



CHALMERS
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Energy System Performance Investigation of Serneke Arena

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

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MASTER'S THESIS ACEX30

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Picture of Serneke Arena in Kviberg

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Department of Architecture and Civil Engineering

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ABSTRACT

Serneke Arena wanted to investigate methods to make the energy systems at the arena more effective. The arena has a high energy demand today where the indoor skiing facility Skidome responds to 33.8 % and 1.54 GWh of the total electricity use. The largest focus on energy efficiency measures was therefore on Skidome in this project.

With only three ski arenas built in Sweden, and a few more in the planning phase, the knowledge regarding optimal operation of indoor cross-country ski facilities are limited today. With little literature and few experts within the area this thesis was made to get a deeper understanding of how the indoor ski facility of Skidome in Göteborg could be more energy efficient.

The main task with the thesis was to create a deeper understanding about the system and how it is operated today and suggest improvements. The system has few sensors installed and the possibilities to get historical data and trends from the energy system was limited. Therefore, one part in the project was to identify temperatures and moisture levels in the ventilation air to Skidome, as well as flows and temperatures of the cooling process. This was made through several different measurements in the system with different methods.

Further five investigations were made to analyse how different actions would affect the energy performance of Serneke arena. The results shows that there are possible ways to make the energy system more efficient compared to how it operates today.

The coefficient of performance of the cooling machines was investigated and could be optimized for the cooling process and save up to 11.5% of the cooling machines total energy demand if the condensing temperature was reduced. The air handling unit operating in Skidome was investigated to determine how it performs today. There are optimization possibilities in terms of how it is operated in different outdoor conditions, to both reach a better temperature and dehumidification operation. The heat in the indirect warm stream in the condensing processes in the cooling machine is utilized 32% for heat recovery to heat pumps and 68% is cooled off in dry coolers. There are possibilities to save money by locally produce hot tap water instead of buying from the district heating net. The investigation to utilize existing boreholes for comfort cooling resulted in saving 2.2% of the total electricity use in Serneke arena.

Key words:

Indoor cross-country skiing, energy efficiency, energy performance, energy system improvements, cooling systems, artificial snow

Undersökning av Serneke Arenas Energisystem

Examensarbete inom mastersprogrammet Sustainable Energy Systems

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SAMMANFATTNING

Serneke arena ville undersöka metoder att göra anläggningen mer energieffektiv. Arenan har idag ett högt energibehov, varav 1,54 GWh går till inomhus skidanläggningen Skidome vilket motsvarar 33,8 % av totala elanvändningen.

Idag finns det tre inomhus skidanläggningar i Sverige, och några fler på gång, vilket gör att det är svårt att hitta kunskap gällande optimal drift av anläggningen. Lite litteratur och få experter inom området gör att examensarbetets syfte var att få en större förståelse för hur Skidome skulle kunna styras mer effektivt.

Huvuduppgiften med arbetet var att få en större förståelse för systemet, hur det styrs idag och hur det kan optimeras. Systemet har idag få sensorer, vilket gör att möjligheterna att få ut trender och historiska data är begränsade. Därmed var en del av arbetet att identifiera temperaturer och fuktnivåer i ventilationssystemet i Skidome samt flöden och temperaturer i kylsystemet, med hjälp av mätningar.

Fem olika undersökningar gjordes för att analysera hur de hade påverkat effektiviteten av energisystemet på Serneke Arena. Resultatet visar att det finns flera sätt att effektivisera energianvändningen jämfört med idag.

COP-värdet på kylmaskinerna undersöktes och visades kunna spara upp till 11,5 % av kylmaskinens totala energibehov genom att sänka kondenseringstemperaturen i kylmaskinen. Undersökningar av ventilationssystemets prestation i Skidome visar att det finns förbättringspotential för hur de drivs vid olika uteförhållanden för att förbättra avfuktungs- och kylprocessen. Den indirekta varma strömmen från kondenseringsprocessen i kylmaskinen återanvänder 32% av värmen till värmepumpar och 68 % kyls ner med fläktar. Det finns möjlighet att spara pengar genom att lokalt producera värme istället för att köpa värme från fjärrvärmenätet. Undersökningen att nyttja existerande borrhål till frikyla till komfortkyla visar att det skulle resultera i besparingar på 2,2 % av den totala elanvändningen på Serneke arena.

Nyckelord: inomhus skidanläggning, energieffektivisering, energiförbättringar, kylsystem, konstgjord snö

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Preface

The last semester has been an intense and developing period for us working with our master's thesis. We have gained knowledge and made research of a challenging energy system with few similar constructions in Sweden. We would like to take this opportunity to thank people who have supported us along the way. We want to thank Linda Fredriksson and Christopher Nilsson, our supervisors at Sweco, for supporting us along the way with new insights and giving us the opportunity to write this master's thesis. We want to thank Anders Trüschel and Torbjörn Lindholm, our examiners from Chalmers for support and development of the project. We also want to thank Michael Nyman and Orsi Ortiz, operating staff at Serneke Arena, for guidance and allowance of making measurements on site.

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Sara Larsson and Frida Ottosson

Nomenclature

Equation letters

C_p	Specific heat capacity [kJ/kg*K]
ε_{el}	Input electrical power [W]
\dot{m}	Mass flow [kg/s]
q_{cool}	Cooling power [W]
q_{heat}	Heat power [W]
RH	Relative Humidity [%]
ΔT	Temperature difference [°C]
X	Absolut humidity/moisture content [g/kg]

Abbreviations

AHU	Air handling unit
COP	Coefficient of performance
GWP	Global Warming Potential
ODP	Ozon Depleting Potential
SE3	Electrical price area 3 in Sweden, in area where Serneke Arena is located

Definitions

Accumulator tank	Water heat energy storage
Cooling machine	All equipment included that is required to produce the cool for Skidome. Consists of evaporator, condensers, compressors, and throttle as well as pumps and dry coolers.

1 Introduction

Serneke Arena is a multi-sports facility located in Kviberg in Gothenburg. Several activities take place there, such as full-scale soccer field, indoor cross-country skiing hall, sports halls, a hotel, school, and a gym. The facility is owned by Serneke and was also built by them in 2015 and Serneke has operated it ever since.

The arena is remarkable for having an indoor cross-country skiing arena, Skidome, at the bottom of the building. It is operated all year around and has a large cooling demand. Artificial snow is produced once a year when the snow is replaced in the ski hall. There is a large cooling demand and large temperature difference across the climate shell between Skidome and other facilities. There are also specific requirements of the air condition in the ski hall to achieve optimum snow quality for the skiers, these factors are just some that contribute to make the arena a rather complex building.

The operating staff experiences some challenges in the system due to the complex structure of the system and energy demand in the building. One such problem is air properties in the cold climate in Skidome which has a large impact on the equipment and envelope. There is also a general problem with the lack of possibilities to maneuver and monitor the cooling system with the current control system. This makes it harder to make operational improvements in the system as well as historical evaluations of the system's performance.

The thesis is received from the consultant firm Sweco, and in 2022 they accomplished an energy mapping of the building. After that mission was complete, it was established that a master thesis could be made to further investigate the arena's energy performance.

As a result of increased energy prices, Serneke Arena wants to investigate opportunities to reduce their energy use. In 2022 Serneke Arena totally used 4.57 GWh of electricity, the distribution of energy use in the arena is presented in Figure 1. During 2022 the arenas total consumed heat from Göteborg Energi's district heating net was 0.46 GWh.

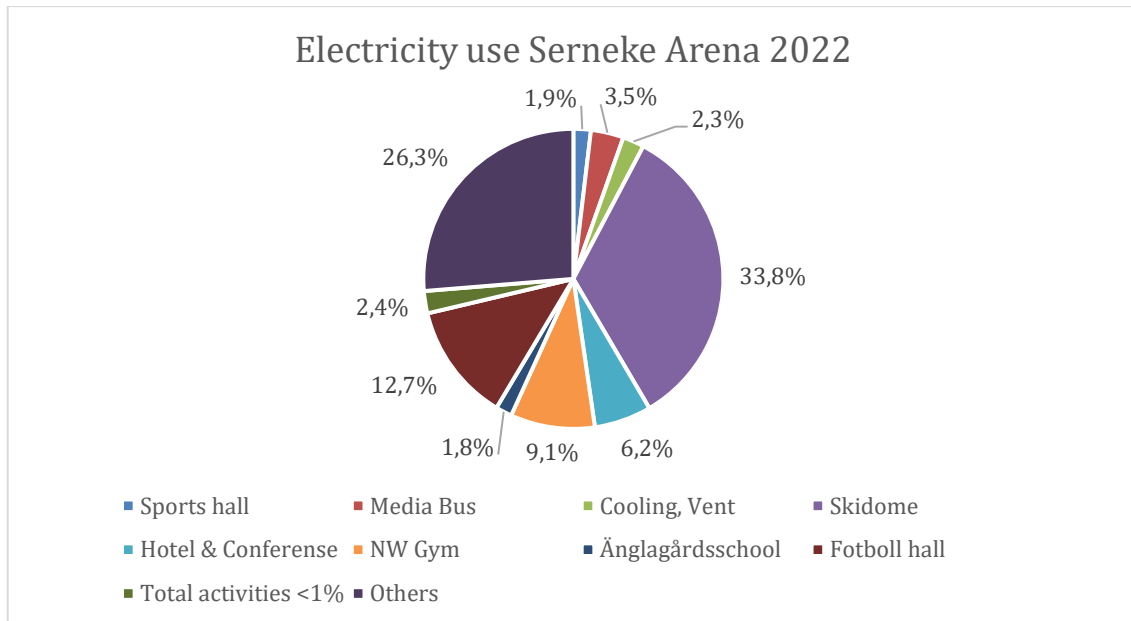


Figure 1: Share of electricity used in Serneke arena for each activity.

Figure 1 shows that Skidome has a share of 33.8% of the total electricity demand at Serneke arena during 2022 which corresponds to 1.54 GWh. This makes it convenient to have a large focus on this activity to reduce the total electricity used at the arena.

1.1 Project aim

The objective of the master thesis is to determine how the energy systems at Serneke Arena is constructed and how the cooling and heating system is operated today. It will create a good understanding of how the system is intended to operate and then compare with the actual operation.

The aim is then to present different investigations which consists of energy saving measures with improvements of the performance of the energy systems. The evaluations will be made from both an economic and energy savings perspective.

1.2 Limitations

The system boundary of the project is defined as the building of Serneke Arena. The project will treat the construction and performance of the energy systems, with extra focus on the cooling system for the indoor cross-country arena Skidome since it stands for 33.8% of the electricity use of the arena. The thesis will not include factors such as energy leakages from building structure.

1.3 Framing of questions

The study is aiming to answer the following questions. These are based on challenges and uncertainties in the energy systems today and are further analysed by several investigations in the report.

- Investigate the performance of the cooling machine at Skidome today. How can it be improved?
- How does the air properties change during the cooling process in Skidome?
- How is heat energy in the condensing stream from the cooling machines operated? How much is recovered and how much is wasted?
- Would it be beneficial to utilize the existing heat pumps for hot tap water production?
- What is the potential of utilizing existing boreholes for free cooling to cover the comfort cooling demand?

1.4 Preview of project method

In this section, a preview of the methodology of the thesis is presented. The method consists of different steps; literature review, case study, measurements, Mollier diagram analysis, and investigations.

1.4.1 Literature review

A literature review was made early in the project to enable a good understanding of the energy system considered. The different components were separately investigated in literature such as cooling coil, compressor cooling and heat pumps. The processes occurring in the system were also investigated, such as cooling process and how air behaves in different conditions in the cooling process. The snow production system which is more specific for the Skidome activity was also investigated. As well as boreholes utilized for heating and the different refrigerants used in the system.

1.4.2 Case study

To create an overview of the energy system at Serneke Arena, drawings were studied and study visits at site were made to get a full picture of the system. Schematic drawing over the cooling system was made to improve the understanding of the cooling system. Electricity use trends were extracted as well as heat energy use. These were analysed in diagrams to facilitate the interpretation. The activity with largest energy use was determined, and further investigations could then be made.

Study visits was made at sites with a similar demand of high cooling demand and high people activity within the climate shell. The purpose with the visits was to find how different challenges in the cooling systems was handled by the different sites.

1.4.3 Measurements

The arena has limited monitoring equipment up running in the energy systems which makes it difficult to analyze trends and historical data. Therefore, measurements were made to identify relevant temperatures and flows in both the cooling and heating system and get a better understanding of energy distributions.

1.4.4 Mollier diagram analysis

The results from the measurements in the cooling process were then evaluated in Mollier diagrams. This to detect the performance of the different components and determine moisture content of the air at different stages in the air-cooling process.

1.4.5 Investigations

The last step in the methodology was to evaluate five different investigations created from energy system challenges and potential improvements. The investigations correspond to the framing of questions presented in previous chapter 1.3.

- Coefficient of performance of the cooling machine
- Performance of Skidomes AHU
- Heat recovery from cooling machine
- Using heat pump for hot tap water production
- Utilize boreholes for comfort cooling

The five investigations were evaluated to determine the energy performance of the energy systems as well as energy saving improvements in the system.

2 Theory

This chapter will include theory within areas considered in the project of cooling-, heating- and ventilation systems. Mollier charts will be introduced that can be used to investigate air properties during different operations of the ventilation. Knowledge about a certain component or process is also presented in this chapter.

2.1 Cooling system

In this section, different cooling system components are presented which are relevant for this report.

In the cooling system a refrigerant, a cooling media, is used to transport heating energy away from where cool is needed in the system to the cooling machine where the heat is transferred to another refrigerant with higher temperature. The system is closed meaning that the refrigerant is flowing around and do not leak to the surroundings outside the system.

By changing the properties of the refrigerant, so it undergoes phase change, energy can be supplied or extracted from the process (Ekroth & Granryd, 2005). To make a media change phase, for example from liquid to gas, extra heat must be added for the phase change. If no phase change occurs, the temperature is directly correlated to the heat added to the refrigerant. If the fluid goes from gas to liquid heat will instead be extracted.

A cooling machine consists of four components: an evaporator, a compressor, a condenser, and an expansion valve with a refrigerant flowing through the components. The components are connected in a closed circuit where the refrigerant is exposed to phase changes over the components. The phases of the refrigerant in the cooling machine are presented in the pressure-enthalpy diagram in Figure 2.

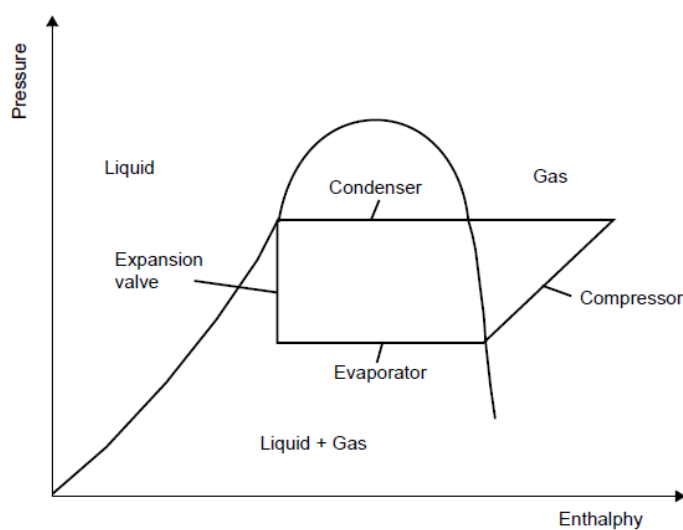


Figure 2: Pressure-Enthalpy diagram of a cooling machine.

In the evaporator the refrigerant evaporates, resulting in a phase change from liquid to gas, see bottom line in Figure 2. This is made by adding heat to the process from an indirect system to make the refrigerant undergo the phase change. The result is a colder temperature in the indirect system of the evaporator, which then can be used for the cooling demand.

The compressor is located after the evaporator and compresses the gas, resulting in higher temperature and higher pressure, which can be seen in Figure 2.

After the compressor a condenser is located. The condenser is like an evaporator but with the opposite function. Heat is removed from the cooling machine and added to a separate indirect system. The indirect system needs to be cooled off and can therefore be utilized for heat recovery for heating demands such as hot tap water or comfort heating.

After the evaporator an expansion valve is located that reduce the pressure of the refrigerant. Lower pressure results in reduced boiling temperature meaning that at constant temperature some refrigerants undergo phase change back to liquid phase. The refrigerant is then a mixture of liquid and gas after the expansion valve.

To calculate the coefficient of performance (COP) of a cooling machine the input power is compared to the cooling power that is being produced with Equation 1.

$$COP_{cool} = \frac{q_{cool}}{\varepsilon_{el}} \quad (1)$$

Where q_{cool} is the cooling power produced and ε_{el} is the input electric power required.

2.1.1 Direct and indirect cooling systems

How the cooling energy is delivered from the cooling machine to the cooling need, can either be through a direct or an indirect cooling system.

A direct cooling system means that the cool is removed directly with the cooling machine, and not heat exchanged to separate systems. A direct system requires larger volumes of refrigerants that is pumped through the system compared to an indirect system (Shirvani Armin & Youssef Rana, 2018). A direct system is illustrated in Figure 3, where the topmost component illustrates a compressor, the components in the middle represent a heating and cooling need and the bottom component is a throttle.

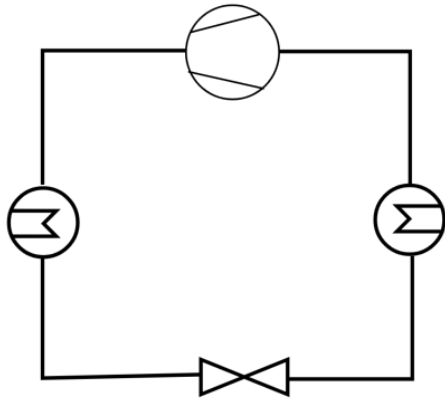


Figure 3: System description of a direct cooling system.

An indirect cooling system is more commonly used at large facilities. The direct system is then connected to one or several indirect cooling systems by exchanging heat or cool, see Figure 4. In Figure 4 does the newly introduced figures represent heat exchangers, often plate heat exchangers.

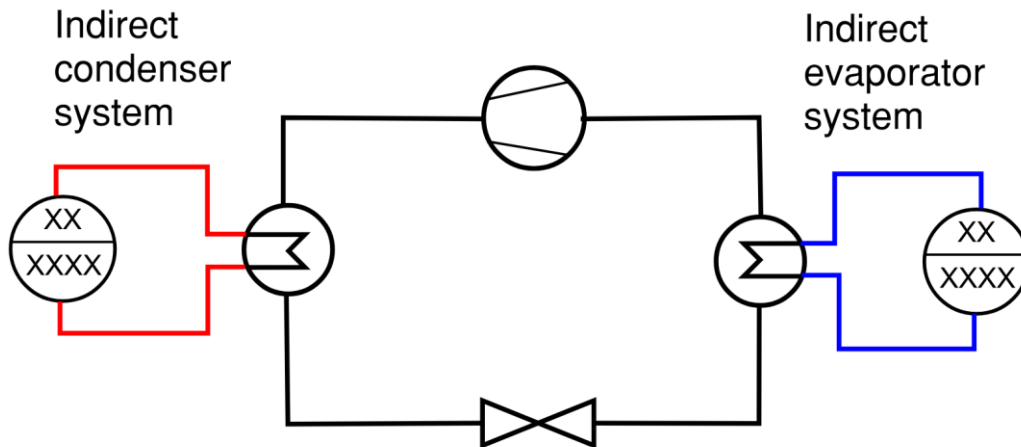


Figure 4: System description of an indirect cooling system.

The indirect condensing stream is heated by the condensing process of the refrigerant, which can be utilized to cover a heat demand. The indirect evaporator system is cooled and can supply a cooling demand.

2.1.2 Refrigerants

Refrigerants are the cool carrier removing heat from locations where cooling is needed, either through direct or indirect cooling. The refrigerant can either be a non-mixed refrigerant substance or a water mixed refrigerant.

Non-mixed refrigerant substances are used in direct cooling systems where the components of the cooling machine or in circuits where the transporting distance of the cooling is short. Non-mixed refrigerants are used in cooling machines, where the phase change conditions are utilised to access heat or cool from the production.

Different refrigerant substances have different phase change temperatures which means that the operating temperature and pressure of the system limits which refrigerant that can be used.

Many non-mixed refrigerant substances are harmful and has large effects on the global warming potential (GWP) and the destruction of the ozone layer with the ozone depletion potential (ODP). Regulations from the Montreal Protocol and the Kyoto Protocol is eliminating the use of harmful refrigerants that affects the ozone layer and the global warming (Algol Chemicals, 2023).

For larger systems the non-mixed refrigerant substance is usually connected to an indirect system. A heat exchanger is utilized to exchange heat to a separate water mixed refrigerant in a separate system.

Benefits of having a separate system for the energy transportation is that less energy is required to pump the liquid through the system compared to compressing a gas with compressors (Duván Chaverra Agudelo, 2020). Another benefit is that water-based flows does not have as high requirements on material properties as gas flows that has to handle high pressures. But the main benefit is that fewer non-mixed refrigerant substances are needed which results in lower impact on the environment at large facilities.

Three examples of water mixed refrigerants that can be used in indirect systems are pure water, brines and glycols.

Pure water-based systems have good thermal conductivity, does not affect the environment and is cheap. However, a drawback with this cooling system the limitation to temperature ranges above 0°C to be able to pump it through the system.

Brines are salt mixed with water; has lower freezing temperature compared to pure water which makes it possible to use in cooling systems to produce temperatures below 0°C. With higher concentrations of salt, the freezing temperature of the water mixture is reduced, until it reaches a maximal concentration, a so-called eutectic concentration, when the freezing temperature increase with higher concentrations (U.S. Department of Transportation, 2023). Adding salts into the water makes it corrosive at some metals which is not beneficial for some types of pipe materials. To avoid this problem, it can be added inhibitors to the media.

Glycols mixed with water is simple to operate, but as a refrigerant it is seldom used. The strengths with glycol are high viscosity and not being toxic but the disadvantage are higher pumping cost and lower heat transfer capacity.

2.1.3 Free cooling

In a cooling process one could utilize free cooling to reduce the amount of power needed to produce cooling. The free cooling could be described by for example utilizing the outdoor air to cool the indoor air while the outdoor temperature is below the wanted cooling temperature inside.

Free cooling could utilize boreholes for cooling when the temperature in the borehole is below the wanted cooling temperature inside. It is also beneficial for the borehole efficiency if heat is extracted during winter and supplied during summer (Swegon, 2023). A more stable temperature in the borehole is then kept because there is a risk of lowering the total temperature in the borehole if only heat is extracted from the borehole.

2.2 Heating system

In this section, different components in a heating system are described like heat pumps, district heating and heat exchangers.

2.2.1 Heat pump

A heat pump is a closed system similar to a cooling machine. It consists of the same four components; an evaporator, expansion valve, condenser, and a compressor with the same functions as they have in a cooling machine, see Section 2.1.

The purpose with a heat pump is to produce heat, meaning that it produces as much heat as possible over the condensers to the indirect condensing system. When choosing refrigerants, the main factor to take into consideration is the condensing temperature and its conditions.

To calculate the COP of a heat pump, a similar equation as for the cooling machine, Equation 1, can be used. Equation 2 is used to calculate the COP of a heat pump:

$$COP_{heat} = \frac{q_{heat}}{\varepsilon_{el}}. \quad (2)$$

Where q_{heat} is the heat produced with the heat pump and ε_{el} is the required electricity.

2.2.2 District heating

District heating is a common heating system in larger cities today. The district heating system is built up with central heat production units that distribute heat. The heat is often in forms of hot tap water to supply the citizens through district heating pipes located in the ground below the city.

The central production unit can produce heat with different methods, like burning waste products, large scale heat pumps or burning fuels, or take up waste heat from industries in the city. The industries then sell the heat to the district heating company.

The advantage of having a building connected to a district heating system is that they often are operated on renewable fuels, it reduces the work input of the property owner and require less space in the property.

The cost of district heating depends on where you live. Göteborgs Energi operate the district heating system in Gothenburg. The pricing of district heating from Göteborgs Energi depends on three factors, the energy use, the return temperature, and the highest mean effect from last twelve months (Göteborgs Energi, 2023).

Consumers energy price differs every month over the year, and a consumer pay for the energy it uses a specific month with the price set for the same period.

If the return temperature from a property is higher than the average in the system, the property owner must pay extra for each MWh and temperature difference. If the return temperature is lower than the system averages the property owner instead gets money in return.

The third parameter affecting the price of the district heating is the highest required mean power needed for a three-day period in the last twelve calendar months. The average power then sets a fixed price that must be paid each year and a variable price that is multiplied with the power to get the yearly cost. If the average power is higher the cost is higher.

2.2.3 Heat exchanger

The purpose of a heat exchanger is either to cool or heat an energy carrier. There are several different kinds of heat exchangers designed for different purposes. The main function is that thermal energy is transferred from the warmer fluid to the colder one.

Heat exchangers can be divided into two categories by their construction, recuperative and regenerative (Brogan, 2011). In recuperative heat exchangers the energy carriers are never mixed meaning that this can be used for closed systems. The carriers pass through one or several heat conducting layers. Examples of recuperative heat exchangers are plate- or tube and shell heat exchanger. A plate heat exchanger is built up of several plates stacked close to each other. In between these plates the warmer and colder energy carrier flows through every second space between the plates. The warmer carrier is cooled down and the colder medium is heated up but is never mixed. A tube and shell heat exchanger has one of the carriers flowing through the pipes and the other flows pass the tubes within the shell.

The second category of heat exchangers are regenerative exchangers. These store heat temporarily in a medium which then is being released into the cold carrier. An example of this can be a rotary heat exchanger, which consists of a rotating wheel in which the warmer energy carrier passes through the rotating wheel and heat the wheel up and then release the heat into the cold stream and heat it up. Rotary exchangers are usually used in ventilation systems to recover heat or cool. Since the system is not a closed system there is a risk of smell and particles from the exhaust air entering the supply air. With a rotary heat exchanger, it is possible to recover moisture with the exchanger.

2.3 Ventilation systems

A ventilation system for comfort cooling is built up by an air handling unit, AHU. The AHU takes air from outdoors and heats or cools it before it enters the room. It also filters away some of the pollutants.

The AHU also handles the extract air that leaves the indoor air before it is released outdoors. Some AHUs also have heat recovery, by using the extract air to heat up the supply air. Other components that can be used for specific systems are humidifiers or dehumidifiers to control the moisture content of the incoming air.

2.3.1 Mollier Diagram

Air properties could be evaluated by utilizing a Mollier diagram, Appendix A. It is a psychometric diagram which can explain the air properties in different conditions with factors such as relative humidity, enthalpy, absolute humidity, and temperature (Swegon, 2022). Different processes could be inserted to the diagram and air properties could be extracted for each stage in the process. Dew point and moisture content of the air can be detected which can have a large impact of the process performance.

The difference between the relative humidity (RH) and absolute humidity (x) is important to have in mind. This since the relative humidity is a factor of the total amount of moist possible to keep in the air at a certain temperature. While the absolute humidity is the actual amount of moisture possible to keep in the air.

2.3.2 Dehumidification of ventilation air

In buildings with high requirements on the humidity of the incoming air, sometimes dehumidification of the air can be required. There are four ways to lower the humidity/relative humidity of moist air: (1) dilute with dry air, (2) sorbent drying, (3) refrigerant dehumidifying and (4) heating (G.W. Brundrett, 1987).

Dilute with dry air is the result of cooled air without changing the absolute humidity of the air. When the air expands the air will be chilled and the moisture deposited. This is an old method that is not used anymore.

Sorbent drying are divided into two main categories, adsorbents, and absorbents. Adsorbents are solids with large heat exchanging area where water molecules from the moist air condense on the surface. Absorbents are hygroscopic material which change their nature when absorbing moist.

Refrigerant dehumidification is made by letting the air flow over a surface which has a lower temperature than the dewpoint of the air. This will result in condensation on the surface. According to Brundrett (1987), the air is then heated up to same temperature as before but with a lower relative humidity.

Heating is made by adding heating energy to the air without affecting the actual humidity. By looking at a Mollier chart, which is described in Section 2.3.1, one can see that this will lower the relative humidity of the air for the condition after the heating.

2.3.3 Cooling coils

Cooling coils are utilized for air cooling in the ventilation system. It is a similar design as a tube and shell heat exchanger, described in Section 0, and work with cold fluid flowing inside the coils and air is flowing over the coils through fins.

The refrigerant flowing through the tubes have different temperatures depending on the cooling need. For comfort cooling the temperatures of the refrigerant are higher compared to if the air is cooled to below 0°C.

If cooling is required for temperatures below 0°C, for example for a freezer, there is a risk of condensation of moist in the air which might freeze around the pipes. This occurs due to lower dew point of the air with lower temperatures. Ice formation around the pipes reduces the cooling capacity of the cooling coil.

To prevent ice coating around tubes there are mainly two ways, either by dehumidification of the air so the air never reaches the dewpoint over the cooling coil while the air temperature is below 0°C or by heating up the coils to melt the ice. The heating of the coils can be made by letting warmer fluid flow through the pipe regularly or by installing electric rods that also melts the ice regularly.

3 Case study

A closer description of the components of the cooling, heating and ventilation system at Serneke arena is described in this chapter and the energy performance of the system today. Specific contributors that are needed for an indoor cross-country skiing facility are also introduced. Study visits were made at two similar sites Oasen and Torsby Ski tunnel. Comparisons between their energy system and Serneke arenas was made.

Schematic overviews were made of the systems, all figures are simplified with details missing to create a better overview of the system.

3.1 Serneke Arena

The case study of Serneke arenas energy systems is presented in this section with a closer description of how the systems works today, its components, set temperatures, and pressures.

3.1.1 Cooling system

The cooling system in Serneke arena is divided into two systems. The first system provides cool to Skidome through an indirect cooling system that both deliver cool to cooling pipes and to the cooling coils in the AHU for the air to the ski hall, Figure 5. The second cooling system provides comfort cooling for the rest of the facilities in the building.

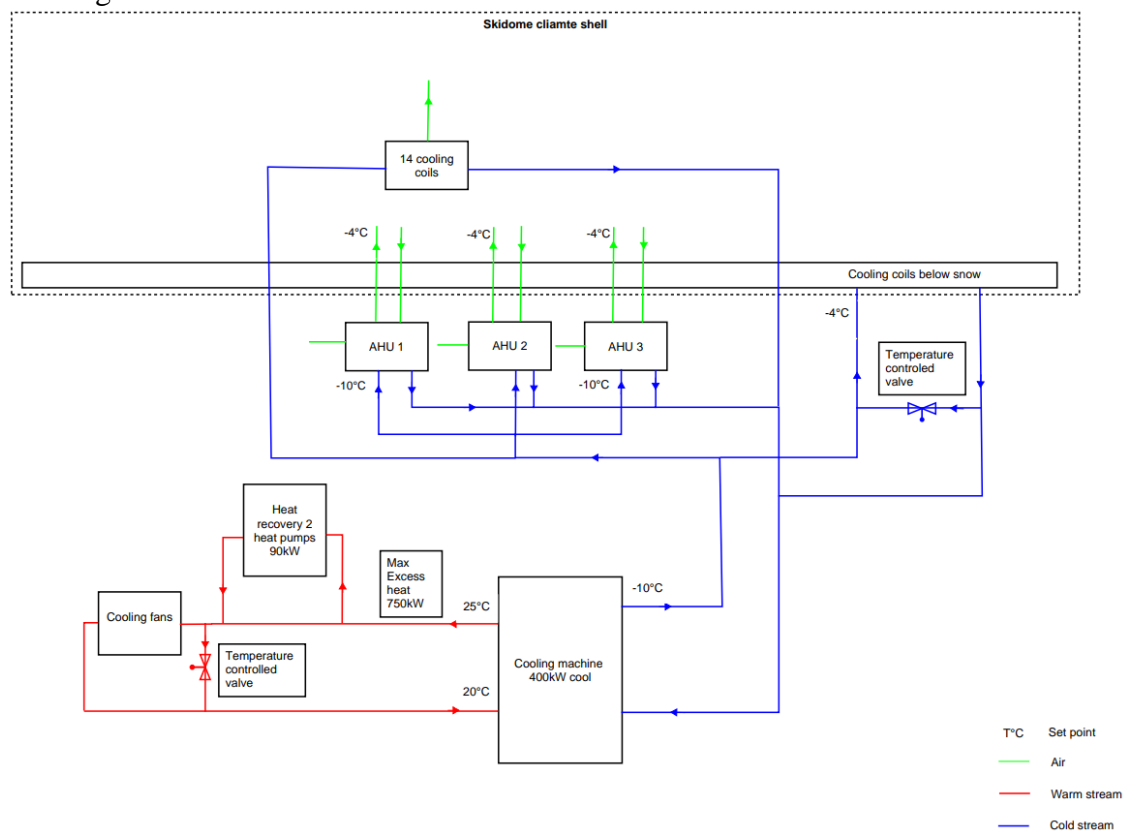


Figure 5: Schematic overview cooling system to Skidome.

The cooling system for Skidome is an indirect cooling system connected to the evaporating side of the cooling machine. The cooling machine is build-up of four compressors, four condensers, an expansion valve, and an evaporator. The refrigerant in the cooling machine is R507. There are two indirect systems connected to the cooling machine, one connecting to the condensers to recover heat and the other to the evaporator to utilize the cool, Figure 6.

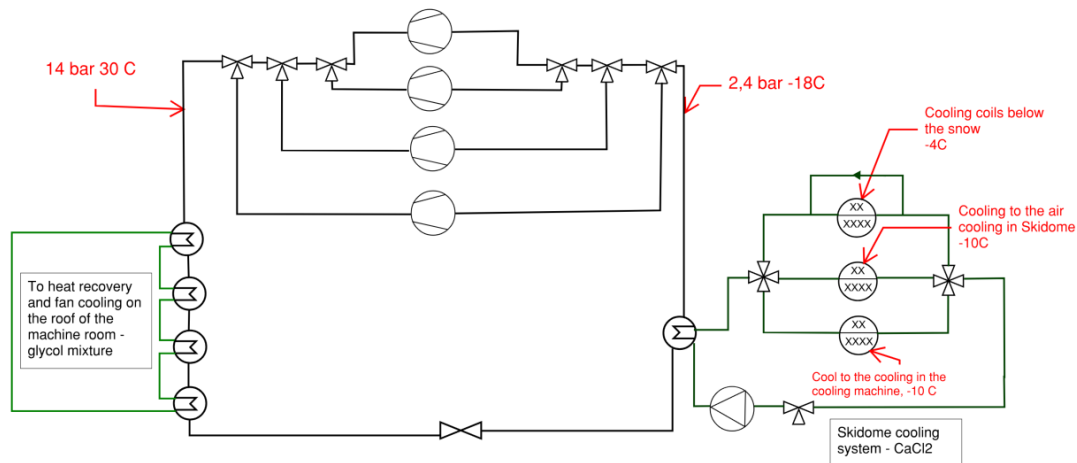


Figure 6: Cooling process overview of the cooling machine for cool to Skidome.

The compressor cooling consists of four compressors working strategically depending on the cooling demand and operating time of each compressor. The load is evenly distributed over the compressors to keep the operation hours similar. The cooling carrier is a brine solution of calcium chloride, CaCl_2 , and is utilized both for cooling under the snow as well as for air cooling.

The indirect evaporator systems are cooled from the R507 system to a separate brine system. The brine solution is connected to two cooling needs in Skidome, the cooling pipes, the cooling coils in the AHU. The brine to the AHU is distributed both for the cooling of the fresh air before entering ski hall as well as the air cooling coils inside the ski hall.

The two cooling purposes have different demand in temperature, where the cooling pipes below the snow require a temperature of $-4\text{ }^\circ\text{C}$ while the ventilation cool require $-10\text{ }^\circ\text{C}$ for operation. Therefore, the cooling fluid are shunted to a higher temperature using the return fluid from the cooling pipes to reach $-4\text{ }^\circ\text{C}$ for the snow cooling.

The indirect condensing system recover heat over the condensers and is presented in Figure 7. There is a special valve working to regulate the indirect condenser system to maintain a certain temperature of $20\text{ }^\circ\text{C}$ at the returning stream to the condenser from the indirect stream. If the returning stream from the dry coolers, Figure 8, and heat recovery is below the set point temperature, the valve opens, and the stream is shunted up by the ingoing stream. This to regulate the return temperature in the condensing process in the cooling machine.

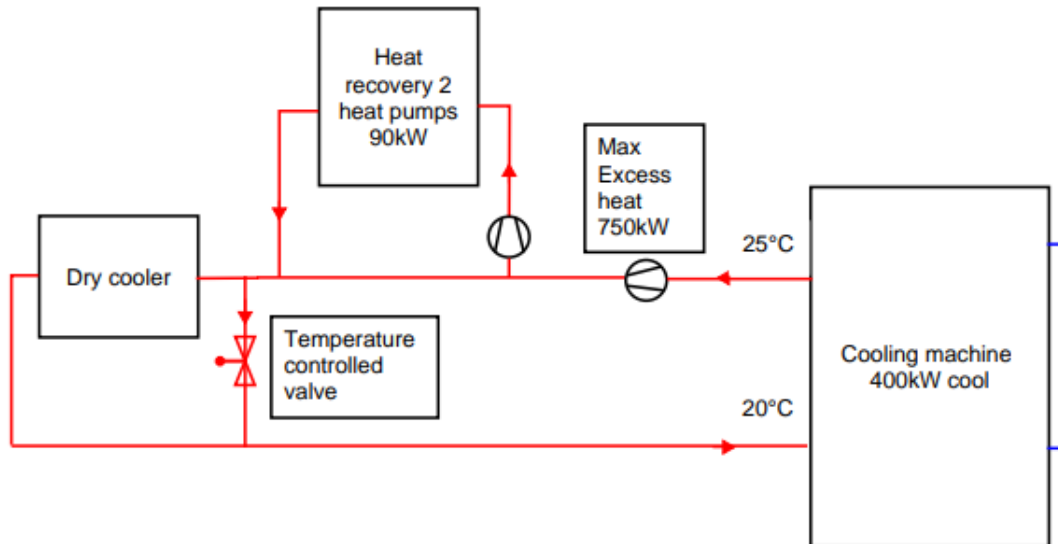


Figure 7: Indirect condensing system in the cooling machine.



Figure 8: Dry coolers for the condensing process in the cooling machine.

The theoretically maximum excess heat from the cooling machine was extracted from process description documents and is determined to be 750 kW. The plate heat exchanger capacity for the heat recovery to heat pumps is determined to be 90 kW. The warm indirect system from the condensing side in the cooling machine has a theoretical temperature of 25°C inlet temperature and 20 °C outlet.

For the other activities in the multifacility of Serneke Arena a separate AHU is installed for the comfort cooling and are not connected with the cooling system for Skidome. An accumulator tank is connected to the system that can store cool and create a more efficient comfort cooling system.

3.1.2 Heating system

The heating system in Serneke arena is divided into two systems one for comfort heating and one for hot tap water. The system for comfort heating is based on seven heat pumps, Figure 9, combined with district heating from Göteborg Energi.



Figure 9: Heat pumps for comfort heating in Serneke arena.

Two of the heat pumps are working with heat that is being recovered from the condensing heat from the cooling machine, which is transferred to the heating system through a 90 kW plate heat exchanger. If the heat recovery system is not able to produce enough heat, five more heat pumps are available that utilize existing boreholes as heat source. If all the seven heat pumps cannot produce enough heat at a time, the district heating system is the last heat source to complement. A schematic overview of the heating system is showed in Figure 10.

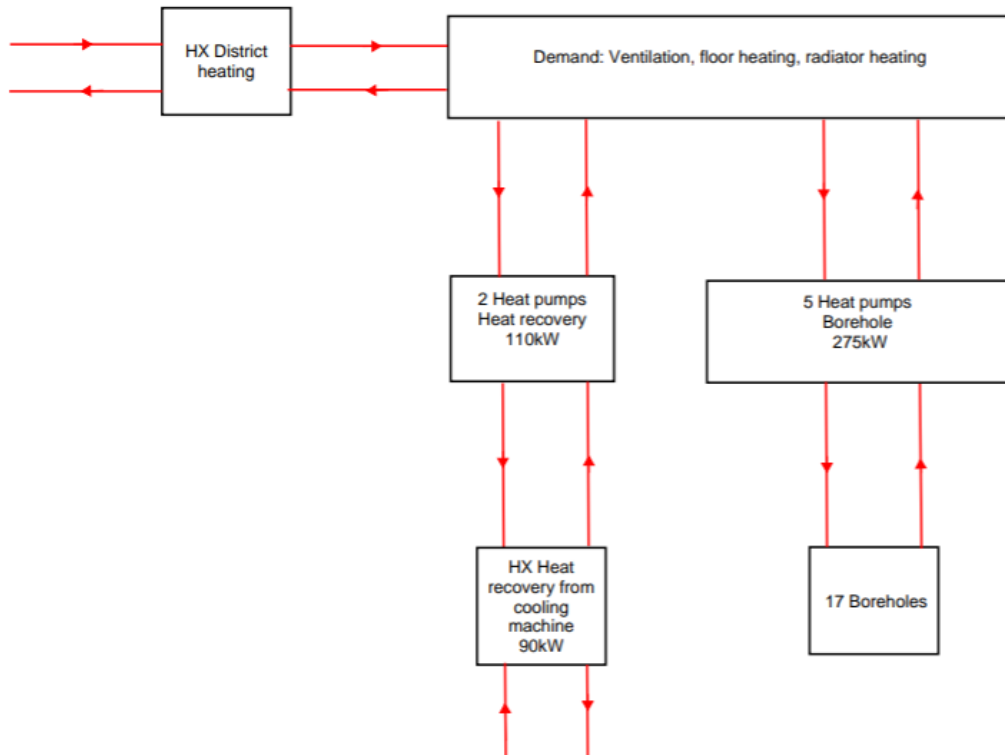


Figure 10: Sketch over the heating system at Serneke Arena.

The recovered condensing heat from the cooling machine is dimensioned to enter the heat exchanger as a glycol mixture at a temperature of 35 °C and leave at 27 °C, which differs from the measured in the system and presented in Figure 7. The supply refrigerant to the heat recovery heat pumps is then heated up from 24 °C to 28 °C at a flow of 2.9 l/s.

The boreholes are connected to the heat pumps to produce heat. Simultaneously, a valve can switch to make it possible to utilize the boreholes as a source for both heat to the heat pumps and cool for the comfort cooling facilities in the arena. However, the free cooling solution is not in operation because of system issues.

The operation of the heat pumps is made to primary produce heat with the two heat pumps connected to heat recovery. Secondly, the other five pumps connected to the boreholes produce heat. The heat pumps are programmed to evenly distribute the load and number of operating hours between the heat pumps.

One accumulator tank is available for heat storage but is not installed and is not able to use in the process today. Hot tap water for all facilities is supplied from Göteborg Energi's district heating net, no local production of hot tap water is done in the arena today.

3.1.3 Ventilation system for Skidome

The ventilation cooling in Skidome is made in two steps. The first step is initially performed in air handling units (AHU). There is three AHU which are located on the same side outside of Skidomes northern wall. The AHUs are lowered into ground pits and preserved in large boxes, Figure 11. The three AHUs are identical, and each consists of a rotary heat exchanger and a cooling coil. The rotary heat exchanger works with the outdoor air and exhaust air from Skidome. If the rotational heat exchanger does not cool enough to the set point temperature, the air will be further cooled by a cooling coil. The cooling coil has a circulating brine solution supplied by the cooling machine and lets the air flow over the coils. The air then enters Skidomes climate shell through several different channels to spread out the inlet air.



Figure 11: Three AHU located down in a ground pit outside the northern wall of Skidome.

The second step of the ventilation cooling to Skidome is circulation of the air inside the climate shell as well as further cooling inside, which is done by 14 cooling coils, Figure 12. Each cooling coil is connected to a fan that sucks the air into the cooling coil and then transports the air through a long ventilation sock which distributes the air in the ski hall with a set point of the indoor air at -4°C . The cooling coil inside the climate shell is, as well as the cooling coils in the AHU, supplied by the cooling machine and the cool is transported to the coils through the brine solution.

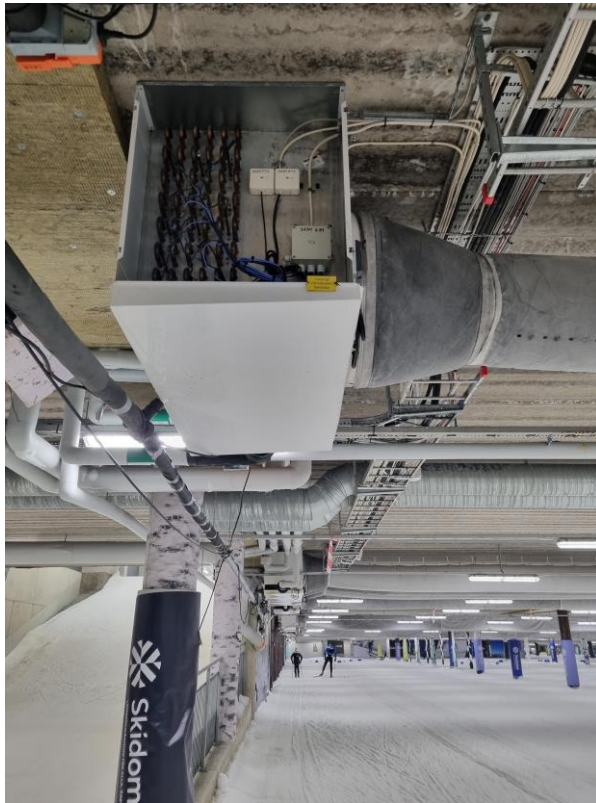


Figure 12: Cooling coil for air cooling inside Skidome.

3.1.4 Energy performance

The energy systems at Serneke arena are a complex system including several components with different purposes. Since the arena is unique with an indoor cross country ski facility, it is difficult to determine its performance by only observing energy use numbers.

To create an idea of the electricity use within the arena one can observe Figure 1 in chapter 1. The average electricity use 2022 is divided for each activity and the share of the total electricity use is illustrated by the pie chart. One can detect that Skidomes activity stands for 33.8 % of the total electricity use in the arena during 2022. It implies that a larger focus should be on the Skidome activity during an energy efficiency project. Other activities with a relatively large electricity use are the football hall 12.7%, and the Nordic Wellness gym 9.1%. The share called other of 26.3% is not measured by a sub meter for the electricity use and is therefore a total electricity use of for example heat pump, ventilation, and others. It is therefore complicated to investigate further at this stage.

To further evaluate how the electricity use has changed during the years, Figure 13 was observed. Year 2022 shows that the electricity use is similar to the 2019 use. An increase from 2021 to 2022 could be caused by the Skidome facility's electricity use. It is not known what the cause of higher demand was in detail, but one contributing reason could be starting to use the recently installed direct electrical heating to prevent permafrost below the snow. One can also see a lower electricity use during 2020 and 2021 which most likely is caused by the Covid-19 pandemic and less activity in the whole arena.

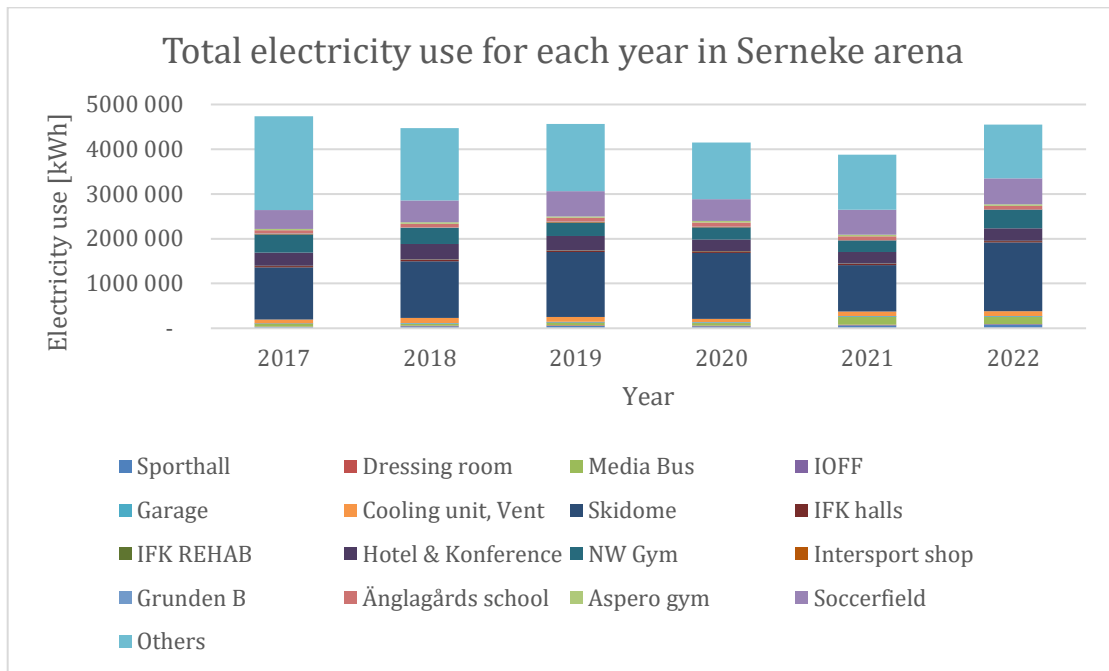


Figure 13: Total electricity use for each year in Serneke arena.

Further investigations looking at the energy share of the electricity use of Skidome is presented in Figure 14.

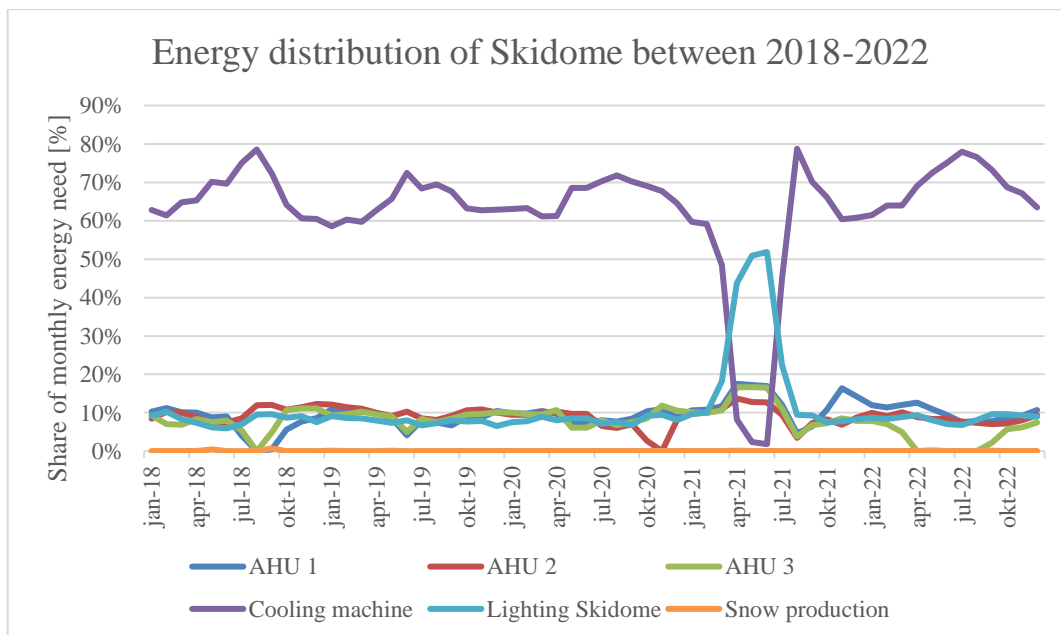


Figure 14: Average share of energy distribution of the facility of Skidome between 2018 and 2022.

Figure 14 shows that the largest contributor to the electricity use of Skidome is the cooling machine. The large peak and dip in the graph of the cooling machine and lighting are because of a reconstruction in the system.

The average total energy consumed for each electricity consumer for Skidome is presented in the pie chart in Figure 15.

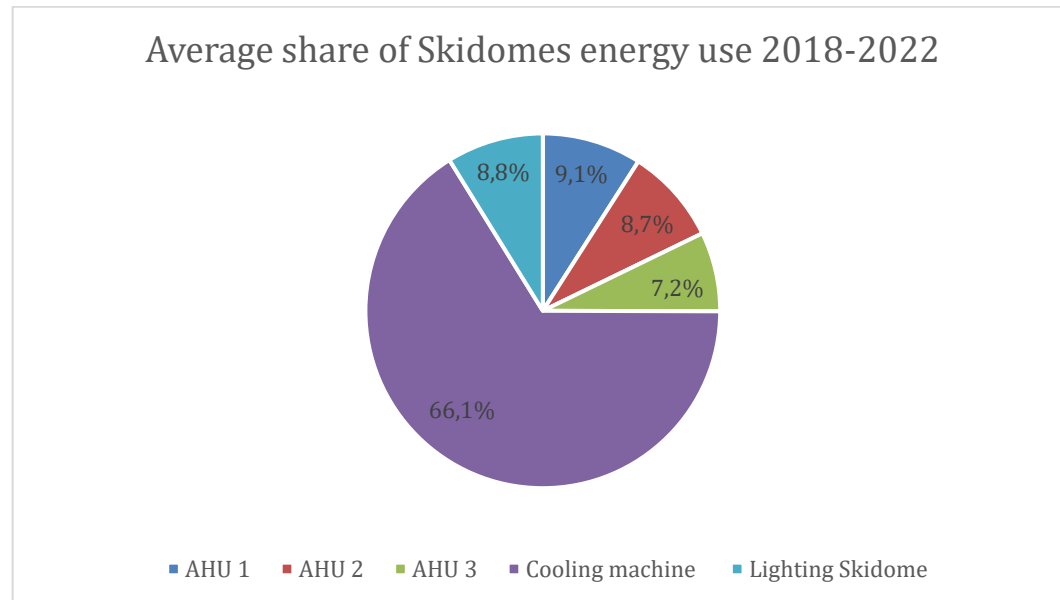


Figure 15: Pie chart of average energy distribution to the facility of Skidome between 2018 and 2022.

This means that the cooling machine in annual average stands for 22.3% of the total electricity use in Serneke Arena and has the largest electricity use.

More detailed distribution of the energy users is not available. This because of the possibility for backtracking in the system is limited due to few sensors connected in the system and lack of a software system overview for the cooling system. This makes it difficult to investigate different conditions in the energy systems and it is therefore hard to find a distinct solution for problems in the different processes.

The amount of district heat energy consumed in 2022 was 463 MWh. Analysis of trends from Göteborg Energi makes it possible to assume that all district heating consumed goes to hot tap water to the facility. The comfort heating is therefore mainly produced with the heat pumps.

3.2 Specific contributions needed for an indoor cross-country skiing arena

In this section some key components needed for an indoor skiing arena are presented. Since it only exists a few indoor skiing areas in Sweden today, some research has been done in ice rinks which has similar need of cooling of the ice as skiing arenas have for the snow.

3.2.1 Snow production

Artificial snow can either be produced with snow canons or with specific snow machines made for indoor facilities.

Snow produced with snow canons is made by forcing water and air at high pressure, 20 bar or more, through small nozzles. This results in formation of snow crystals from the water droplets. With today's technology it requires 1 kWh of electricity to produce 1 m³ of artificial snow (SkiStar, 2023). This technology is usually used at outdoor ski resorts to lengthen the skiing season, but it is also used at an indoor skiing arena in Dubai (Haseeb Jamal, 2017) .

At Skidome, the artificial snow is produced with special snow machines for indoor snow needs. These machines are built up of three components, an icemaking unit, a supply valve, and a fan.

The function of these snowmaking machines is that a saltwater mix is pumped from a tank and distributed at the cold surface of the icemaking units. This results in a thin layer of subcooled ice which then is crushed by a mechanical ice scraper. The crushed ice is then transported through the supply valve, where the ice is further crushed into smaller ice crystals. The small crystals are then fed into a piping system with a fan that takes cold air from an indoor skiing hall and blow out air and the small snow crystals into the skiing hall. The piping system can also be connected to a flexible pipe that can be used to lead the snow to specific parts in the hall.

When the snow is produced, a piste-machine is needed to distribute the snow evenly in the arena and make ski tracks in the snow for the cross-country skiers.

3.2.2 Pipes below cold surface

To make sure that the snow inside a skiing hall do not melt and is not heated from the ground, pipes must be placed below the snow with cool refrigerants flowing through to keep the temperature low.

For ice rinks, the most common piping system is PEM pipes with CaCl₂ flowing through (Shirvani Armin & Youssef Rana, 2018). It is also possible to have copper or steel pipes and other refrigerants.

In Shirvani and Youseff (2018) report they present the construction below the ice of hockey rinks, where cooling pipes are placed below the snow, which cold refrigerant pumped through that cools the ice from underneath to minimize impact of heat from the ground flowing up to the ice. Under the pipes insulation and the concrete are located and at the bottom a sand bed.

It is not clearly known in detail what the structure looks like below the ski hall of Skidome. It is known that CaCl₂ flows through PEM pipes below the snow. The size of the insulation, concrete and sand base is not known, not either the dimensions of pipes or total length.

3.2.3 Heating coils to prevent permafrost

To prevent the risk of permafrost under the cooling pipes, heating coils could be placed below the insulation and concrete to make sure that the ground does not permanently freeze.

The risk with having a large surface permanently at temperatures below 0 °C, is that the ground below the concrete could be frozen all year around which results in permafrost in the ground. Water has its highest density at 4 °C. During ice formation the volume increases, which means that if water crawls into the cracks of the concrete there is a large risk that the cracks expand resulting in frost blast. This would have a large impact on the ground and the building standing on it.

To prevent permafrost occurring, heating coils could be installed. The heating coils can either be piping systems with hot fluid flowing through or direct electrical heating to make sure that the temperature of the ground is kept at temperatures above 0 °C, and no permafrost is formed. At Serneke arena, direct electrical heating is used with electrical wires heating up the ground.

3.3 Investigation of similar systems

Two study visits were made to get an understanding of different operation principles of similar systems. First study visit was made at Oasen, which is a building with a hockey rink and indoor swimming pools. Information regarding the system at Oasen is received from technical manager Pierre Hillgard. The second study visit were at Torsby Ski Tunnel, which is a similar indoor cross-country skiing facility like Skidome. Information regarding the system at Torsby Ski tunnel is received from technical manager Jan Larsson.

3.3.1 Oasen – Hockey arena and indoor swimming pool house

Oasen, located in Kungälv municipality, consists of a full-scale hockey rink and an indoor bath house with one 25-meter swimming pool and two smaller for kids and rehab activity (Kungälv's Kommun, 2023). The excess heat from the condensing side of the cooling machine is used for heating the swimming pools, while the cooling from the evaporator is connected to the cooling of the ice rink.

The ice in the arena is cooled with 2 compressors working with ammonia, they cool to around -12°C . Under the ice where the cooling pipes are located, a brine solution is circulating to cool the ice. To prevent permafrost under the ice, heating pipes are installed below the cooling pipes and insulation.

The heating in the pipes utilizes the excess heat from the compressor cooling process. The heat recovery from the cooling machine is also used as the only heat source in the building, such as hot tap water for showers and swimming pools as well as heating the air in the swimming pool area.

The excess heat produced during night are stored in several accumulator tanks to then be used during daytime. In a few extreme cases when the outdoor air temperature is below -8°C , district heating is used because the heat recovery is not enough to fulfil the demand. Otherwise, the whole buildings heating energy use is supported from the cooling machine.

During summer when the swimming pool bath are closed and the need for heating is low, the heat is rejected in a dry cooler on the roof of the building. The electricity demand of the dry cooler is rather high but the need for heat is low and can therefore not be recovered.

To maintain a reasonable relative humidity in the hockey arena, a ventilation system with integrated dehumidification is installed. Moist is released from the ice surface as well as from the people during activity.

Comparison between Oasen and Serneke arena

Some distinct differences between the Oasen facility and Serneke arena is the amount of cooling needed, the air in the ice hall at Oasen is $+6$ degree Celsius. The risk for ice freezing on the equipment is much lower, as well as the air supply is not below freezing point. Another large difference is that Oasen does not have heat pumps, it is the cooling machines that also acts as a heat pump. While Serneke arena utilizes heat recovery with a heat exchanger to feed two heat pumps.

3.3.2 Torsby Ski Tunnel

Torsby Ski Tunnel is a 1.3 km indoor ski tunnel in Torsby that is built on naturally hilly ground. The tunnel is constructed with concrete half circles placed on the ground which creates a loop. A soil layer is covering the concrete and acts as an insulating layer. Figure 16 shows how the tunnel looks like from outside. The two tunnel ends are located at the same place in a large arena building built in wood which also contains a full-scale biathlon shooting gallery and a smaller ice rink.



Figure 16: Figure showing Torsby ski tunnel from outside. Ground soil covering concrete structure.

The cooling system in the tunnel is supplied by totally eight compressors which are divided into two cooling machines with four compressors in each. A total of 800kW of cooling is available but rarely fully utilized. The cooling is supplied into the building through eight AHUs which each contain two cooling coils for cooling the air inside the tunnel. The eight stations are divided evenly through the whole tunnel. Each station also supplies the cooling pipes under the snow which also is supplied from the cooling machines. Defrosting in the cooling coils is done in the same way as in Skidome with direct electric heating around the coils.

The intake air is precooled before each station through a cross heat exchanger with the outlet air from the tunnel. After the heat exchanger a cooling coil is used for further cooling before the air entering the tunnels climate shell.

There is a modernization ongoing in the cooling system and therefore a new test station has been implemented to the tunnel to improve the system, since it is almost 20 years old. The test station consists of two cooling coils, and the major difference between the old and new station is the defrosting function.

In the old station, electric defrosting is installed in the cooling coils, while in the new one a hot liquid circuit is installed to the same inlet as the cold circuit in the coil. A

valve is then used to control the defrosting, when defrosting is needed the valve is opened and the hot circuit is running through the coils and ice is removed. After completion the valve closes, and the cooling can begin again. The fluid type for the hot and cold circuit is the same, and the hot fluid is heated by an electric heater. Electricity is still used for heating, but the difference is that the maintenance of the electric rods inside the cooling coils are avoided.

The intake air to the new station is cooled off through a rotational heat exchanger with the outlet air from the tunnel. This AHU is more efficient than the old stations and the demand for further cooling after the heat exchanger process is decreased.

An additional cooling recovery feature is added to the new station. When the outdoor air is colder than the wanted inlet air, $-3\text{ }^{\circ}\text{C}$, a cooling coil transfers the extra cool after the heat exchanger to the cooling inside the tunnel for cooling coils and cooling pipes under the snow. This also then secures that the inlet air is not colder than the set point temperature inside the tunnel.

Comparison between Torsby Ski tunnel and Skidome

It seems like the project planning for the cooling system is done by the same company for both Torsby ski tunnel and Skidome. This is reflected in the unit choices in the two facilities. However, the building structure is very different as well as the geographical location. Since Torsby is a tunnel the cooling system must be divided evenly through the tunnel and then factors such as location of the cooling machines and the AHUs must be planned in beforehand as well as tube laying for long distances.

While Skidome arena is one big open zone, and the cooling system can supply all cooling from one side of the building and by that reduce the length of transport distances of the cool from the cooling machine to the demand. The air flow in Torsby ski tunnel is more natural and let the air flow through the tunnel in two different directions.

The snow production at Torsby is made with snow canons producing snow outdoors when the outdoor temperatures is cold enough. Then the snow is transported into the ski tunnel when the snow is about to be replaced.

4 Method of measurements and investigations

In this chapter the methodology of the measurements in the heating and cooling system will be presented. Further evaluation of the measurement results in Mollier diagrams will be showed. Lastly the method for the evaluation of the five investigations are presented.

4.1 Measurements

To facilitate the investigation of the different stages in the system, measurements at predetermined places were made. A measurement plan was made for each occasion to keep track of what factors that is targeted.

4.1.1 Measurements in cooling system

Different stages in the cooling process were investigated with measurements to determine the properties of the air. Both the relative humidity and temperature were measured by placing the measurement equipment Tinytag Plus 2 at different locations in the cooling process. Data was taken every 5 minutes during the measurements.

Three measurements were made in the cooling system that further will be named winter case, spring case and intake air condition. Where the winter- and spring case was identically made on an AHU where the measurement equipment had the same location during both measurements. This to get an understanding of how for example outdoor conditions affect the operation during different seasons. The intake air condition measurement was made to get a better understanding of how placement of the AHU down in a ground pit affects the air properties.

Measurement 1: Winter case

The winter measurement was made during outdoor winter conditions between 13th and 15th of February. It included five measurement units that was placed in different spots. The measurement equipment was placed at the following locations, see Figure 17:

1. Air intake before AHU
2. Supply air to Skidome
3. Exhaust air from Skidome
4. Inside Skidome

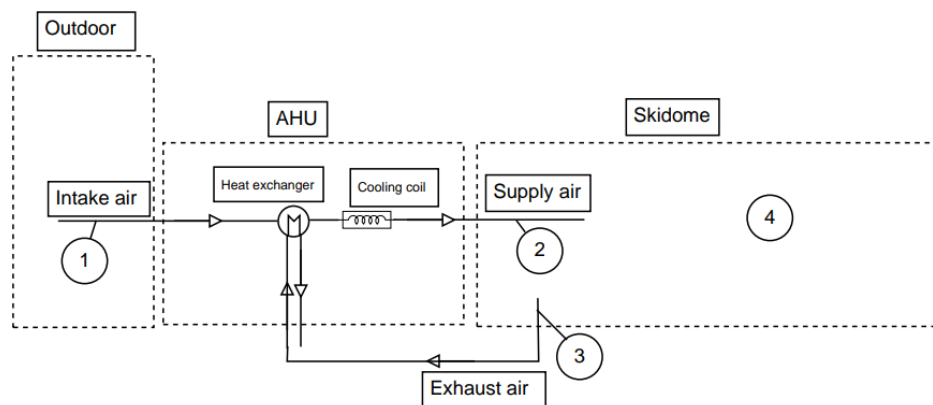


Figure 17: Placement of measurement equipment from the first measurement of the air cooling.

The purpose with this measurement was to determine different steps in the air-cooling process simultaneously. This would give a better view of how the different components acted dependent on each other, for example how the air supply changed with the outdoor conditions. The data obtained from the measurement were presented in graphs and were further evaluated.

Measurement 2: Spring case

The spring case was made between the 4th and 17th of April. The measurement included the same placement of the equipment as for the winter case, see Figure 17. The purpose of the measurement was to identify different operation conditions of the AHU with different outdoor conditions compared to the winter case.

The data results from the measurement were then analysed in graphs and average values were extracted. The average temperature and RH from the spring case was then compared with the average measured temperatures and RH from the winter case.

Measurement 3: Intake air condition

The intake air condition measurement was made during half a day in February, to identify the properties of the outdoor air when the air intake to AHU is lowered into a ground pit compared to if the intake is placed at a higher altitude. Two measurement equipment were used:

1. Intake air to AHU at low level
2. Air condition at high level

The purpose of the measurement was to identify the levels of temperature and moisture at the two locations. The data from measurements were summarized in graphs and further evaluated. Data from SMHI was also extracted to evaluate the results from the measurement (SMHI, 2023), both to validate the data as well as to determine how the location of the air handling unit is compared to other possible conditions.

An average value of temperature and relative humidity was then identified during the measurement and analysed in a Mollier diagram to get the moisture content of the air.

4.1.2 Measurements in indirect warm stream from the condensing process in the cooling machine

This measurement was performed to collect more data trends in different parts of the indirect warm stream from the condensing process in the cooling machine. Both flow and temperature were measured during five days between 23th and 28th of March, and the measurement spots showed in Figure 18 are presented below.

1. Outlet indirect condensing stream
2. Inlet indirect condensing stream
3. Supply heat recovery stream
4. Return heat recovery stream

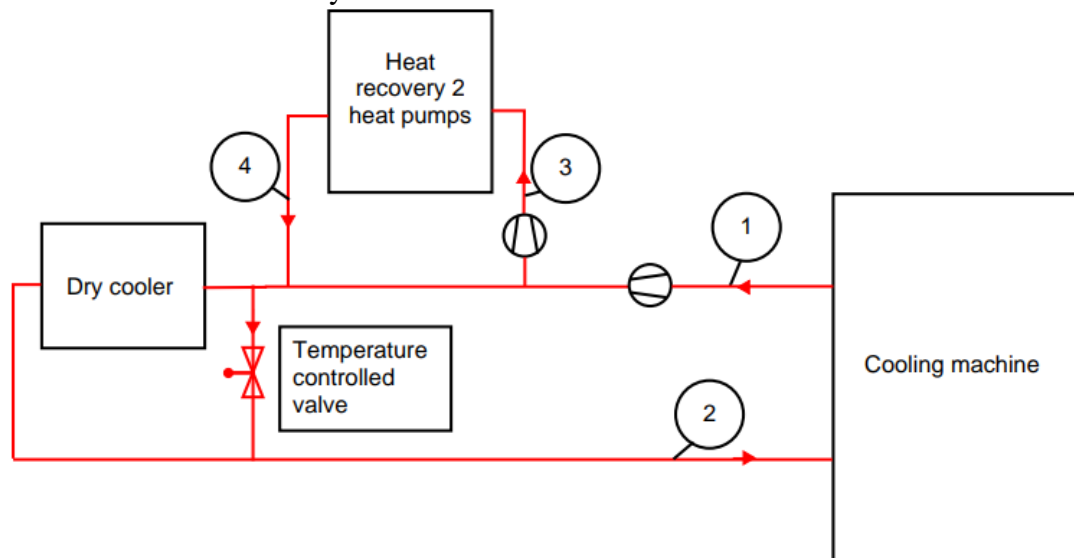


Figure 18: Measurement spots in indirect warm stream from the condensing process in the cooling machine.

A flow meter using ultrasound was installed in point 1 and measured the total flow of the indirect warm stream from the condensing process in the cooling machine. The pipe properties were inserted to the flow meter as well as fluid type, the fluid type was inserted as water to facilitate the measurement. Simultaneously the temperature was measured in point 1, 2, 3 and 4, using a temperature meter mounted on the pipes. The total power released from the cooling process could then be extracted by the fluid properties, flow, and in- and outgoing temperatures, Equation 3.

$$q_{heat} = C_p * \dot{m} * \Delta T \quad (3)$$

A pump is located on the stream after measurement point 1 and its pump curve could be utilized to validate the results from the flow measurement. The pump properties were extracted from site and are presented in Table 1, and the unique pump curve was given for the specific pump model (Kolmeks, 2023b). The pump curve was interpreted with the properties and a flow could be extracted and be compared with the measured one.

Table 1: Pump properties for the pump on the indirect warm stream from the condensing process in the cooling machine.

Pump properties	Value
Pump wheel diameter	232mm
Head	16m

To then find the flow in the heat recovery stream the unique pump curve from that pump was utilized (Kolmeks, 2023a). This because of limited access to measurement equipment and sensors to be able to measure two flows at the same time. As well as practical problems with installing a flow meter on the pipes in the process. Properties for the pump are presented in Table 2.

Table 2: Pump properties for the pump on the heat recovery stream.

Pump properties	Value
Pump wheel diameter	256mm
Head	20m

With the data from both the measurement and pump curves, all flows in the circuit could be determined as well as the energy content in each flow. The heat that must be cooled off by the dry cooler that is located on the roof of the machine room was then calculated by extracting the heat recovery energy from the total heat energy stream.

4.2 Mollier diagram analysis

After the measurements, the results from the measurements in the cooling process were evaluated and studied in a Mollier diagram (Bernard, 2023). Both winter and spring case measurements were investigated to detect the air properties in the AHU. Average values were utilized to avoid extreme spots in the measurement data. The values were inserted in a Mollier chart where the AHU was divided into two processes, the rotary heat exchanger and cooling coil.

It was assumed that the rotating heat exchanger both have moisture recovery and temperature-based recovery. The cooling coil surface temperature was assumed to be constant when inserted to the Mollier chart.

The air properties at different stages in the measurement was specified to which component in the AHU it corresponds to. The measurement spots are specified in Table 3 and could then be inserted to a Mollier diagram. The air properties between the rotary heat exchanger and cooling coil were not possible to measure and is therefore not included.

Table 3: Placement of the measurement spots in the air-cooling process in the AHU.

Placement	Component
Air intake to the AHU	Rotary heat exchanger inlet
Exhaust air from Skidome	Rotary heat exchanger inlet
Supply air Skidome	Cooling coil outlet

The efficiency of the rotary heat exchanger and cooling coil were adjusted in the Mollier diagram input data until the supply air to Skidome conditions was achieved. The actual efficiency of the two units was therefore iterated dependent on the measurement results.

4.2.1 Winter case evaluation

The input data from the winter measurement results are used in this evaluation. The rotating heat exchanger exchanges fresh air with the exhaust air from Skidome and both is a measured value. These values were inserted to the Mollier chart processes for the rotating heat exchanger. Moisture content of the air in the different stages in the process could then be extracted and evaluated.

It was assumed for the winter case that the cooling coil in the AHU was not operating. This because the rotating heat exchanger easily could operate alone to reach the supply temperature to Skidome, without further cooling with the cooling coil.

4.2.2 Spring case evaluation

The input data used from the spring measurement are used in this evaluation. The rotating heat exchanger intake cool recovery from exhaust air in Skidome is a measured value from the spring case measurement, as well as the intake outdoor air. These values were inserted to the Mollier chart processes for the rotating heat exchanger and cooling coil. Air properties for the different stages in the process could then be extracted and evaluated.

In the spring case it was assumed that both the rotating heat exchanger and cooling coil was operating. This because the rotating heat exchanger was not enough to reach the supply temperature to Skidome.

4.3 Investigations

Five investigations were made of the existing energy system at Serneke Arena, they are based on the framing of questions of the report. The five investigations are: (1) Coefficient of performance of the cooling machine, (2) Performance of Skidomes AHU, (3) Heat recovery from cooling machines, (4) Using heat pump for hot tap water production, and (5) Utilize boreholes for comfort cooling.

4.3.1 Coefficient of performance of the cooling machine

This investigation was made since the cooling machine stands for 66,1% of the electricity use that goes to Skidome, see Figure 14. The COP of the cooling process was therefore investigated to find energy efficient measures in the process. However, this parameter also affects the heat recovery system since different COP generates different condensing temperatures. Therefore, this must be taken into consideration during the energy calculations.

The compressors in the cooling machine are from Frascold of the model W75-240Y. Frascold offers a software named FSS3 for their products that can be used to model the cooling machine. The investigation of the COP value was made both with the software FSS3 as well as from conversations with a refrigeration expert Jonas Schön from Sweco.

Four main data were used from the program FSS3; (1) Which temperatures the compressors can work with, (2) Which refrigerants the compressors can use, (3) Operating condensing- and evaporating temperatures and (4) The COP for the process at different operating temperatures.

Today the cooling machine use the refrigerant R507 and the investigation will analyse which is the optimal condensing temperature. A requirement of the investigation was to keep the same refrigeration capacity and thereby the same evaporating capacity as today. Different efficiency methods were discussed with an expert to validate the reliability of the investigation.

4.3.2 Performance of Skidomes AHU

During the case study in an early stage of the project, problems with ice coating on the cooling coils inside Skidome was pointed at. Therefore, an investigation within the area was made from several perspectives.

The initial stage in this investigation was to evaluate the measurements made in the cooling system. Results from these measurements from both winter and spring case could enable an interpretation of how the AHU for Skidome performs and how the indoor climate is affected by the outdoor conditions. Actual air properties in form of temperature and relative humidity gave an idea of how the condition of the air corresponds to the set point values for the system.

It could also be detected how the AHU performs with inserted measured values compared with expected performance with the component properties in the AHU. This by comparing with similar product as the components in the AHU. The rotating heat exchanger is compared with a similar model which has an efficiency of 75-90% (Heatex, 2023).

The evaluation of the properties of the ventilation air condition were further prolonged by analysing the Mollier charts in Section 5.2. A theoretic overview of how the air properties changes in the AHU was then made. The amount of dehumidification of the air in the AHU was then determined with results from the Mollier diagram. A comparison of the supply air to Skidome and the air inside was made to detect any improvement possibilities.

The data from the two measurements during winter and spring case were then compared to detect how the performance of the AHU varied with different outdoor conditions. The location of the air intake to the AHU was explored to see if it is a large factor for AHU improvements.

An analytic evaluation of how the air properties could affect the ice coating on cooling coils inside Skidome was then made. Suggestions of improvements of how the problem could be mitigated were stated.

4.3.3 Heat recovery from cooling machine

It is earlier stated, in Section 3.1.1, that the indirect warm stream in the condensing process in the cooling machine is connected to heat recovery for heat pumps, as well as dry coolers. Concerns about excess heat waste from the cooling machines was mentioned early in the project. Where it was assumed to be a large amount of excess heat that was cooled off with dry coolers instead of being utilized for heat recovery.

The process properties in the heat recovery were further evaluated by looking at the different components involved from the case study chapter. The pre-set values in the process were decided to be further investigated to find if the actual values correspond to the theoretical ones. Since there is a lack of data trends in the process as well as instant values, measurements had to be made. A measurement was performed and described in Section 0, results from this was further evaluated.

Results could be used to calculate the energy balance in the indirect condensing stream in the cooling machine. The energy balance could then be used as a basis for how large share of the excess heat that are ventilated away.

4.3.4 Using heat pump for hot tap water production

The hot tap water use at Serneke Arena is today supplied from Göteborg Energi's district heating net. This investigation was made to evaluate if it is profitable to locally produce hot tap water with heat pumps.

The output temperature from the cooling machine is dimensioned to be 25 °C and was used in the calculations. There are seven heat pumps available at the arena today of the model Nibe F1345 60 kW (NIBE, 2023). Two of these heat pumps is fully operated with heat recovery from the cooling process. Five pumps are connected to boreholes and are not fully operated. In this evaluation it was assumed that one of the pumps that is connected to the boreholes instead would be used to produce hot tap water. No new heat pump was assumed to be invested in. The evaluation did not consider investments of new accumulator tanks that might be needed, if the existing one is not enough.

The economic evaluation was done by looking at the costs of district heating from the year 2022 from Göteborg Energi. Also, by determining the arenas district heating use during 2022. The cost of district heating was then compared to historical electricity prices and the cost it would have resulted in 2022 if heat pumps instead would have produced the hot tap water with the cost of electricity from the year.

With the cost analysis, an analysis was made to investigate if it would be beneficial to locally produce heat with heat pumps and store it in accumulator tanks when the electricity is cheap.

4.3.5 Utilize boreholes for comfort cooling

The opportunity to utilize boreholes to extract cool during summer for comfort cooling was investigated. An assumption was made that the boreholes were available to supply cool during the whole year simultaneously as the heat pumps extract heat for heating. The historic electrical use of the comfort cooling unit during six years was extracted. An annual average electricity use during the period was then calculated to avoid any peaks or lows and get the most valid value for a calculation. It was assumed that the sub electricity use meter named: Cooling unit ventilation, corresponded to the total electricity use for comfort cooling in the arena.

The cool from the boreholes was assumed to cover the whole need of the comfort cooling unit, thus no further cooling was assumed to be needed. The electricity use from the borehole pump was neglected in the calculations. The cost of electricity was set to the average electricity cost each month during 2022 and was used to estimate a cost saving of the measure. The electricity use from the comfort cooling unit could then be multiplied with the assumed electricity price to find the saved electricity expenses by instead utilizing cool from the boreholes.

5 Results and analysis

In this chapter are results from the measurements in the cooling and heating system presented. As well as results from Mollier diagram analysis and investigations. Discussion regarding the results is made under each section in this chapter.

5.1 Measurements

In this section results and discussion from measurements in both the cooling and heating system are presented. In graphs are average values per hour from the measurements presented to facilitate the interpretation.

5.1.1 Measurement in the cooling system

The results show temperature and relative humidity during three measures, while the absolute humidity is further evaluated in the Mollier diagram analysis chapter. The results are illustrated in graphs and compared with tables.

Measurement 1: Winter case

Results from the first measurement are presented in Figure 19 and Figure 20. The temperature from the measurement is presented in Figure 19.

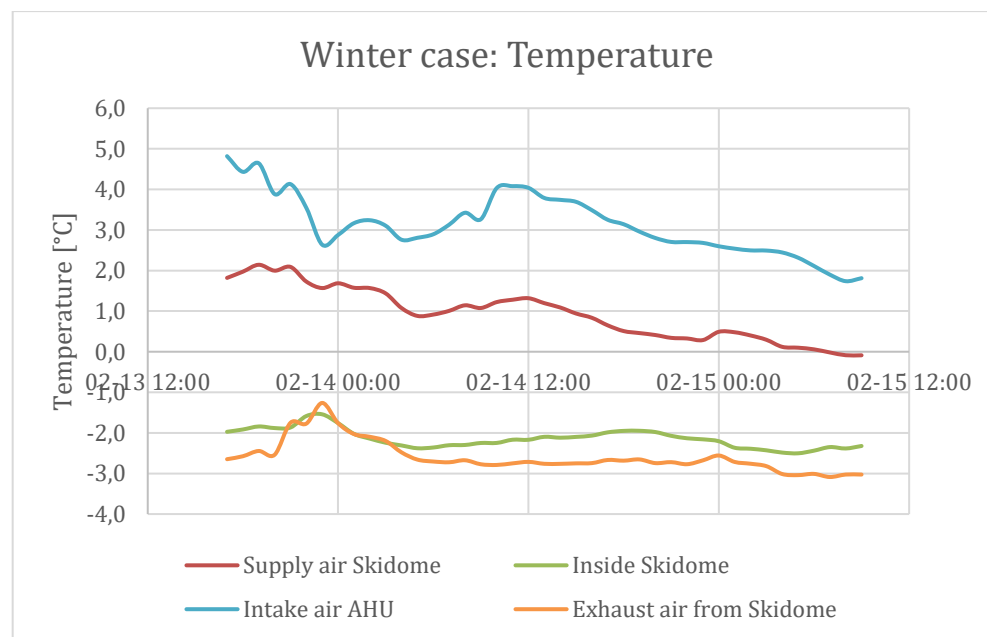


Figure 19: Temperatures from winter case measurement.

The blue line is the intake air to the AHU and fluctuates with the outdoor temperature, it ranges between 4.8 and 1.7 °C. The red line, the supply air to Skidome, follows the intake air to the AHU to some extent but with a constant lower temperature. It ranges between 2.1 and -0.1°C which could be considered as a rather large span for the supply temperature. The cooling of the air in the AHU during winter conditions could therefore be determined to be very dependent on the outdoor air temperature.

The supply air to Skidome is then further cooled inside with the 14 cooling coils which then could be analyzed by the green line. It has a rather constant temperature ranging between -2.5 and -1.5°C. The exhaust air from Skidome, the orange line is almost constantly a little colder than the indoor air temperature. The two sensors are located a long distance between each other inside the ski hall. The deviation could then be because of different temperatures at different spots inside.

The relative humidity from the measurement is presented in a graph in Figure 20.

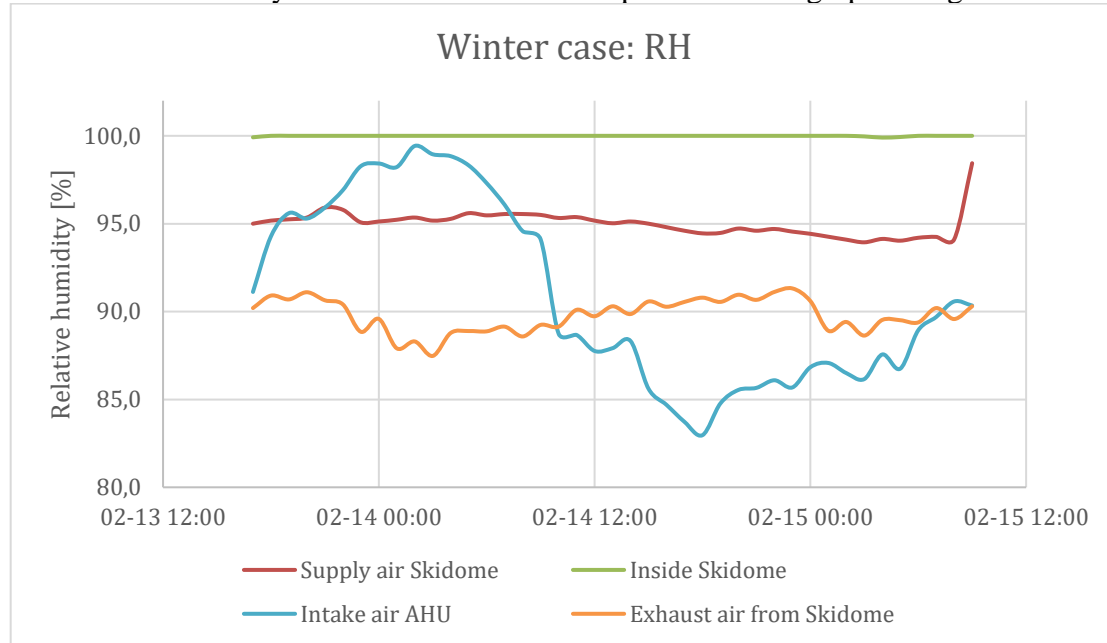


Figure 20: Relative humidity from winter case measurement.

The blue line shows the air intake to the AHU and correspond to the outdoor RH, it ranges between 83-99 %. The supply air, the red line, shows that the RH is rather constant at around 95 %. It does not follow the intake air to the AHU as the temperature graph did. However, it is not convenient to compare the RH at different temperatures since it is directly connected to a certain temperature.

The RH inside the ski hall, green line, is 100 % RH during almost the whole measurement. This can be a cause of high RH at the point or a water droplet on the sensor. The sensor that measured the exhaust air from Skidome which also is located inside the ski hall is showed by the orange line. It fluctuates between 87-91%, this could either be a large difference between different spots in the hall or a measurement error for the inside Skidome sensor, as previous mentioned.

The average temperatures and RH at the different measurement spots from the winter measurement are presented in Table 4.

Table 4: Average temperature and RH from the winter case measurement.

Average data winter case measurement of temperature and RH				
	Intake air AHU	Supply air Skidome	Inside Skidome	Exhaust air from Skidome
Temperature	3.1 °C	0.9 °C	-2.1 °C	-2.6 °C
RH	90.9 %RH	95.0 %RH	100.0 %RH	89.8 %RH

The average temperature inside the ski hall is $-2.1\text{ }^{\circ}\text{C}$ which differs from the set point temperature of $-4.0\text{ }^{\circ}\text{C}$ that is wanted to keep a good quality of the snow and requested from the people working at Skidome. However, the RH does not have a defined set value as the temperature. The average supply air temperature to Skidome is $0.9\text{ }^{\circ}\text{C}$, it is almost a $5\text{ }^{\circ}\text{C}$ temperature difference between the set point and the supply air temperature. The intake air to the AHU has an average temperature of $3.1\text{ }^{\circ}\text{C}$ and the average temperature difference over the AHU is then $2.2\text{ }^{\circ}\text{C}$.

Measurement 2: Spring case

The temperature and the relative humidity data from the spring case are presented in graphs in Figure 21 and Figure 22. The results from temperature measurements from the spring case measurement are presented in Figure 21.

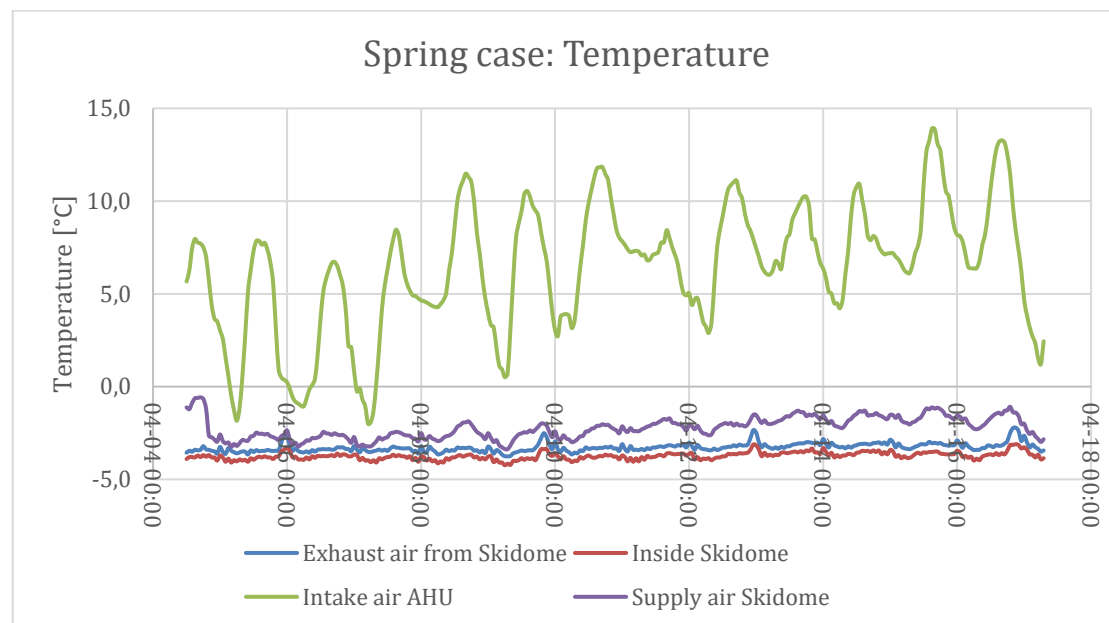


Figure 21: Temperature from spring case measurement.

The intake air to the AHU is illustrated by the green line and fluctuates between $-2.0\text{ }^{\circ}\text{C}$ and $14.0\text{ }^{\circ}\text{C}$. The supply air to Skidome ranges between $-0.5\text{ }^{\circ}\text{C}$ and $-3.4\text{ }^{\circ}\text{C}$, purple line, it is possible to see that the graph has an increasing trend in parallel with the intake air to the AHU. Meaning that the supply air to Skidome is somewhat dependent on the outdoor air temperature.

The red line reflects the inside air temperature in Skidome, and it changes between $-3.1\text{ }^{\circ}\text{C}$ and $-4.2\text{ }^{\circ}\text{C}$ which can be seen to be directly connected with the exhaust air from Skidome. The exhaust has a slightly higher temperature ranging between $-2.2\text{ }^{\circ}\text{C}$ and $-3.7\text{ }^{\circ}\text{C}$.

The relative humidity data from the spring case measurement is presented in Figure 22.

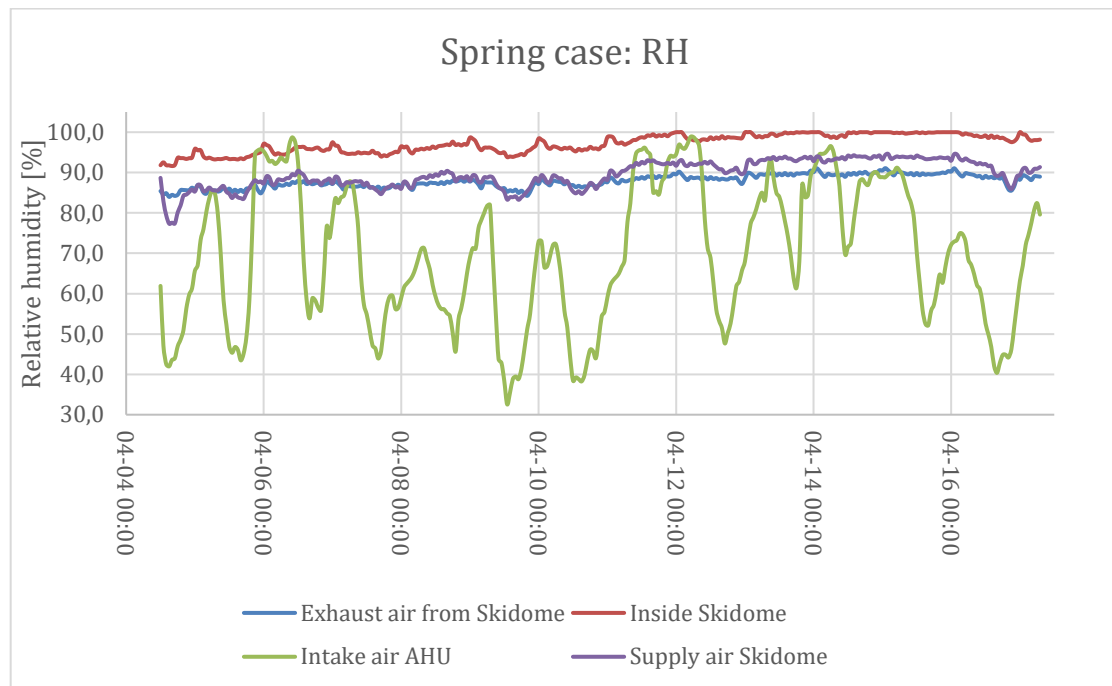


Figure 22: Relative humidity from spring case measurement.

The green line reflects the RH of the intake air to the AHU and by that also the outdoor condition, it has a large range between 33% and 99%. The supply air temperature to Skidome fluctuates between 77% and 95% and is trending with the exhaust air from Skidome. The RH inside Skidome is rather constant between 92% and 100%.

The average measured temperatures and RH from the spring measurement are presented in Table 5.

Table 5: Average temperature and RH from the spring case measurement.

Average spring case measurement data temperature and RH				
	Intake air AHU	Supply air Skidome	Inside Skidome	Exhaust air from Skidome
Temperature	6.4 °C	-2.2 °C	-3.7 °C	-3.3 °C
RH	69.6 %RH	89.6 %RH	97.2 %RH	87.9 %RH

The average temperature inside Skidome is – 3.7 °C which is close to the wanted set temperature of -4.0 °C in the ski hall. The average supply air temperature to Skidome is -2.2 °C and the temperature difference over the AHU is then 8.6 °C.

Comparison between the winter and spring case measurement

Comparison between the differences of the minimum, maximum and average temperatures from the spring and winter measurement are presented in Table 6. Positive values indicate that the temperature was higher during the spring case than winter case. Negative temperatures means that the temperature was lower in spring case than winter case.

Table 6: Comparison of temperature between the winter and spring case measurement.

Difference in temperature [°C]				
	Intake air AHU	Supply air Skidome	Inside Skidome	Exhaust air from Skidome
Min	-3.7 °C	-3.3 °C	-1.7 °C	-0.7 °C
Average	3.2 °C	-3.2 °C	-1.6 °C	-0.7 °C
Max	9.1 °C	-2.7 °C	-1.6 °C	-1.0 °C

The supply air is averagely 3.2 °C colder in the spring case compared to the winter case. The temperature inside Skidome is 1.6 °C colder and the exhaust air is 0.7 °C colder. This while the average intake air is 3.2 °C warmer during the spring measurement compared to the winter measurement.

Differences in RH between the spring and winter measurements are presented in Table 7.

Table 7: Comparison of RH between the winter and spring case measurement.

Difference in RH [%]				
	Intake air AHU	Supply air Skidome	Inside Skidome	Exhaust air from Skidome
Min	-50,4 %RH	-16,6 %RH	-8,3 %RH	-3,5 %RH
Average	-21,4 %RH	-5,5 %RH	-2,8 %RH	-1,9 %RH
Max	-0,6 %RH	-3,8 %RH	0,0 %RH	-0,2 %RH

The RH inside Skidome and the supply and exhaust air are similar between the two measurement cases and only varies a few percentages. The RH of the intake air before the AHU is different, in average 21.4% lower RH during the spring case compared to the winter case. This is of course because of the difference in temperature between the two cases. A comparison of the moisture content in each measurement case is presented in next chapter Mollier diagram analysis.

Measurement 3: Intake air condition

The temperature and relative humidity data of the measurement are presented in figures below. The results from temperature measurements are presented in a graph in Figure 23.

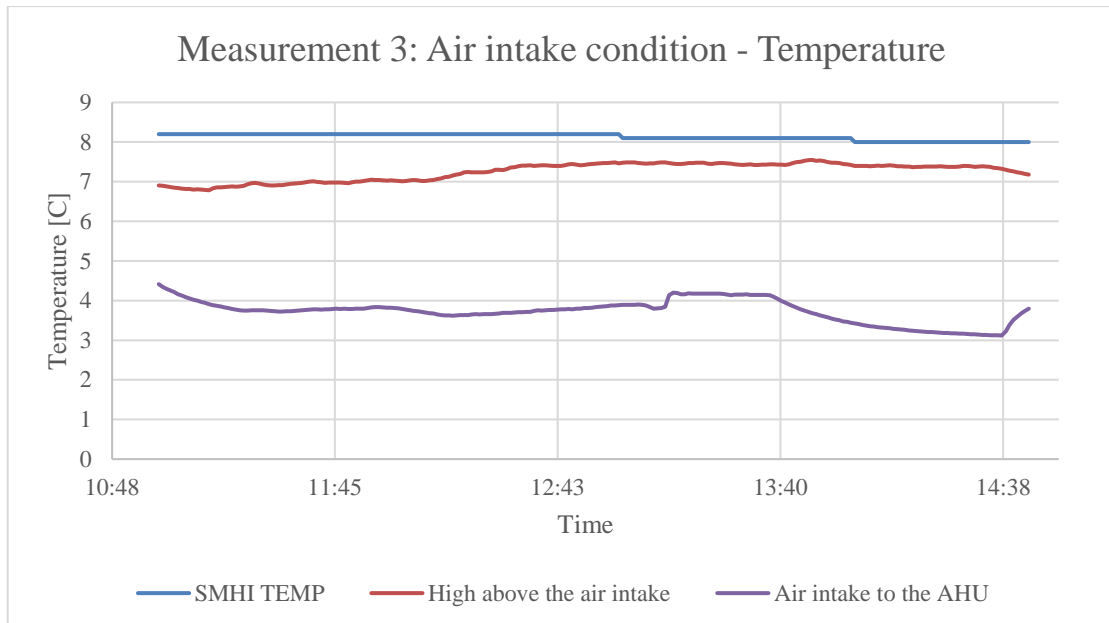


Figure 23: Temperature from measurement of air intake condition.

The graph shows that the temperature at the air intake of the AHU, purple line, has the lowest temperature ranging between 3 °C and 4.5 °C. The red line is a measurement at a higher altitude than the AHU air intake, it is more stable and ranges between 7 °C and 7.5 °C. The blue line is created by extracted SMHI data during the same period from a weather station nearby and keeps an almost constant temperature of 8 °C. The data shows that the temperature of the air down in the AHU ground pit is significantly colder than both higher altitude and SMHI data. The air at higher altitude is also colder than the SMHI data.

Results of relative humidity data measurements are presented in Figure 24.

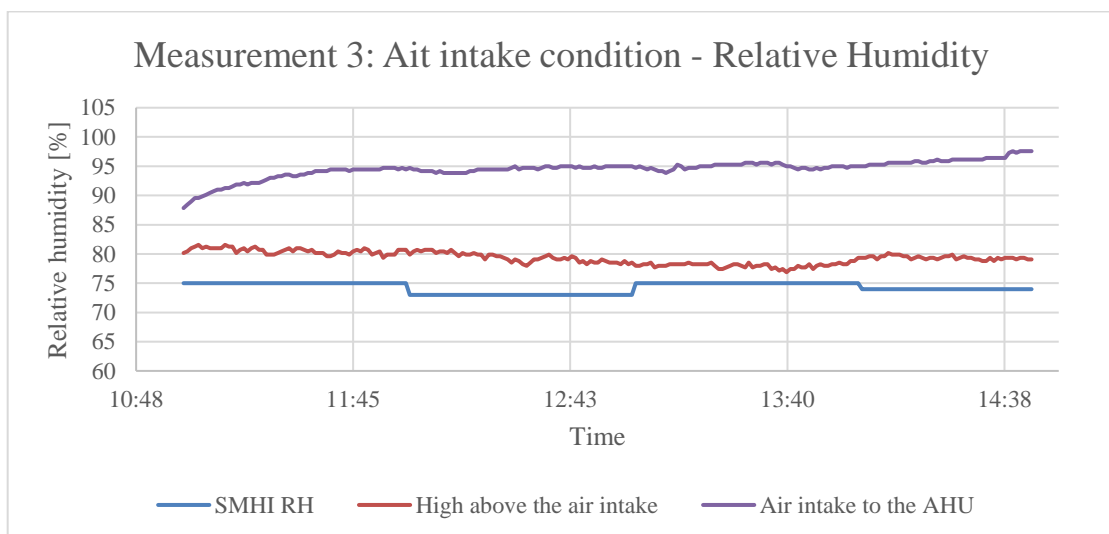


Figure 24: Relative humidity of measurement 3 of air intake condition.

The RH at the air intake to the AHU is illustrated by the purple line, it ranges between 89 % and 98 %. While the RH at higher altitude, the red line, is rather constant and ranges between 77 % and 81%. The SMHI has the lowest RH ranging between 73 % and 75%. Data from the measurement shows that the relative humidity was higher at the AHU air intake down in the ground pit compared to SMHI and higher altitudes.

Table 8 shows the average temperature and RH from each sensor, and from SMHI during the measurement. The results from inserting the data into a Mollier charts to get the absolute humidity (x) at each sensor location is also displayed in the same table.

Table 8: Average temperature and RH from measurement of the ventilation air condition.

Average	SMHI	Higher altitude air	Air intake AHU
Temperature	8.1 °C	7.3 °C	3.7 °C
RH	74.3 %RH	79.3 %RH	94.5 %RH
x	5 g/kg	5 g/kg	4.7 g/kg

The average temperature difference between the air intake to the AHU and SMHI data is 4.4 °C. This indicates that there is a large benefit in terms of temperature to have the AHU and the intake air in a ground pit, because the lower the intake temperature the lower amount of cooling is needed. The RH on the other hand is significantly higher, but since the RH is directly correlated with the temperature it is better to compare the moisture content, x. Results from inserting data into a Mollier diagram shows that the absolute humidity was lower at the air intake to the AHU, 4.7 g/kg, compared to air intake at higher altitudes, 5.0 g/kg. The air down at the AHU air intake is then both colder and has less moisture content, during the measurement occasion.

Discussion - Measurement in the cooling system

The measurements had to be made between January and April during the time of the master thesis. Unfortunately, the average outdoor temperature did not differ as much as expected and was only 3.2 °C warmer during the spring measurement compared to the winter measurement. It would have been interesting to measure temperatures both during much cooler outdoor conditions as well as during warmer conditions at summertime to see how larger outdoor air condition difference affect the air at the measured spots.

It is also worth noting that the Tinytag Plus 2 has a measurement temperature uncertainty of ± 0.5 °C. This could affect the temperature measurement results since the temperature differences between the measurement points are not so high neither during the winter or spring measurement.

The uncertainty of the RH is not defined in the product sheet. During the winter case the RH of the supply air were constantly 100 %, which most likely is not valid information. It is more likely caused by formation of a water droplet over the sensor, which makes the comparison of the humidity between the winter and spring case more difficult to compare.

Another point worth noting is that if the measurement sensors were placed at other locations in the process and especially at other locations inside the ski hall would probably give other results. During the measurements the location of the sensors was identical to be able to analyse and compare results. Since the distribution of the air inside the hall most probably does not reach all corners, further analyses could be made of the distribution of the air within the hall.

The Tinytag Plus 2 measures temperature and RH, but it is not representable to directly compared the RH between the winter and spring measurement. This because the moisture content of the air differs with the same RH at different temperatures. The measurements were made to be able to analyse differences in Mollier diagrams.

5.1.2 Measurements in indirect warm stream from the condensing process in the cooling machine

The measured temperature and flow in the indirect warm stream from the condensing process in the cooling machine is presented in Figure 25.

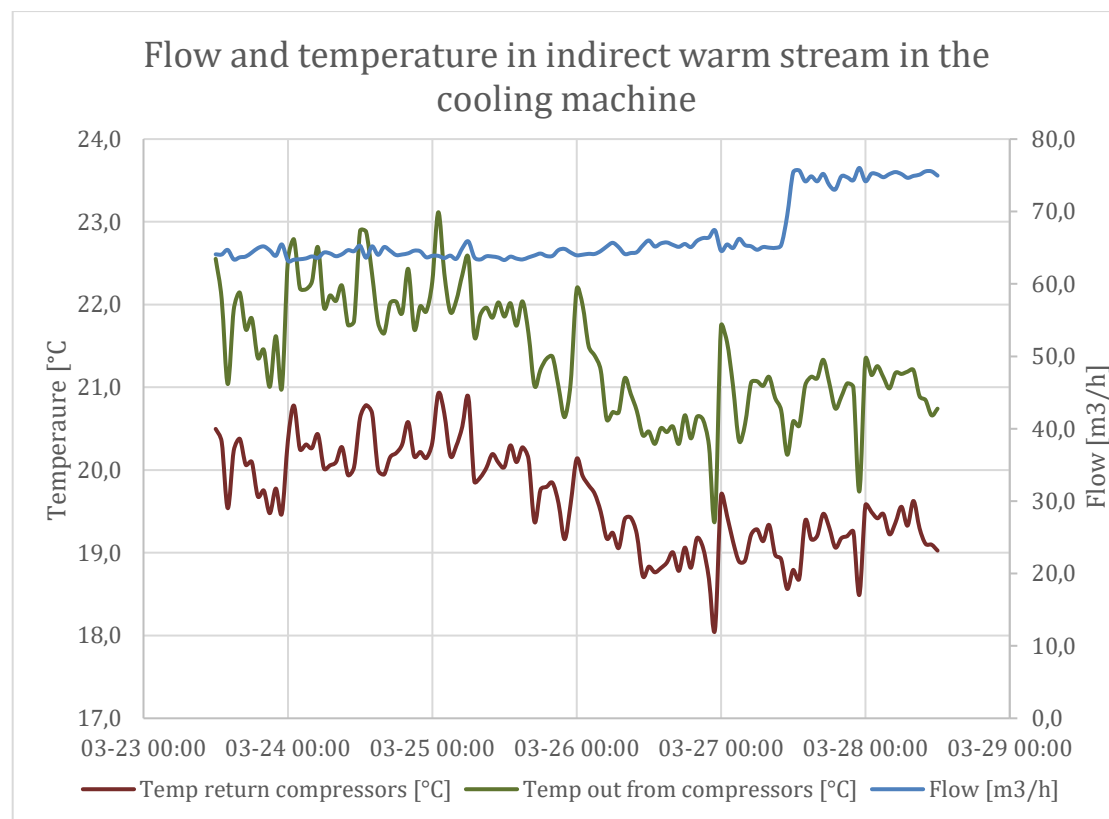


Figure 25: Flow and temperature in indirect warm stream from the condensing process in the cooling machine.

The data is plotted over the time the measurement was made. The out- and ingoing temperature in the compressors are rather constant or varies with each other. However, the difference between them is relatively small which also then explains the changes in the effect plot, Figure 26. Small temperature changes have a large impact in the energy calculation due to the original low temperature difference.

The flow is also relatively constant in the stream except from a case where the flow rapidly increases for an unknown reason and then stays a higher value.

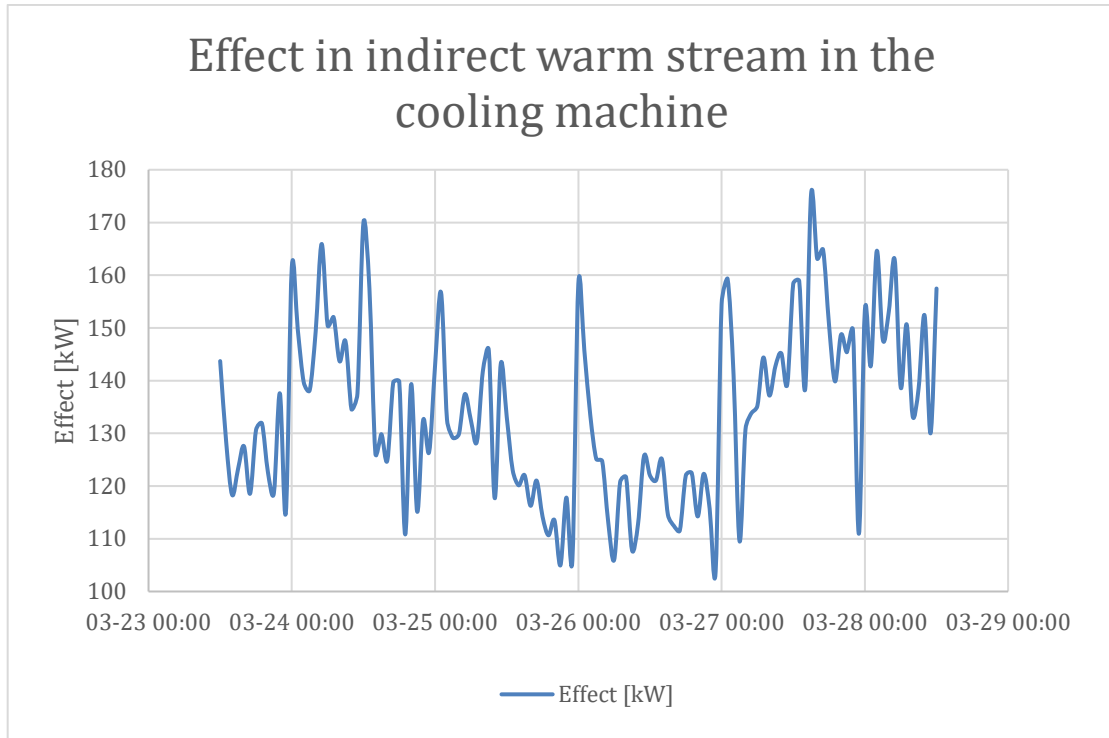


Figure 26: Effect in indirect warm stream from the condensing processes from the cooling machine.

Temperature results from the measurement on the supply and return heat recovery stream is plotted in Figure 27. The plot shows that the two streams mostly change with each other, with some exceptions where measurement errors probably occurred where the graphs overlap. The temperature difference between the supply and return stream is rather low, spanning between 0 to 5°C.

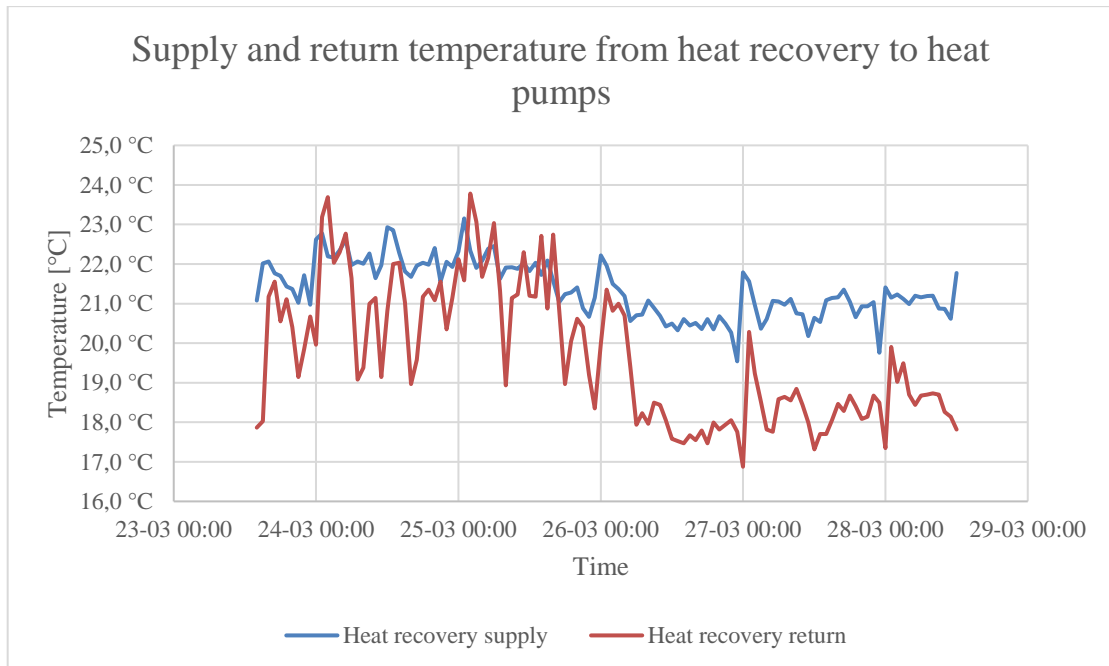


Figure 27: Temperature plot for the supply and return heat recovery stream.

The measured flow in the indirect warm stream from the condensing process in the cooling machine could be validated by observing the unique pump curve for the pump on the stream, Appendix B. The Y axis in the diagram represent the pump performance, $H[m]$, which in this case is determined by the pressure drop in the pump extracted from the manometers on site and is 16m. The impeller diameter is set by the pump properties, 232mm. This dimension is not marked in the diagram and therefore an interpolation had to be made. The intersection between the pump performance and impeller diameter marks the flow on the X-axis, $82m^3/h$.

The pump located on the heat recovery stream to the heat pumps could be utilized to find the flow in that stream, with the same method as for the pump above. Appendix C shows the pump curve for the heat recovery pump where H is 20 m and the impeller diameter 256 mm. The intersection marks a flow of $14 m^3/h$.

All the average temperatures and flows in the streams in this measurement is presented in Table 9. The average outlet temperature in the indirect condensing stream is $21.4\text{ }^\circ\text{C}$ and $19.6\text{ }^\circ\text{C}$ in the inlet. Average flow in the indirect condensing stream is $66.6 m^3/h$.

The supply heat recovery streams average temperature at the outlet and inlet are $21.4\text{ }^\circ\text{C}$ and $19.7\text{ }^\circ\text{C}$ respectively. The supply to the heat recovery stream is the same as the outlet from compressors while the return stream is almost the same as the return indirect condensing stream. The flow in the heat recovery stream was determined with the pump diagram to $14 m^3/h$.

Table 9: Average measured temperature and flow in the indirect warm condensing stream in the cooling machine.

Measurement spot	Average Temperature	Average Flow
Outlet indirect condensing stream	$21.4\text{ }^\circ\text{C}$	$66.6 m^3/h$
Inlet indirect condensing stream	$19.6\text{ }^\circ\text{C}$	$66.6 m^3/h$
Supply heat recovery stream	$21.4\text{ }^\circ\text{C}$	$14 m^3/h$
Return heat recovery stream	$19.7\text{ }^\circ\text{C}$	$14 m^3/h$

Discussion - Measurements in indirect warm stream in the condensing process in the cooling machine

The measurement in the heat recovery was done over five days in March. It is therefore an unsecure factor if the results can correspond to an everyday operation case. The energy calculations in the indirect warm stream in the condensing process in the cooling machine should therefore be considered as initial investigation results and encourage further investigations.

The flow in the stream that leads to the heat recovery for the two heat pumps was not measured like the total flow was. Instead, the unique pump curve for the pump on that stream was utilized, by using the pressure difference from the manometers located on the pump. The manometers could have deviations from the actual pressure drop, as well as it was an instantaneous value and could deviate depending on when the extraction was made.

When utilizing the measurements in the heat recovery process there is factors that is important to consider while evaluating the results. The accuracy in the measurement tools is always an uncertain factor, especially when small deviations have a large effect on the results. Such as a temperature deviation of 0.5°C could affect the energy content in the stream with 25% in some conditions. The temperature of the streams is measured with a sensor that is attached to the surface of the pipe, with isolation around. The surrounding temperature could therefore impact the temperature measurements. However, both the in- and outgoing temperature are measured in the same way and therefore the temperature difference should not be affected.

5.2 Mollier diagram analysis

In this section, results from Mollier diagram evaluation are presented for both the winter case and spring case measurement.

5.2.1 Winter case evaluation

The input data used from the average air properties from the winter measurement is presented in Table 10.

Table 10: Input values for the AHU components to Mollier diagram winter case.

Input values	Temperature [°C]	RH [%]
Heat exchanger intake cool recovery	-2.6	89.8
Heat exchanger intake air	3.9	83.7

The air properties from the input to Mollier diagram is presented in Table 11, where each stage in the process in the Mollier diagram is showed in Figure 28.

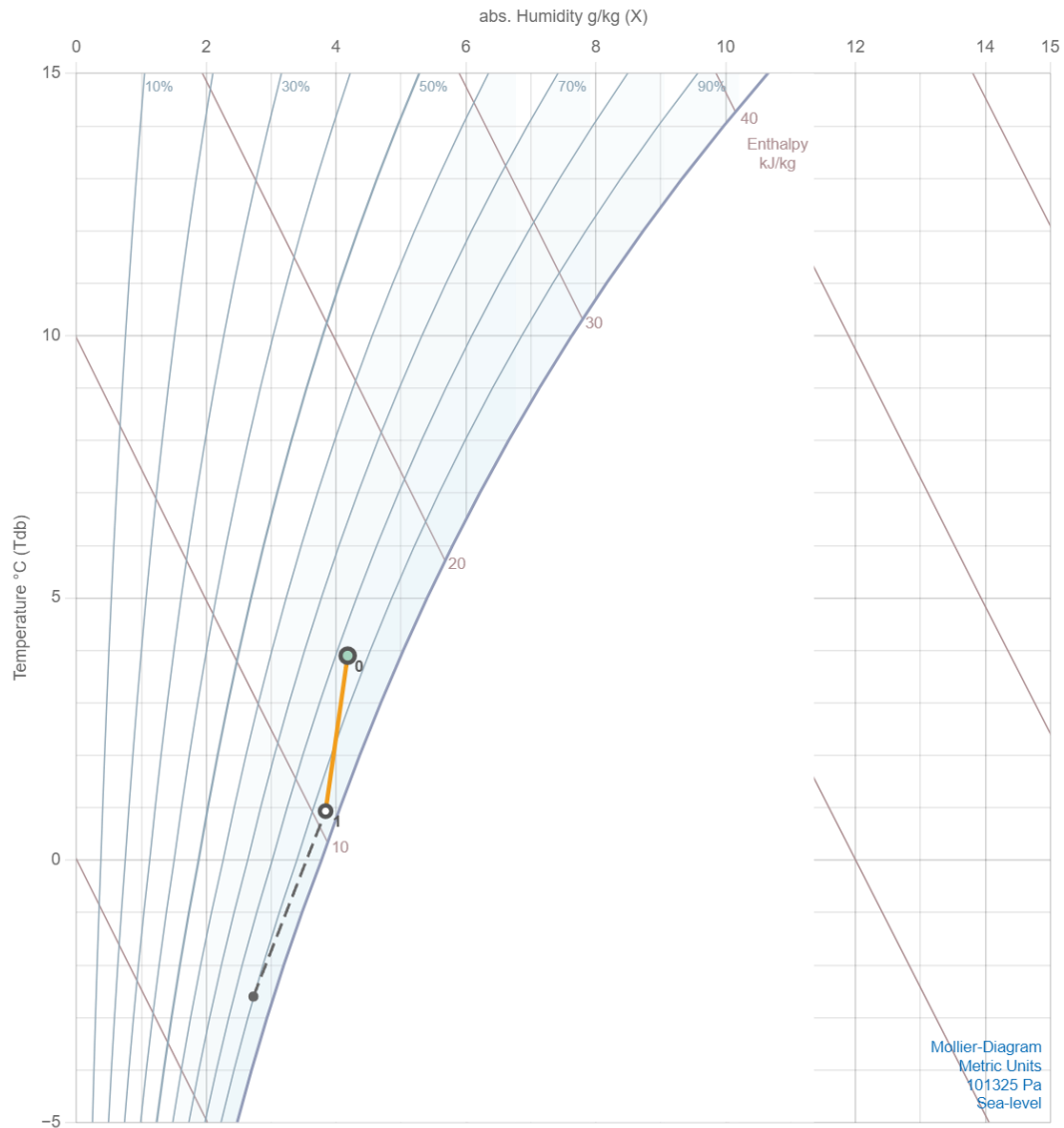


Figure 28: Mollier diagram with input measured values from winter case. (Bernard, 2023)

Stage 0 is the measured average inlet air properties to the AHU and stage 1 is the measured supply temperature to Skidome which also is the outlet from the AHU. The moisture content decrease from 4.2 g/kg in the inlet air to the AHU to 3.8 g/kg in the supply air to Skidome.

Table 11: Mollier diagram results from average measured values in winter case measurement.

Stage	Temperature [°C]	RH [%]	x [g/kg]
0	3.9	83.7	4.2
1	0.9	95.0	3.8

The efficiency of the rotating heat exchanger is adjusted to reach the measured air outlet properties in stage 1 which resulted in 45% for the temperature recovery and 23% for the moisture recovery.

5.2.2 Spring case evaluation

The input data used from the average air properties from the spring measurement is presented in Table 12.

Table 12: Input values for the AHU components to Mollier diagram spring case.

Input values	T [°C]	RH [%]
Heat exchanger intake cool recovery	-3.3	89.9
Heat exchanger intake air	6.4	69.6
Cooling coil surface temperature	-5	-

The air properties from the input to Mollier diagram is presented in Table 13, where each stage in the process in the Mollier chart is showed in Figure 29.

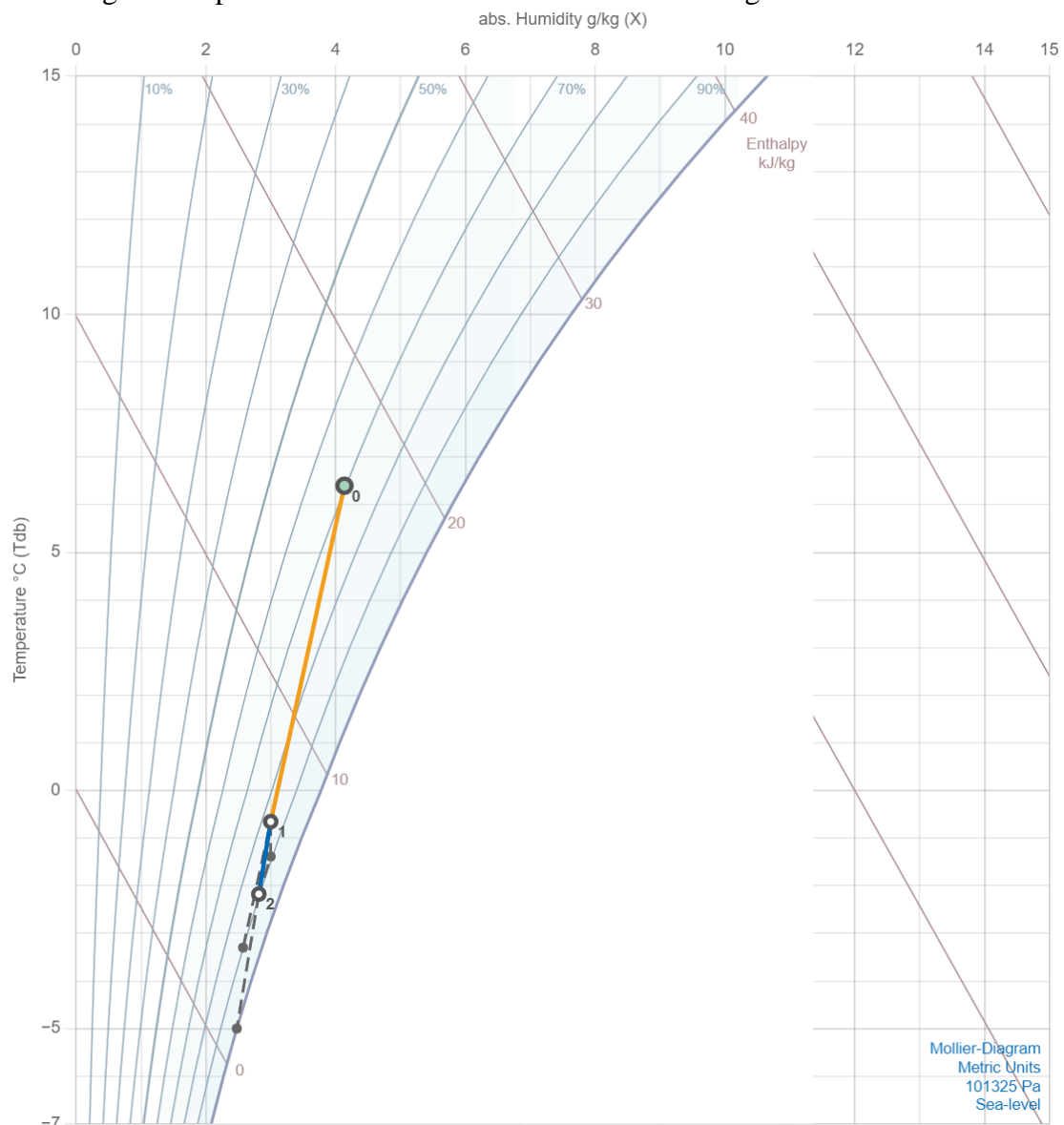


Figure 29: Mollier diagram with input measured values from spring case. (Bernard, 2023)

Stage 0 is the measured average inlet air properties to the AHU. Stage 1 is the air conditions between the rotating heat exchanger and cooling coil in the AHU. This stage is a result after adapting the efficiencies of the two components to reach the measured outlet temperature of the AHU. Stage 2 is the measured supply temperature to Skidome which also is the outlet from the AHU.

The moisture content from the inlet air to the AHU is 4.1 g/kg and before the cooling coil 3 g/kg. The supply air to Skidome has a moisture content of 2.8 g/kg.

Table 13: Mollier diagram results from average measured values in spring case measurement.

Stage	Temperature [°C]	RH [%]	x [g/kg]
0	6.4	69.6	4.1
1	-0.7	84	3
2	-2.2	89.5	2.8

The efficiency of the rotating heat exchanger and cooling coil is adjusted to reach the measured air outlet properties in stage 2. It resulted in 72% for the temperature recovery and 72% for the moisture recovery in the rotating heat exchanger, and 35% efficiency in the cooling coil.

Discussion - Mollier diagram

By observing the efficiencies of the two components in the AHU and how it deviates between spring and winter case one can see a large difference. It was assumed that only the rotating heat exchanger was working during winter case because it was more than enough to supply the measured air properties to Skidome. This could also be validated by the results from the spring evaluation, where the efficiency of the same component was higher. This proves that the heat exchanger did not even run at full capacity during winter case measurement and therefore it would be unlikely if the cooling coil would be activated as well.

It could to some extent be incorrectly to state efficiencies of the cooling coil and rotating heat exchanger in the AHU in these terms because it is very dependent on the cooling need and is therefore not linear. However, it is useful in this case to evaluate if the AHU is running at full capacity as well as to adjust the components to reach the measured air properties.

5.3 Investigations

Results from the five investigations invented from the framing of questions in this project is presented in this chapter. Discussion regarding each investigation is also presented in the end of each section.

5.3.1 Coefficient of performance of the cooling machine

Today the cooling machine operates with an evaporating temperature of $-18\text{ }^{\circ}\text{C}$ and a condensing temperature of $30\text{ }^{\circ}\text{C}$. From the software FSS3, the refrigeration capacity with the four compressors at the arena with these temperatures will result in a total refrigeration capacity of 456 kW for all four compressors, a power demand of 162 kW and a COP of 2.82, see orange bar in Figure 30.

The software shows that if it is assumed that the evaporation temperature is kept at $-18\text{ }^{\circ}\text{C}$, the lower the condensing temperature is, the higher refrigeration capacity will be and the higher the COP resulting in lower electricity use.

Figure 30 shows that if the condensing temperature is reduced to $20\text{ }^{\circ}\text{C}$ and the evaporating temperature would be kept at $-18\text{ }^{\circ}\text{C}$, the refrigeration capacity would theoretically be 513 kW, the power need 143 kW and the COP 3.59. This would theoretically reduce the power use with 11.5% from the cooling machines energy use.

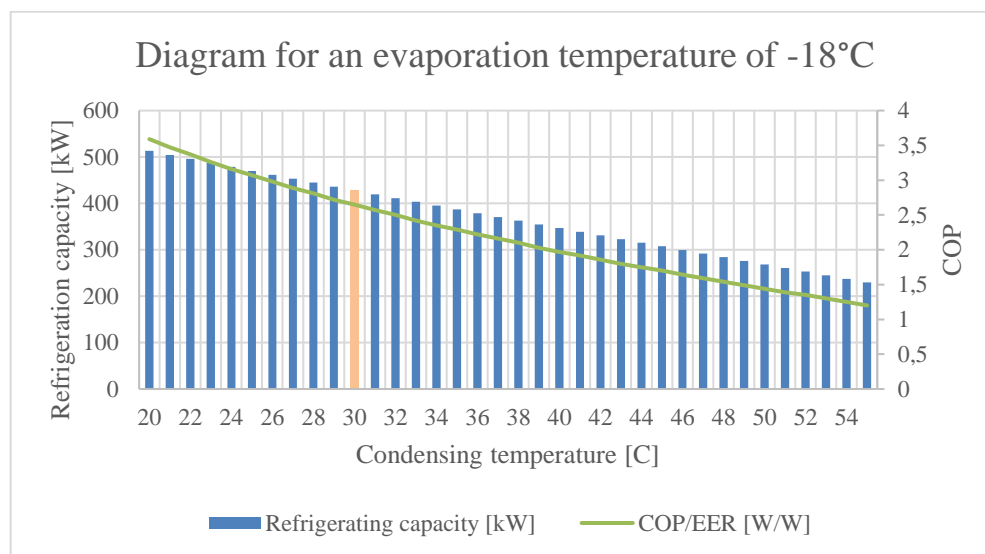


Figure 30: Refrigeration capacity at different condensing temperature if the evaporation temperature is kept at $-18\text{ }^{\circ}\text{C}$. The orange staple represents the temperature the cooling machine is operated on today.

Reducing the condensing temperature will result in other possibilities to recover heat by the heat pumps. Meaning that lower temperatures will be introduced into the heat pumps that run with heat recovered from the cooling machine. This will affect the electric power required for the heat pump to produce hot tap water. How it will affect the heat recovery possibilities has to be further investigated.

Discussion - COP of performance of the cooling machine

The investigation was mainly made by analysing data from Frascold's FSS3 software, which results in theoretical values and not actual values, from the process, that were analysed.

The investigation did not make any further investigations if it is practically possible to adjust the condensing temperature with the existing compressors and equipment that are in the cooling machine today. The analysis was theoretical and focused on possibilities for further investigation.

Reducing the condensing temperature would reduce the possibilities to recover heat from the cooling machines. Worth mentioning, is that the full capacity of heat recovery is probably not utilized today. The heat that is not recovered is cooled off through dry coolers. Thereby the heat recovery is not fully utilized today. Further investigations if reduction in condensing capacity still would be enough for the heat production with heat pumps has to be made.

It is worth noting that the cooling machine is operating at a refrigerant that is not allowed to fill if leakages occur. In the close time the refrigerant must be changed, and thereby most possibly the components of the cooling machine. The investigation should therefore be considered when designing the new cooling machine.

Lack of possibilities to log data from the cooling machine and analyse trends reduced possibilities with this investigation. Further investigations would include actual values from the process and analysis of how changes affect different parts of the process.

5.3.2 Performance of Skidomes AHU

By combining results from both the Measurement in the cooling system in section 5.1.1 and Mollier diagram in section 5.2 an evaluation of the performance of the AHU to Skidome can be made. Efficiencies of the AHU components were determined using a Mollier diagram and the results from measurements. Since it is stated that the rotating heat exchanger was not running at full capacity in the winter measurement, the spring case will be evaluated. The calculated efficiencies of the rotating heat exchanger in spring case are 72% for the moisture and temperature recovery. It is close to the theoretical efficiency of 75- 90% extracted from a product sheet from a similar product. Either the rotating heat exchanger is not fully optimized and should be further investigated or it was not running at full capacity during the measurement occasion.

By observing results from the two measurement occasions, spring- and winter case. The average difference of the outdoor temperature from Table 6 shows that the average outdoor temperature was three degrees warmer during the spring measurement. Also, that the supply temperature to Skidome was three degrees colder. This could be because of a shift in the AHU, and it operates differently during colder conditions and the measurements were made during two different types of operation. Which is also assumed during the Mollier diagram evaluation, in the winter case it was assumed that only the rotating heat exchanger was operating. While during the spring case it was assumed that both the rotating heat exchanger and cooling coil was operating. However, it should be further investigated and strive for a more stable supply air temperature to Skidome.

The warmer supply temperature during the winter case comes with higher moisture content in the air. It would therefore be desirable to lower the temperature to both reach the set point temperature as well as possibly lower the moisture content inside Skidome.

Results from measurements in Section 5.1.1 is utilized to detect how large the moisture content in the supply air to Skidome is compared to the air inside. In Table 14 is the average measured values from spring and winter measurements presented. It is detected that the moisture content in the supply air is higher than the moisture content of the air inside Skidome, in both spring and winter measurements. In spring case the difference in moisture content is 0.1 g/kg and in winter case the difference is 0.6 g/kg.

Table 14: Average measured values from spring and winter measurement comparison supply- and indoor air.

Average values	Spring measurement		Winter measurement	
	Supply air Skidome	Inside Skidome	Supply air Skidome	Inside Skidome
T	-2.2°C	-3.7°C	0.9°C	-2.1°C
RH	89.6%	97.2%	95.0%	100.0%
X	2.8 g/kg	2.7 g/kg	3.8 g/kg	3.2 g/kg

This could then be a contributing factor for increased ice coating on the cooling coils inside Skidome. Because the air is dehumidified somewhere inside the climate shell due to the decrease in moisture content from supply air to air inside Skidome. The dehumidification in the cooling coils inside Skidome is sorbent dehumidification. The condense created on the surface of cooling coil is then freezing due to the low temperatures both inside Skidome and inside the coils.

Results from Measurement 3: Intake air condition in section 5.1.1 showed that the location of the AHU down in the ground pit is beneficial for the intake air properties to the AHU. The air is both colder and has lower moisture content than air at higher altitude in a different location. The measurement is done during a short period during a day in February and a similar measurement should also be made during summer to detect if the properties changes during the year.

By observing Table 15 one can detect how the moisture content changes in the AHU, from the air intake to the AHU to the supply air to Skidome. In the spring measurement the moisture content decreases with 1.3 g/kg while in the winter measurement the air is dehumidified with 0.5 g/kg. During the spring case the dehumidification in the AHU is 60% larger. The difference is large, and the AHU operation conditions should be further investigated to get a more efficient air-cooling system.

Table 15: Average measured values from spring and winter measurement comparison in and outlet AHU.

	Spring		Winter	
	Intake air before cooling machine	Supply air Skidome	Intake air before cooling machine	Supply air Skidome
T	6.4°C	-2.2°C	3.1°C	0.9°C
RH	69.6%	89.6%	90.9%	95.0%
x	4.1 g/kg	2.8 g/kg	4.3 g/kg	3.8 g/kg

From the study visit at Torsby Ski tunnel another solution for defrosting the cooling coils was detected. It uses a warm fluid circuit connected to the same cooling circuit with a valve. When defrosting in the cooling coil is needed a valve is opened and the warm fluid runs through the cooling coil and the ice coating is melting. Compared with the electric heating there is less wear on the equipment since the electric rods that is located between the coils has a limited lifetime and is complicated to replace. The warm circuit could in this case in Skidome be supplied by the indirect warm stream in the condensing process in the cooling machine through heat recovery.

Discussion - Performance of Skidome's AHU

It is rather difficult to determine what relative humidity and temperature inside the climate shell in Skidome that contributes to less or more ice coating on the cooling coils. However, after the study visit at Torsby it is evident that it is a common problem. It might be a problem that is hard to eliminate but possible to decrease.

The moisture content in the air inside Skidome cannot be too low because it would affect the snow quality. Therefore, there could be a tradeoff between ice coating on the cooling coils inside Skidome and to keep an optimum indoor climate for snow quality and the skiers.

There could be several factors that affect the indoor air condition in Skidome, such as air leakages and activity level. The air leakage to surrounding environments through the envelope could be a factor that should be considered in this investigation. The ski hall only has one wall facing outdoor conditions, other walls and floor face ground or other facilities within the arena. These other facilities have rather constant temperatures throughout the year and therefore the outdoor conditions should not affect the indoor temperature significantly through leakages.

One possible cause of lower temperature inside the ski hall during the spring compared to the winter is that there is a drastically lower activities in the ski hall after the ski race of Vasaloppet in the beginning of march. Both the operating staff and the people working with Skidome see large differences in the activity before and after Vasaloppet. Fewer skiers result in lower internal heat gain which most probably will keep temperatures inside the ski hall lower.

5.3.3 Heat recovery from cooling machine

The heat recovery from cooling machine investigation is partly based on the heat recovery system measurement. Average values in the indirect warm stream from the condensing process in the cooling machine are presented in Figure 31. The black values are measured and is an average value from the data from the measurement in heat recovery system. The red values are calculated with the measured data as well as extracted from the unique pump curves.

The total average flow in the stream is $67\text{m}^3/\text{h}$ and the average out- and ingoing temperatures are 21.4°C and 19.6°C respectively. This results in a total average excess heat of 134 kWh/h . The set point temperature for this stream is presented in Section 3.1.1 and is 20°C and 25°C , there is a large deviation from the measured temperatures and should be further investigated.

The temperature measured on the heat recovery stream to the heat pumps has an average supply temperature of 21.4°C and average return temperature of 19.7°C . The flow on this stream was not measured and therefore the pump curve for the pump on that stream could be utilized. This resulted in a flow of $14\text{ m}^3/\text{h}$, and the heat recovery to heat pumps is then calculated to 43 kWh/h in average.

The average excess heat to the dry coolers was then left and calculated to 91 kWh/h . However, the temperature-controlled valve, which can be seen in Figure 31, is a blind spot where the flow through is unknown. The valve controls the temperature in the returning stream to the cooling machine to maintain a stable supply temperature. Therefore, the heat through the dry coolers could be lower depending on the flow through the control valve and should be considered as a maximum value.

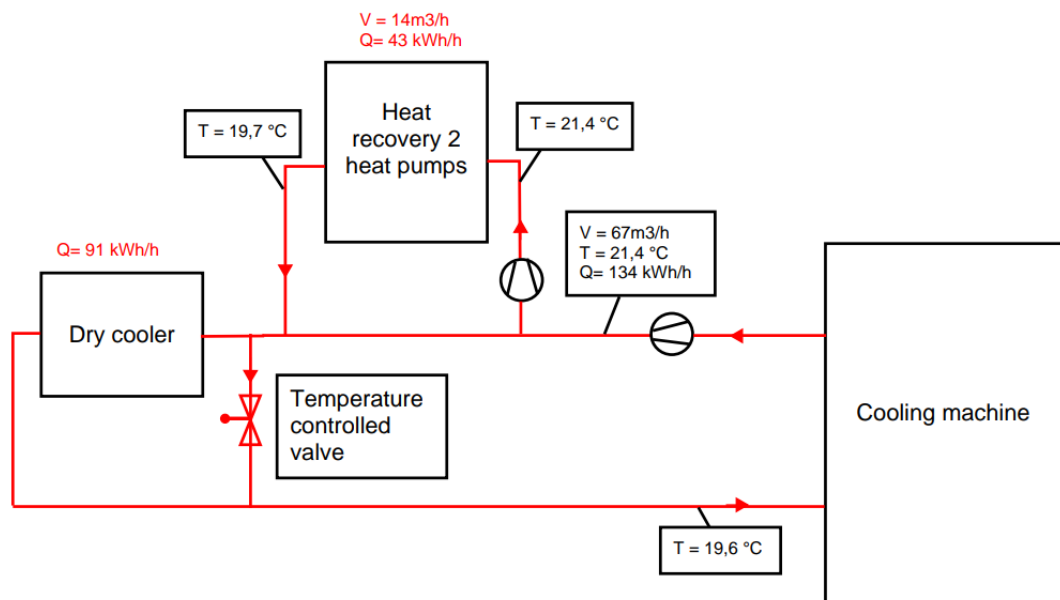


Figure 31: The indirect warm stream from the condensing process in the cooling machine, measured average values (black) and calculated average values (red).

By utilizing the calculated heat balance values in the indirect warm stream in the condensing process in the cooling machine it is determined that 69 % of the excess heat from the cooling machine were cooled off in the dry coolers. This means that 31 % of the excess heat is utilized for heat recovery to heat pumps for heating the building, Figure 32.

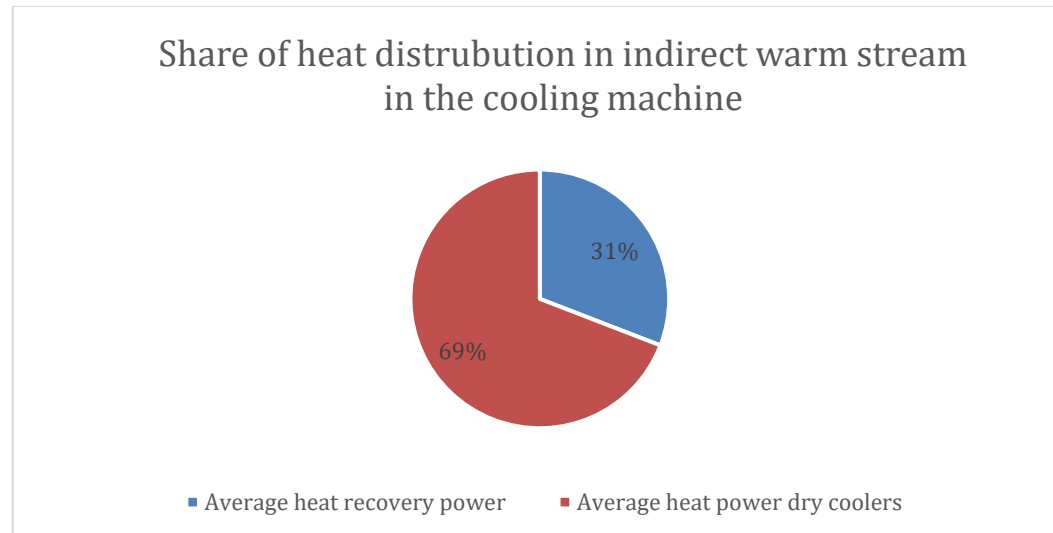


Figure 32: Share of heat distribution in the indirect warm stream in the condensing process in the cooling machine.

Discussion - Heat recovery from cooling machines

In the case study of the cooling system in Skidome it was found that the constructed maximum excess heat from the cooling machine is 700 kW. This value deviates from the measured value of 134 kW in the measurement in indirect warm stream in the condensing process, see Section 5.1.2. This could be because the constructed maximum is based on all four compressors working simultaneously. As well as the constructed temperature difference is 5 °C from the set point temperatures for the indirect warm stream in the condensing process in the cooling machine presented in Section 3.1.1. Which is significantly larger than the measured temperature difference of 1.8 °C.

During the calculations it was assumed that the valve in Figure 31 was closed and did not let any flow through. Therefore, the calculated heat that is cooled off by the dry coolers at 91 kWh/h is a maximum value for that calculation. The amount of heat that is cooled off through the dry coolers could therefore be less and should be further investigated.

The measured flow in the indirect warm stream in the condensing process in the cooling machine in Section 5.1.2 of 66 m³/h does not correspond to the flow outdrawn from the pump curve of 82 m³/h. This deviation could be because the pump curve is very sensitive to small changes. As well as the potential errors during the extraction of pressure data from the manometers on the pump.

The quality of the excess heat from the indirect condensing stream in the cooling machine is rather low since it measures between 20-25 °C. It is too low to give back to the district heating net as well as utilize directly for heating inside the building without heat pumps. Therefore, investments in equipment such as heat pumps must be made to utilize the excess heat. Practical limitations should be included in investment calculations for the system to be able to utilize more of the excess heat than today. Parameters such as installation distance between the heat and demand could be costly.

One thing the low tempered excess heat could be used for is the heating pipes below the snow. Today the heating pipes are operated with direct electrical heating, if instead pipes were installed with the low tempered heat flowing through, a larger share of heat recovery could be used. This installation would not be as directly dependent on the electricity price as it is today.

5.3.4 Using heat pump for hot tap water production

In 2022, Serneke Arena totally used approximately 463 MWh of district heating for the hot tap water use at a total cost of 241 648 SEK. The cost of district heating varies each month as well as the cost of electricity. The average cost of district heating is given from Göteborg Energi and the average monthly cost of electricity is the average cost per kilowatt hour in SE3 each month 2022 (Elbruk, 2023). To the electricity price 0.45 SEK per kWh is added for taxes and 25 % for fees. The total electricity price with taxes and fees as well as the district heating price is presented in Table 16.

Table 16: Cost of district heating and electricity 2022 with taxes and fees included.

Month	Energy price 2022 district heating [SEK/MWh]	Ave electricity price SE3 2022 with taxes and fees [SEK/MWh]
January	521	1 493
February	521	1 225
March	521	1 753
April	359	1 342
May	164	1 479
June	100	1 713
July	100	1 316
August	100	2 681
September	145	2 736
October	359	1 257
November	414	1 759
December	521	3 140

With statistics of the average power output from the district heating and the monthly electricity price the costs of producing hot tap water with a heat pump can be compared to the cost of consuming district heating, see Table 17.

Table 17: Cost of district heating compared to electricity cost if the hot tap water instead would be produced with a heat pump.

Month	Cost of district heating 2022 incl taxes [SEK]	Electricity cost heat pump 2022 Borehole [SEK]	Electricity cost heat pump 2022 Heat recovery [SEK]
January	31 503	14 464	14 149
February	34 564	13 508	13 214
March	37 560	21 641	21 170
April	27 511	15 454	15 119
May	17 564	16 772	16 407
June	13 751	16 935	16 567
July	13 763	13 048	12 765
August	13 638	25 809	25 248
September	16 404	30 099	29 445
October	28 408	15 186	14 856
November	33 024	22 915	22 416
December	34 369	34 363	33 616
TOTAL	302 060	240 193	234 972

This result in a total cost for district heating of 302 060 SEK. If Serneke Arena instead produced their own hot tap water 2022, the total operating cost if utilizing the boreholes would be 240 193 SEK which is around 62 000 SEK savings (20.5%) compared to the cost of district heating. If instead utilising heat recovery heat pumps the cost would have been 234 972 SEK, which is around 67 000 SEK savings (22.2%) of the district heating cost.

More detailed look at the numbers from Table 17 shows that the district heating is cheaper during warmer months between May and September, while locally producing heat with heat pumps was cheaper during colder months.

It would be possible to take advantage of this and locally produce heat with heat pumps when the electricity price is lower than the cost of district heating. The heat produced could be stored in accumulator tanks which will keep the temperature up until the heat is needed.

An analysis of the highest electricity cost each month was made and resulted in that the locally production of hot tap water was beneficial. This means that if the electricity price is equal to or lower than presented cost in the green graph in Figure 33, it would be beneficial to produce hot tap water with the heat pump. The graph also shows the monthly average electricity price in SE3 from 2022 in comparison.

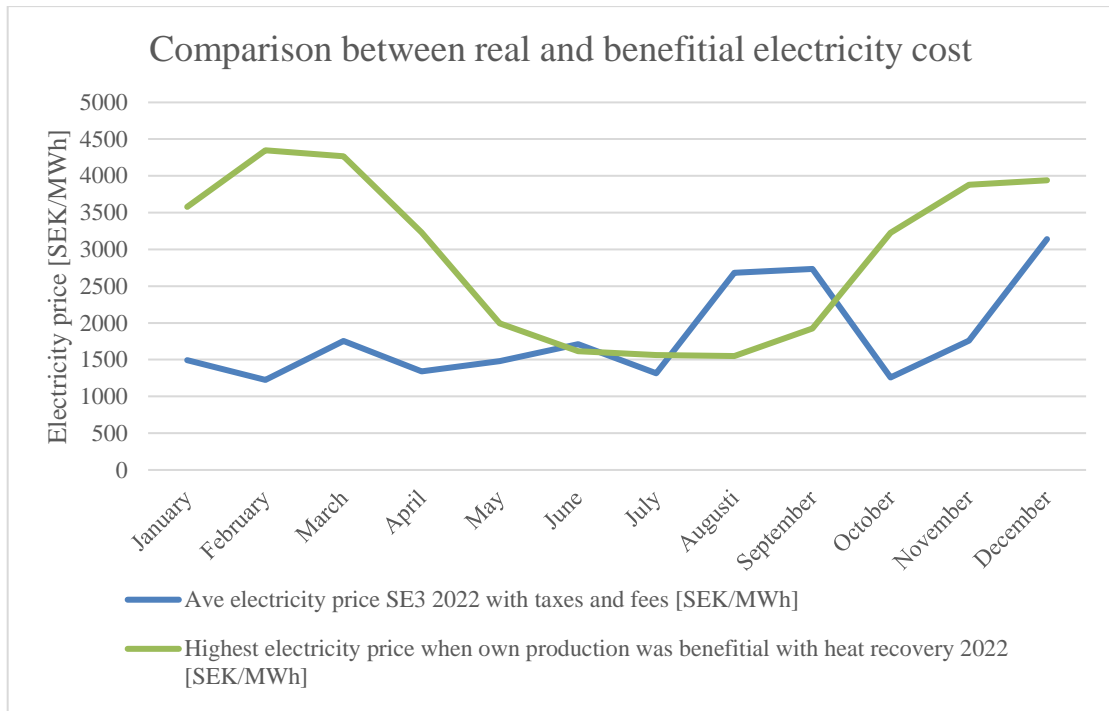


Figure 33: Comparison between real and beneficial electricity cost of using a heat pump to locally produce hot tap water instead of buying from the district heating net during 2022.

One thing worth mentioning is that there was an electricity crisis in Sweden during 2022 and especially in southern Sweden SE3, where the arena is located. Since the costs of local production of hot tap water is strongly dependent on the electricity cost this must be considered.

If the average paid electricity price is compared with years before 2022, Figure 34 shows that during these years it would be beneficial to locally produce hot tap water.

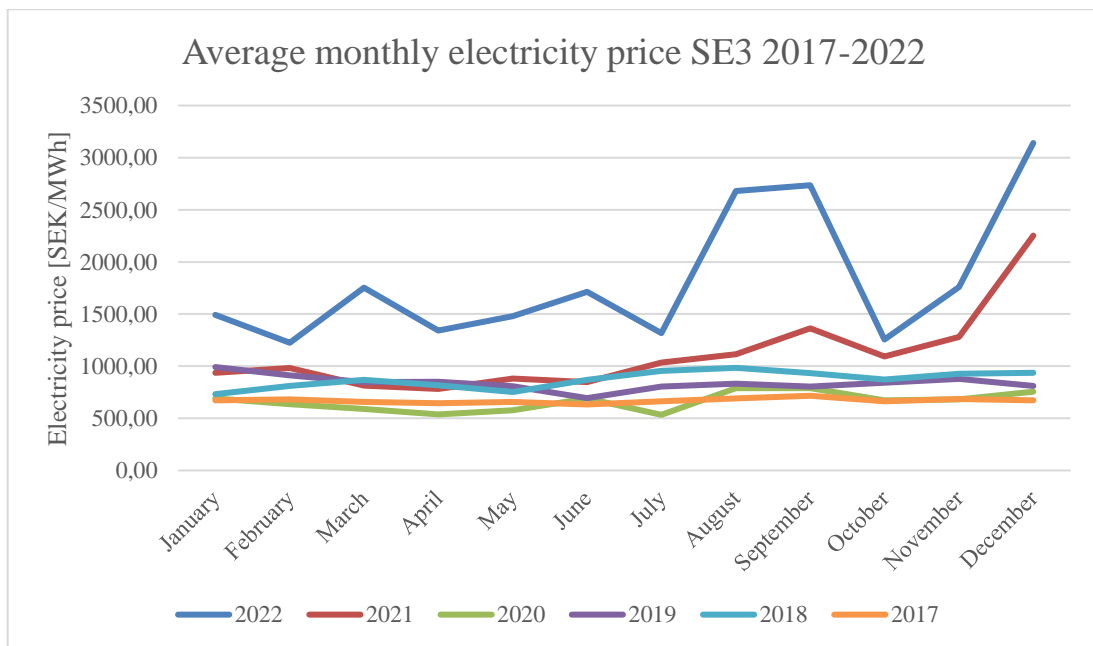


Figure 34: Average monthly electricity price in SE3 between 2017 and 2022 with taxed and fees included.

Figure 34 shows the higher electricity prices that occurred in SE3 2022 compared to years before.

Discussion - Utilizing heat pump for hot tap water production

The analysis was made with the price of district heating from Göteborg Energi 2022, the price of district heating will possibly change over the years as well as the price of electricity. Therefore, historical costs should not be considered because of future prices. Figure 34 shows how the electricity price has changed the last five years. Even if 2022 included an energy crisis in Sweden it could be assumed that it will not go back to the levels of electricity prices that was before. The price of electricity in the future is not sure. Therefore, it is not fair to make assumptions regarding future electricity prices by looking at historical levels. The same is applied with the price of district heating and its future. It is not either known how the electricity price will vary compared to the price of district heating.

It is also worth noting that the analysis was made assuming the COP from the product specification of the heat pumps and not actual values were taken. The electricity need at different input temperatures was calculated using the same COP from the product specification, even though the COP might vary with different input temperatures to the heat pumps. This because of lack of possibilities of measuring the power use at different input temperatures.

Another thing worth mentioning is that the two heat pumps working with heat that is being recovered from the cooling machine is operated around 20 000 hours more per heat pump compared to the five heat pumps operated with the boreholes since they started to operate at the arena. To distribute the load of the pumps it can be worth looking at switching the load between all seven heat pumps.

5.3.5 Utilize boreholes for comfort cooling

The opportunity to utilize free cooling from existing boreholes is evaluated in this section. The electricity use of the comfort cooling unit in years 2017-2022 is showed in Figure 35. It can be detected that the highest electricity use is during summer but there is a demand of comfort cooling during the whole year, even during wintertime.

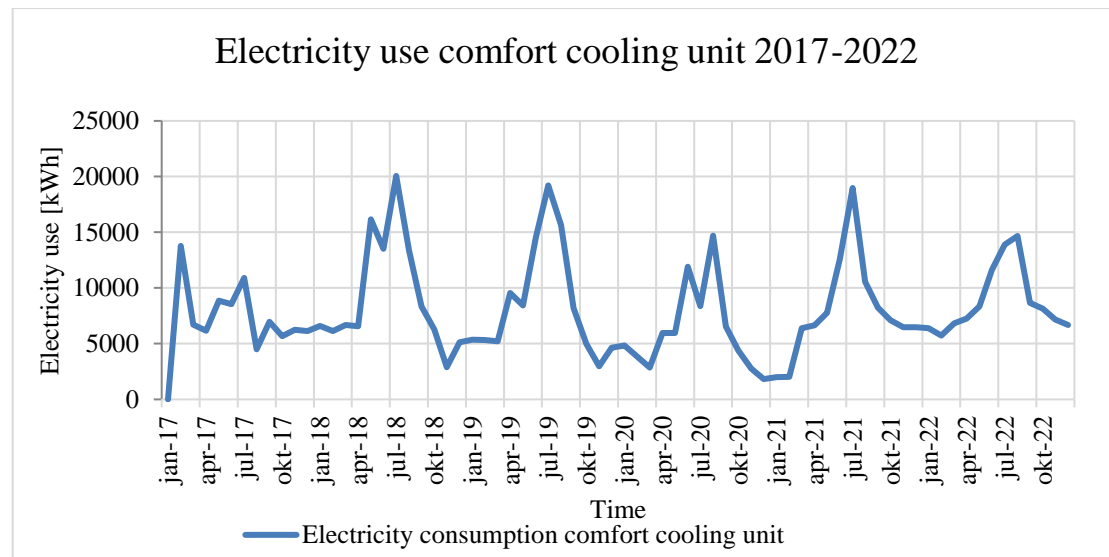


Figure 35: Electricity use comfort cooling unit Serneke arena 2017-2022.

According to Figure 1 it is detected that the cooling ventilation responds to 2.2% of the total electricity use in Serneke arena. The whole 2.2% of electricity use could then be saved since it is assumed that the whole cooling need for comfort cooling can be covered with free cooling from the boreholes.

The annual average electricity use from comfort cooling is 96.2 MWh. By utilizing the monthly average electricity price, presented in Figure 34 in earlier Section 5.3.4, an average yearly cost of the ventilation cooling is calculated. The annual average cost of electricity for comfort cooling in Serneke arena is 118 320 SEK. This is also then the potential savings per year by utilizing the existing boreholes for comfort cooling.

Discussion - Utilize boreholes for comfort cooling during summer

This investigation is directly dependent on the assumption that it is possible to extract heat and cool simultaneously. However, the installation of the system is already done but needs a closer investigation to function. If the cost to fix the problem with the free cooling system would be lower than 118 320 SEK, the pay-back time for the fix is significantly short. Therefore, it should be an attractive investigation to proceed.

Another possibility for the free cooling from boreholes could be for cooling to Skidome. Such as for cooling the indirect warm stream in the condensing process in the cooling machine, instead of the dry cooling. Or as a precooling function for the fresh air inlet to the AHU. However, this would come with a rather large project to investigate.

6 Conclusion

According to the five investigations that has been made, there are several ways to improve the energy efficiency of Serneke Arena compared to how it is operated today.

Lowering the condensing temperature and increasing the COP of the cooling machine could result in energy use reduction of up to 11.5% of the total energy demand for the cooling machine. This assumes that the evaporation temperature and the refrigeration capacity are kept at levels of today, and only affects the condensing capacities.

Ventilation air in the AHU in Skidome has different properties depending on how the AHU is operated at certain outdoor temperatures. The performance of the AHU deviates between winter and summer conditions and could be further optimized to sustain a stable condition of the supply air. The supply air to Skidome has a slightly higher moisture content than the indoor air in Skidome and could be a factor for ice coating on the cooling coils. Measures such as new defrosting options for the cooling coils inside Skidome could be installed to sustain an efficient air-cooling process.

31% of the heat from the indirect warm stream in the condensing process in the cooling machine is utilized for heat recovery to heat pumps for comfort heating. While the remaining 69% of the heat is cooled off with dry coolers. This is however a maximum heat that is cooled off in the dry coolers due to an unknown flow through a temperature-controlled valve.

In 2022 Serneke Arena had a total hot tap water use of 463 MWh that was fully distributed from the district heating net. If the hot tap water instead had been locally produced with the existing heat pumps money could have been saved. If the heat pumps utilize heat from the existing boreholes the total cost would be reduced with 20.5% compared to what was paid to the district heating net. If the heat pumps instead were connected to heat recovery the total cost would instead be 22.2% lower compared to the cost of district heating.

To utilize the existing boreholes for comfort cooling during the year it would save in average 95.8 MWh of electricity use per year. This corresponds to an average annual saving of 118 026 SEK in electricity use costs. Given that the boreholes could be utilized for free cooling all year around.

6.1 Further recommendations

Further investigations of Serneke Arenas energy systems should investigate the costs of investing in a building management system (BMS). This would give possibilities to analyze temperatures and energy flows in both the cooling system to Skidome and the heating system. It would then facilitate significantly to do energy system analysis by both analyze trends and historical data.

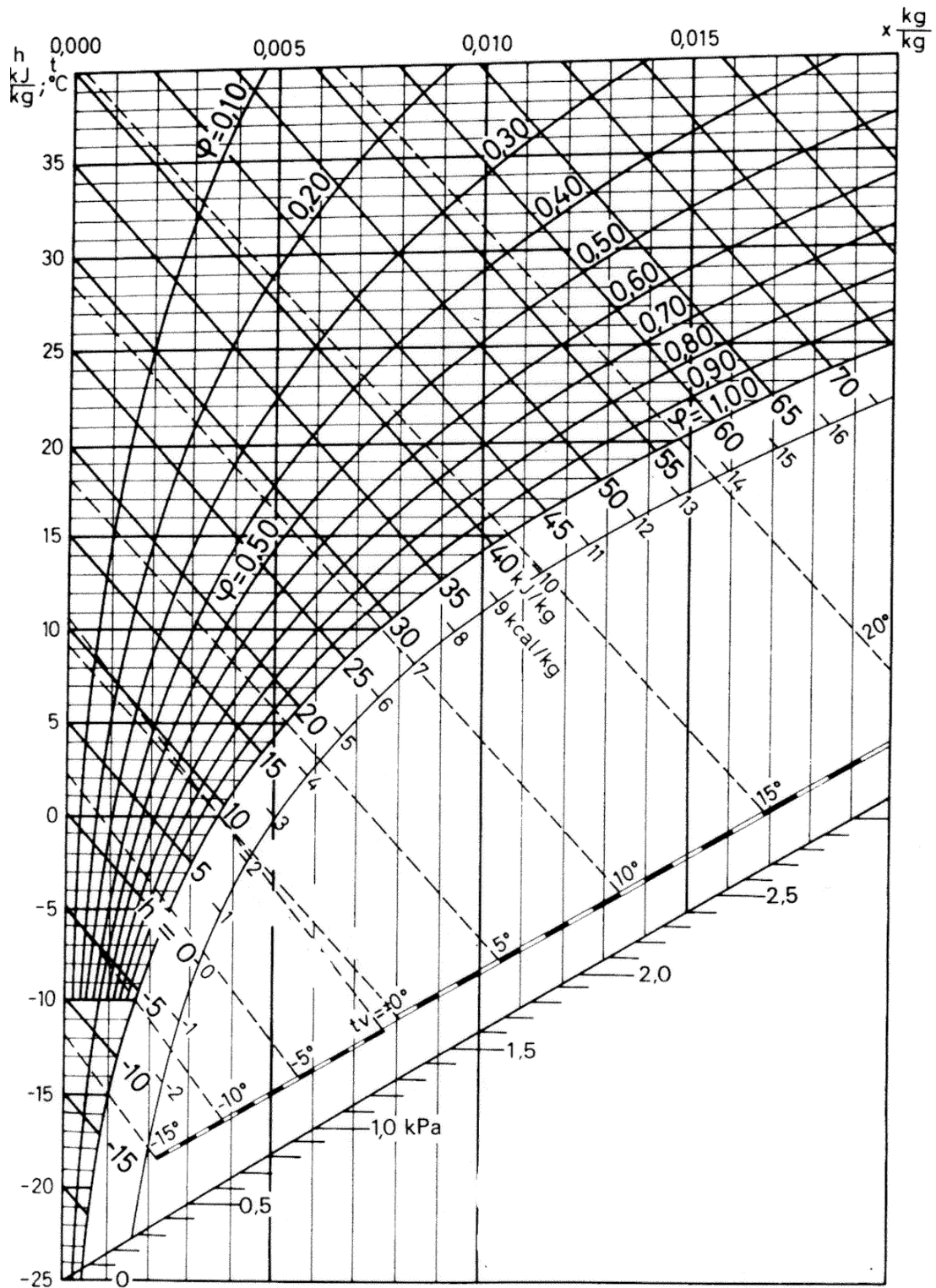
It would also be recommended to further investigate the energy performance in more detail at other facilities within the building since this project had a large focus on Skidome. There are most likely possibilities to improve energy performance in more activities in the building even though they are not the largest electricity consumer.

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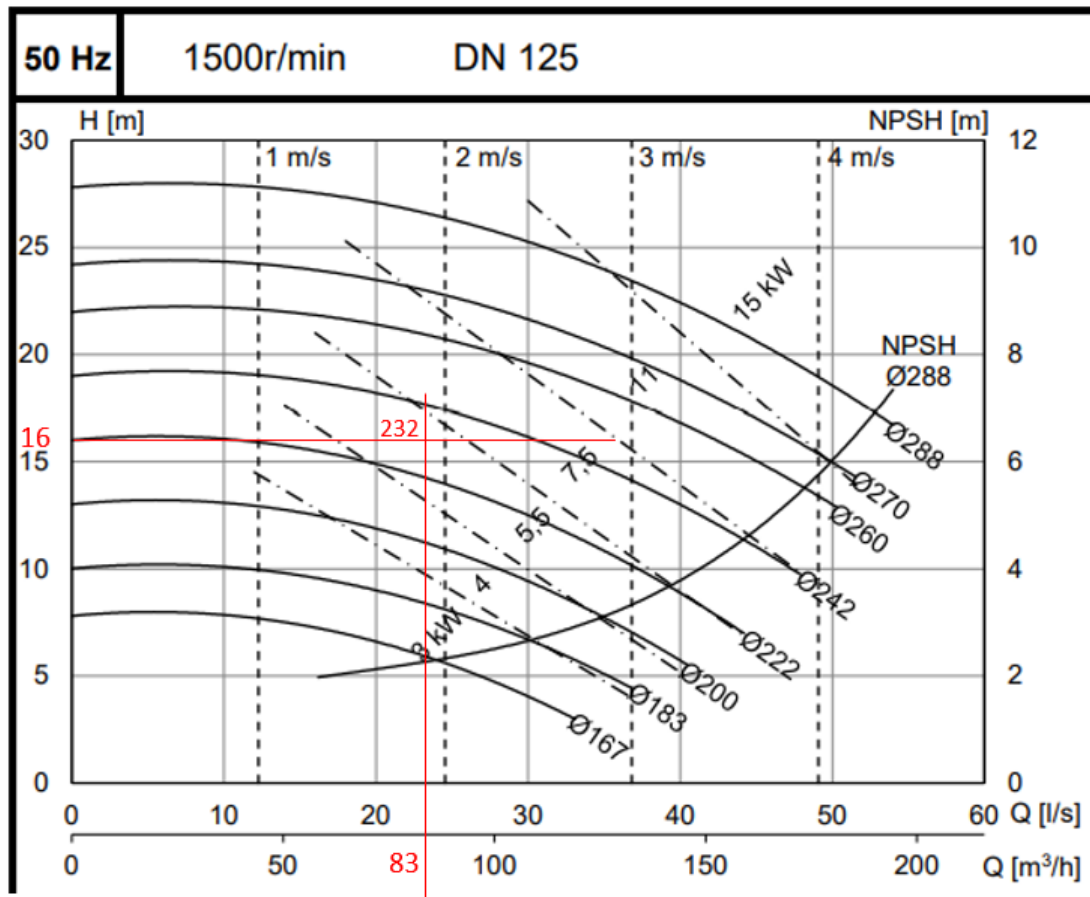
Appendix

A Mollier chart



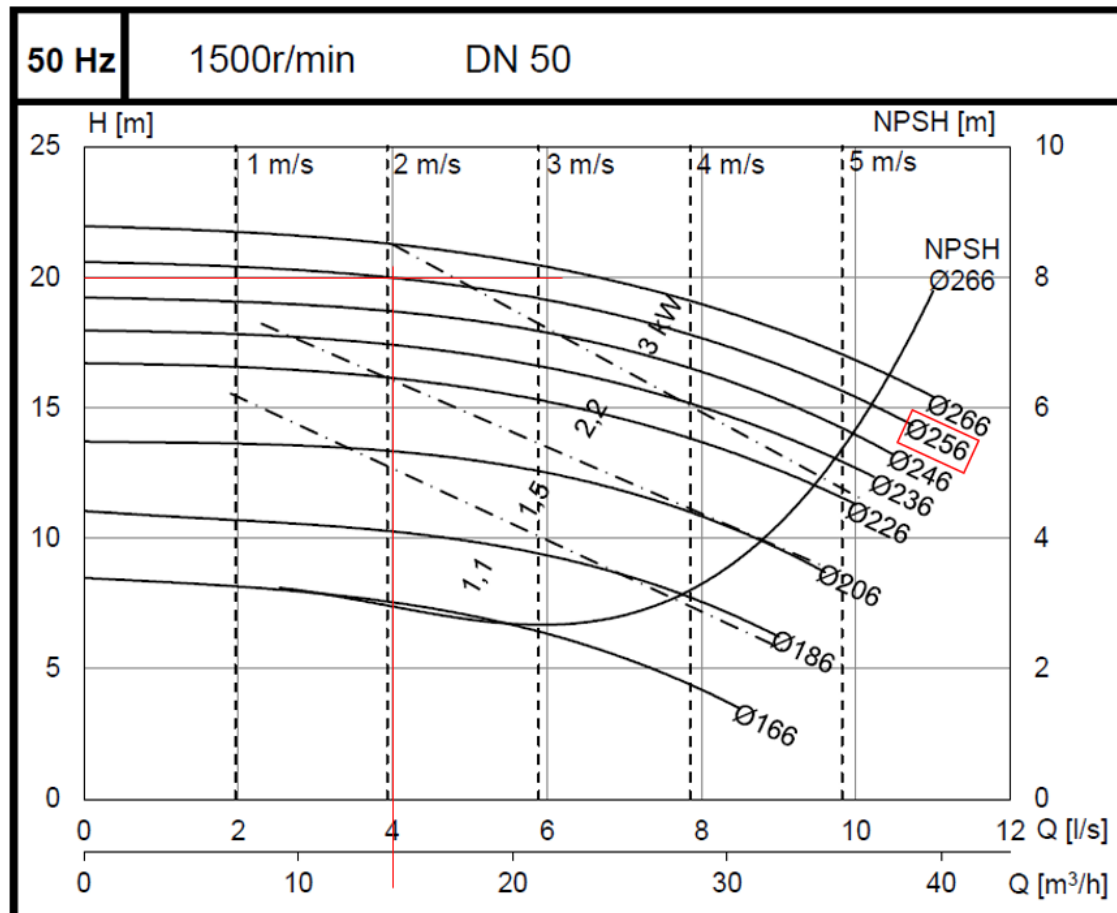
B Pump curve indirect warm stream in the condensing process

Pump curve for the pump on the indirect warm stream from the condensing process in the cooling machine.



Source:(Kolmeks, 2023b)

C Pump curve heat recovery



Source: (Kolmeks, 2023a)



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