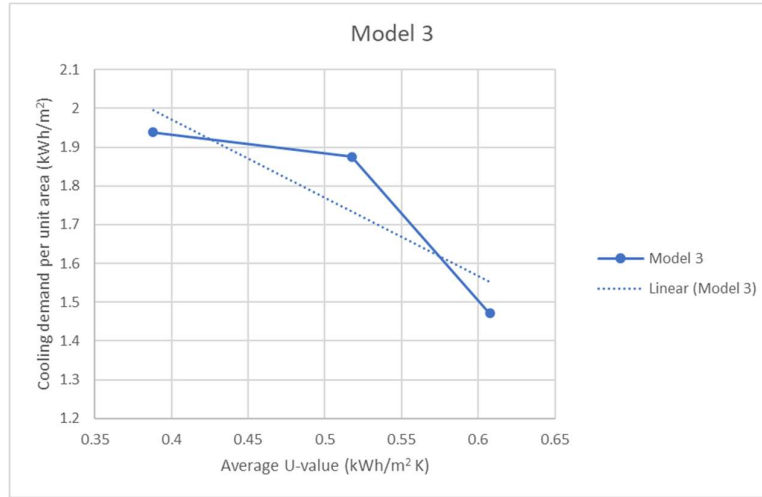


Figure 17 Model-3: Relationship between cooling demand and average U-value

4.2. Cooling Capacity

The cooling capacity required for the buildings in the different cases was calculated using two different approaches. The two different approaches are average cooling capacity and peak load cooling capacity.

4.2.1. Average cooling capacity

Average cooling capacity was calculated using the equation presented in section 2.5). Moreover, a safety factor of 20% have been considered for all the capacities of the models in order to operate safely. All the cooling capacities and operating hours can be found in the table below (Table 10).

Table 10 Required average cooling capacity for each model

Models		Cooling demand	Cooling demand	Operating time	Cooling Capacity		Cooling capacity 120%	
Model nr.	Case nr.	kWh	kWh/m ²	Hours	kW	W/m ²	kW	w/m ²
Model-1	Case I	533.1	1.333	561	0.95	2.38	1.14	2.85
	Case II	721.2	1.803	771	0.94	2.34	1.12	2.81
	Case III	717	1.792	710	1.01	2.52	1.21	3.03
Model-2	Case I	3678.8	1.716	877	4.19	1.96	5.03	2.35
	Case II	4916.3	2.293	1253	3.92	1.83	4.71	2.20
	Case III	4655.9	2.172	1091	4.27	1.99	5.12	2.39
Model-3	Case I	2206.9	1.471	895	2.47	1.64	2.96	1.97
	Case II	2906.8	1.938	1182	2.46	1.64	2.95	1.97
	Case III	2813.1	1.875	1087	2.59	1.72	3.11	2.07

4.2.2. Peak demand cooling capacity

In the previous section, the cooling capacity of the buildings was calculated based on the average cooling demand during the operating time. However, the average cooling capacities are not the only technical criteria that should be considered when designing the cooling system. The peak load demand has a big role in the designing process, as the system should be able to deliver cooling during the peak demand periods, which in most cases occur during days with the highest outdoor temperature. Moreover, in this approach the safety factor of 20% was also considered in case more extreme weather events occur in the future. The suggested cooling capacities are shown in the table below (Table 11). For the district cooling, cooling capacity (thermal power) comes in different ranges which allow for the selection of the desired capacity that falls into that range at the substation heat exchanger. However, for the absorption cooler, Yazaki provides models with different cooling capacities to meet the required demand. The models SC-5, and SC-10 were selected to be installed into the models (SC-5 for models 1 and SC-10 for models 2 and 3)[4].

Table 11 Suggested cooling capacities for the buildings

Models		Peak load (kW)	Peak demand cooling capacity 120%		Cooling Capacity for district cooling		Cooling capacity for Absorption chiller	
Model nr.	Case nr.		kW	W/m ²	kW	W/m ²	kW ⁵	W/m ²
Model-1	CASE I	5.97	7.17	14.93	10	25	17.6	44
	CASE II	5.70	6.84	14.25	10		17.6	
	CASE III	6.29	7.55	15.73	10		17.6	
Model-2	CASE I	28.86	34.63	13.46	35	16.32	35.2	16.41
	CASE II	26.11	31.33	12.18	35		35.2	
	CASE III	28.60	34.32	13.34	35		35.2	
Model-3	Case I	18.27	21.92	12.18	25	16.67	35.2	23.5
	Case II	16.67	20.00	11.11	25		35.2	
	Case III	18.30	21.96	12.20	25		35.2	

Moreover, due to the low cooling demand of buildings compared to the capacities provided by Yazaki, the buildings can be considered as one district and a single absorption chiller unit can provide the cooling demand for each of the buildings. Since all the peak loads fall on the same day, which is the 13th of July, the system should be able to provide adequate performance during the high demand period. The table below (Table 12) shows the required cooling capacity of the group of buildings.

Table 12 Cooling capacities of the absorption chillers for the three different districts

Models		Peak load	Total Peak demand	Peak demand cooling capacity 120%		Cooling capacity for Absorption chiller	
Model nr.	Case nr.	kW	kW	kW	W/m ²	kW ⁶	W/m ²
Case 1	Model 1	5.97	53.1	63.72	15.75668	70.3	17.38
	Model 2	28.86					
	Model 3	18.27					
Case 2	Model 1	5.7	48.48	58.176	14.38576	70.3	17.38
	Model 2	26.11					
	Model 3	16.67					
Case 3	Model 1	6.29	53.19	63.828	15.78338	70.3	17.38
	Model 2	28.60					
	Model 3	18.30					

⁵ Based on the capacities provided by Yazaki [4]

⁶ Based on the capacities provided by Yazaki [4]

4.3. Primary energy number

The primary energy is calculated by using the simulation results and the equation presented in chapter 2 (Equation 2). The table below (Table 13) shows the primary energy for the models for each of the suggested technology.

The primary energy number of the building (during cooling) has been calculated using the results obtained from the simulation, as well as the equation (Equation 2) and the primary energy factors presented in chapter 2 (section 2.6).

Table 13 Primary energy number of the cooling systems

Models		Cooling Demand (kWh)	Floor Area (A_{temp}) (m^2)	Primary energy number (kWh/m^2 year)	
Model nr.	Case nr.			District cooling	Absorption cooling
Model-1	CASE I	533.1	400	0.80	1.34
	CASE II	721.2	400	1.08	1.81
	CASE III	717	400	1.08	1.80
Model-2	CASE I	3678.8	2144	1.03	1.73
	CASE II	4916.3	2144	1.38	2.31
	CASE III	4655.9	2144	1.30	2.19
Model-3	Case I	2206.9	1500	0.88	1.48
	Case II	2906.8	1500	1.16	1.96
	Case III	2813.1	1500	1.13	1.89

5. Discussion

The main objective of this thesis was to quantify the cooling demand in a group of residential buildings. This was done by using a mathematical approach via IDA-ICE. The results obtained from the simulation were used in further calculations to determine the optimum cooling capacity for the suggested systems, which are in our case absorption cooling system and district cooling system.

The selection of the model properties and the different cases were based on the nature of the Swedish building (older building regulations), as most of them were built in the last century and renovated to match today's needs. The cases also show the development of the building criteria and properties in that period, as the interest is the shift toward more efficient and better-insulated buildings to reduce heating demand. Moreover, this trend has continued until these days, and we can see the developed version of it as the new nZEBs, which have an average U-value of nearly zero [26]. In addition, this implementation produced energy-efficient buildings that require less heating energy during the wintertime, due to the well-insulated building envelope that limits heat losses due to infiltration and transmission. However, this will cause a problem during summertime as heat will be gained within the building envelope, which in turn increases the cooling demand of the building.

This correlation between the average U-value and the cooling demand has been noticed in the results of the simulation. All of the models shared the same trend to the change in the cooling demand as their U-value decreased (see Figure 18). The models show a noticeable slope between case II and III, however the slope tends to decrease to almost constant between cases I and III. Moreover, the second model has higher cooling demand than other models, which may be due to the lack of coolers in the open spaces of the model and the higher floor area. The lack of coolers can stimulate heat transfer from and to the open spaces, which can increase the amount of heat within the apartments. However, this trend depends on the outdoor temperature since the heat can be transferred only from higher to lower zones. This trend might not apply to countries with warmer climates due to the higher average outdoor temperature. Moreover, another trend was also noticed in the results, which is the cooling demand of the different cases during July. case III had the highest cooling demand in 2 of the 3 models. This was mainly caused by the different in the windows properties as windows in case II have lower solar heat gain coefficient.

However, another factor can also play a role in this trend, which is the subjection duration to the solar radiation. Most of the apartments within model 2 have windows on one side of the building, which decreased the duration where the apartments are subjected to the radiation. However, in model 2 and 3 some of the apartments have windows in different direction, which will increase the subjection duration, which in its turn will increase the heat gained due to solar radiation through the windows.

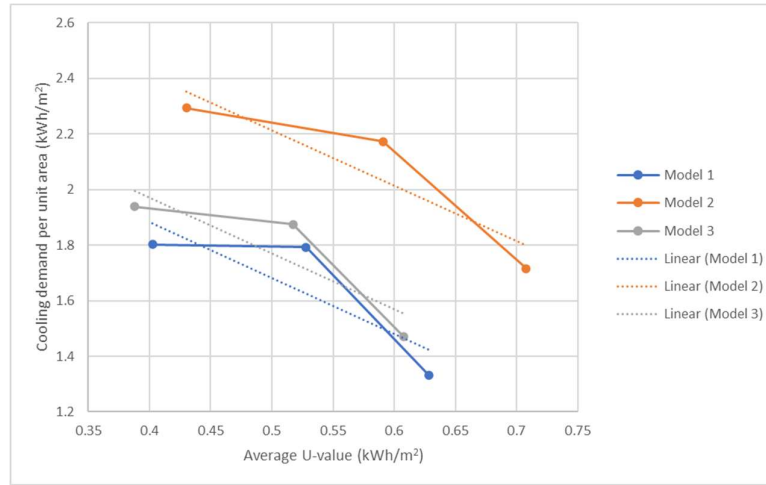


Figure 18 Relationship between cooling demand and the average U-value of the building

Moreover, the selection of the cooling system is based on the cooling capacity required to fulfill the demand of the building. The determination of the capacity is based on the total demand as well as the average demand during the operating period. However, the system should also be able to provide cooling during the peak load period and should also have enough capacity in case of interruptions such as extreme events, which in our case are defined as heatwaves [8]. The implementation of the peak load capacity will provide a more resilient option to face future heatwaves. The suggested capacities have been presented in the results (Table 11). Due to the pre-determined capacities of the absorption cooling systems, different models were selected for each building according to the required capacity during the peak load. However, the required capacities were way less than the provided capacities, which will make the system oversized for the building, hence using way more energy to generate cooling effect.

Moreover, another approach has been suggested, which was assuming that all three buildings were in one district. The assumption will ease the process of selecting the capacity of the absorption cooling system since one system can be installed to provide the required cooling to all the buildings. Meanwhile, the district cooling capacity is determined by the heat exchanger capacity at the substation, which provides more flexibility for installation and can be installed easily in each building.

Another important criterion is the primary energy number, which shows the amount of Primary energy required. Using the equation presented in (Section 2.6), we were able to determine the primary energy number. From the results of this calculation, it can be noticed that the primary energy number of the district cooling system is lower than the absorption cooling system. The difference in the primary energy number is due to the source that generates the cooling power. Both electricity and district heating have higher primary energy factors (weight factor) than district cooling, which will result in higher energy required to generate the same amount of cooling. The main reason is that district cooling is mainly generated via the free cooling method, while the electricity and the heat used in the absorption chiller are produced by fuels such as oil, gas, or biofuel, which all have a higher weight factor than district cooling. Moreover, the values used in the calculations are based on mean values provided by Boverket (0.7 for district heating and 0.6 for district cooling)[23]. However, the true primary energy values of the local district energy systems vary considerably. Furthermore, as the calculations were made with these values, district cooling will be favored due to its low primary energy factor.

Moreover, future studies can be conducted for buildings that fall into today's regulations. This can be done according to the National Swedish Board of Housing's implementation of nearly zero energy buildings, to obtain the required cooling capacities of these buildings and to study their behavior during extreme events such as heatwaves. These studies will provide a better grasp on the subject and will provide a chance to compare the new results with this study's results to see if the results will follow the same trend if cases with lower U-values were used.

6. Conclusion

6.1. Study Results

This study has evaluated the cooling demand of 3 types of residential buildings, which were rowhouse, apartment building, and terraced apartment house, each of which had different building characteristics such as ground area, number of floors and number of zones, etc. The three buildings were simulated in 3 different cases, where the thermal properties of the buildings were based on old building regulations from the late 1960s, mid-1970s, and early 1980s, on which the U-values of the building components were based on. The cooling demand was obtained by simulating the models in the different cases using IDA-ICE. Further analysis of the results showed a negative correlation between the average U-value of the buildings and cooling demand, which was shown in all three buildings. Moreover, the adapted capacity of the studied systems (district cooling and absorption cooling) was based on the peak load demand, which will provide a more resilient solution especially during extreme events. Two models of Yazaki absorption chillers were selected to be installed in the buildings, each of which has a different cooling capacity to match the required capacity of the buildings. However, due to the low cooling demand in the models compared to the absorption chiller's available capacities, another approach can be made to provide cooling more efficiently. The new approach suggests that all buildings can be assumed as a district where one absorption chiller can be installed to provide cooling for all three buildings. Moreover, the same procedure was used to determine the cooling capacity of the district cooling system, that needs to be installed. The capacity of the heat exchangers in the substations determine capacity of the district cooling installed in the buildings, which will provide more flexibility during the installation process.

Nevertheless, the primary energy number was set as a criterion to compare both suggested systems in the different cases. District cooling showed lower values of primary energy number, ranging from 0.8-1.4, compared with the absorption cooling system, ranging from 1.3-2.35, in all cases. The difference in the required primary energy and its type, as the absorption cooling system requires both electricity and heat to provide cooling, hence higher primary energy factor. A higher primary energy factor implies more primary energy use as well as higher risk toward the environment. Meanwhile, district cooling, which in most cases is generated by free cooling, has a lower primary energy factor, which makes it more resource friendly and project less harm to the environment.

6.2. Perspectives

The implementation of technologies such as district cooling and absorption refrigeration will have major effects on the environment and energy systems. these technologies will ease the shift from the traditional technologies such as vapor cycle compression systems, which require a higher amount of energy to operate and also projects higher harm to the environment due to the refrigerants that can cause ozone depletion. In comparison, both district cooling and absorption cooling, require less energy to operate, which is often provided as a by-product of other processes. The utilization of low-grade energy, such as waste heat, and techniques, such as free cooling, will lead to better handling of energy as well as less use of the existing resources. These can be considered as the starting steps toward more sustainable cooling systems, which subject less harm toward the environment.

7. References

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Appendix A

Technical data of the available models of Yazaki's water fired absorption chiller.

Table 14: Technical data of the available Yazaki's absorption chiller model [4]

SPECIFICATIONS				SC 5	SC 10	SC 20	SC 30	SC 50	M 100		
Cooling Capacity				kW	17.6	35.2	70.3	105.6	175.8	352	
Chilled	Cooling Temperature			°C	12.5 In / 7 Out						
	Evaporator Pressure Loss			kPa	52.6	56.1	65.8	70.1	40.2	72.6	
	Max Operating Pressure			kPa	588					785	
	Rated Water Flow			l/s	0.77	1.52	3.05	4.58	7.64	15.29	
	Allowable Water Flow			%	80% - 120%						
	Volume of the exchanger			l	8	17	47	73	120	121	
Cooling Water	Heat Rejection			kW	42.7	85.4	170.8	256.2	427	855	
	Temperature			°C	31 In / 35 Out						29.4 In 35.4 Out
	Absorber Pressure Loss			kPa	38.3	85.3	45.3	46.4	41.2	66.0	
	Fouling factor			m³hr°K/kW	0.086						
	Max Operating Pressure			kPa	588					785	
	Rated Water Flow			l/s	2.55	5.1	10.2	15.3	25.5	34.04	
	Allowable Water Flow			%	100% - 120%						
	Volume of the exchanger			l	37	66	125	194	335	422	
	Heat Medium	Heat Input			kW	25.1	50.2	100	151	251	503
Temperature			°C	88 In / 83 Out						90 In 80 Out	
Allowable Temperature			°C	70 min - 95 max							
Generator Pressure Loss			kPa	95.8	90.4	46.4	60.4	85.2	29.7		
Max Operating Pressure			kPa	588					785		
Rated Water Flow			l/s	1.2	2.4	4.8	7.2	12	12.01		
Allowable Water Flow			%	30% - 120%							
Volume of the exchanger			l	10	21	54	84	170	250		
Electrical Supply	Power Supply			V/Hz	220 V / 1-phase / 50 Hz	400 V / 3-phases / 50 Hz					
	Consumption²			W	48	210	260	310	590	630	
	Circuit Amps			A	0.22	0.43	0.92	1.25	2.6	1.83	
Heat medium valve check				On - Off						On-Off;Prop	
Construction	Dimensions²	Width	mm	594	760	1060	1380	1784	1672		
		Depth	mm	744	970	1300	1545	1960	3654		
		Height	mm	1736	1900	2010	2045	2085	2200		
	Weight	Dry	kg	365	500	930	1450	2100	4947		
		Operating	kg	420	604	1156	1801	2725	5740		
	Noise Level³		dB(A)	46	49	49	46	57	56		
Piping	Chilled/hot Water			mm	DN 32	DN 40	DN 50	DN 50	DN 80	DN 100	
	Cooling Water			mm	DN 40	DN 50	DN 50	DN 65	DN 80	DN 125	
	Hot Water			mm	DN 40	DN 40	DN 50	DN 65	DN 80	DN 100	

1 - Power consumption does not include external pumps or motors.

2 - Height does not include removable lifting lugs. Width/Depth does not include the junction box or mounting plates.

3 - Noise level is measured in a free field at a points 1m away from the cabinet and 1.5m above ground level.