CHALMERS
UNIVERSITY OF TECHNOLOGY

Commercial Building Energy Performance

Room cooling principles and hydronic cooling system temperatures

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

CHARLOTTA DAHLBERG

Department of Architecture and Civil Engineering
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis BOMX02-17-27
Gothenburg, Sweden 2017

MASTER'S THESIS BOMX02-17-27

Commercial Building Energy Performance

Room cooling principles and hydronic
cooling system temperatures

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

CHARLOTTA DAHLBERG

Department of Architecture and Civil Engineering
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2017

Commercial Building Energy Performance
Room cooling principles and hydronic
cooling system temperatures

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

CHARLOTTA DAHLBERG

Examensarbete BOMX02-17-27/ Institutionen för arkitektur och samhällsbyggnadsteknik, Chalmers tekniska högskola 2017

Department of Architecture and Civil Engineering
Division of Building Services Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2017

Commercial Building Energy Performance

Room cooling principles and hydronic
cooling system temperatures

Master's thesis in the Master's Programme Structural Engineering and Building Technology

CHARLOTTA DAHLBERG
Department of Civil and Environmental Engineering
Division of Building Services Engineering
Chalmers University of Technology

ABSTRACT

In commercial buildings, considerable amounts of energy are being used for removal of heat and air borne pollutants. Besides negative environmental impact, high energy use also results in high building operation costs, making improved energy performance interesting for property owners.

This thesis aims to map typical cooling demands in a commercial building and explore the possibilities, limitations and basic energy demands associated with different room cooling principles. Another aim is to investigate the possibilities of improving hydronic cooling system energy performance by utilisation of "free" cooling sources, and illustrate how the system temperatures in hydronic cooling systems influence the energy performance.

In the thesis, an existing commercial building has been studied. With the building as a base, an energy simulation model was developed using the software IDA ICE. The model was used to perform a parametric study through simulations of alternative room cooling principles. The design software AIACalc was used for the analysis of the hydronic cooling system temperatures and the free cooling possibilities.

The results show that the cooling demands in the studied building vary mainly depending on the heat load patterns from the businesses in the building. Furthermore, cooling principles utilising airborne cooling were shown to have a lower energy demand compared to those utilising waterborne cooling. The thermal cooling supply was also concluded to be important for the cooling energy performance when utilising waterborne cooling.

Regarding the system temperatures and the free cooling possibilities in the hydronic cooling system, conclusions are that the energy performance of the studied building could benefit from an increased free cooling capacity and that deviating system temperatures impairs the energy performance of the cooling system. Evaluating the possibilities of extended heat recovery is identified as a suitable area for further studies due to the existence of many simultaneous building heating and cooling demands.

Key words: energy performance, comfort cooling, commercial building, free cooling, airborne cooling, room cooling principle, waterborne cooling, free cooling, system temperatures

Energiprestanda i kommersiella fastigheter
Principer för rumskyla och systemtemperaturer i vattenburna kylsystem

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

CHARLOTTA DAHLBERG
Institutionen för Arkitektur och samhällsbyggnadsteknik
Avdelningen för Installationsteknik
Chalmers tekniska högskola

SAMMANFATTNING

I kommersiella fastigheter används betydande mängder energi för att avlägsna värme och luftburna föroreningar. Utöver negativa miljömässig påverkan, bidrar en hög energianvändning också till höga driftskostnader, vilket gör frågan intressant för fastighetsägare.

Denna rapport syftar till att kartlägga kylbehoven i en kommersiell byggnad, samt undersöka möjligheter, begränsningar och energibehov associerade till olika lösningar för rumskyla i kommersiella fastigheter. Vidare syftar rapporten till att undersöka förbättringsmöjligheter för energiprestandan hos vattenburna kylsystem genom att utnyttja”fri” kyla, samt att illustrera hur systemtemperaturerna i vattenburna kylsystem påverkar energiprestandan.

I rapporten studeras en befintlig kommersiell byggnad som har fungerat som bas för en energimodell som skapats med hjälp av programvaran IDA ICE. Modellen har använts för att simulera den energianvändning som uppstår då olika principer för rumskyla används. För analysen rörande systemtemperaturer och möjligheter till frikyla i vattenburna kylsystem, har produktvalsprogramvaran AIACalc avänts för att simulera ett exempel på effektuttag från en kylmedelskylare vid olika systemtemperaturer och utetemperaturer.

Resultaten från analyserna visar att kylbehovet i den studerade byggnaden framför allt varierar med aktiviteterna och värmelasterna i byggnaden och att påverkan det yttre klimatet har en mindre betydelse. Gällande principerna för rumskyla visar analysen att luftburen kyla kräver mindre energi för att tillgodose ett kylbehov jämfört med vattenburen kyla. Vidare visar analysen att det termiska energibehovet i det vattenburna kylsystemet är en viktig parameter för energiprestandan vid nyttjande av vattenburen kyla.

Analysen gällande frikyla och systemtemperaturer i det vattenburna systemet visade att den studerade byggnaden kan dra nytta av en ökad kapacitet för frikyla samt att övervakning av kylsystemet för att säkerställa att det fungerar som avsett är viktigt för att inte påverka energiprestandan negativt. För vidare arbete rekommenderas en utvärdering av möjligheter till utökad återvinning av värme inom byggnaden då flera samtidiga värme- och kylbehov finns, vilket skapar goda underlag för utökad värmeåtervinning.

Nyckelord: energiprestanda, komfortkyla, kommersiell byggnad, systemtemperaturer, frikyla, luftburen kyla, vattenburen kyla, princip för rumskyla

Contents

Preface

In this report, the energy performance of commercial buildings is targeted with a focus on room cooling principles and hydronic cooling system temperatures. The cooling demands of a commercial building are mapped, and the energy performance of different commercial building room cooling principles is evaluated together with free cooling possibilities and hydronic cooling system temperatures. The work has been conducted at Gicon Installationsledning AB in Gothenburg from January to June 2017.

I would like to express my gratitude to my supervisor at Gicon, Göran Andersson, who with his neverending enthusiasm and ingenuitiveness have supported and inspired me during the work with this thesis. I am thankful for all our rewarding discussions where I learned a lot, not only within, but also beyond the scope of the thesis.

I also want to thank my Chalmers supervisor, Jan Gustén for the support, wise advice and help with organizing my work. I am thankful for your help with finding new directions when I got stuck and for being a valuable sounding board.

Furthermore, I want to express my appreciation to Eric Eliasson at Vasakronan, who has provided me with valuable inputs from the property owner perspective and helped with site visits and retrieving information.

Finally, I want to thank the team at Gicon Installationsledning for taking time to answer my neverending stream of questions and for providing a pleasant and welcoming working atmosphere.

Göteborg, June 2017

Charlotta Dahlberg

Symbols, abbreviations and definitions

Symbols

A	Area	m^2
c_p	Specific heat capacity	$\frac{kJ}{kg \cdot K}$
h	Specific enthalpy	$\frac{J}{kg}$
$\dot{Q}$	Heat flow	W
t	Temperature	$°C$
U	Heat transfer coefficient	$\frac{W}{m^2 \cdot K}$
$\dot{V}$	Volumetric flow	$\frac{m^3}{s}$
Δt_m	Design mean temperature difference of a heat exchanger	K
ρ	Density	$\frac{kg}{m^3}$

Abbreviations

AHU	Air handling unit
CU	Circulation unit
BBR	(*Boverkets byggregler)* The Swedish National Board of Housing, Building and Planning – Boverket's Building Regulations
HVAC	Heating ventilation and air conditioning
IDA ICE	IDA Indoor Climate and Energy
LOA	*(Lokalarea)* The rentable area in non-residential buildings. Does not include staircases or corridors.

Definitions

A_{temp}	The heated area of a building, defined by Boverket (Boverket, 2016) as "the internal area for all floors, attic and basement floors included, that is heated to more than 10ºC". A_{temp} is the area to which the specific building energy use and the building energy performance is related to.
Bought energy	The total amount of paid for energy delivered to a building.
Building cooling system	The complete technical system for room heat removal, transport and disposal of surplus heat in a building.
Building energy performance	"A measure of the amounts of energy needed for heating, comfort cooling, domestic hot water and facility electricity" (Boverket, 2014). The energy needed is divided with the heated area in the building, resulting in a measure expressed as kWh/m^2 A_{temp} and year. The building energy performance is the measure used in the energy performance certificates implemented in Sweden in 2006 according to the EU Energy Performance of Buildings Directive (EPBD). The measure is equivalent to the building's specific energy use, used in the Swedish Building Regulations (BBR).
Building energy use	All energy used within a building.
Commercial buildings	Buildings used for commercial purposes. Examples are retail, culture (galleries, theatres, movie theatres, concert halls etc.), restaurants and offices. Commercial buildings can contain one or several different types of commercial businesses.
Complex commercial building	Commercial building with multiple tenants and/or areas used for different activities with different heat load patterns and operation hours.
Cooling	Disposal of surplus heat.
Cooling demand	The amount of heat needed to remove from a room or a building in order to maintain a desired air temperature.
Cooling energy demand	The amount of energy needed to supply to the technical systems to meet the cooling demand.

Cooling energy performance	The amount of purchased energy needed for comfort cooling, related to the heated area in the building. Similar to *building energy performance.*
Facility electricity	Electricity used for property operation and operation of common technical systems. Includes e.g. electricity for fans, pumps, elevators and fixed lightning.
Free cooling	The possibility to supply cooling without paying for the actual heat disposal.
Heat removal	The process of removing heat from a room or a building.
Heating/cooling load	The heat necessary to supply or remove to maintain a desired indoor climate.
Heat load pattern	The magnitude and pattern according to which the heat load connected to a certain activity, business or area varies over time.
Latent cooling	Cooling of air with changes in both sensible and latent heat.
Mixed-use retail building	Building used for retail purposes in combination with other activities such as restaurants, offices or dwellings.
Primary circuit/side	Related to hydronic cooling systems: The primary circuit refers to the circuit/side closest to the cooling supply/source. Compare to *secondary circuit/side.*
Retail	Small quantity sales of goods or commodities directly to customers.
Retail areas or spaces	Areas in a building used for retail purposes.
Retail facilities	Buildings or parts of buildings housing retail areas.
Room cooling principle	The cooling system(s) and to which extent they are utilised for room heat removal, i.e airborne heat removal by ventilation air and waterborne heat removal by chilled beams.
Secondary circuit	Related to hydronic cooling systems: The secondary circuit refers to the circuit/side closest to the component. Compare to *primary circuit/side.*
Sensible cooling	Cooling of air with changes in sensible heat only.
Specific energy use	See *building energy performance.*

Specific heating and cooling demand	The heating or cooling demand per area, expressed in W/m^2.
System temperatures	The supply and return temperature in a hydronic circuit.
Tenant electricity	Electricity used by the tenants for activities within their area of business.
Waste heat	Unwanted heat due to e.g. food refrigeration or other heat generating activities in the building.

1 Introduction

Of the total building area in Sweden, about a third is used for non-residential purposes (European Comission, 2017b). The activities in the non-residential areas are many, but offices, wholesale and trade businesses account for about two thirds. In commercial buildings like these, considerable amounts of energy is being used for removing heat and air borne pollutants due to high internal heat generation and extended periods of occupancy (2014). In both the EU (European Comission, 2017a) and in Sweden (Statens Energimyndighet, 2015), energy use in buildings constitutes about 40% of the total energy use, making it an important area to target when trying to reduce the national as well as international energy use.

Besides negative environmental impact, high energy use also results in high building operation costs, making improved energy performance of buildings especially interesting for property owners. Improved energy performance in buildings can also increase the value of the building, making investments for improved energy performance economically feasible.

Vasakronan, Sweden's largest real estate company, specialized in commercial buildings containing office and retail spaces, has focused on improving the energy performance of their building stock for several years (Vasakronan, 2016). In Gothenburg, Vasakronan owns several properties in central locations. One of them, Object 6, in Nordstan, was built in 1973 and has been subject to several measures for improved energy performance since it was built. Despite the improvements made, there still is a large demand for cooling energy, currently constituting of almost half the specific energy use in the building during one year.

The building has been chosen as the object of a case study to represent a typical commercial building when it comes to cooling demands, technical solutions and energy performance. With the building as a base, different room cooling principles and the energy demands associated with each principle will be studied to evaluate the possibilities and limitations regarding both energy performance and other practical aspects. The hydronic cooling system in the building will also be used to study how the system temperatures influence the energy performance of the system through the possibilities of free cooling extraction.

1.1 Scope and limitations

The purpose of the thesis is to contribute with knowledge facilitating decision-making regarding investments for improved cooling energy performance in commercial buildings. The thesis targets several parameters influencing the cooling energy performance with the aim of creating an understanding of the performance of each part as well as of the whole system and how the parts together contribute to the total cooling energy performance.

The thesis aims to map typical cooling demands in a commercial building, giving insight to the prerequisites for commercial building heat removal. Furthermore, the thesis aims to explore the possibilities, limitations and basic energy demands associated with different room cooling principles possible utilise in commercial buildings.

Another aim is to investigate the possibilities of improving the hydronic cooling system energy performance by utilisation of “free” cooling sources, and illustrate how the system temperatures in hydronic cooling systems influence the energy performance.

Figure 1 shows how the parameters targeted in the thesis are interrelated and how they together influence the building cooling energy performance.

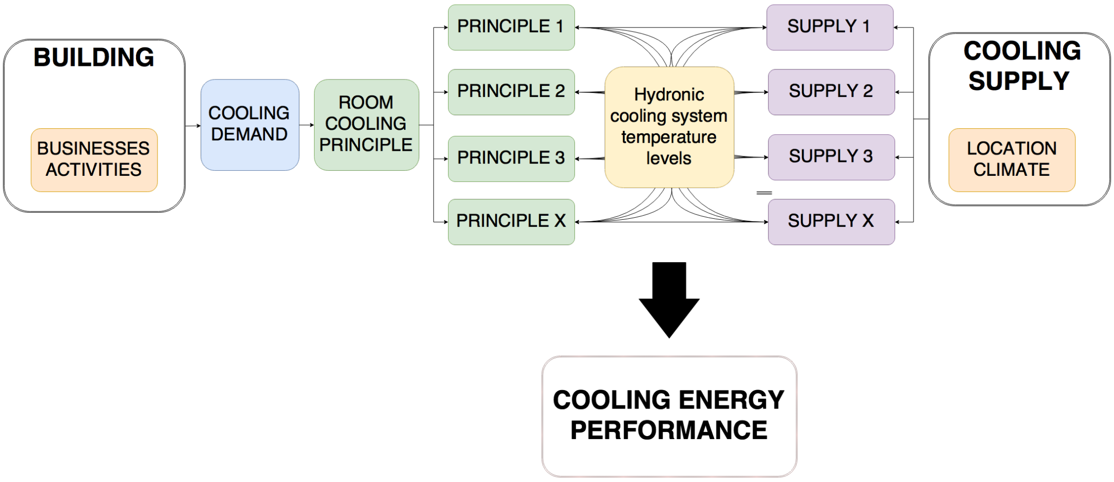


Figure 1. *Outline of the targeted parameters, how they are interrelated and how they together influence the total cooling energy performance.*

The results presented in this thesis are a consequence of a surrounding Nordic climate and are not valid for other climates, especially due to the fact that available “free” cooling sources varies with the climate. The study is based on an existing building in central Gothenburg and the evaluated cooling sources have been limited to options relevant and realistic for the studied building and buildings similar to it.

The thesis focuses on the cooling energy use and cooling energy performance and will not consider embodied building energy. Neither will the total energy use in the building, already addressed in other studies regarding e.g. energy use in shopping malls (Stensson, 2014), be a subject of proposed improvements. Energy for heating and facility electricity will be mentioned but will not be the focus of the analysis.

1.2 Methodology

Initially, theory regarding HVAC and energy related concepts in connection to commercial buildings were studied and an overview of the most important concepts and aspects such as the building heat balance, heating and cooling demands and different technical systems used for heat removal in commercial buildings are described in the initial part of the thesis.

To be able to demonstrate the energy demands and practical challenges associated with different room cooling principles used in commercial buildings, a case study of an existing commercial building chosen to represent the building type when it comes to cooling demands, technical solutions and energy performance, was performed.

With the building as a base, a 3D building energy simulation model was developed using the software IDA Indoor Climate and Energy 4.7.1 (IDA ICE). The model was used to perform a parametric study through simulations of alternative room cooling principles on a zone level, mapping the energy demand associated with each alternative.

For the analysis of the hydronic cooling system temperatures and the free cooling possibilities, the design software AIACalc, provided by the heat exchanger manufacturer LU-VE Sweden (LU-VE Sweden, 2017), was used to simulate the power and temperature outputs depending on changes in system temperatures.

With the use of the software IDA ICE, a numerical energy model of the studied building was created with the aim of mapping heat loads and heat load patterns. IDA ICE is a whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy consumption of entire buildings. Due to the size and complexity of the building, the internal geometry and room division of the building was simplified to 60 zones. The zones were divided based on businesses, occupation, heat loads, room heating and cooling units and type of ventilation supply.

Data regarding the case study have been provided by the property owner Vasakronan, by Gicon Installationsledning and through site visits. Due to the size and complexity of the studied building, it was not possible to retrieve detailed input data regarding all areas and activities in the building. The missing inputs have been estimated according to BBR recommendations regarding energy calculations, in line with other published reports in the field or with the help of advice from experienced engineers at Vasakronan and GICON Installationsledning. The data used in the simulations is summarized in an internal report (Gicon, 2017) and will not be included in the thesis due to its sensitive nature.

Weather data used in the the simulations is ASHRAE IWEC2 weather file for Landvetter (ASHRAE, 2017). The surroundings of the building in form of shading buildings and other structures were included in the model, and the parts of the building adjoining the indoor areas of Nordstan were modelled through induced constant temperatures of 20 degrees on the areas facing indoor climate.

1.3 Thesis outline

The thesis starts with an introductory chapter where background, objectives and delimitations are described. It then continues with a chapter providing a theoretical framework regarding HVAC and energy related concepts in connection to commercial buildings. When the theoretical base is established, the following chapters target the different parameters included in the scope.

Figure 2 shows the parameters covered, how they are interrelated and in which chapter each part of the system providing the prerequisites for the building energy performance is addressed.

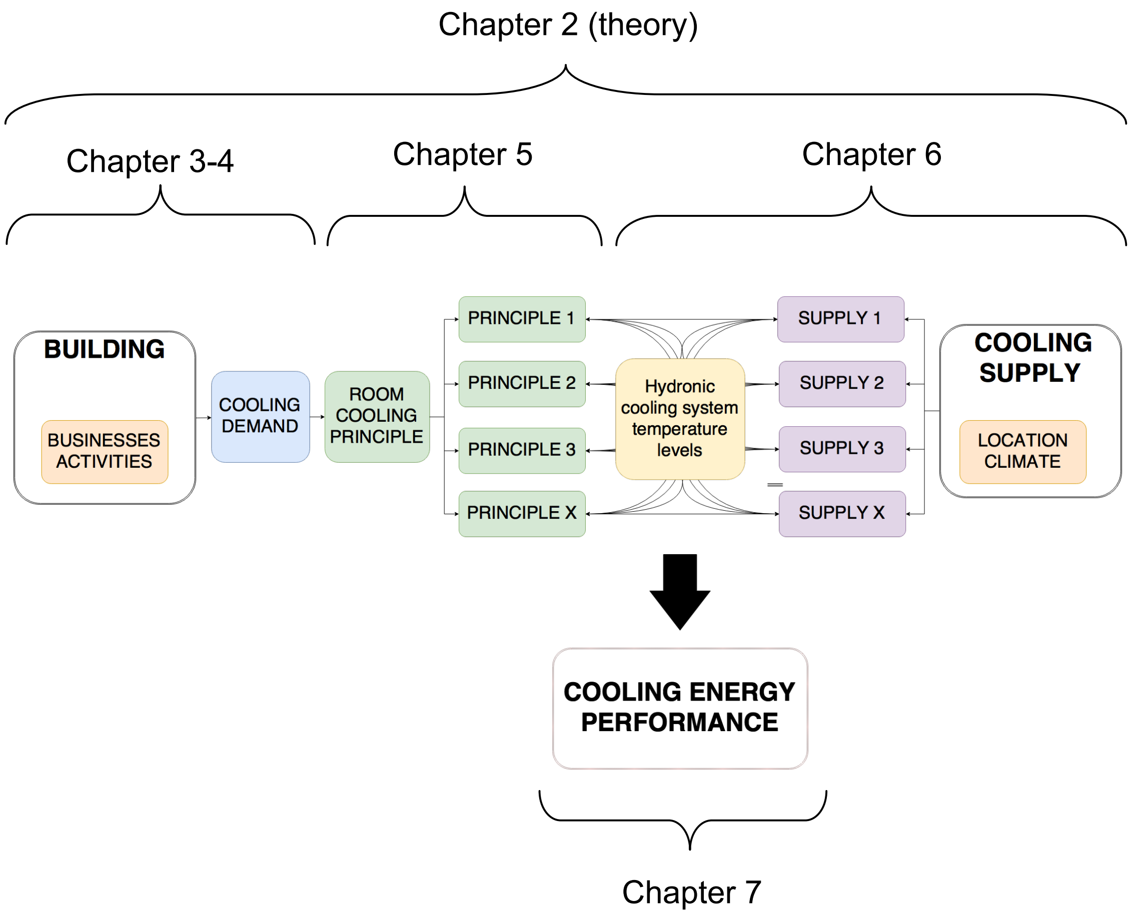


Figure 2. *Parameters covered in the thesis and in which chapter they are addressed.*

Chapter 3 introduces the case study, a mixed-use retail building with several different businesses and varying heat load patterns. The use of the building, occupying businesses and operation hours of different areas are described together with the technical solutions used in the building and the current building energy performance. Chapter 4 describes the typical cooling demands in the studied building.

Chapter 5 includes an analysis of the influence of different room cooling principles on the cooling energy performance. The analysis covers parameters as amount and type of energy used to provide sufficient cooling to different areas in the building, as well as practical design aspects and limitations.

Chapter 6 focuses on analysing an expansion of the free cooling generation currently used in the studied building, as well as describing how the system temperatures in the hydronic cooling system influence the free cooling power output. Finally, the results and the methods used in the thesis are summarized and discussed, conclusions are drawn and areas suitable for further studies are identified.

2 Energy System Boundaries and HVAC Systems in Commercial Buildings

This chapter provides a theoretical framework for understanding the character of the commercial building heat balance and how it affects the requirements on HVAC systems as well as the building energy use and building energy performance.

To avoid confusion, clear definitions of system boundaries regarding energy concepts and buildings are important. This chapter therefore starts by defining the different notions used in this thesis, starting with the building heat balance, thereafter expanding to the building cooling energy demand and the cooling energy performance.

Furthermore, the chapter gives a theoretical base regarding HVAC, cooling techniques and different types of cooling supply that is commonly used in commercial buildings.

2.1 Commercial building heat balance and cooling demands

The temperature in a room or building is a result of the relationship between heat transported to or from the room and the heat generated inside the room. If no heat is removed, high internal heat generation will increase the room temperature. In a similar way, the temperature will decrease if too much heat is lost without being replaced.

To maintain the desired room temperature, different amounts of heat must be supplied or removed depending on the outdoor conditions and the heat from activities in the room. To maintain the heat balance within the building, there must be a heat source or sink available to compensate for heat losses or surpluses in the building (Abel, 2003).

The heat balance of any building without technical systems, is according to Abel (2003) determined by the following factors:

- Heat transport through the building envelope by transmission and infiltration
- Heat storage in the building structure
- Internal heat generation from solar irradiation, people and equipment

In commercial buildings with commercial activities like retail or offices, with high occupancy, extended operating hours and substantial amounts of heat emitted from lighting and equipment, both Abel (2003) and Stensson (2010) state that heat is usually also removed using some sort of technical system, designed and operated to contribute to the heat balance in such way that the indoor temperature is kept at a desirable level. The heat balance in such a case (with technical systems) is illustrated in Figure 3.

The building (or room) "*cooling demand*" is defined as the amount of heat necessary to remove from the building in order to maintain the desired indoor temperature. The cooling demand is illustrated with a blue arrow in Figure 3 for a case of heat surplus inside the building and lower temperatures outside the building. In cases where there is a large exposed thermal mass in the building, there will also be a considerable heat transport to or from the thermal mass (e.g. the a concrete building structure), influencing the cooling demand, if the indoor temperature is allowed to vary.

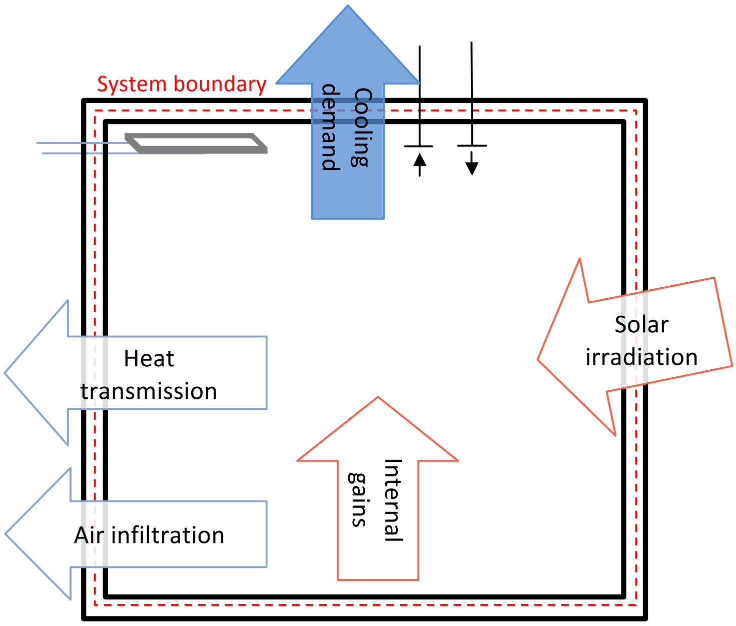


Figure 3. *Illustration of the heat flows to and from a building with technical systems for heat removal installed. The building cooling demand is defined as the heat removed to maintain a desired indoor temperature, marked with a blue arrow in the figure.*

2.2 Building cooling energy demand

When expanding the system boundaries to include the technical systems utilised for heat removal, the building *"cooling energy demand"* can be defined. The cooling energy demand here refers to the energy necessary to provide for operation of the technical systems used to meet the cooling demand (i.e. remove the necessary amount of heat). This is depicted in Figure 4, where the cooling energy demand is marked with orange arrows, including both thermal and electrical energy.

In cooling applications, the thermal energy in fact refers to a heat sink, a way to dispose the surplus heat from the building. This function will be referred to as *"cooling supply"* in the thesis. The electrical energy is used for operation of pumps and fans utilised in the distribution systems. Different types of cooling supply and technical solutions for heat removal are further described in Sections 2.5 - 2.7.

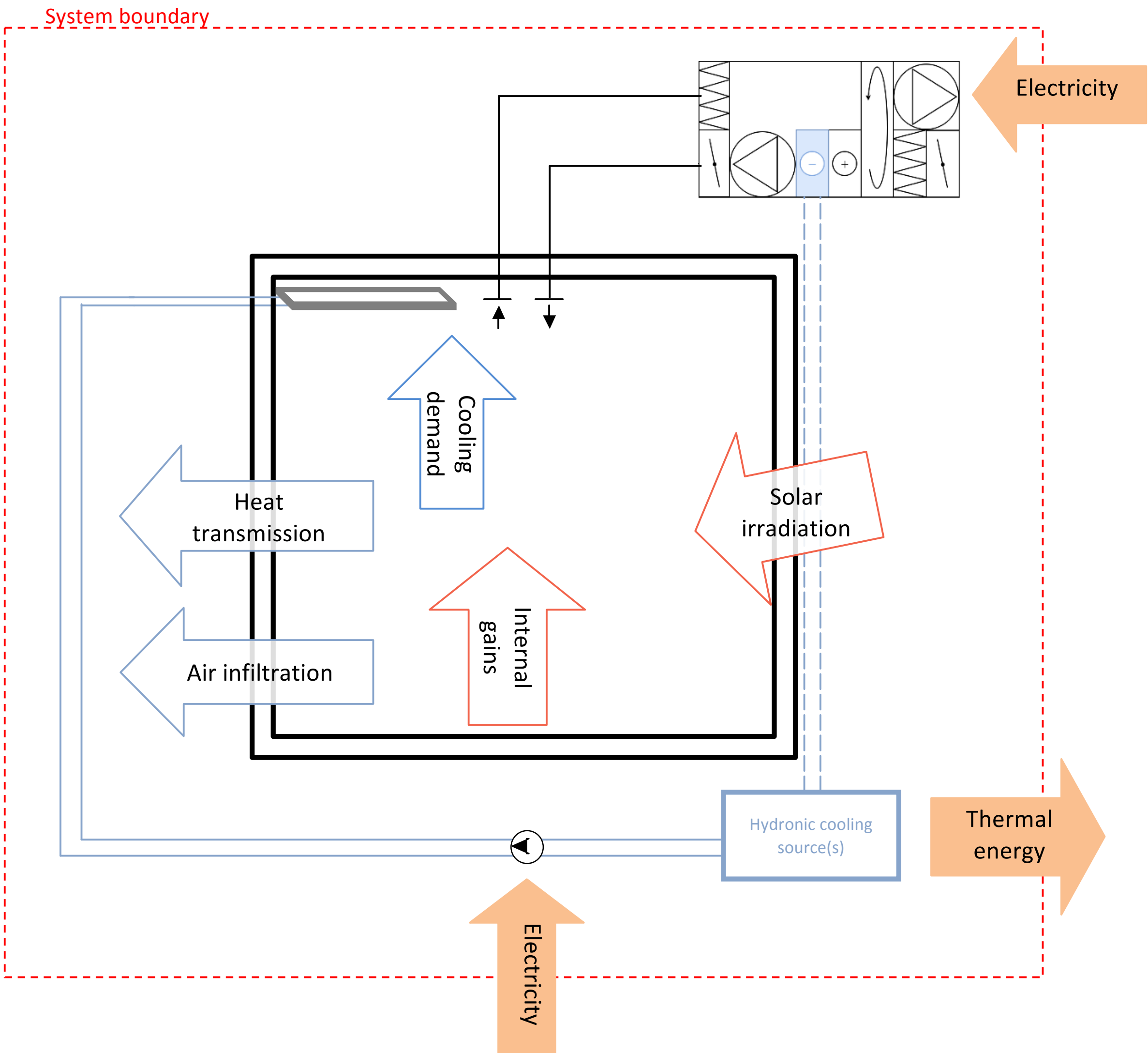


Figure 4. *Illustration of the building cooling energy demand: the thermal and electrical energy needed for cooling and operation of the technical systems used for building heat removal.*

2.3 Building energy performance

The *"building energy performance"* is defined by the The Swedish National Board of Housing, Building and Planning (Boverket) as "a measure of the amounts of energy used for heating, comfort cooling, domestic hot water and facility electricity" (Boverket, 2014). The energy needed is related to the heated area in the building and measured in the unit kWh/m^2 heated area and year. One part of the building energy performance will therefore stem from the cooling energy use.

Like previously mentioned, commercial buildings usually have high internal heat generation, resulting in extended periods of heat surplus, in turn leading to a high energy use due to a need for removal of heat and air borne pollutants. Stensson (2010) states that the energy use in commercial buildings is dominated by energy for air conditioning, space cooling and operations of pumps and fans, unlike the energy use in residential buildings, which often is dominated by energy for heating and hot water preparation.

The energy performance of different types of commercial buildings tends to vary depending on the use of the building. Stensson (2014) have analyzed the energy performance of 50 shopping malls with energy performances ranging from 36 to 345 kWh/m^2 A_{temp} and year. The average energy performance of the shopping malls was 151 kWh/m^2 A_{temp} and year

During 2009 a comprehensive inventory of the energy use in Swedish office buildings was performed on behalf of the Swedish Energy Authority (Statens Energimyndighet, 2007). The results showed a mean specific energy use of 145 kWh/m^2 A_{temp} and year in existing office buildings.

The energy demands for new commercial buildings in Sweden depend on the building heating source and the geographical location of the building. For commercial buildings heated with other sources than electricity, the basic demand ranges from 65 (in southern Sweden) to 105 kWh/m^2 A_{temp} and year (in northern Sweden) (Boverket, 2016). For electrically heated buildings the demands are stricter, ranging from 45 - 85 kWh/m^2 A_{temp} and year.

2.4 Heat loads in commercial buildings

Due to the character of the heat loads and the extended use of commercial buildings, both Stensson (2014) and Abel (Abel, 2003) states that the heating demands are a minor problem and that considerable amounts of energy instead are used for removal of surplus heat, i.e. cooling. This chapter describes the character of the heat loads in commercial buildings.

2.4.1 Heat loads and building geometry

The shape of a building tend to influence on the heating and cooling demands. The areas closest to the exterior walls will be influenced by the outdoor climate (temperature, sun and wind) to a much larger extent than parts situated in the middle of the building, surrounded by areas with indoor climate. In such areas, there are no considerable heat losses to the surroundings and if the internal heat generation is high, the result might be a heat surplus during the entire year, even at low outdoor temperatures.

In the areas close to the exterior parts of the building, there will be considerable heat losses during the cold part of the year. If there are windows there will also be a lot of heat gains from solar radiation during sunny days. As long as the local surpluses and deficits are compensated for in the edge zone, the heating and cooling demands of the remaining part of the building stays relatively unaffected by the outdoor climate.

In buildings with varying use, housing several businesses with different hours of operations, the heating and cooling demands can vary a lot in both time and space. To maintain a good thermal climate in an energy efficient way, the technical systems need to be adapted to the operation hours of the businesses they serve to avoid unnecessary energy use.

2.4.2 Indoor climate – characteristics and demands

The indoor climate in a building is influenced by several parameters such as indoor air temperature, odours, noise and light. Ekberg (2003) states that the demands on indoor climate and which parameters to consider vary a lot between building types such as residential, offices, hospitals etc. Common for all buildings is that the technical systems must be selected after the demands are set to be able to achieve a good indoor climate.

Physical climate factors to consider are thermal climate, indoor air quality, sound and light. Due to the scope of this thesis, focus will be on thermal climate and indoor air quality. Light is not considered to be influenced by the systems treated in the scope and although the systems could influence the sound properties, those effects are not included.

Thermal climate is defined by Ekberg (2003) as a result of the parameters: air temperature, surrounding surface radiant temperatures, air velocity and water vapor pressure. Regarding indoor air quality, Ekberg writes that it can be regarded as a denomination for the cleanliness of the indoor air and the amount of polluting substances present in the air. The amount of polluting substances is influenced by both the quality of the air supplied to the building through the ventilation and the activities inside the building, where emissions of odours from the human body or from volatile compounds from building products.

When the premises serve as a a workplace (like offices and retail premises do) there are also demands on the indoor climate from the Swedish Work Environment Authority (Arbetsmiljöverket, 2015), Arbetsmiljöverket. The employer is required to ensure that the climate in workplaces complies with the regulations. Usually, the demands regarding the indoor climate in commercial buildings are regulated in the lease between the tenant and the property owner.

The demands from the Swedish Work Environment Authority mainly regulate the indoor temperatures which are recommended to be 20-24 °C during winter and 20-26 °C during summer. At heat waves during the summer, higher indoor temperatures are also accepted for limited periods. Likewise, lower temperatures than normal are accepted indoors during extreme cold outdoor winter temperatures.

The authority has no limits regarding the relative humidity of the air, however, there are recommendations regarding air movements and draught. Fresh air is recommended to be supplied with velocities below 0.2 m/s during wintertime in premises where people are conducting sedentary work to avoid discomfort.

2.5 Comfort cooling

While residential buildings rarely demand installations for removing surplus heat, this is usually the case in commercial buildings due to the desire to achieve a defined thermal climate for commercial or work environmental reasons. Compared to the relative simplicity of heating systems, Abel (2003) states that systems for removing surplus heat tend to be both costly and voluminous in comparison.

In order to maintain a desired temperature in a room with a lot of surplus heat, the heat needs to be removed and disposed, according to the symbol, shown in Figure 5.

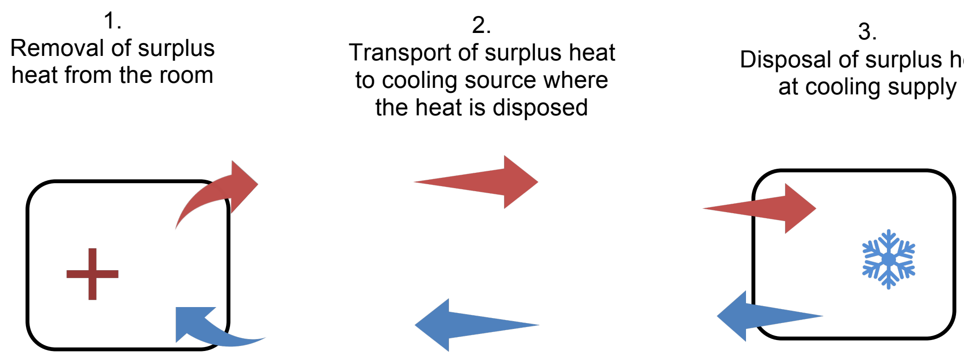


Figure 5. *Schematic overview of the process of space cooling including necessary room heat removal to maintain the desired room temperature, transport and disposal of the surplus heat at the cooling source.*

After being removed from the room, the heat is transported to the cooling supply where it is disposed. The number of technical solutions available for heat removal and disposal are several and the choice of which ones to utilise depends on the conditions in the building in question. In mixed-use retail buildings with several types of businesses and varying heat load patterns, there is often a need for different types of room cooling solutions in order to meet the cooling demands and maintain a satisfactory indoor climate in all areas. This chapter introduces different techniques for room heat removal, heat transport and cooling supply.

2.5.1 Heat removal with airborne systems

When air is supplied at a lower temperature than the room air temperature, the air flow has a cooling effect, influencing the room air temperature (Abel, 2003). The cooling power of the air depends on of the flow and the magnitude of the temperature difference between the supplied air and the room air, according to the equation below. The equation describes a case of “dry” cooling when only the sensible heat in the air is changed. Cooling of moist air is treated separately in Section 2.6.2.

$$\dot{Q} = \dot{V}_a \cdot \rho_a \cdot c_{pa} \cdot (t_{supply} - t_{room}) \qquad (1)$$

One limitation of cooling with air, is the impact of low supply air temperatures on the thermal climate in the room. Low temperatures might induce draught or uncomfortable temperature distributions in the room (Abel, 2003) and the lowest acceptable supply air temperature varies with the activities in the room and the type and position of the inlet air devices.

When using air as a heat transferring fluid, the air is usually distributed by the ventilation system (Abel & Elmroth, 2012). To supply rooms with enough cooling power, larger air flows than the ones needed for ventilation purposes only, might be necessary. This means the airflow for the cooling demand might be the deciding parameter when designing an air distribution system for both ventilation and cooling purposes.

The fan work required to distribute the air depends on the fan efficiency, the airflow and the required pressure rise. In order to minimise the fan power demand, it is desirable to have an efficient fan and fan engine, small pressure drops over components in the AHU as well as in the distribution system (Jagemar, 2003). An airtight AHU and distribution system minimises air leakage, contributing to less use of fan energy and well-insulated ducts minimises the heat flow to or from the air in the ducts, reducing the thermal energy demand. The final energy use is then minimised by adapting the operating hours of the fans and only use the system when there is a cooling or ventilation demand.

In airborne cooling systems, the cool outdoor air can be supplied directly to the room, if necessary after being treated in the AHU to obtain the right condition (temperature, humidity, cleanliness). In this way, the supply air only needs additional cooling when the outdoor air temperature is higher than the supply air temperature. This means the higher the supply air temperature, the less energy is needed for additional cooling. On the other hand, high supply air temperatures demand larger air flows to provide the same cooling power, which in turn results in increased fan energy use and larger volumes for AHUs, ducts etc. and more space for technical areas.

With increased airflows due to cooling, increased heating demands will arise during wintertime. Using this solution therefore demands some type of heat recovery in order to not induce additional energy use for heating. An example of this is illustrated in Figure 6. The exhaust air temperature in the example is constant 22 °C, the supply air temperature is 17 °C and a heat recovery unit with a temperature efficiency of 75% is installed.

The total thermal energy demand for conditioning the outdoor air to the supply air temperature in a Gothenburg climate is marked in red and green (as areas with the unit °Ch). The green area represents the heat recovered in the recovery unit and the red area the remaining heating demand for the heating coil. When the temperature after heat recovery is higher than the desired supply air temperature, the efficiency of the recovery unit can be regulated to reach the aimed temperature. The remaining cooling demand is illustrated as a blue area in the same manner as the heating demand, assumed that no cooling recovery is possible.

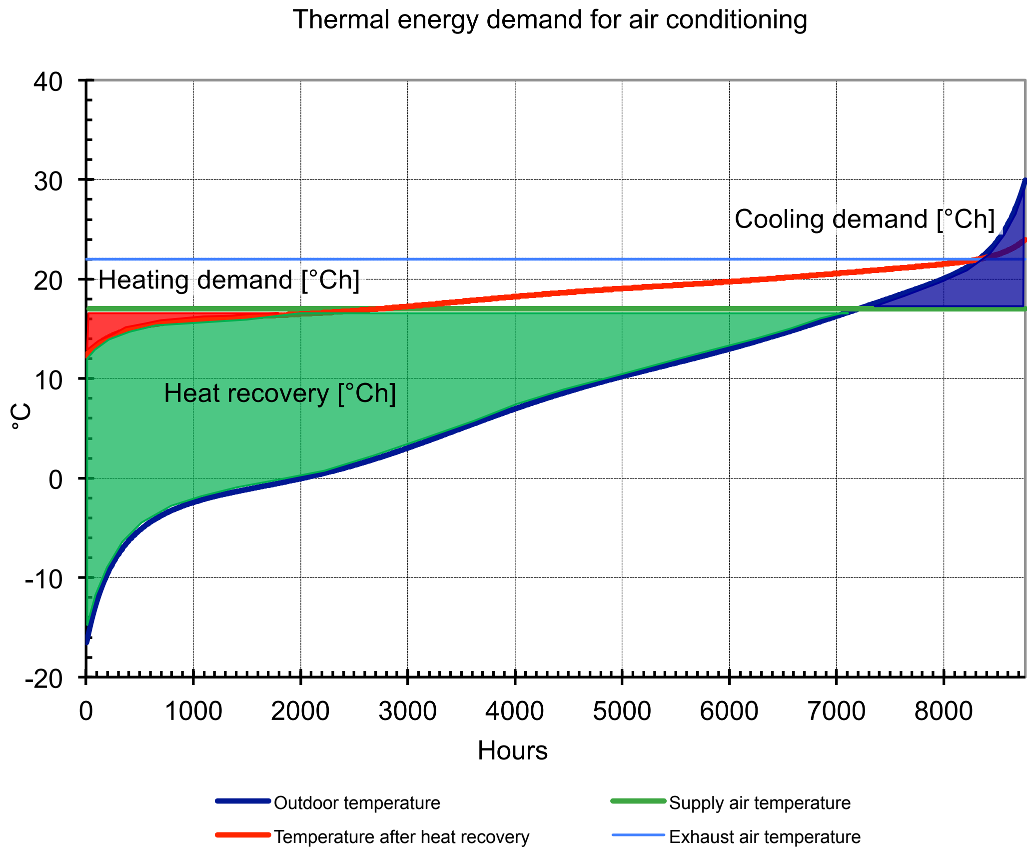


Figure 6*. Illustration of the thermal energy demands for conditioning outdoor air to a supply air temperature of 17 °C in a Gothenburg climate with a constant exhaust air temperature of 22°C and a heat recovery unit with a 75% temperature efficiency.*

2.5.2 Heat removal with waterborne systems

When water is utilised for room heat removal, a common solution is to place water-chilled surfaces in the room (Abel, 2003). The actual heat transfer takes place in terminal units, e.g. a ceiling beam or a fan-coil unit. The terminal units are supplied with circulating chilled water, transporting the heat from the room. The amount of heat removed by the chilled water depends on the flow rate and the magnitude of the temperature difference between the supply and return water, according to equation (2).

$$\dot{Q} = \dot{V}_w \cdot \rho_w \cdot c_{pw} \cdot \left(t_{w,supply} - t_{w,return}\right) \quad (2)$$

The heated water returning from the terminal units is circulating in a pipe distribution system to the cooling supply where it is chilled and recirculated back to the terminal units. This type of system is usually referred to as a *hydronic cooling system*.

The amount of heat transferred from the room air to the water in the unit can be described by equation (3) where the coefficient of heat transfer (U) includes factors as terminal unit design, material, size, flow and fluid temperatures (Trüschel, 2003b). Combined with the heat transferring area, it determines the capacity of the heat exchanger.

$$\dot{Q} = U \cdot A \cdot \Delta t_m \quad (3)$$

The mean temperature difference (Δt_m) between the hot and the cold medium (in this case the water and the ambient air) depends on the flow configuration of the heat exchanger and can be estimated in several ways, where the logarithmic mean value calculation is always preferable and gives the closest approximation to reality, according to Trüschel (2003b).

An issue when using chilled surfaces for room cooling is the risk of condensation, especially in areas with a lot of moisture sources or outdoor air leaking in to the room. One example of this is retail buildings, where the large number of people in one place provide a lot of moisture, and where continuous door openings cause outdoor air to flow in to the rooms (ASHRAE, 2010).

2.6 Hydronic cooling

As mentioned in the previous section, the chilled water distribution system consists of pipes connecting the terminal units with the cooling supply. The hydronic cooling system is usually also connected to other types of cooling units, like cooling coils in AHUs, food refrigeration systems etc. The system also contains control functions facilitating the right functionality during operation. Figure 7 shows a schematic example of a hydronic cooling system.

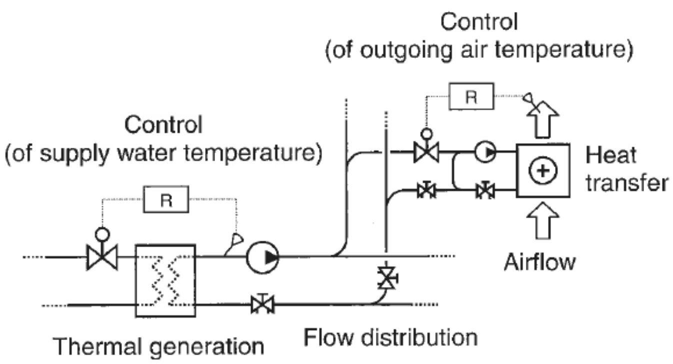


Figure 7. Schematic example of a hydronic system including thermal generation, flow distribution system, unit for heat transfer and control processes (Trüschel, 2003b).

The fact that the same system is connected to different types of heat transferring units usually demands that the system is divided in parts where different temperatures for supply and return water are used. Higher temperatures, which might be necessary due to the risk of condensation on terminal units in some rooms, require larger unit heat transferring areas according to equation (3). To limit the size of e.g. cooling coils in AHUs, lower temperatures are usually used in these applications, resulting in a division of the hydronic cooling system. The choice of system temperatures for different cooling applications is further described in Section 2.6.1.

To make the water in the hydronic system flow, a pressure difference is required. This is usually created by a pump, according to Trüschel (2003b). To reduce the energy use, a low pump power demand is desirable. This can be obtained by small water flows, small pressure drops over components (valves, filters etc.) and in the distribution system. Also, the final energy use can be minimised by adapting the pump power and operating hours and only utilise the system when it is needed.

2.6.1 Hydronic cooling system temperatures

When choosing design system temperatures in a hydronic cooling system, several factors need to be taken in to account. The lower temperature limit is usually restricted by function and/or comfort requirements. For example, at fluid temperatures below 0°C, water vapour will condense on the terminal units and start to freeze, influencing the function of the unit (Abel, 2003). Too low supply temperatures can also result in condensation on room units if the temperature is lower than the air dew point temperature in a room.

The higher limit of the chosen design system temperatures is influenced by the suitable size of the room cooling units, according to Equation (3). The driving force of the heat flow is the mean temperature difference between the hot and the cold medium. The smaller the temperature difference is, the larger heat transferring area is needed (Trüschel, 2003b). Since there is a limited amount of ceiling space available in any building, and other functions such as lighting or air supply or exhaust devices might need to fit in to the same area, the area available for cooling units is usually limited. The same reasoning applies to other heat transferring units as cooling coils in AHUs and CUs.

According to Trüschel (2003b) commonly used design temperatures in hydronic cooling systems are supply temperatures of 6-7°C and return temperatures in the range of 12-18°C. Depending on the cooling supply, there might also be limitations due to limited temperatures from the source or restrictions or requirements regarding the design system temperatures in the building hydronic cooling system. The temperatures in the hydronic system might also influence the efficiency of the cooling generation equipment, e.g. if chillers/heat pumps are used for generating the cooling supplied to the hydronic system. An example of this is described in closer detail in Section 2.7.1 dealing with district cooling.

2.6.2 Cooling of moist air

When cooling moist air with a cooling coil (which usually is chilled by the hydronic cooling system) with a surface temperature lower than the air dew point temperature, condensation will occur on the coil. This results in an increased power demand when both sensible and latent heat (vapour) is removed from the air.

The total cooling power demand is then described by equation (4) where the letter h denotes the specific air enthalpy, describing the condition of the moist air, including both humidity and temperature.

$$\dot{Q}_{req} = \dot{V}_a \cdot \rho_a \cdot (h_{supply\ air} - h_{outdoor\ air}) \quad (4)$$

Figure 8 depicts a simplified case of cooling of air with two different starting conditions, a coil temperature of 14 °C and a desired supply air temperature of 15 °C. The red dot indicates the starting condition (23°C, 55% relative humidity (RH)) of a case of sensible cooling, where only the air temperature will change. The green dot indicates the starting condition (23°C, 70% RH) of a case of latent cooling, where the coil temperature is lower than the air dew point temperature and both the temperature and specific humidity of the air will change. The enthalpy change in the case of latent cooling (green Δh) is clearly larger than in the sensible case (red Δh), resulting in a larger energy demand for cooling.

In reality, the surface temperatures of cooling coils will not be constant but will change as the chilled water in the cooling the coil is heated by the air. This means condensation will occur only on parts of the coil where the coil surface temperature is lower than the air dew point temperature.

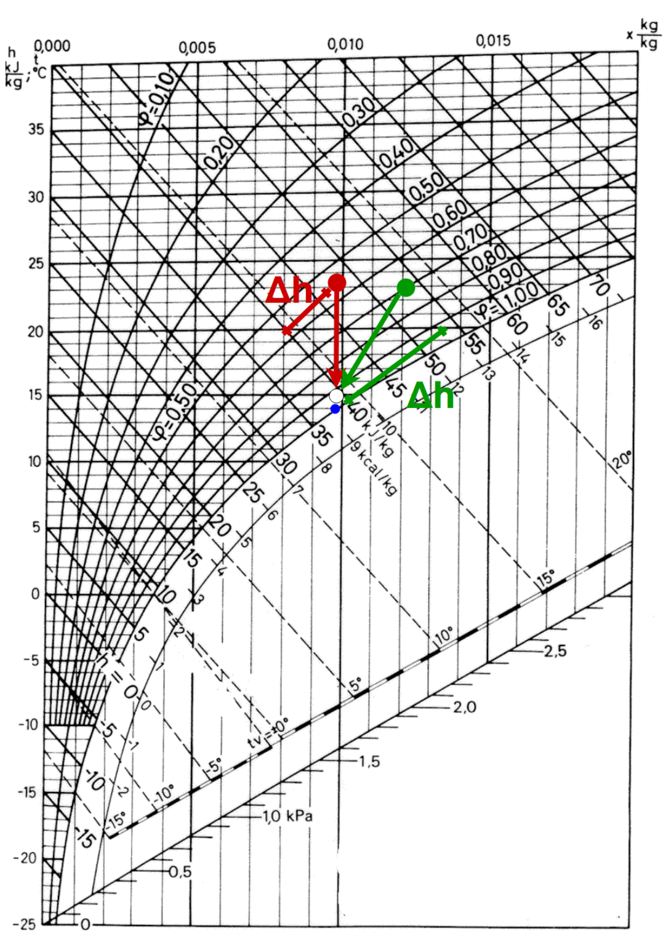


Figure 8. *Psychrometric chart where the difference between sensible (marked in red) and latent cooling (marked in green) is depicted.*

2.7 Cooling supply

While cooling, as explained earlier, in reality is a matter of removal and disposal of heat it is here reffered to as "cooling supply" to ease the communication. Whether air or water is utilised as heat transferring fluid, some type of cooling supply is necessary to obtain the desired supply fluid temperature. According to Trüschel (2003b), there are only a few basic methods for cooling supply used. The variations of these on the other hand, are many. The cooling can be generated and supplied within the building, or the generation takes place elsewhere and cooling is supplied to the building. The following section introduces some common building cooling supply techniques used in commercial buildings.

2.7.1 District cooling

District cooling consists of a chilled water distribution system, supplying multiple buildings with cooling from one or a few central cooling generation plants (Trüschel, 2003a). In district cooling systems, the generation plants usually consist of absorption chillers, mechanical chillers and/or cold-water storages.

In each building connected to the district cooling system there is a substation where the chilled water flow is regulated. The supply temperature can vary, according to ASHRAE (2015) it is usually about 5-7°C although lower temperatures are occasionally used. A high return temperature is usually desired to minimise the heat gains from the soil to the chilled water in the distribution system, and improve the overall efficiency of the central cooling generation.

In Gothenburg, Göteborg Energi is providing district cooling to the central parts of the city (Göteborg Energi, 2017). The water is supplied with temperatures according to Figure 9 and there are limitations regarding the return temperature, also seen in Figure 9. The demand on the secondary (building) side is a temperature difference of at least 10°C for the supplied and returned water during the warmer months (May to October).

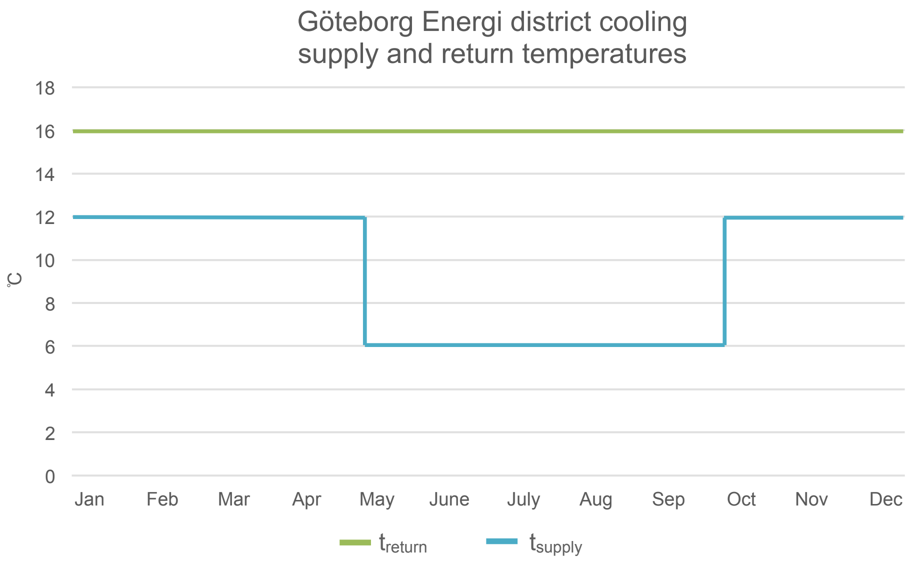


Figure 9. *District cooling supply and return temperatures from Göteborg Energi (Göteborg Energi, 2017)*

Göteborg Energi also refers to technical guidelines regarding district cooling, issued by Svensk Fjärrvärme (2012) where limits for the temperatures in the hydronic system in the building are listed. Figure 10 shows the recommended variations for the supply and return water of the hydronic cooling system and Table 1 shows recommended hydronic supply and return temperatures for different terminal units.

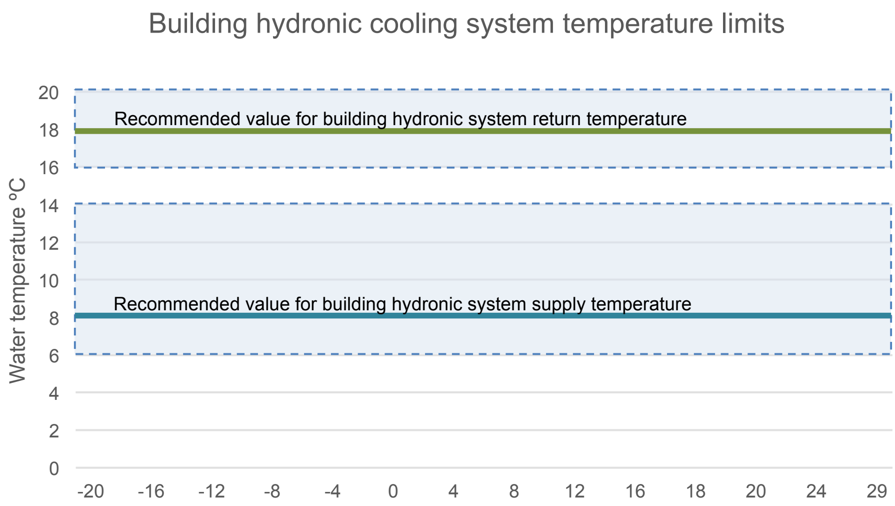


Figure 10. *Limits for temperature levels in the building hydronic cooling system (Svensk Fjärrvärme, 2012).*

Table 1. *Recommended design supply and return temperatures by Svensk Fjärrvärme (2012).*

Component	Supply temperature [°C]	Return temperature [°C]
Air coil	+ 8	≥ + 18
Chilled beam	+ 14	+ 17
Chiller condenser	+ 14	+ 20

2.7.2 Chillers and heat pumps

When generating cooling inside the building, it is common to use chillers. Chillers work in the same way as heat pumps, the only difference is which part of the process that is of interest, the cooling or heating generation (Trüschel, 2003a).

To supply a heat pump process (or function as a heat sink in the chiller process), some type of low tempered heat source is needed. Common examples are outdoor air, exhaust air or ground heat. When simultaneous heating and cooling demands exist in a building, a heat pump can be utilised in a heat recovery process, e.g. by absorbing excess heat in a hydronic cooling system and rejecting it to the heating system, making both sides of the process useful. As the temperature difference between the evaporator and condenser in the heat pump decreases, the COP rises (Trüschel, 2003a). In chiller applications, high temperatures in the hydronic cooling systems yields higher COPs.

According to the Swedish Building Regulations (Boverket, 2016) the use of electricity for chillers providing comfort cooling in new buildings, should be multiplied by 3 when included in the building's specific energy use (with the exception of electrically heated buildings).

2.7.3 Free cooling with outdoor air

As mentioned earlier, outdoor air can also be used to cool the water in a hydronic cooling system. This is usually done in an air-cooled heat exchanger or a cooling tower. Bergsten (2009) writes that a simplified distinction between the two is that the air cooled heat exchangers are based on sensible heat transfer only while a cooling tower exchange both sensible and latent heat.

2.7.3.1 Free cooling with air cooled heat exchangers

In an air-cooled heat exchanger, the coolant circulates in a closed loop connected to a heat exchanger, and is never in direct contact with the air. The heat transfer is driven by the temperature difference between the dry bulb temperature of the ambient air and the temperature of the coolant. Sufficient air movement over the heat exchanger is usually provided by one or several fans. The principle is illustrated in Figure 11.

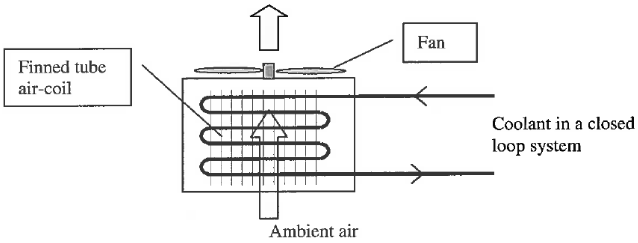


Figure 11. *Schematic illustrations of the principle design of an air-cooled heat exchanger (Bergsten, 2009).*

Depending on the desired supply water temperature and the available outdoor temperature the possibilities of cooling water using outdoor air varies. The air needs to be cooler than the fluid to function as a heat sink, i.e. the higher the supply water temperature is, the longer it is possible to use the outdoor air for cooling purposes.

When utilizing free cooling with outdoor air in air cooled heat exchangers, the capacity of the unit is determined by the UA-value of the heat exchanger, as described in Section 2.5.2. The logarithmic mean temperature difference (Δt_{lm}) of the heat exchanger depends on whether the heat exchanger has a parallel or counter flow configuration. According to Trüschel (2003b) the actual flow configuration in reality is somewhat of a mix between the both, referred to as cross flow. Cross flow configuration is more complicated to handle but is based upon the two basic configurations. Equations for mean temperature difference for counter and parallel flow configurations are described by Trüschel (2003b).

2.7.3.2 Free cooling with cooling towers

Besides heat transfer, a cooling tower uses additional mass transfer to cool the water. The water is distributed in the tower, e.g. by spray nozzles, in a manner that exposes a large water surface to the ambient air. Air movement is achieved by fans, natural draught or the induction effect from water sprays. A part of the water absorbs heat to change phase from a liquid to a vapour at constant pressure. The heat is then transferred from the water remaining in the liquid state into the airstream (ASHRAE, 2015). The principle is illustrated in Figure 12.

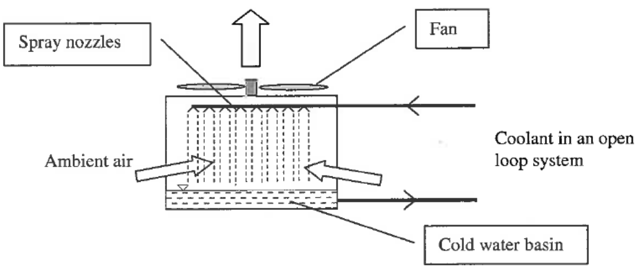


Figure 12. *Schematic illustration of the principle design of a cooling tower (Bergsten, 2009).*

The extended heat transfer in a cooling tower makes it more space efficient compared to an air-cooled heat exchanger. On the other hand, the open loop system also requires more maintenance to function properly. Another issue with cooling towers is the risk of spreading legionella bacteria, although there are recommendations on how to minimise the risk (ASHRAE, 2015). The legionella bacteria activity varies with the temperature and below 20°C the bacteria is typically resting. Bergsten (2009) means that due to the low water temperature range, typically 13°C - 20°C in comfort cooling applications, the risk of legionella growth is reasonably small.

2.7.4 Other free cooling options

Besides outdoor air there are several other free cooling sources possible to use for building cooling purposes. Some examples are the ground, the ground water, lakes or rivers, which can be used either directly or with heat pumps in different configurations. This section describes some alternative free cooling sources beside outdoor air.

Banks (2012) writes that while the surface temperature of the ground in Sweden might vary by around 20 °C, at 6 m depth, the variation is smaller than 1 °C. According to Banks, the Nordic countries have a ground temperature at 10-150 m depth of typically 2-11°C, normally corresponding to the annual mean temperature at the geographical location in question. The constantly low temperatures make the ground suitable to utilise for cooling purposes.

Circulating ground water through the building, using it for cooling purposes is one version of free ground cooling. This is also possible to do with water from lakes and rivers, which also have a more stable temperature variation than the outdoor air. Another possibility is to circulate the heated return flow of chilled water from a hydronic cooling system in to closed-loop boreholes, disposing the excess heat into the ground. This principle can be utilised both with and without heat pump, as shown in Figure 13.

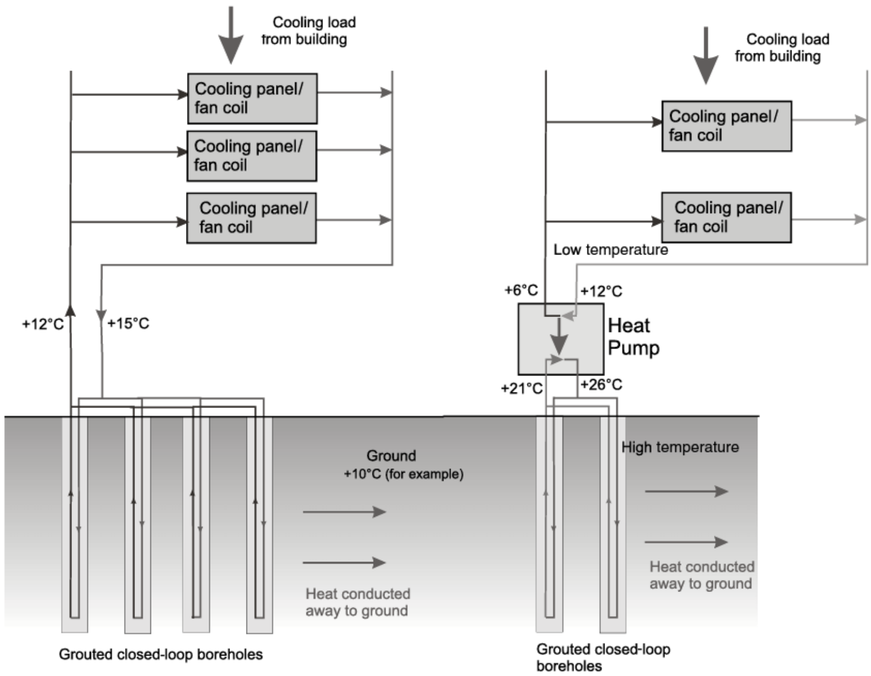


Figure 13. *Examples of ground source cooling by circulation of the return flow from the hydronic cooling system in the building in through boreholes in the ground (left) and ground source cooling using a ground source heat pump in cooling mode. Adapted after Banks (2012).*

At Arlanda Airport in Stockholm, another version of free ground cooling is used. The airport is situated on top of an aquifer naturally divided in two parts. During the summer, the water in the aquifer is pumped from one side to the other via the terminal buildings, transferring the surplus heat from the terminal buildings, heating one side of the aquifer. During the winter the reversed is done and the water on the "warm" side of the aquifer is pumped via the terminal buildings and is utilised for different heating purposes, before being pumped down to the "cold" side of the aquifer (Banks, 2012). Figure 14 shows the principle operation during summer mode.

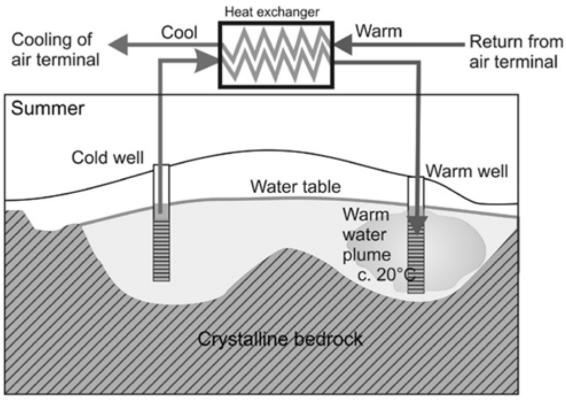


Figure 14. *Seasonally reversible aquifer thermal energy storage at Arlanda Airport in Stockholm (Banks, 2012).*

2.7.5 Heat recovery

In buildings where simultaneous heating and cooling demands occur during the year, there is a theoretical possibility to use heat recovery to minimize bought heating and cooling demands in the same process.

One example of this is heat recovery from chiller condenser water which is usually wasted and cooled off by outdoor air (ASHRAE, 2015). By adding a water-to-water heat pump in the chilled water system, the heat can be boosted to create hot water. The hot water can be used for several purposes, including domestic hot water, for heating air coils in ventilation systems and other space heating applications. Other examples of heat sources possible to utilise are exhaust air heat recovery or waste heat sources from other buildings or applications such as food refrigeration.

The ASHRAE handbook of heating, ventilation, and air-conditioning applications (2015) have many examples of when heat recovery might be suitable and gives a good overlook of practical considerations and important design aspects.

3 Case Study: Mixed Use Retail Building in Nordstan

The commercial building that is subject of the case study is situated in the Gothenburg city center and contains mainly retail and office spaces. This chapter introduces the building in its present state, the types of businesses occupying the space, technical systems utilised and the evolution of building energy use during the past years.

The lower floors of the building are a part of the shopping center Nordstan, and as shown in Figure 15, the building is connected to the public areas of the shopping center on two sides (adjacent to the green area). Nordstan consists of several properties connected with indoor walkways and public areas. The different properties are denoted with numbers and the studied property is referred to as number six, as shown in Figure 15.

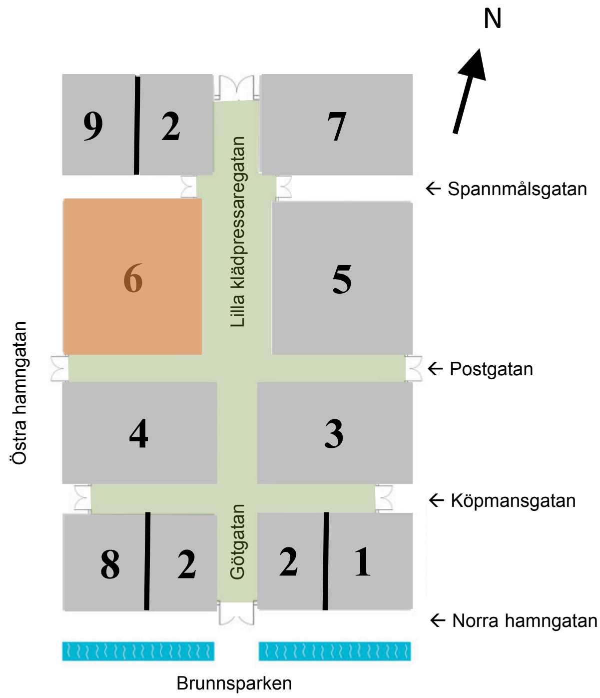


Figure 15. *Map of Nordstan shopping centre with the studied building marked in orange and indoor walkways marked in green. Adapted from Nordstan (2017) and Vasakronan.*

The building was originally built in 1973 by Skandinaviska Enskilda Banken (SEB) to house their central office as well as other offices and retail facilities. Although SEB remains a tenant the building was eventually sold and the real estate company Vasakronan currently owns the property.

The building is certified with LEED, an environmental certification system considering several aspects, e.g. building energy use, the impact on climate change, how solid waste is handled and the impacts from transports to and from the building.

3.1 Tenants and occupancy

The total building area is approximately 48 000 m^2 divided in seven floors where floors one to six are about 7000 m^2 each and floor seven somewhat smaller. In total, the rentable area is divided into 47 % retail, 50 % offices and 3 % common spaces.

Table 2 shows how the rentable area (LOA) is distributed between different types of tenants on each floor. The category “office” refers to companies who rent the area for office purposes although the area might include other office related functions as well.

Table 2. *Distribution of rentable area per floor in Object 6.*

Floor	Retail [%]	Office [%]	Common spaces [%]	Property management [%]	Restaurant [%]
1	76	18	6		
2	96	3	1		
3	91	9			
4	29	54			17
5	3	96		1	
6		100			
7		100			
8		100			

The bottom floors mainly include retail spaces, as described earlier. Examples of tenants are the department store Åhléns as well as several fashion and home decor shops, a bank, a grocery store, a small restaurant/café and a lunch restaurant.

The facades of the first three floors above ground facing Postgatan and Lilla Klädpressaregatan are a part of the public areas of Nordstan which means the shops mainly have the same opening hours as the shopping center, 10-20 on weekdays and 10-18 on weekends. The grocery store Hemköp is situated on floor one and two and have extended opening hours, 7-21 on weekdays and 8-20 on weekends.

The upper floors essentially consist of office spaces and house several different companies. Most offices occupied during regular office hours only, but some spaces are used by companies providing customer services by phone, operating evenings and nights as well as during regular office hours. Parts of the SEB offices in the building are operating 24 hours a day and other parts also have extended opening hours, from 7-22. Figure 16 shows a rough sketch of the distribution of retail and office areas on each floor.

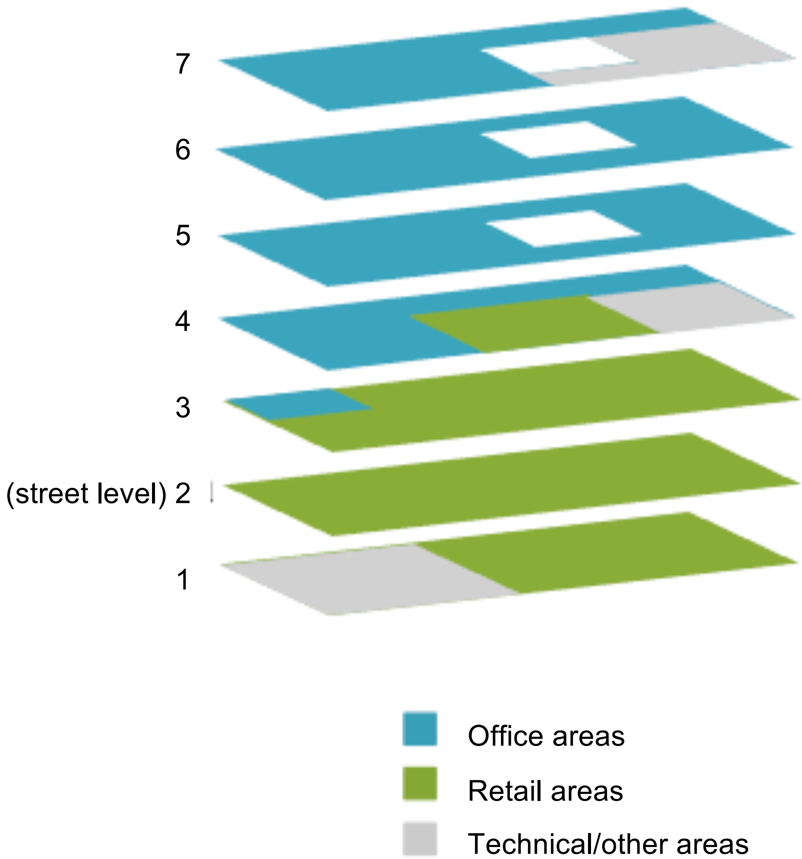


Figure 16. *Principal sketch of the distribution of retail and office areas on each floor in the building.*

3.1.1 Thermal indoor climate demands

The demands on thermal indoor climate in the building are roughly the same for all areas and commercial activities. Individual variations or special requests are regulated in each tenant's lease and will not be described in detail since the influence on the overall energy performance of the building is considered to be limited.

The allowed temperature range in the building is mainly 18 - 25°C if the outdoor temperature is below 25°C. There are of course local variations, e.g. in offices and areas where people are conducting sedentary work, where the lowest allowed temperatures are higher. In cases of outdoor temperatures above 25°C, the indoor temperature is allowed to be equal to the outdoor temperature. The technical systems providing cooling are controlled to keep an indoor temperature of 22°C. Newer units are designed to provide enough cooling to sustain an indoor temperature of 25°C at outdoor temperatures of approximately 28°C.

3.1.2 Dominating heat loads

The heat loads in the retail areas are dominated by heat from lightning and to a certain extent people. According to Vasakronan, the fashion retail shops tend to have the highest installed levels of lighting with around 60 W/m^2 in shop areas. Other shops also have high levels of installed lightning and on average, the installed lighting power ranges from approximately 20 W/m^2 to 60 W/m^2 or higher.

In the office areas, the heat loads derive mainly from the large numbers of people and equipment occupying limited areas in the office landscapes. At on-site visits, offices with high occupancy and 2 - 3 computer screens per person and desk were observed. Many businesses are also downsizings their office area without decreasing the staff, when performing refurbishments. This leads to large concentrations of people in small areas, usually demanding higher installed cooling power to ensure a satisfactory thermal indoor climate.

In some areas, distributing enough cooling power without impairing the thermal climate and induce draught or uncomfortable temperature gradients, have turned out to be a challenge. Due to a heat pillow effect caused by the large concentration of people the air tend to stratify and no air circulation is achieved. This has demanded new innovative approaches on air inlet and distribution to achieve a good thermal climate.

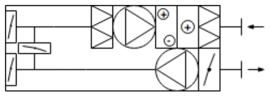
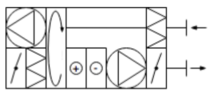
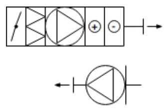
3.2 Building services

The design and performance of the technical systems in the building have a large influence on the building energy performance. This chapter describes the main functions and performance of the technical systems in the building.

3.2.1 Ventilation and air conditioning

The building, is supplied with fresh air through eleven central AHUs. The AHUs use three ventilation principles, all described more closely below. Table 3 shows an overview of the principles and to which extent the air is supplied by each principle.

__Table 3.__ AHU configurations and corresponding parts of the total fresh air flow supplied to Object 6.

Ventilation principle	AHU configuration	No. of units	Max. supply air flow [m3/s]	Fraction of total supply air flow	Return air flow [m3/s]	Fraction of total return air flow
Exhaust and supply air with recirculation		3	80.7	68%	78.7	69%
Exhaust and supply air with heat recovery		7	25.4	21%	23.5	21%
Separate exhaust and supply air		1	12.3	11%	12.3	10%

Based on airflow rates, the most common AHU configuration is the one with possibility of exhaust air recirculation, including a combined heating/cooling coil supplied from return pipe of the hydronic cooling system, an additional heating coil supplied by the hydronic heating system, filters and fans. There are three big units of this type in the building, supplying the building with around 70 % of the total air volume, covering several areas with different businesses and operation hours.

The AHUs are equipped with pressure control, adjusting pressure and flow according to the outdoor temperature. The recirculation rates are controlled to obtain the desired supply air temperature, and CO_2-sensors placed in the rooms control the minimum fresh air rate, making sure enough fresh air is provided at all times. The units were installed when the building was built in 1973 and have been in operation since.

The second most common AHU configuration is an AHU with supply and exhaust air, rotary heat exchanger, regular heating and cooling coils, filters and fans. About 20 % of the total air volume is supplied through seven AHUs of this type. The AHUs are newer than the recirculation units and each unit supply separate premises in the building with air, facilitating ventilation adapted to the needs of the businesses.

The third type of AHU includes supply air only. The exhaust air is removed by separate exhaust air fans and there are no possibilities of heat recovery from the exhaust air. The AHU include double heating coils, one heated by the return flow of the hydronic cooling system (further described in the Section 3.2.2), a cooling coil supplied by the regular hydronic cooling system, fan and filter. Corresponding exhaust air fans are placed on the roof. The AHU of this type is supplying about 10% of the total air volume flow to the building.

The basic control strategy of all AHUs is to utilise heat recovery or recirculation when suitable, in order to reduce the thermal energy demand for heating the air. The AHUs are equipped with temperature and pressure control and the hours of operation and the air flow rates are adapted to the businesses in the areas the units supply to as large extent as possible. Some of the AHUs supply several large areas with different businesses with individual hours of operation, making the adaptation somewhat troublesome. A consequence is large airflows to unoccupied areas and distribution of large amounts of air even though the demand is low, leading to unnecessary energy use.

3.2.2 Systems for heating and cooling

The property is supplied with district heating from Göteborg Energi. The local hydronic heating system includes hot water preparation, hot water circulation and heat supply to local room heating units like radiators, induction units and air curtains. The heating system also supplies the heating coils in the central AHUs as well as circulation units and air curtains in the entrance areas.

District cooling is supplied to the building from the Nordstan Community (NC), an economical community including all property owners in the shopping mall. NC is producing and distributing cold water to its members in a small-scale district cooling system.

Surplus heat in the building is removed by a combination of supplying air with a lower temperature than the room air and by utilising chilled surfaces. In the retail spaces, the waterborne heat removal is achieved by air circulation units (CUs) placed in proximity to the areas they serve. There are also a few fan coils and chilled beams in some retail spaces. In the office areas, chilled beams are also the most common solution. The cooling system is also utilised to cool a few server rooms in the building.

The room cooling units and the central AHUs are all supplied by a hydronic circuit divided in two main parts, utilising different system temperatures. The cooling coils in the central AHUs are designed and installed during different time periods, resulting in different designs with respect to system temperatures. Currently, the hydronic design system temperatures for the central AHUs are 10/18 °C and for room units 14/17 °C.

The cooling system has a heat recovery circuit where surplus heat is moved between the hydronic heating and cooling circuits by heat pumps. The recovery circuit is also utilised to pre-heat the air in the AHU that has no other heat recovery possibilities (AHU configuration 3).

The recovery circuit also includes a dry cooler placed on the roof of the building to enabling use of free cooling when possible. There is also a connection between the return pipe of the high-temperature part of the hydronic circuit to enable pre-heating of incoming outdoor air in some of the central AHUs where there is no heat recovery installed.

The grocery store in the building utilises cooling machines and a separate cooling system for food refrigeration. Figure 17 gives a principal overview of the basic design of the hydronic cooling system.

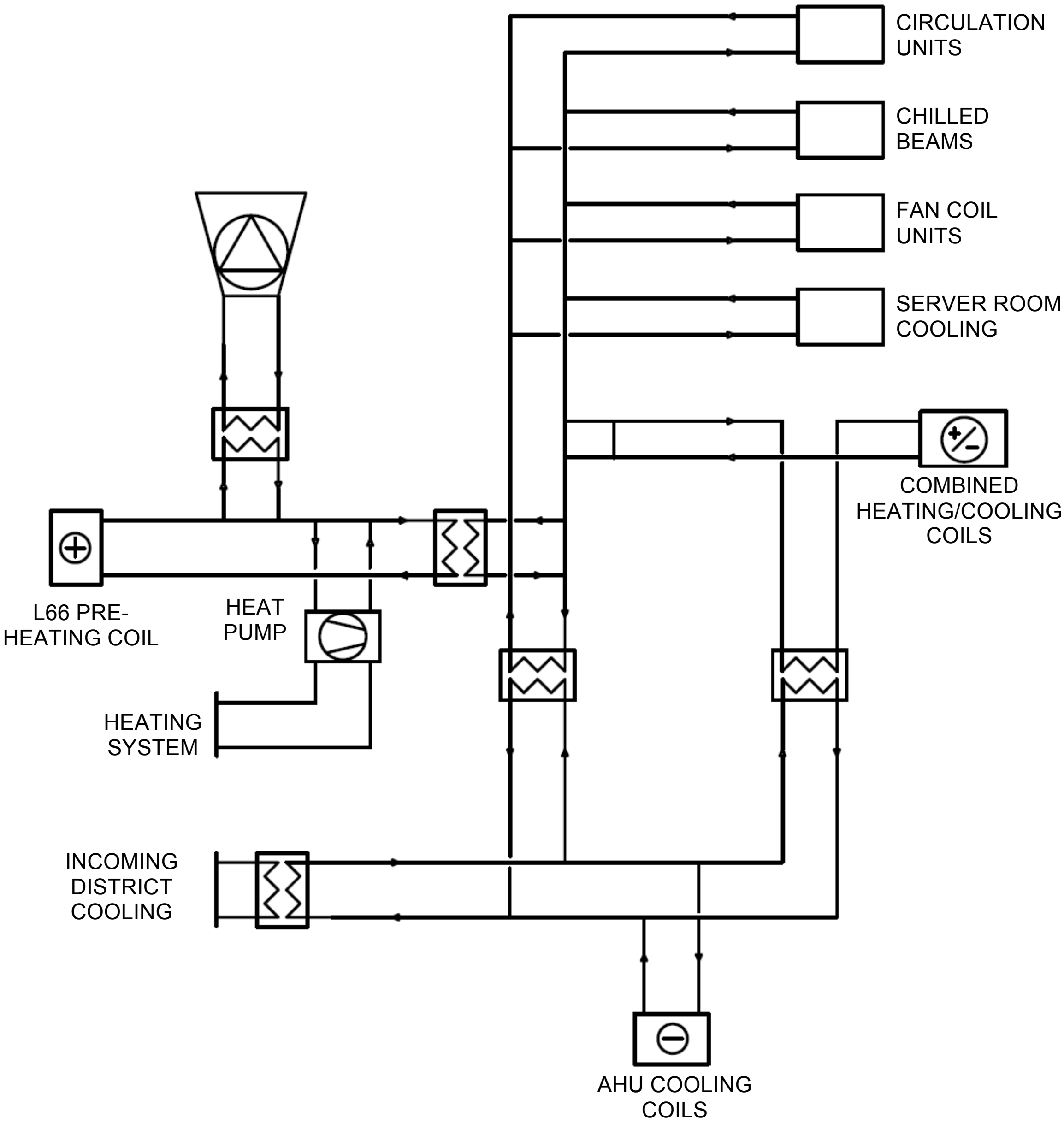


Figure 17. *Simplified sketch showing the principal design of the hydronic cooling system in the building.*

Recent measurements have shown that the temperatures on the circuit supplying the room units are closer to 14/15-15.5 °C than the 14/17 °C it is designed for. This is likely due to overflows, contributing to unnecessary pump work and increased energy use. The effects of deviating system temperatures are further evaluated in Chapter 6.

3.2.3 Electricity

The building is supplied with high voltage electricity, which is transformed to low voltage in two transformer substations inside the building. Vasakronan measures the electricity use of each tenant and bill them accordingly.

Situated on the roof is a large area of photovoltaics (PVs), producing about 80 MWh of electricity each year, corresponding to about 4.5 % of the facility electricity use during 2014. Installing the PVs was a part of Vasakronan's ongoing work with improving the energy and environmental performance of their buildings. The PVs were also considered to provide economic as well as marketing advantages by enhancing the environmental profile of the building, which attracts new tenants.

3.2.4 Technical areas

The main technical areas are located on floor one and seven. The areas on floor seven include nine out of eleven central AHUs, a boiler room for district heating redistribution as well as elevator engine rooms. On floor one, the technical areas include the two remaining AHUs, another boiler room for incoming district heating and areas for cooling machines. There are also technical areas on the floors with retail premises, where smaller air circulation units are placed.

Transformer substations for transformation of the incoming high voltage electricity are placed on floor one in proximity to other the other technical areas. The building has four shafts for vertical distribution of air as well as hot and cold water.

3.3 Building energy performance

The building energy performance has been monitored during several years and the results have acted as a base for different implementations of energy efficiency measures. Figure 18 shows the specific energy use in the building during 2004, 2010 and 2014.

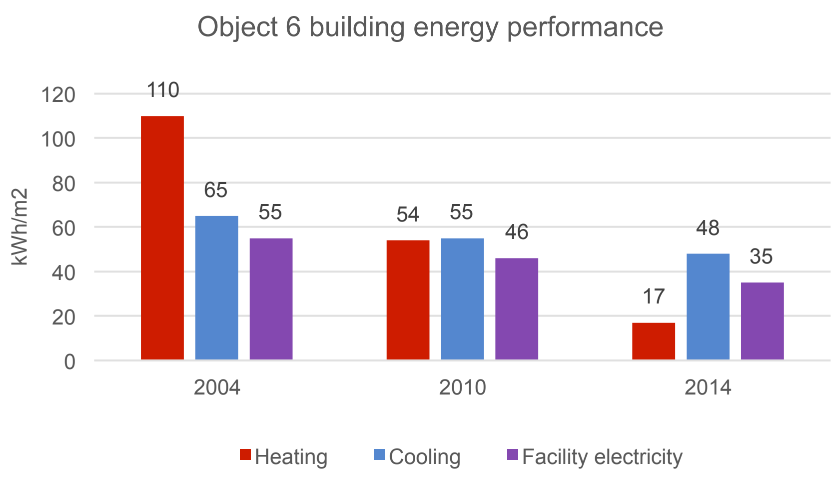


Figure 18. *Measured specific energy use in the studied building during 2004, 2010 and 2014.*

3.3.1 Energy for heating

During its lifetime, the building has been subject of several minor refurbishments, tenant adaptations and measures to improve the building energy performance. The heating demand has been reduced through replacement of old windows to improve the thermal insulation, installation of several new AHUs as well as connection of several old exhaust air ducts to the AHUs, to enable heat recovery of the exhaust air. The installation of new AHUs has also allowed better ventilation control and adaptation of ventilation rates according to the use and operating hours of different parts of the building.

Between 2004 and 2014, the specific energy use in the building was reduced by almost 60%, as shown in Figure 18. The biggest change is a reduction in thermal energy used for heating, mainly due to the removal of a large number of re-heating coils formerly placed in the ventilation ducts. Another part of the reduction in heating energy use is the implementation of the heat recovery circuit in the hydronic cooling system, where heat pumps connected to the hydronic heating system moves surplus heat from the return pipe of the cooling system to the heating circuit, reducing the demand for purchased thermal energy. The combined heating/cooling coils connected to the hydronic cooling system also helps reducing the heating demand in the AHUs where they are placed.

3.3.2 Energy for cooling

The energy for cooling consists of thermal energy supplied to the AHUs, chilled beams, fan coils and circulation units. The mentioned implementation of the heat recovery circuit (including the dry cooler, pre-heating of ventilation air in the larger AHUs and the heat pump connected to the heating circuit) in the hydronic cooling system has besides from reducing the need for bought energy for heating, also reduced the specific cooling energy. Today limited amounts of district cooling are used during December, January and February, as shown in Figure 19. Although some measures have been taken, energy for cooling is still a big part of the energy use and there is a large potential for further improvement in this area.

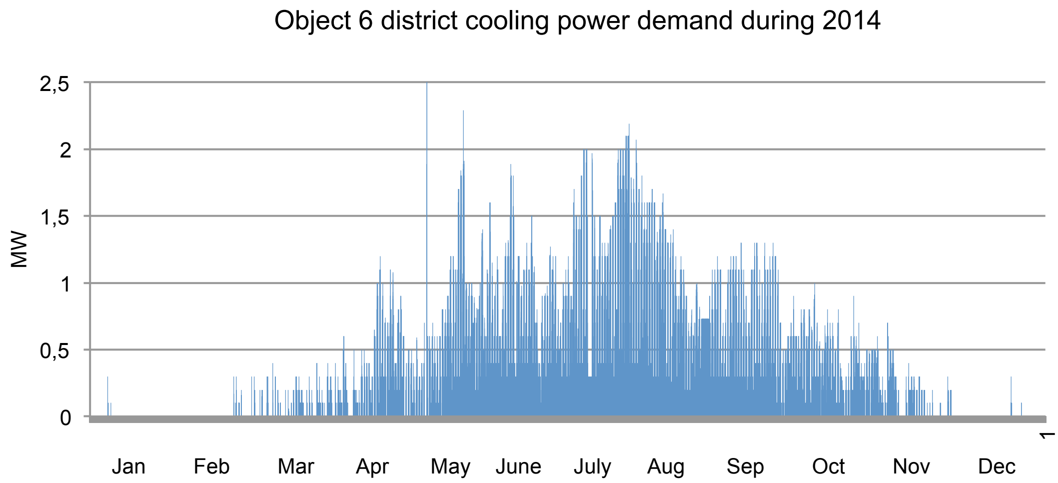


Figure 19. *District cooling power demand in Object 6 during 2014.*

3.3.3 Facility electricity

The facility electricity use has also been decreased since 2004. The removal of reheaters in the retail areas has apart from thermal energy savings also contributed to reduced pressure drops and decreased fan energy use. The PVs on the roof also reduces the electricity demand to some extent.

This area have also been identified as a potential area of improvement, especially since there is a known problem with unnecessary pump work in the hydronic cooling system.

3.3.4 Energy billing

The tenants in the building pays for heating, and cooling and hot water through fixed rent supplements to the property owner Vasakronan. The electricity is billed in a similar way where the electricity use for each tenant is measured and the tenants are billed accordingly.

4 Case study: Heating and Cooling Demands

As mentioned in Chapter 2, the heating demands in commercial buildings usually are a minor problem and instead, considerable amounts of energy instead are used for removal of surplus heat. In buildings with varying use, housing several businesses with different hours of operations, the heating and cooling demand can vary a lot in both time and space.

This chapter covers the heating and cooling demands of the studied building, important input parameters for the choice of technical solutions for heating and cooling and for the possibilities to use free cooling sources. Figure 20 marks the area targeted in this chapter and shows its role in the system providing the prerequisites for the building energy performance.

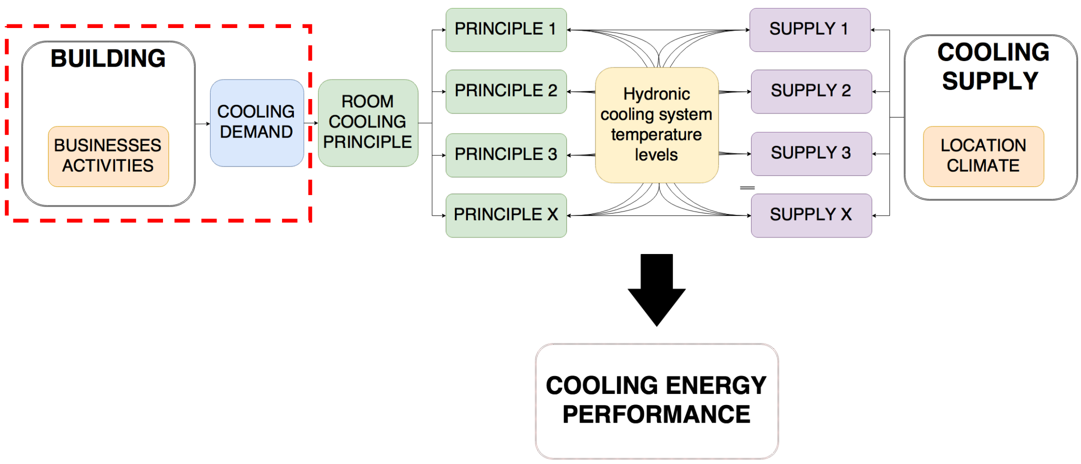


Figure 20. *Marking of the area covered in Chapter 4 and where it fits in to the system providing the prerequisites for the building energy performance.*

The heating and cooling demands of the building have been simulated using the software IDA ICE. Data regarding the thermal and technical properties of the building has been retrieved from Vasakronan and GICON Installationsledning. Unknown inputs have been estimated according to BBR recommendations regarding energy calculations, in line with other published reports in the field or with the help of advice from experienced engineers at Vasakronan and GICON Installationsledning. All data used in the simulations is summarized in an internal report (Gicon, 2017).

The purpose of simulating the cooling demands is to give an indication of the size and variation of the cooling demands in a building of this type. Due to constantly changing businesses, heat loads and outdoor temperatures, the heat loads and associated cooling demands will not be constant over time and these values should be seen as an example rather than exact values.

4.1 Estimated building heating demands

The heating and cooling demands in the building are, as described in Section 2.1, a result of the building heat balance. The heat balance is influenced by the technical properties of the building itself, U-values, air tightness of the building envelope and window properties, as well as the heat loads deriving from the activities in the building.

As described in Section 3.2.2 the building is mainly heated by radiators. There are also a few fan coils and air curtains contributing with smaller amounts of heating power. Besides the room heating units there is a heating energy demand (after heat recovery/recirculation) for the heating coils in the AHUs.

Figure 21 shows an estimation of how the basic heating power demand for the whole building varies over the year, and to which extent each type of heating unit is estimated to contribute to cover the total heating demand. The heating power demand here refers to the hourly power necessary to provide by the heating units to keep the indoor temperature within the desired levels. Included in the figure is also the thermal power demand for domestic hot water and the outdoor temperature variation during the year.

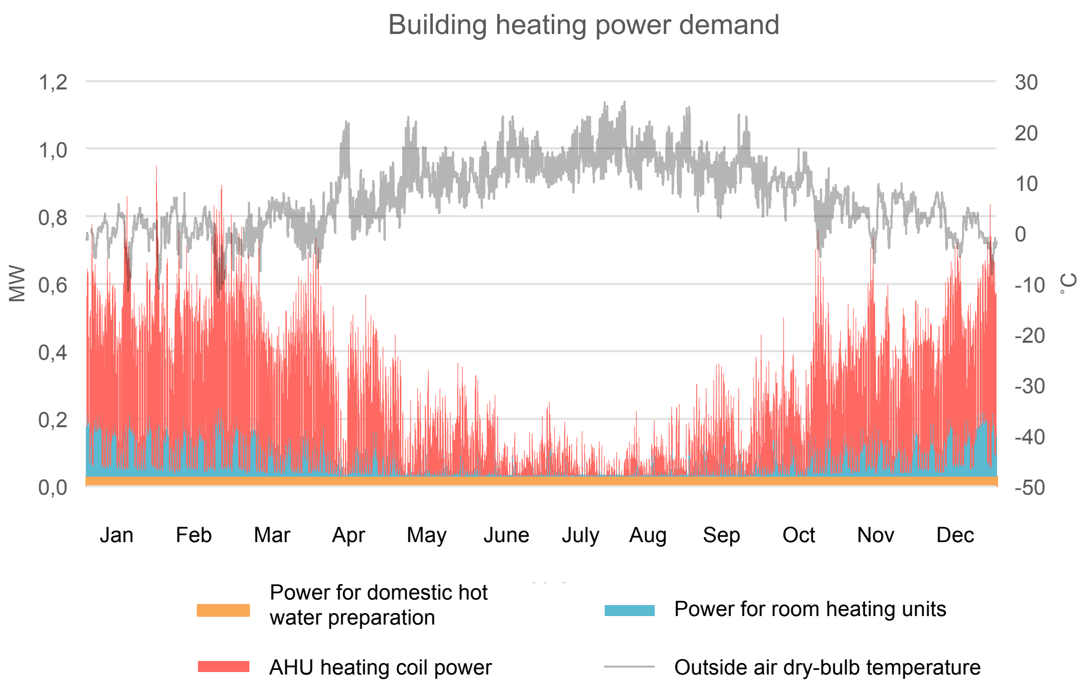


Figure 21. *Estimated building heating demand and corresponding outdoor temperature variation during the year.*

The “room heating units” category here refers to radiators, air curtains and fan coil units while the “AHU heating coil power” describes the estimated heating demand for all AHUs heating coils in the building. There is also an evenly distributed use of power for hot water preparation, contributing to the heating demand during the entire year. Note that this graph presents the estimated basic power demand and not the demand for bought thermal power to cover the heating demand.

A large part of the heating demand is covered by the heat pump on the recovery circuit, the pre-heating coil in the AHU without energy recovery possibilities and the combined heating and cooling coils in the AHUs utilising the return branch of the hydronic cooling system to pre-heat the air in the AHUs when there is a heating demand. These actions minimises the need for bought energy, improving the building energy performance.

4.2 Estimated building cooling demands

Figure 22 shows an estimation of how the building cooling power demand (the removed heat) varies over the year and to which extent each type of cooling unit is estimated to contribute to cover the total cooling power demand. The total cooling power demand here refers to the hourly heat power removed by the cooling units (AHUs and local units) to keep the indoor temperature within the desired levels. Note the difference in scale on the left vertical axis compared to the same axis in Figure 21 showing the heating power demand.

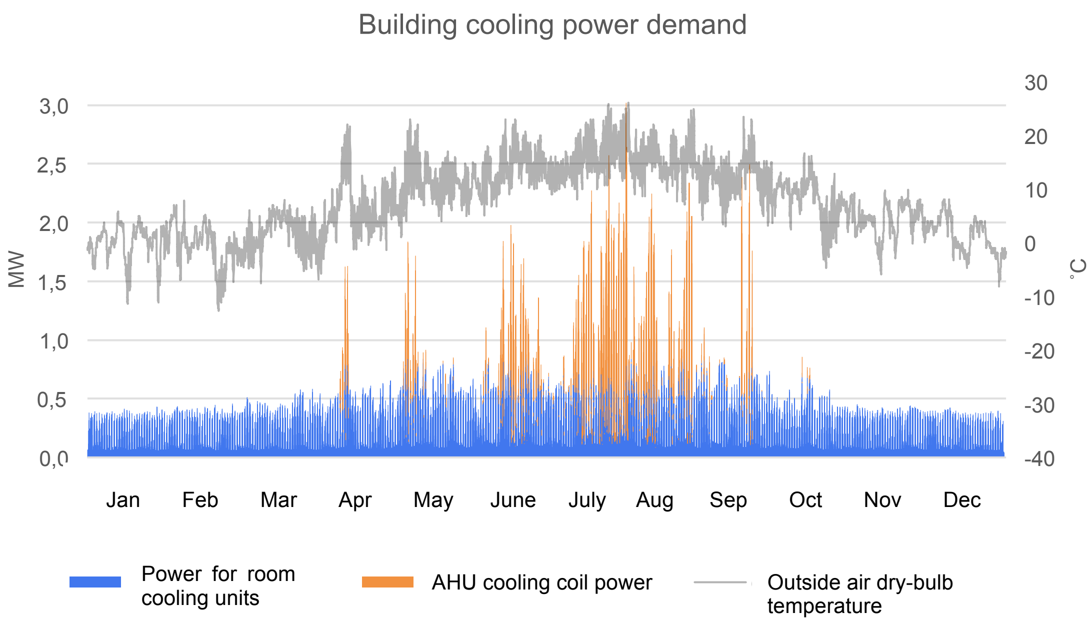


Figure 22. *Estimated gross building cooling power demand and corresponding outdoor temperature variation during the year.*

The cooling principles utilised in the building are as mentioned in Section 3.2.2, a combination of removal of surplus heat by chilled air and cool surfaces. Due to the internal heat generation in the building, there is a cooling demand in the building during the entire year.

During the colder parts of the year cooling energy is mainly needed for the room cooling units, where the hydronic cooling system provides the cooling power. The air in the AHUs only needs cooling when the outdoor temperature is higher than the desired supply air temperature, resulting in AHU-related cooling demands only during the warmer part of the year. The cooling energy demand for the room cooling solutions currently utilised as well as the energy demand for other room cooling principle possible to utilise is further studied in Chapter 5.

4.3 Estimated local cooling demands

Due to the varying use of the areas in the building, the character and duration of the heat loads and the room heat balance in different spaces tend to vary. For example, the different opening hours as well as different levels of installed lighting and occupancy in offices and retail areas contribute to differences in the heat balance.

This section presents examples of the cooling demand variations during the operation hours (corresponding to the operation hours of the technical systems) for each of the two main business types (office and retail) for one year.

4.3.1 Estimated cooling demands in office areas

The main technique for heat removal in the office areas is a combination of heat removal by air and water through the use of chilled ceiling beams through which the fresh air from the AHUs is supplied.

Figure 23 shows the duration of the cooling demand at different outdoor temperatures during one year, for an office area situated on floor four, facing south and west exterior walls. The figure also shows the duration of the corresponding outdoor temperature during the same period.

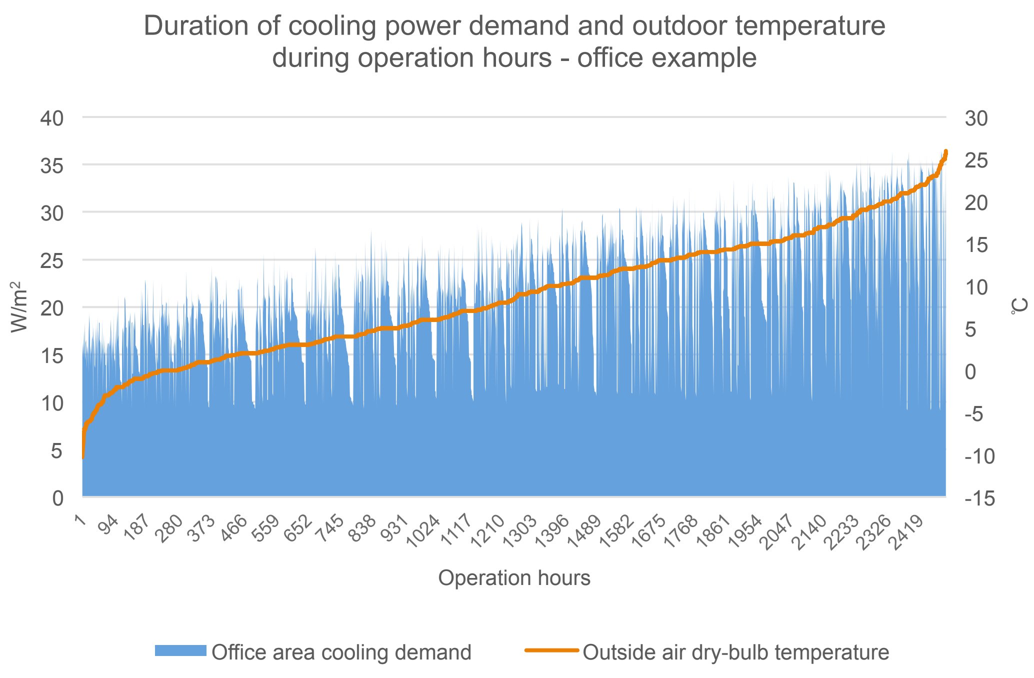


Figure 23. *Duration of estimated cooling power demand and corresponding outdoor temperature during operation hours in an example office area.*

The office space is mainly used from 8-17 during weekdays but the technical systems have somewhat longer operating hours (+1.5 hours) to ensure a good indoor climate. The total cooling power demand varies from 10 – 35 W/m^2 during the year. Due to the large exposure to exterior walls and windows, the cooling power demand in this office area is influenced by the outdoor temperature and the maximum cooling power demand varies accordingly. Although, there are also variations independent of the outdoor temperature due to variations in heat loads during the day. Even at low outdoor temperatures a cooling power demand exists and the main influence is the size of the internal heat loads.

The cooling power demand is displayed as a mean value for the full office including areas like corridors, toilets and canteens. Local cooling power demands within the office areas are therefore both higher and lower and the areas with the highest occupation (the office landscape) have higher installed cooling power per m^2 than indicated here. There are also variations within the different office areas in the building where some areas require larger installed cooling power than others due to high occupation in the office landscape areas.

4.3.2 Estimated cooling demands in retail areas

In the retail areas, heat is also removed using a combination of heat removal by air and water. The ventilation air is supplied at a lower temperature than the room air temperature through the central AHUs and covers one part of the cooling demand. The remaining heat surplus is removed by separate circulation units equipped with water chilled cooling coils, placed in proximity to the retail areas. Figure 24 shows the duration of the cooling demand during operation hours (opening hours + 1.5 hour) for one year.

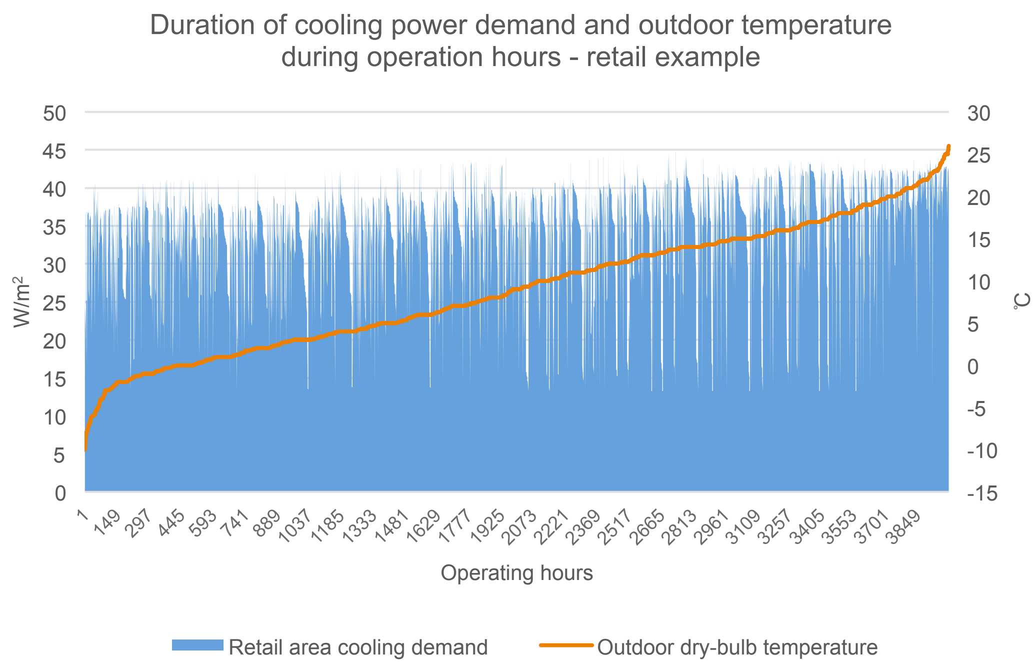


Figure 24. *Duration of estimated cooling power demand and corresponding outdoor temperature during operation hours in an example retail area.*

In this retail area, the cooling demand varies, from about 15 - 45 W/m2. The cooling demand changes almost independent of the outdoor temperature, indicating that the main contribution and largest influence is the internal heat loads. The lower levels of cooling demand mainly occur outside of the opening hours when the lightning and people occupancy is low. The high heat loads typically appear during Saturdays when the shop lighting is on and there are a lot of people occupying the area.

As mentioned initially, commercial buildings tend to have cooling demands during the entire year due to high internal heat generation. This is the case in the studied building as well, which was shown in Figure 22. In some areas, the cooling demand varies according to exterior circumstances like climate but the main influence is from the heat loads and activities inside the building.

5 Case study: Analysis of Alternative Room Cooling Principles and Consequences for Cooling Energy Demand

As described in Chapter 4, two separate room cooling principles are utilised for office and retail areas in the studied building. Both principles combine airborne and waterborne heat removal but the technical equipment used is different. In the retail areas, a part of the cooling power is provided by supplying chilled air through a central AHU. The other part is provided by circulating the room air through circulation units equipped with water chilled cooling coils. In the office areas, one part of the cooling power is also provided by chilled supply air from a central AHU. Additional cooling power is achieved by chilled ceiling beams.

As mentioned in Section 2.1 - 2.3, there are distinct differences between the cooling demand, cooling energy demand and cooling energy performance. This chapter focuses on the cooling energy demand and describes how it varies depending on the room cooling principle utilised. Figure 25 marks the area targeted in this chapter and shows its role in the system providing the prerequisites for the building energy performance.

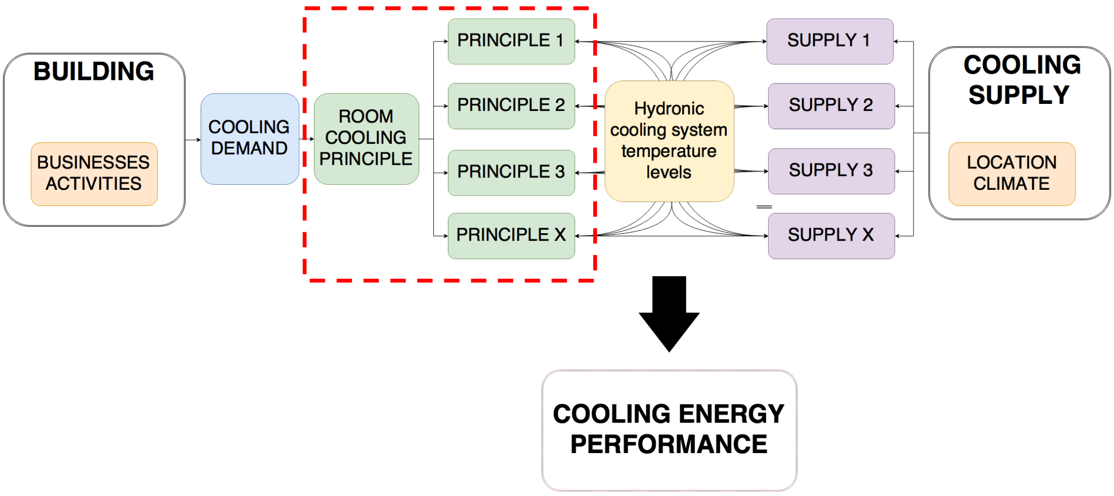


Figure 25. *Marking of the area covered in Chapter 5 and where it fits in to the system providing the prerequisites for the cooling energy performance.*

5.1 Cooling energy demands in retail and office areas

The basic energy demand for cooling in retail areas consists of thermal (cooling) energy provided by the hydronic cooling system to the cooling coils in the AHUs as well as in the CUs. It also includes electricity for fans and pumps in both AHUs and CUs.

In the office areas, the basic energy demand for cooling also consists of thermal (cooling) energy provided by the hydronic cooling system to the cooling coils in the AHUs and to the chilled ceiling beams. Also included is electricity for fans in the AHU and pumps in the hydronic cooling system supplying the chilled beams and the cooling coils.

5.2 Description of evaluated room cooling principles

From the existing room cooling principles for retail and office areas in the building, two additional combinations of air and waterborne room cooling principles has been developed for each area (office/retail).

In the additional principles, the basic technical equipment in form of AHUs and room units is kept, but the share of the heating demand covered by air and water respectively, is varied through increased or decreased air flow rates.

Figure 26 and 27 shows to which extent the cooling demand is covered by air and waterborne cooling respectively, for all alternatives in both office areas (Figure 26) and retail areas (Figure 27).

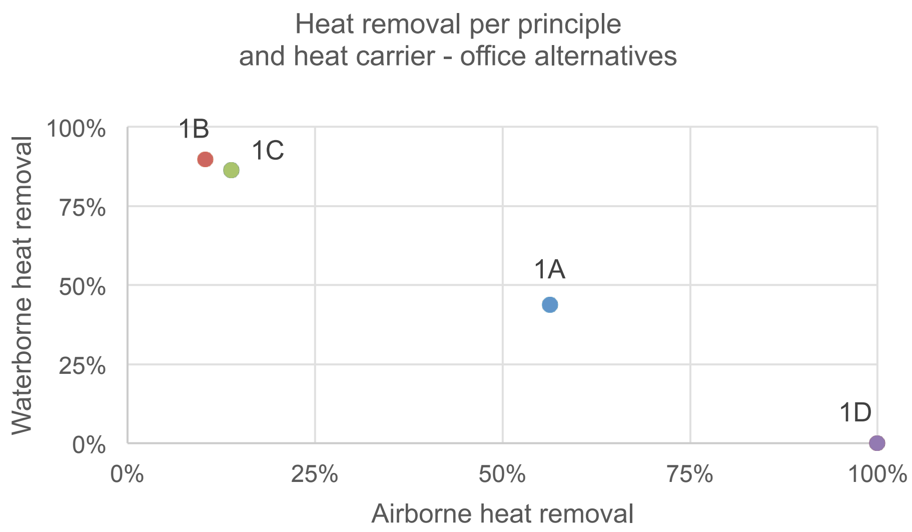


Figure 26. *Displaying the share of heat (thermal energy) that is removed by airborne and waterborne cooling systems respectively during one year, for all evaluated office room cooling principles.*

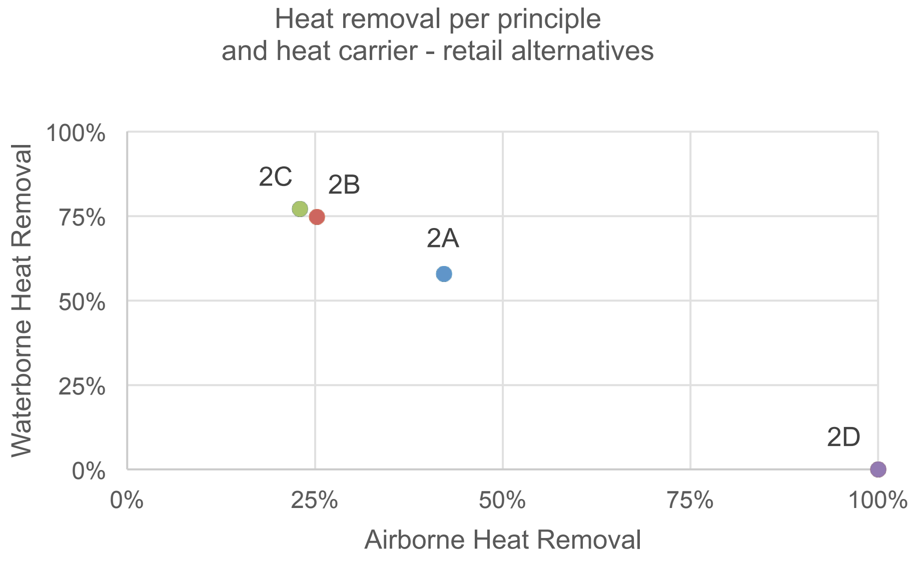


Figure 27. *Displaying the share of heat (thermal energy) that is removed by airborne and waterborne cooling systems respectively during one year, for all evaluated retail room cooling principles.*

Table 4. *Evaluated room cooling principles in both retail and office areas.*

Business	**Offices**	**Retail**
Waterborne cooling	Active beams outdoor air	Circulation Units
Ventilation / airborne cooling		
(Scheduled) CAV BASE CASE	1A	2A
CAV Hygiene flow	1B	2B
DCV (VAV) CO_2 control	1C	2C
VAV temperature control	1D	2D

Table 4 shows a compilation of all evaluated combinations with additional information about the technical equipment and control approach utilised in each alternative. Detailed inputs and information on each alternative are collected in Appendix I. The base cases (1A and 2A) represents the current solutions utilised for room heat removal in the studied building.

The alternatives with the smallest amounts of airborne heat removal (1B-C and 2B-C) are designed with low air flow rates, covering only the hygiene demands for each area. On the other end of the scale (1D/2D), all heat removal is airborne and the waterborne system is not utilised at all.

Each alternative was simulated on a zone level for a full year, using the IDA ICE building model with the purpose of mapping the total energy demand (thermal and electrical) associated with each room cooling principle. Since the analysis aims at providing general guidance regarding the difference in cooling energy demand depending on the chosen alternative, parameters influencing the energy demand (e.g. specific fan power (SFP), pressure losses over components and efficiency of pumps) have been chosen to represent contemporary average properties of these types of components. The components and details of each alternative are not optimized with regard to energy and there are additional potential to make each alternative more energy efficient in different ways, which should be kept in mind when analyzing the results.

5.3 Alternative room cooling principles and consequences for cooling energy demand

In this section, the consequences for the cooling energy demand when using the different room cooling principles described in Section 5.2, is analyzed.

Figure 28 shows the results for the alternative office room cooling principles (1A-D) and Figure 29 shows the corresponding results for the alternative retail room cooling principles (2A-D).

The bars in the diagram are grouped two and two, each pair of bars representing values for one room cooling principle. The top bar represents the total amount of removed heat (thermal energy), expressed in kWh/m^2. The bright orange and bright blue parts of the bar represent the amount of heat removed by air and by water respectively.

The bar below represents the cooling energy demand. Pale orange parts indicate energy provided to the technical systems providing airborne cooling and pale blue parts indicate energy provided waterborne cooling system.

The cooling energy demand is divided into thermal energy (cooling energy provided by the hydronic cooling system) and electrical energy for fans and pumps. In the cases where air is utilised as a heat carrier to a large extent, the fan energy demand becomes quite big. The pump energy on the other hand, is rather small compared to the other values and is just barely visible in some cases.

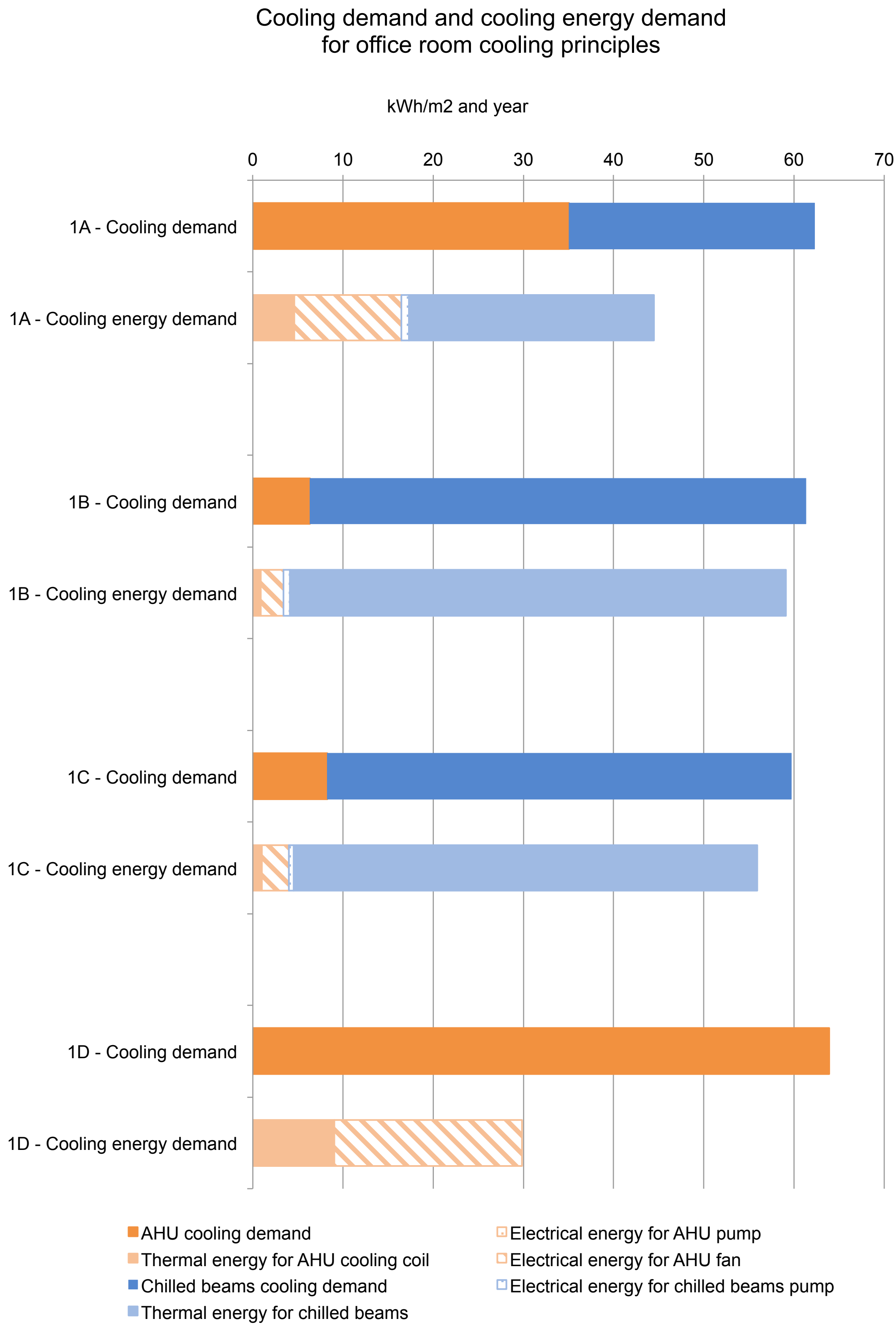


Figure 28. *Cooling demand and the associated basic cooling energy demand for all office room cooling principles evaluated. The energy demand for the chilled beams in the office is the energy (thermal and electrical) associated with the hydronic cooling system supplying the beams with chilled water.*

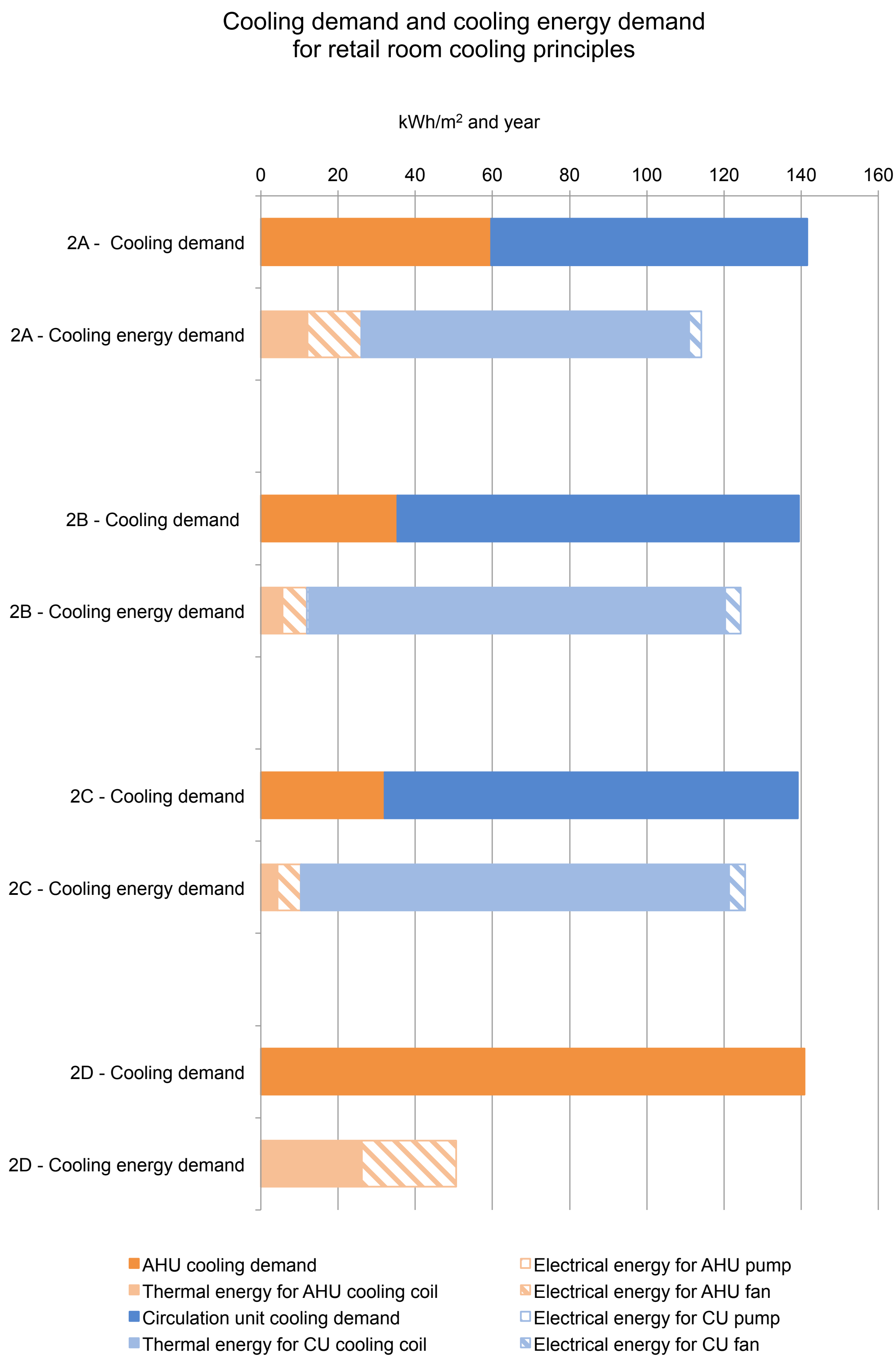


Figure 29. *Cooling demand and the associated basic cooling energy demand for all retail room cooling principles evaluated. The energy demand for the circulation units in the retail areas is the energy (thermal and electrical) associated with the hydronic cooling system supplying the cooling coils with chilled water and electricity for fans.*

The results of the simulations show that airborne heat removal requires less supplied energy to remove the same amount of heat, compared to waterborne heat removal. This is due to the fact that as long as the outdoor temperature is lower than the desired supply air temperature, there is no need to cool the air. In the offices, the supply air temperature varies between 17-18 °C and in the retail areas the maximum supply air temperature is 16 °C, making is possible to utilise the outdoor air during a majority of the year, minimising the thermal energy demand for cooling.

Of the total energy demand for airborne cooling, electricity to fans is a substantial part, for the office area it is even larger than the thermal energy demand to the cooling coil of the AHU. The amount of energy required for running the fans depends on the SFP of the system as well as the hours of operation. This makes investing in a system with a low SFP extra important when working with airborne cooling only.

Focusing on the waterborne part, the thermal energy dominates the demand in both office and retail areas. The possibilities to influence the thermal energy demand and in turn the cooling energy performance, are highly depending on the cooling source utilised and the amounts of purchased energy that is needed to cover the thermal demand. Utilising “free” cooling sources can minimise the need for bought thermal energy for the waterborne cooling, making it a competitive option with regards to demand for purchased energy.

The hydronic system temperatures for the room units in these examples are 14/20 °C for CUs and 14/17 °C for chilled beams (detailed information regarding the inputs for each alternative is found in Appendix I). In theory, this means it would be possible to cool the water in the hydronic circuit with outdoor air as long as the outdoor temperature is lower than 14 °C if utilising a heat exchanger with an infinitely large area.

To visualise the potential influence on the cooling energy demand, Figure 30 and 31 shows the basic energy demand for each room cooling principle together with the remaining energy demand if the water in the hydronic circuit is chilled (neglecting additional energy use for e.g. fans and only considering the thermal energy), using outdoor air when the outdoor temperature is below 14 ° C. The values are theoretical but can be seen as an indication of the potential for the given prerequisites.

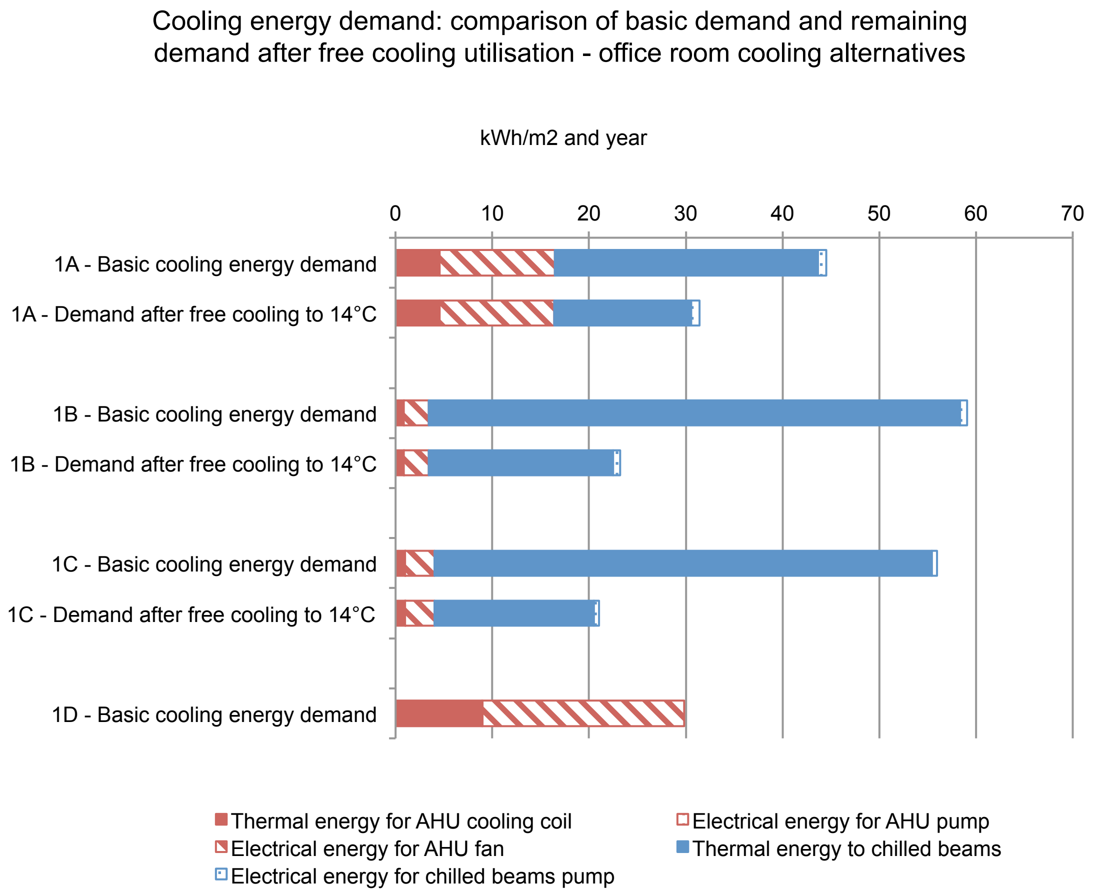


Figure 30. *Comparison between the basic cooling energy demand and the remaining cooling energy demand after utilising outdoor air to cool the water in the hydronic circuit. Office room cooling alternatives.*

The bars in the diagram are grouped two and two, with the top bar representing the basic cooling demand of the room cooling alternative. The bottom bar represents the remaining cooling demand after utilising free cooling with outdoor air to cover the whole thermal energy demand when the outdoor air is below 14 °C.

For the office room cooling alternatives, the reduction in hydronic thermal energy demand was 48 % (1A), 65 % (1B) and 68 % (1C) respectively. For both alternative 1B and 1C the total energy demand after free cooling utilisation becomes smaller than the all-airborne alternative 1D. This shows that for the office alternatives, the waterborne alternatives do have potential to become competitive regarding energy use, compared to the airborne cooling.

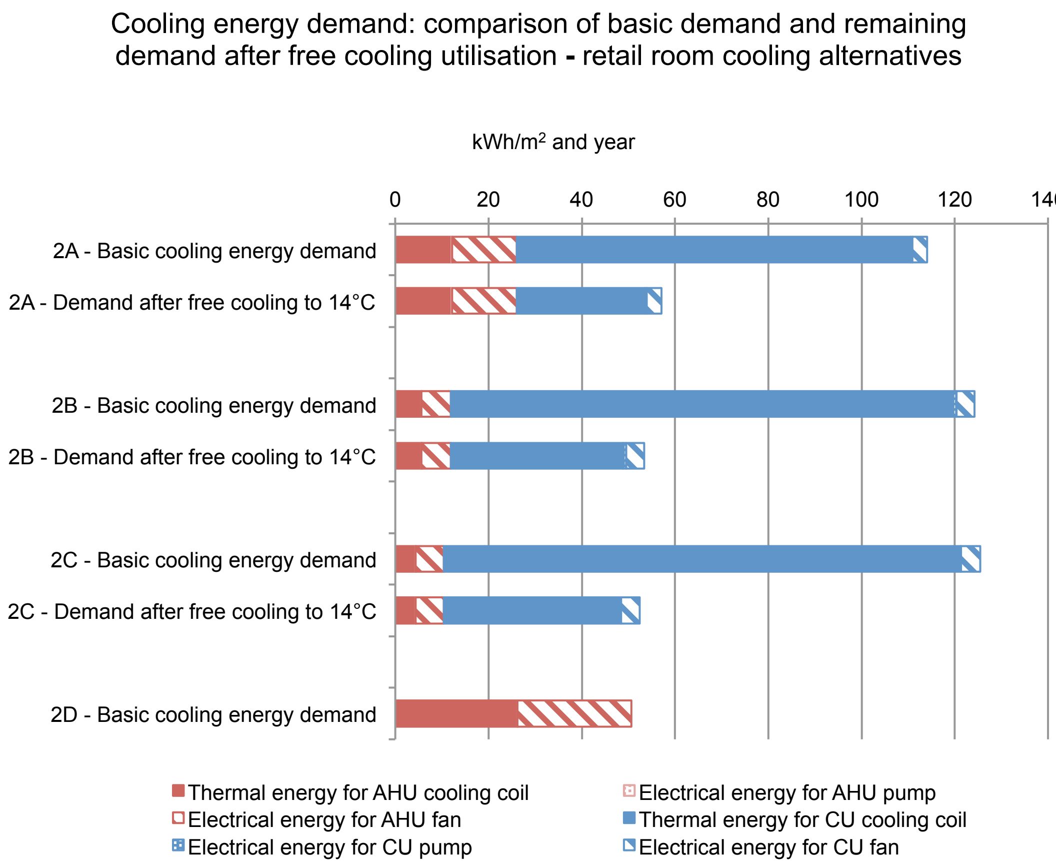


Figure 31. *Comparison between the basic cooling energy demand and the remaining cooling energy demand after utilising outdoor air to cool the water in the hydronic circuit. Retail room cooling alternatives.*

The reduction in hydronic thermal energy demand for the retail room cooling alternatives was 67 % (2A), 66 % (2B) and 66 % (2C) respectively. For the retail room cooling solutions, none yield a lower energy demand than the all-airborne room cooling principle, although the differences are not big. Apart from this example there are many other ways of utilising "free" cooling sources minimising the need for bought thermal energy. The thermal energy supply to the waterborne cooling system is further analysed in Chapter 6.

To facilitate comparison between the energy demands of each room cooling principle, an "efficiency" of each principle is defined according to equation (5) in this chapter. The efficiency for each alternative room cooling principle is shown in Table 5.

$$Room\ cooling\ principle\ efficiency = \frac{\text{Total removed heat [kWh]}}{\text{Total energy demand [kWh]}} \tag{5}$$

Table 5. *Total removed heat divided by the total energy demand [kWh/kWh] for all evaluated room cooling alternatives. Showing both the efficiency of the basic demand and the remaining demand after maximum utilisation of free cooling with outdoor air when the outdoor air temperature is below 14 ° C.*

		Office area			Retail area	
Room cooling principle		Basic demand	Demand after free cooling		Basic demand	Demand after free cooling
Scheduled CAV + BEAMS or CUs	**1A**	1.4	2.0	**2A**	1.2	2.5
Scheduled Hygiene CAV + BEAMS or CUs	**1B**	1.0	2.7	**2B**	1.1	2.6
VAV CO_2 + BEAMS or CUs	**1C**	1.1	2.9	**2C**	1.1	2.7
VAV Temp	**1D**	2.1	-	**2D**	2.8	-

As mentioned in Section 5.3, alternatives 1B and 1C show potential of becoming equally or more efficient than the all-airborne cooling principle in alternative 1D when utilizing free cooling in this way. Alternatives 2A-C all have improvement potential but the all-airborne cooling principle utilised in the retail areas still has the best efficiency.

5.4 Practical aspects and considerations

Beside the energy aspects, there are several practical issues to consider when deciding which room cooling principle to use. Thermal climate demands from the businesses occupying the area, the size of the heat load, and available space for technical areas are examples of aspects needed to be evaluated together with the energy demand when choosing the cooling principle. This section highlights some important qualitative aspects and secondary effects arising from the choice of the different room cooling principles analysed.

5.4.1 Supply air temperatures

One parameter strongly influencing the thermal energy demand connected the airborne cooling is the desired supply air temperature. As mentioned before, the air only needs cooling (thermal energy) when the outdoor temperature is higher than the desired supply air temperature.

By utilising high supply air temperatures, the possibilities to use the outdoor air and avoid thermal energy use increases. High supply air temperatures also decrease the risk of people experiencing draught or discomfort when supplying the air. On the other hand, higher supply temperatures require larger volumetric air flows to provide the same cooling power. The results shown in this analysis are strongly dependent of the supply air temperatures used which needs to be taken in to account if using the results for comparison to other principles.

5.4.2 Thermal climate

The room cooling principle used does not only influence the energy demand but also the indoor climate. When utilising air for room heat removal, a consequence of high airflows is a higher air exchange rate, potentially improving the indoor air quality. There are studied where increased ventilation rates are related to fewer sick building syndrome symptoms among employees and decreased short-term absence (ASHRAE, 2013).

Drawbacks of high outdoor air flows are the risk of higher indoor air concentrations of outdoor air pollutants, associated with a broad range of negative health effects, making filtration of the outdoor air important (ASHRAE, 2013). Extensive ventilation with outdoor air during the winter might also lead to low RH levels indoors, causing discomfort for the occupants in the area. Figure 32 shows the simulated RH in both retail and office areas during the year.

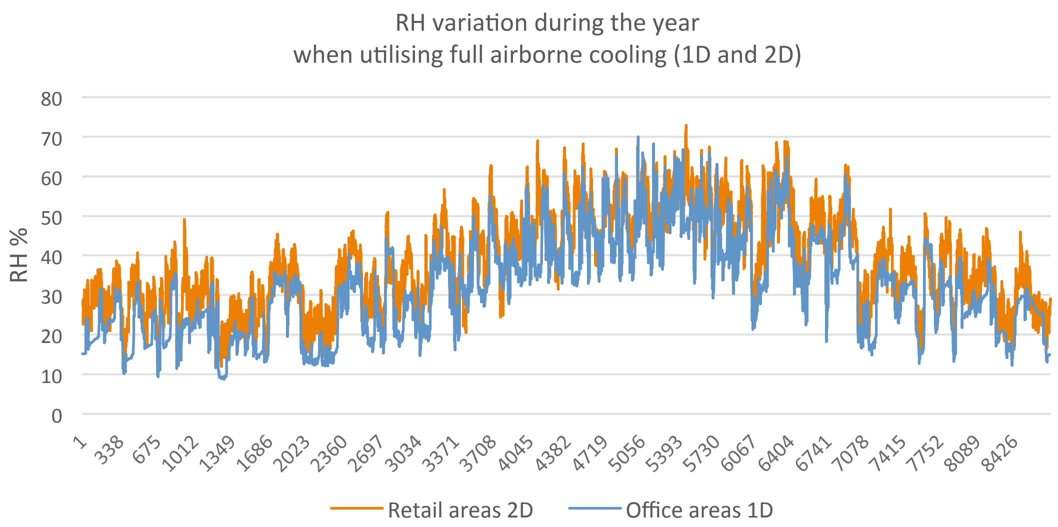


Figure 32. *Simulated RH variation in the example office and retail area during one year.*

The RH levels in both the office and the retail areas during the driest parts of the winter range from 10-30% (retail) and 10-20% (offices). Low RH levels can be avoided by humidifying the air or by recirculation of the indoor air, although air humidification requires additional thermal energy.

5.4.3 Volumes for technical installations

The differences in specific heat capacity and density between air and water, results in a need for very large volumetric air flows to supply the same cooling power with air as with water. In existing buildings, access to volumes to utilise for technical installations is limited and it might be hard to acquire space for technical areas where the AHUs are placed, as well as for shafts and ceiling space to accommodate the necessary air ductwork.

Today, with the present technical systems, the maximum possible volumetric airflow to the studied building is 118 m^3/s. Assuming that the whole Åhléns retail area had the same heat load patterns in the retail example and cooling was supplied with air only, the design flow would be close to 113 m^3/s, almost as much as what is able to supply to the whole building today. The Åhléns shop area only accounts for about 30 % of the total rentable area in the building, meaning that much larger areas than the ones currently used would be necessary to acquire if the whole building would be cooled using air only.

5.4.4 Flexibility and management of local cooling demand variations

Due to the large volumes and the extensive ductwork required for airborne heat removal, the flexibility is somewhat limited. Moving or adding a large duct to supply a new space with additional cooling power is technically more challenging than adding a chilled beam in the ceiling and supplying the room with a pipe of chilled water from the central system. Also, supplying a certain area with high cooling power by air requires a lot of space, which is hard to re-acquire for other purposes if the tenant or business would move and the cooling demands decrease.

In buildings where the use of the premises, the tenants or the layout often is changing, waterborne cooling offers better possibilities for adjusting the cooling system according to new demands. On the other hand, the placement of e.g. ceiling beams also can hinder layout changes or moved walls.

When using air for cooling purposes there might be necessary to install a subdivided system with different supply air temperatures for different areas, in order to avoid too low indoor air temperatures in spaces that are not frequently occupied. This can e.g. be done by installing re-heating coils in proximity to rooms with low occupancy to compensate for the cooling power from the supply air. This is not accounted for in this analysis and would result in an additional thermal energy demand to heat the already cooled air. Using waterborne cooling would offer possibilities of easier adaptation to local demands by adjusting the area of the chilled surface in each room to match the cooling demands.

5.4.5 VAV control issues

Using VAV with CO_2 control is done to ensure that all areas have the right amount of supply air at all times. In this way, both excess flows causing unnecessary energy use, and lack of fresh air, influencing the indoor climate negatively, is avoided. This is especially useful in areas where the people occupancy, and thereby the demand for fresh air, varies a lot.

One issue with the CO_2-control is how to facilitate control and establish the demand in a reliable way. An issue in areas like retail shops is the placement of the CO_2-

sensors. Few places are available due to all available space being used for commercial purposes and getting a fair picture of the demand is hard. In view of this, constant scheduled ventilation rates might be a better alternative.

Scheduled ventilation rates are suitable in retail areas since the flows of people are rather well-known due to its role as an important parameter for sales management, planning of campaigns, scheduling staff and purchasing. If the occupancy levels can be predicted in a reliable way, there is no need to install in a technically more complicated VAV-system requiring advanced control and reliable inputs to function properly. If the occupancy is known, a scheduled CAV-solution require roughly the same energy as a VAV-solution, according to the results in Figures 28 and 29.

6 Case study: Hydronic Cooling System Energy Performance and System Temperatures

To minimise the need for bought thermal energy, the thermal part of the energy demand in a hydronic cooling system can be covered in other ways using free thermal energy, as described in Chapter 3.4.3 and 3.4.4. This section aims to show how the cooling energy performance could be influenced by the use of free cooling with outdoor air and how the system temperatures influence the possibilities of free cooling extraction and in turn the cooling energy performance. Figure 33 marks the area targeted in this chapter and shows its role in the system providing the prerequisites for the building energy performance.

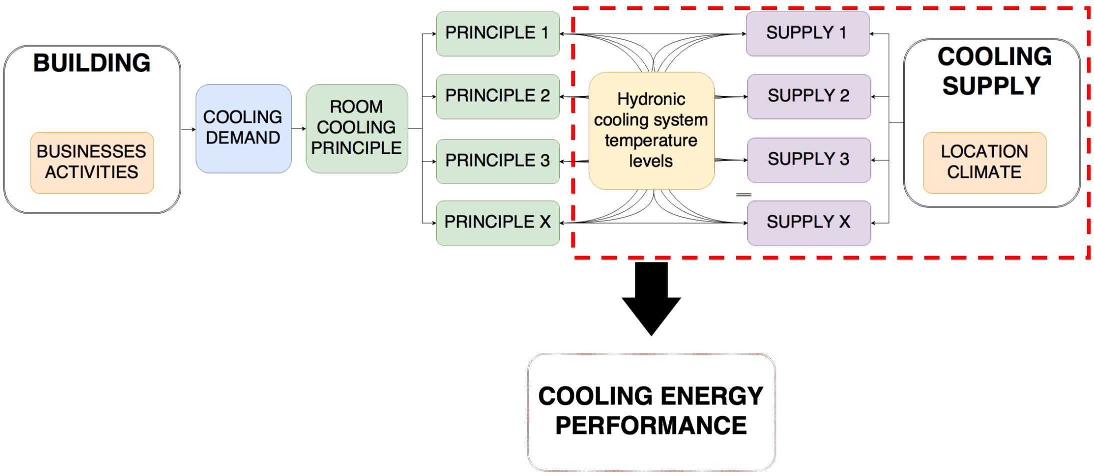


Figure 33. *Marking of the area covered in Chapter 6 and where it fits in to the system providing the prerequisites for the building energy performance.*

6.1 Free cooling possibilities in Object 6

In Object 6, the current hydronic cooling system utilises free cooling with outdoor air through one 430 kW dry cooler (an air-to-water heat exchanger) in the heat recovery circuit on the part of the hydronic cooling system supplying the room units (chilled beams and circulation units). Initially, two identical dry coolers were planned to be installed, and the circuit is designed and prepared for another dry cooler. This section evaluates the possible thermal energy savings of installing another similar dry cooler.

By analysing the bought energy and the outdoor temperature at the time of purchase, together with the possible power output from an additional dry cooler, an indication of the energy saving potential can be done. Due to variations from year to year in several inputs influencing both heat loads and cooling extraction possibilities (e.g. occupancy, outdoor temperatures, to which extent high internal heat loads coincides with hot outdoor temperatures etc.) the result will never be exact but can give an indication of a likely outcome. By using the design software AIACalc from the heat exchanger manufacturer LU-VE Sweden (2017) calculations of the power output at different outdoor temperatures have been performed. Figure 34 shows the duration of the maximum power output from the additional dry cooler in relation to the purchased district cooling during 2014 (i.e. the remaining cooling power demand) and the outdoor temperature.

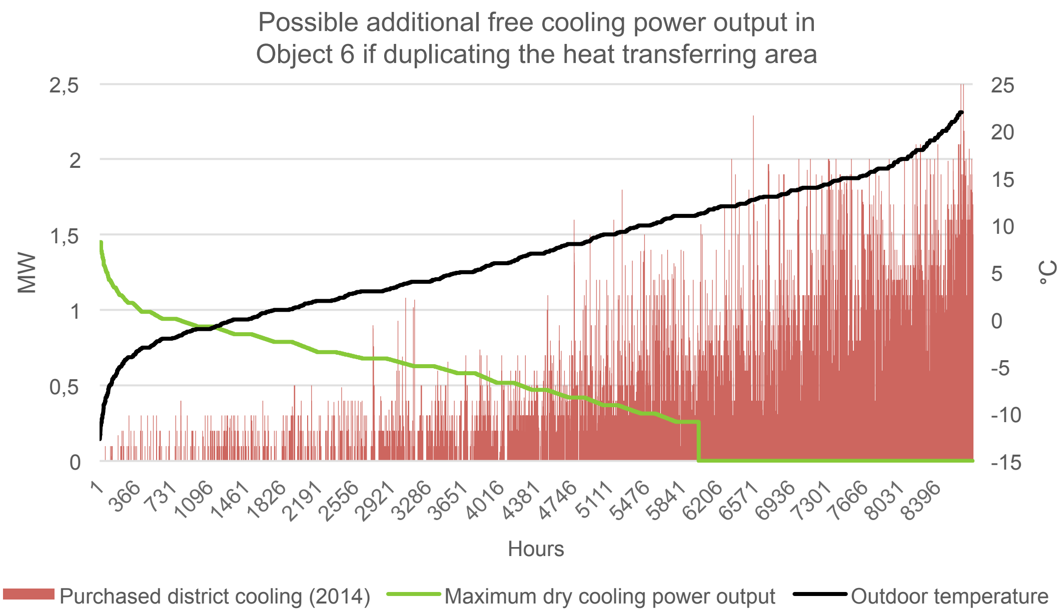


Figure 34. *Visualisation of the duration of the maximum power output in relation to the purchased district cooling (2014) and the outdoor temperature.*

Based on the levels of purchased district cooling from 2014 it would be possible to save 217 MWh thermal energy by installing the extra dry cooler (visualised in the graph as the area of the demand below the green line). Running a dry cooler do require electrical energy for the fans. Assuming the fans are operating on full power during all operation hours (a very conservative assumption since the fans can be run on part power when the demand is smaller than the maximum output) would result in an 11 MWh electricity demand. The actual energy saving would then be 206 MWh, corresponding to 9 % of the total purchased district cooling during 2014 or about 4.3 kWh/m^2 A_{temp} during one year.

As seen in Figure 31, there were substantial amounts of cooling purchased at rather low outdoor temperatures. In theory, the demand for cooling to the AHUs should be non-existing below the lowest supply air temperature (which is about 12 degrees), and the only demand remaining would be for room units. Since the room units are being supplied with a water temperature of 14 degrees and there during 2014 still was a large cooling demand at 14 degrees, an even larger part of the cooling demand would be able to be met with free cooling by outdoor air.

6.2 System temperatures considerations regarding free cooling extraction

After choosing a suitable cooling source to a hydronic cooling system, making sure that the system is operating as intended is a key parameter for avoiding unnecessary energy use and making sure the cooling system performs as intended.

The possibilities to utilise free cooling are influenced by the available outdoor air temperature, the available heat transferring area in the dry cooler as well as the flow and temperatures of the heat transferring fluid. As mentioned before, the hydronic cooling circuit is designed for a supply temperature of 14 °C and return temperature of 17 °C. Due to suspected overflows in the system the current system temperatures are about 14/15 °C instead. This contributes to unnecessary pump work and electricity use, but also to a decreased power output from the dry cooler. The next section visualises the impact of system temperature deviating from the design system temperatures.

Since the aim is to show the influence of deviating system temperatures, a simplified version of the real circuit is used and the influence of other parts of the circuit are neglected. Figure 35 shows a simplified sketch of the current principle for free cooling extraction. The dry cooler is designed to provide 430 kW at 8 °C outdoor temperature and is placed on a separate ethylene glycol circuit due to the risk of freezing. The fluid flow in the dry cooler circuit is 35 l/s and the heat exchanger connecting the dry cooler circuit to the return pipe of the high temperature part of the hydronic cooling system is designed to transfer 1100 kW from 16/13 °C on the dry cooler side to 14/17 °C on the hydronic side.

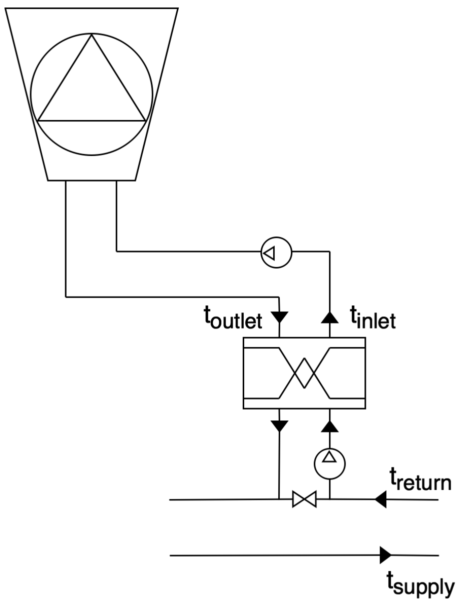


Figure 35*. Simplified sketch of the current dry cooler configuration with the supply, return, inlet and outlet temperatures marked.*

By using the design software AIACalc (LU-VE Sweden, 2017), calculations of the power output from the dry cooler at different inlet temperatures, have been performed. The simulated product was chosen to resemble the existing dry cooler in the building with regard to design properties. Beside the design inlet temperature, two additional inlet temperatures were used. Table 6 and Figure 36 show the temperature setups of the three different calculations.

Table 6. *Overview of used temperatures in the calculated scenarios. Notations according to Figure 28.*

		Design	Scenario 1	Scenario 2
t_{supply}	[°C]	14	14	14
t_{return}	[°C]	17	16.5	15.5
t_{inlet}	[°C]	16	15.5	14.5

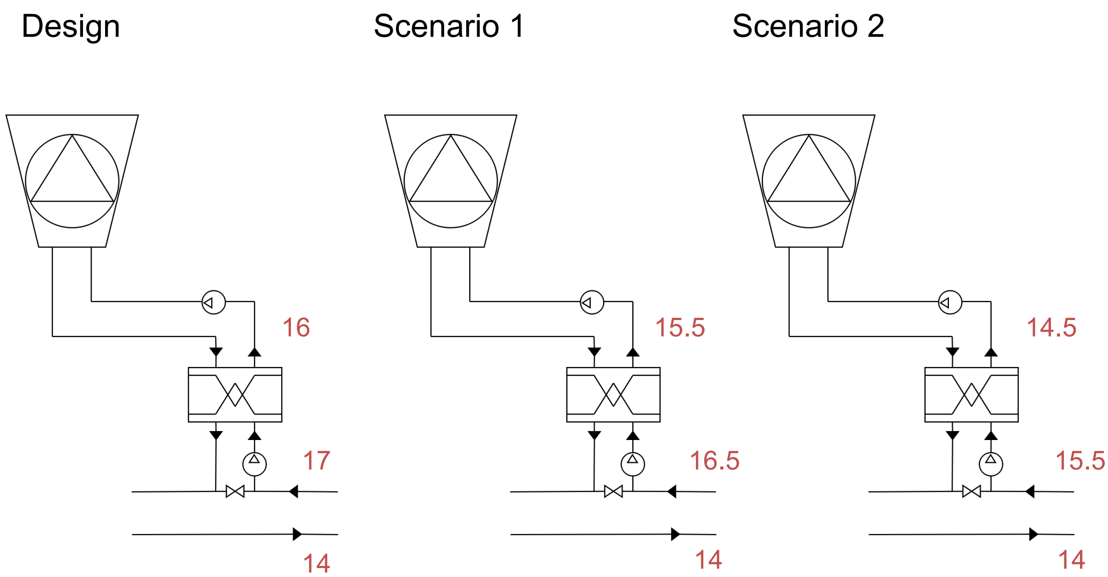


Figure 36. *Visualizations of the used temperatures in the calculated scenarios. Temperatures in [°C].*

Air and water flows through the dry cooler were assumed to be constant and maximised. The temperature drop over the heat exchanger was assumed to be 1 °C in all cases. The power output was then plotted as a function of the outdoor temperature for each inlet temperature according to Figure 37. At low inlet temperatures, the mean temperature difference becomes smaller hence the power output decreases.

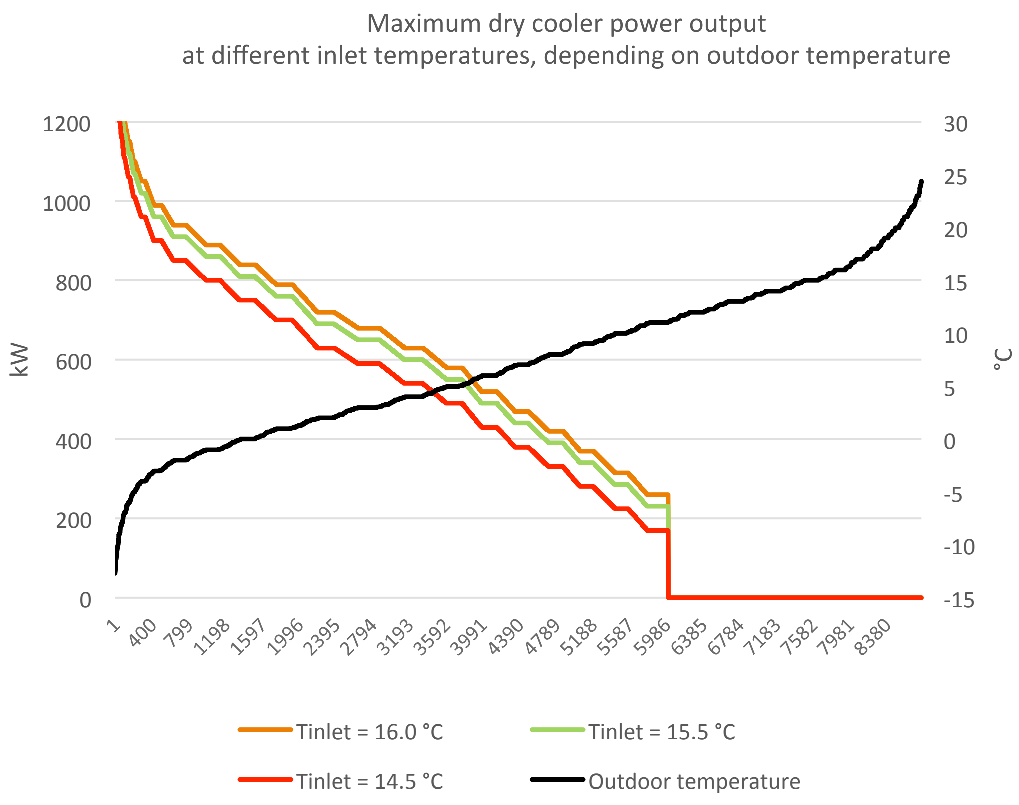


Figure 37. *Maximum power output from the dry cooler for different inlet temperatures as a function of the outdoor temperature.*

For every degree the inlet temperature decreases, the maximum power output decreases with 50 kW. Based on the demand for purchased district cooling power, shown in Figure 34, the difference in useful thermal power output from the dry cooler at different inlet temperatures can be calculated, and the decrease in “free” energy supply can be evaluated.

Assuming a system return temperature of 1.5 degrees below the design temperature, applied on the example with the additional dry cooler in Section 6.1, would result in a 48 MWh reduction of free thermal energy during one year. The fact that the system temperatures are too low also means the pump energy demand is unnecessary high, also contributing to impaired cooling energy performance.

7 Discussion and conclusions

In this chapter, the main findings of the thesis are summarised and discussed together the strengths and weaknesses of the chosen thesis methodology. Finally, conclusions are drawn and subjects suitable for further studies are targeted.

7.1 Summary and discussion

The aim of the thesis is to demonstrate an example of the cooling demands in a complex commercial building and show how the basic cooling energy demands vary depending on which principle is utilised for room heat removal. Another aim is to evaluate the possibilities of improving the hydronic cooling system energy performance by utilising available free cooling sources, and illustrate how the system temperatures can influence the cooling energy performance.

7.1.1 Case study: Mixed use retail building

The case study is an existing commercial building in Nordstan, Gothenburg. The building houses mainly retail and office areas and considerable amounts of energy are used for removal of surplus heat, all year round, due to large heat loads from people, lights and equipment in the building. The building cooling demands were analysed in Chapter 4 and showed the same patterns as described for commercial buildings in general, with cooling demands all year round, even at cold outdoor temperatures. In some areas, the cooling demand varied according to exterior circumstances like climate but the main influence was from the heat loads and activities inside the building.

Working with a case study, inducing local properties do make the study less general and decreases the possibilities for comparison with other objects. On the other hand, all buildings are different and the inputs to any mathematical model will differ, resulting in differing results as well. It is impossible to find two identical buildings with the exact same functions, used in the same way, therefore, studying a real case at least allows for a deeper insight to how the building group or type functions as long as differences and their impacts are kept in mind when applying the result in general.

Due to the size and complexity of the studied building, the energy model has been simplified and the building has been divided in a number of zones in the simulations. Simplifying the layout by working with fever zones than the actual room layout for the building, tends to decrease the building energy demand, according to Stensson (2010). In the office areas, a lot of people are working in the same place, contributing to large local heat loads and corresponding cooling demands. Local demands of this type are usually overseen if the zone division is too rough. In this case, the analyses regarding energy for heat removal easily can be scaled if there are larger cooling demands than the ones indicated and the results will show the same tendencies.

7.1.2 Room cooling principles, cooling energy demand and practical aspects

In the building, two main principles used for room heat removal were identified: ventilation air and chilled beams in office areas and ventilation air and circulation units in the retail areas. With the two main principles as a base, six additional alternative room cooling principles with different amounts of heat removed by air and waterborne systems respectively, were developed and in total, eight different principles were analyzed with regard to basic energy demand.

The results show that airborne cooling requires less energy to remove the same amount of heat as waterborne cooling. This is due to the utilisation of the free cooling effect from the outdoor air, which is possible to use as long as the outdoor air has a lower temperature than the desired supply air temperature. Furthermore, the analysis also shows that the largest part of the cooling energy demand corresponds to thermal energy required for the hydronic cooling system. Not considering the thermal source to the hydronic cooling system, airborne cooling appears to be the option with the smallest energy demand. However, the theoretical potential of utilising free cooling with outdoor air for the hydronic circuit as well, was also analysed. The results showed that all other room cooling principles have a potential of becoming as efficient as the airborne cooling, indicating that the cooling source for the hydronic cooling system is a key parameter when utilising waterborne heat removal.

Besides the energy aspects, there are several practical issues to consider when deciding which room cooling principle to use. Large outdoor airflows can influence the indoor climate and there is research testifying to both positive consequences such as increased productivity in offices and negative consequences in forms of dry air or high indoor air concentrations of outdoor air pollutants. Another aspect worth considering is the space issue, since airborne systems are identified as bulky and less flexible to changes, compared to waterborne systems. Waterborne systems were also concluded to be more suitable for managing local variations in cooling demand and the issue of gaining right input to VAV-systems in retail areas was addressed. The conclusion that can be drawn is that principles have their individual advantages and drawbacks and the local prerequisites needs to be evaluated when choosing which principle to use.

In buildings like the one in the case study, with changing businesses and heat loads, a combination of the energy efficient airborne cooling and the somewhat more flexible waterborne cooling might be a good solution. Focusing on free cooling sources for the hydronic system can create possibilities to achieve a good cooling energy performance as well as a well-functioning system with regard to practical aspects. In a simpler building with more homogenous use and heat loads, one room cooling principle could on the other hand be sufficient to meet the demands. Using airborne cooling only could then be a better option, both due to the good energy performance and the simpler and more manageable technical system, operation and control strategies.

7.1.3 Hydronic cooling system temperatures and cooling energy performance

To minimise the need for bought thermal energy, the thermal part of the energy demand in a hydronic cooling system can be covered in other ways using free thermal energy, as described in Chapter 3.4.3 and 3.4.4. In Chapter 6, the use of additional free cooling with outdoor air (besides the one already in use in the studied building) was analysed. Furthermore, the effect of system temperatures unintentionally deviating from the design temperatures on free cooling extraction possibilities was also analysed.

The analysis of the free cooling possibilities implicated that there is a continued potential of thermal energy savings if another dry cooler unit is installed. Based on the purchased district cooling during 2014 about 206 MWh or 4.3 kWh/m^2 A_{temp} could be saved through the use of another dry cooler like the one already installed. The results should be seen as indications rather than facts due to the output depending on several varying inputs, like the outdoor temperature, varying cooling demands, whether high internal heat loads coincide with hot outdoor temperatures etc. Predicting what will happen next year and the year after is practically impossible, but the outcome will likely be similar to the one presented.

Regarding the deviating system temperatures, the analysis showed that with the dry cooler currently installed in the studied building, each deviating degree of the return water temperature decreased the maximum power output from the dry cooler with 50 kW, contributing to larger demand for bought cooling energy and an impaired cooling energy performance.

7.2 Conclusions

The heat loads of the evaluated commercial building are partially influenced by the outdoor air temperature but the main influence are the heat loads from the activities inside the building.

The utilised room cooling principle was shown to have a large influence on the basic cooling energy demand. Airborne cooling have a lower energy demand since the free cooling effect from the outdoor air is possible to utilise during a large part of the year. Furthermore, the largest part of the cooling energy demand can be concluded to be the thermal energy demand for the hydronic cooling system. This means that the thermal cooling supply is a key parameter for the cooling energy performance when utilising waterborne cooling. The theoretical potential of utilising outdoor air for free cooling of the hydronic circuit as well, showed that the remaining cooling energy demand of the hydronic part could be in the same range as the basic demand for the airborne system.

Besides the energy aspects, there are also multiple practical considerations necessary to make when choosing which room cooling principle to use. The evaluated principles all have their individual advantages and drawbacks and close attention should be paid to the demands regarding the functionality and the thermal climate of different areas in a building, on both long and short term, in order to choose the best possible principle.

Regarding the system temperatures and the free cooling possibilities in the hydronic cooling system, the conclusion is that the studied building could benefit from an increased free cooling capacity. Another conclusion is that monitoring the functionality of the cooling system is important since every degree of decreased return water temperature decreases the free cooling output power from the installed dry cooler by 50 kW.

7.3 Recommendations for further work

One aspect not addressed in this thesis is possibility to extend the heat recovery solutions within the building. There are several simultaneous heating and cooling demands in the building throughout the whole year, creating good conditions for economically feasible heat recovery. With the knowledge about the influence, possibilities and restrictions of parts of the system provided in this report, an interesting continuation would be to work with the whole building on a system level, including both heating and cooling, optimizing the system as a whole.

Another interesting continuation could be to evaluate the possibilities of extended free cooling in combination with some type of heat storage to help reducing the peak cooling power demands that arise from the cooling coils in the AHUs during warm summer days.

8 References

Abel, E. (2003). The Energy Balance of a Building. In P. E. Nilsson (Ed.), *Achieving the Desired Indoor Climate - Energy Efficiency Aspects of System Design*. Gothenburg: Studentlitteratur.

Abel, E., & Elmroth, A. (2012). *Byggnaden som system* (3 ed.).

Arbetsmiljöverket. (2015). Temperatur och klimat. Retrieved from https://www.av.se/inomhusmiljo/temperatur-och-klimat/ (2017-01-04)

ASHRAE (2010) *ASHRAE greenguide: the design, construction, and operation of sustainable buildings* (Vol. 3rd). Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (2013) *2013 ASHRAE handbook: fundamentals* (SI ed.). Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Incorporation.

ASHRAE (2015) *2015 ASHRAE handbook: heating, ventilating, and air-conditioning applications* (SI ed.). Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (2017) ASHRAE International Weather Files For Energy Calculations 2.0 (IWEC2). Retrieved from https://www.ashrae.org/resources--publications/bookstore/iwec2 (2017-01-30)

Banks, D. (2012). *An introduction to thermogeology: ground source heating and cooling* (2nd;2. Aufl.;2; ed.). Hoboken, NJ: John Wiley & Sons, Ltd.

Bergsten, B. (2009). *Evaporative Cooling Tower and Chilled Beams. Design Aspects for Cooling in Office Buildings in Northern Europe.* (Ph. D. Thesis), Chalmers University of Technology, Gothenburg.

Boverket. (2014). Vad är en energideklaration? Retrieved from http://www.boverket.se/sv/byggande/energideklaration/vad-ar-en-energideklaration/ (0)

Boverket (2016) BFS 2016:13 BBR 24

Ekberg, L. E. (2003). An Introduction to Indoor Climate as a Concept. In P. E. Nilsson (Ed.), *Achieving the Desired Indoor Climate - Energy Efficient Aspects of System Design*. Gothenburg: Studentlitteratur.

European Comission. (2017a). Buildings. Retrieved from https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (2017-02-13)

European Comission. (2017b). EU Building Factsheets. Retrieved from https://ec.europa.eu/energy/en/eu-buildings-factsheets (2017-02-13)

Gicon (2017). Object 6: Energy Simulation Input Report.

Göteborg Energi. (2017). Lokala anvisningar för fjärrkyla - Göteborg Energi AB. Retrieved from https://www.goteborgenergi.se/Files/dok/produkter/Lokala%20anvisningar%20GE_2.pdf?TS=636105550967509212 (2017-04-05)

Jagemar, L. (2003). HVAC Systems. In P. E. Nilsson (Ed.), *Achieving the Desired Indoor Climate - Energy Efficient Aspects of System Design*. Gothenburg: Studentlitteratur.

LU-VE Sweden. (2017). Beräkningsprogram. Retrieved from http://www.aia.se/Default.aspx?PagId=96 (2017-04-28)

Nordstan. (2017). Nordstan för företag. Retrieved from http://nordstan.se/nordstan-for-foretag/ (2017-02-12)

Statens Energimyndighet. (2007). *Förbättrad energistatistik för lokaler - Stegvis STIL. Rapport för år 1. Inventeringar av kontor och förvaltningsbyggnader.* (ER 2007:34)

Statens Energimyndighet. (2015). *Energiläget 2015* (ET2015:08)

Stensson, S. (2010). *Energy efficiency in shopping malls: energy use and indoor climate.* (2010:1), Chalmers University of Technology, Gothenburg.

Stensson, S. (2014). *Energy Efficiency in Shopping Malls - Some Aspects Based on a Case Study.* (Dissertation/Thesis), Chalmers University of Technology, Gothenburg.

Svensk Fjärrvärme. (2012). *Fjärrkylecentralen Utförande och Installation. Tekniska Bestämmelser.*

Trüschel, A. (2003a). Generation of Heating and Cooling. In P. E. Nilsson (Ed.), *Achieving the Desired Indoor Climate - Energy Efficient Aspects of System Design*. Gothenburg: Studentlitteratur.

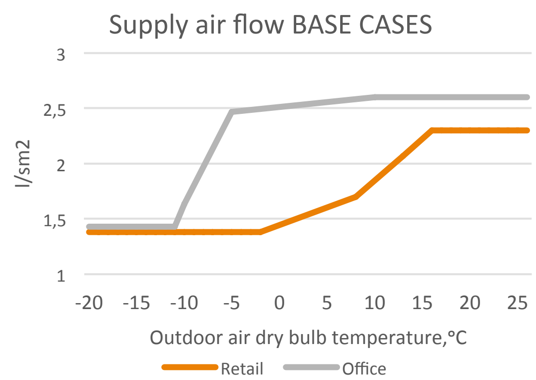
Trüschel, A. (2003b). Hydronic Heating and Cooling Systems. In P. E. Nilsson (Ed.), *Achieving the Desired Indoor Climate - Energy Efficient Aspects of System Design*. Gothenburg: Studentlitteratur.

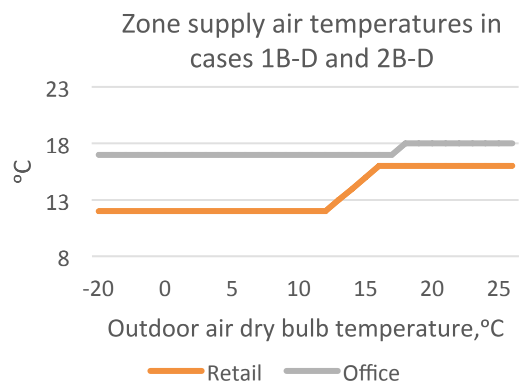
Vasakronan. (2016). *Annual Report 2016*. Retrieved from: http://vasakronan.se/wp-content/uploads/Vasakronan_arsredovisning_2016.pdf (2017-04-20)

Appendix I – Detailed inputs to alternative room cooling principle simulations

General assumpions and inputs

- Constant flows in hydronic circuits
- Alternatives B-D are presumed to include heat recovery
- $\eta_{pump + motor}$ = 0.55 in all cases
- Variable air flows in CUs
- CAV Hygiene air flows chosen according to: 0.35 l/sm^2 + 7 l/s and person
- CO_2 limits: max. 900 ppm in office areas and 1000 ppm in retail areas (outdoor concentration assumed to 400 ppm)
- Temperature setpoints: 18°C (heating) and 22°C (cooling)
- Energy for latent cooling included for AHUs and CUs





Inputs for ALTERNATIVE room cooling principle scenarios – retail areas

	2A (BASE)	2B	2C	2D
AHU				
Ventilation principle	Scheduled CAV	Scheduled hygiene flow	VAV	VAV
Ventilation control	Schedule + Outdoor temperature flow compensation	Schedule	Room CO_2-concentration	Room air temperature
Max air flow	6.75 m^3/s 2.3 l/sm^2	5.2 m^3/s 1.8 l/sm^2	5.2 m^3/s 1.8 l/sm^2	23.7 m^3/s 8.1 l/sm^2
Min air flow	2.5 m^3/s 1,43 l/sm^2	2.5 m^3/s 0.35 l/sm^2	2.5 m^3/s -	2.5 m^3/s -
Assumed SFP	2 kW/(m^3/s)	1.5 kW/(m^3/s)	1.5 kW/(m^3/s)	1.5 kW/(m^3/s)
Assumed waterside pressure drop in hydronic circuit	20 kPa	20 kPa	20 kPa	20 kPa
Calculated Pump Power	0.14 kW	0.73 kW	0.48 kW	
Additional cooling units	Circulation units	Circulation units	Circulation units	-
Total air flow (max)	3 m^3/s	5 m^3/s	5 m^3/s	-
Supply air temperature	15^0C	15^0C	15^0C	-
Assumed SFP	1 kW/(m^3/s)	1 kW/(m^3/s)	1 kW/(m^3/s)	-
Assumed waterside pressure drop in hydronic circuit	15 kPa	15 kPa	15 kPa	-
Δt water	6 (14/20)	6 (14/20)	6 (14/20)	-
Water flow (constant)	3.1 l/s	5 l/s	5 l/s	-
Pump Power	0.1 kW	0.13 kW	0.13 kW	-

Inputs for ALTERNATIVE room cooling principle scenarios – office areas

	1A (BASE)	1B	1C	1D
AHU				
Ventilation principle	Scheduled CAV	Scheduled hygiene flow	VAV	VAV
Ventilation control	Schedule + Outdoor temperature flow compensation	Schedule	Room CO2-concentration	Room air temperature
Max air flow	7.8 m3/s 2.8 l/sm^2	2.05 m3/s 0.75 l/sm^2	2.7 m3/s 0.95 l/sm^2	26 m3/s 9.3 l/sm^2
Min air flow	m^3/s 1,43 l/sm^2	1.6 m^3/s 0.6 l/sm^2	x m^3/s x l/sm^2	x m^3/s x l/sm^2
Assumed SFP	2 kW/(m^3/s)	1.5 kW/(m^3/s)	1.5 kW/(m^3/s)	1.5 kW/(m^3/s)
Assumed waterside pressure drop over coil	20 kPa	20 kPa	20 kPa	20 kPa
Additional cooling units	Chilled beams	Chilled beams	Chilled beams	-
Δt water	3 (14/17)	3 (14/17)	3 (14/17)	-
Water flow (constant)	5.6 l/s	8.4 l/s	5.6 l/s	-
Pump Power	0.46 kW	0.7 kW	0.46 kW	-