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sweet swiss energy research for the energy transition

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Summary

This report evaluates different sources estimating current and future heating and cooling demand. Different projections of district heating penetration and cooling demand trends are combined to predict the district cooling potential in the range of 0.7 to 6 TWh/y, given the large differences in the data analysed. There is a significant potential for district cooling, with a range of technologies available, from the economic and energy efficient option of direct cooling with low temperature networks, through compression cooling for higher temperatures, to absorption heat pumps, desiccant and evaporative cooling in networks with higher temperature waste heat. In addition, various storage options, including sensible heat storage as the most common, can be used to increase network flexibility on a daily or seasonal basis. A simulation of different district cooling configurations for the high-temperature district heating network in Losone has shown that wood consumption in summer can be reduced or eliminated by using decentralised compression chillers, which condense into the network in a similar way as the solar thermal system. The introduction of compression chillers is compared to the combination of absorption chillers with a solar thermal system, which resulted in higher wood consumption in summer.

1 Introduction

Switzerland's climate goals are to achieve net-zero CO_2 emissions by 2050. The provision of heat plays an important role and heat networks are a key technology for achieving these climate targets. They help reduce the use of fossil fuels and promote renewable energies. In 2016, half of the final energy consumed in Switzerland was used for heating, totalling 389 PJ. The heating sector is responsible for 18 million tonnes of CO_2 emissions, 38% of Switzerland's total CO_2 emissions. District heating covered 5% of Switzerland's heating needs. Most of this district heating, 80% was supplied by renewable energies or waste heat, while 13% of district heating was supplied by fossil fuels. [1]
According to Energy Perspectives 2050+, in 2019, 6.5 TWh/y was supplied by district heating. In a continue as before scenario, this will not increase by 2050. In the ZERO baseline scenario, district heating increases up to 15 TWh/y, in the ZERO C scenario even up to 18.2 TWh/y. In particular, the domestic sector is attributed the highest expansion potential. [2]
The VFS Strategy white paper analysed various sources of district heating potential in Switzerland. It reports a district heating potential of 17.3 TWh/y, which corresponds to 38% of the heat demand. The lakes represent the largest potential source with 5.1 TWh/y, which corresponds to 29% of district heating. The second largest potential source is waste heat from waste incineration plants with 3.6 TWh/y and a share of 21%. [3]
According to a study by AEE Suisse and the Swiss Heat Initiative, 27% of Switzerland's heat demand can be met through district heating, even with low heat distribution costs and incentive systems or regulations. The service sector, industry, and multifamily houses are identified as having great potential[4].

Estimating future cooling requirements can be challenging due to the not comprehensive data and the evolving buildings and requirements, but the cooling demand is expected to increase in the future caused by the rise of the temperature from climate change. Despite of the rise in cooling demand and the fact that the demand for heating is expected to fall due to efficiency improvements in heating systems, buildings, industry and services, the demand for cooling will remain significantly lower than the demand for heating for all scenarios. According to Energy Perspectives 2050+, the number of cooling degree days is projected to increase to double or even five times higher by 2050, depending on the RCP scenario. The service sector will account for approximately half of the future cooling demand. A study by AEE Suisse estimates that Switzerland's future cooling demand could reach up to 11.5 TWh/y, with the service sector alone requiring 8.8 TWh/y, while the household sector will require 1.2 TWh/y [4].
According to VSE's Energy Supply 2050, the current cooling usage stands at 4.8 TWh/y. The forecast predicts a cooling demand of 7.7 TWh/y, which represents a significant increase. It is important to consider the cooling demand, even though it is lower than the heating demand, especially in the future. The potential for district cooling should be analysed and this gets executed in this paper. [2,4,5].

2 Potential of district cooling in Switzerland

The potential and future amount of district cooling depends on several parameters. The future cooling demand in general has an impact as well as where the cooling demand is geographically and at which time and temperature, as well as which sources are available and where are they. Regulations on environmental impact and heat use, economic interests, available technologies and the efficiency of them are also important factors. District heating, the existing or planned infrastructure and the possibility to combine heating and cooling or other applications can also influence district cooling in the future. Some of these subjects get analysed in the following sections. The data is rare on the district cooling, as the amount of cooling demand and interest in district cooling systems is still limited.

2.1 Present and future cooling and heating demand

The present heating and cooling demand in Switzerland get monitored by the Swiss Federal Office of Energy. The analysis of energy consumption by specific use shows the distribution of total energy consumption in Switzerland. In 2022, out of the 99 TWh of energy consumed for heating and cooling, 56 TWh was used for space heating, 13 TWh for hot water, 1.7 TWh for space cooling and 6.2 TWh for VAC processes in general. 25 TWh was used for process heating and 3.5 TWh for process cooling, mainly in the service sector. [6]
Figure 1 shows the energy consumption in Switzerland in 2022 for the different sectors. The energy consumption for cooling includes values for ventilation, air conditioning and building technology and not only for space cooling. Therefore, the energy consumption for cooling may not be accurate.

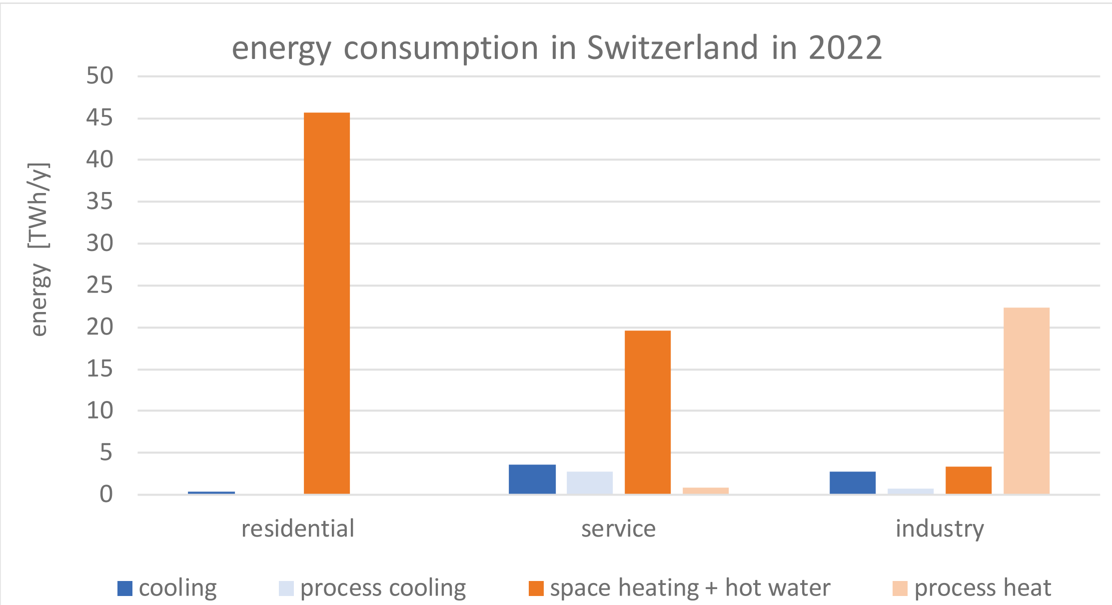

Figure 1: Energy consumption of sectors for heating and cooling in Switzerland in 2022 [6].

Figure 2 on the right shows the specific space heating and cooling demand of different building types in Switzerland from different studies. The different buildings are office, residential, old, low energy or "Minergie" buildings. They also distinguish between different insulation and different cooling measures such as night ventilation and shading. Therefore, the values especially for heating in different building types spread a lot. On the left is the total space heating and cooling demand in Switzerland for the period 2015 to 2022 and for the future 2050 to 2060, depending on the study. The process heat and cold is not included. The cooling demand today varies between 1.1 TWh/y and 8.1 TWh/y in different studies and scenarios. In the future, cooling demand is mostly higher as today in almost all studies. It ranges from 1.9 TWh to 17.5 TWh theoretically and for different scenarios. The heating demand is overall much higher. It is on average 14 times higher than the cooling demand today and about 7 times higher in the future. The table with all values and studies can be found in Annex 9.1.

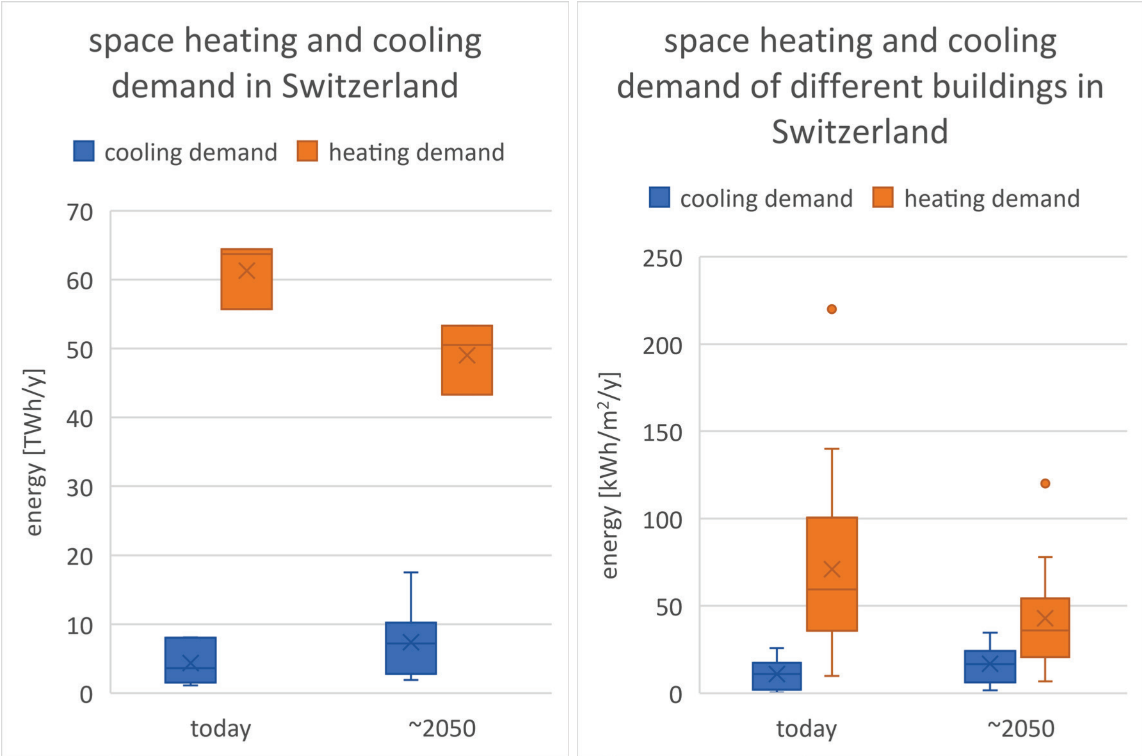

Figure 2: space heating and cooling demand today and in the future in Switzerland (data from appendix 9.1).

Most studies indicate that cooling demand will increase, and heating demand will decrease in the future due to climate change for cooling and efficiency for heating. Data for future demand, especially for the cooling demand varies greatly in different studies. The cooling demand is an important factor for the estimation of the district cooling potential in the future.

2.2 Estimation district cooling in future

2.2.1 District heating

The Energy Perspectives 2050+ presents a number of different scenarios for the development of Switzerland's energy system. The scenarios differ in the speed of the transition to renewable energies and the combination of different technologies. The ZERO C scenario is the one with the highest use of district heating in the future, this scenario is used to estimate the district cooling potential as well as WWB which is the continue as before scenario. The WWB scenario states a future district heating development of 6.5 TWh/y so no extension of the district heating.
Figure 3 shows the heating and cooling demand of Switzerland in 2019 and 2050 for the different sectors without process heat and cold. In addition, the district heating in 2019 and in the future in the ZERO C scenario is shown. The Energy Perspectives 2050+ shows a decrease in heating demand of almost 30% due to refurbishment. Cooling demand includes not only space cooling, but also ventilation, air cooling and building technology. Thus, they state that energy demand will be lower in the future due to efficiency. The other studies show an increase in cooling demand, but the value of the Energy Perspectives 2050+ is in the range of the other cooling demand studies and therefore this value is used for the estimation. Cooling demand is and is expected to remain much lower than heating demand in the future. In the ZERO C scenario, district heating is expected to increase almost three times to 18.2 TWh/y, most of which is expected to be in the residential sector. [2]

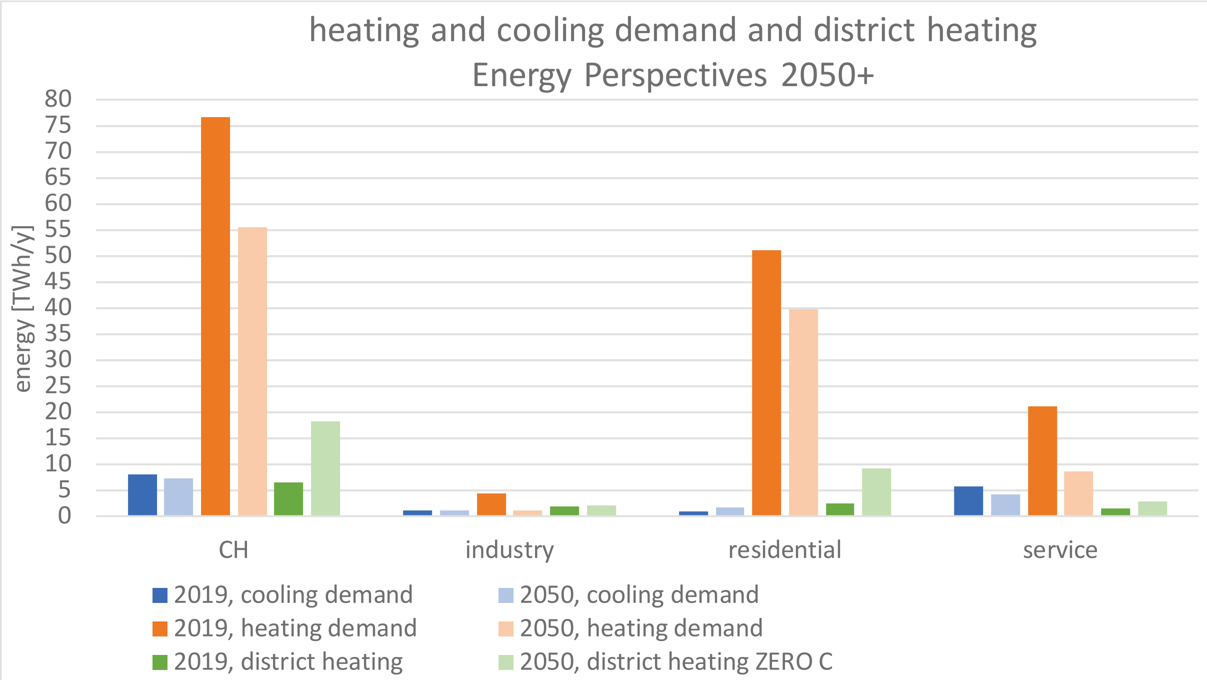

Figure 3: cooling and heating demand and district heating in 2019 and in 2050 from the Energy Perspectives 2050+, without process heat and cold [2].

The strategy of Verbund Fernwärme Schweiz (VFS), today Thermische Netze Schweiz (TSN), analyses the district heating potential from various energy sources. The sum of the allocated potentials is 17.3 TWh/a, almost as high as the Energy Perspectives 2050+ scenario ZERO C. The VFS strategy locates a very high potential of heating sources in lakes and geothermal energy. They also allocated the potential with geographical data of heating demand and this allocated district heating potential is shown in Figure 4. Lakes still have the highest potential with 5.1 TWh/y, but the geothermal potential is limited as it is stated as the last priority. [3]

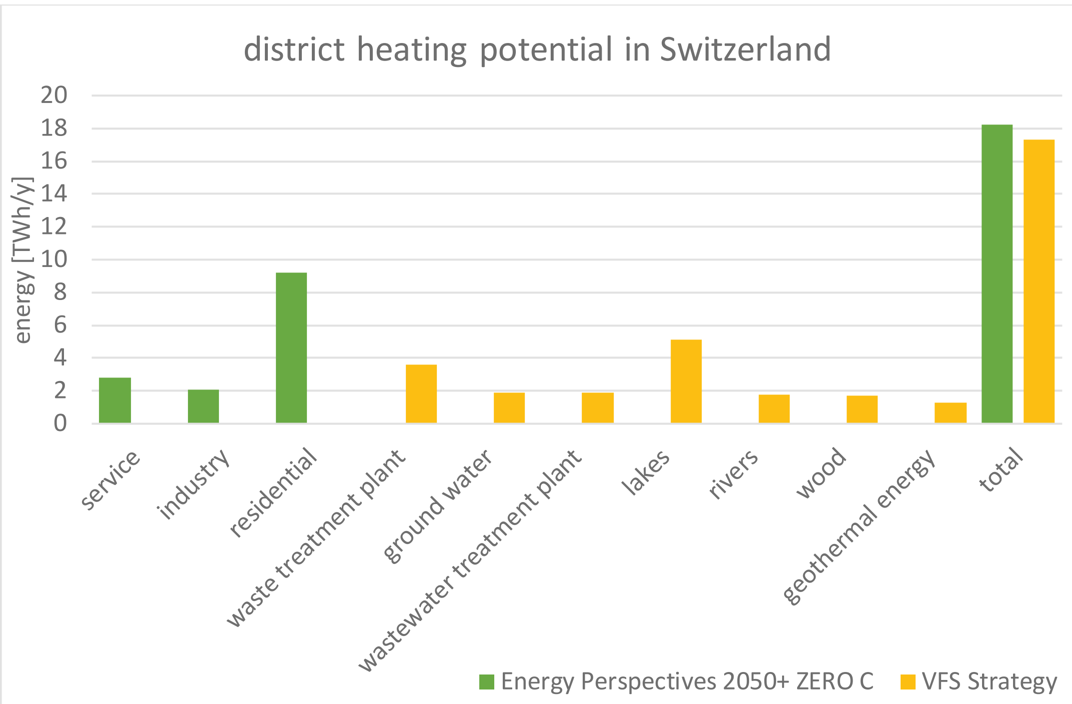

Figure 4: District heating potential in Switzerland in sectors [2] and for different energy sources [3] in the future.

2.2.2 District cooling

The potential for district cooling is difficult to estimate as data on cooling is scarce and imprecise. As the cooling demand is much lower than the heating demand, finding solutions or developing systems for district cooling is not a priority. Therefore, the data from different studies varies a lot and no study was found analysing the district cooling potential itself.
The district cooling potential gets estimated based on the district heating potential of the Energy Perspectives 2050+ scenario ZERO C and the VFS strategy. Three different calculation variants have been carried out. The calculation tables for these variants can be found in Annex 9.1.

The first variant works with the district heating development based on the Energy Perspectives 2050+ scenario ZERO C. It takes the values of coverage with district heating in the sectors residential, industry and services. The cooling demand is allocated to the same sectors and it is assumed that district heating can cover also the cooling demand with its infrastructure. Therefore, if the cooling demand is lower than the district heating in the sector, the cooling demand can be covered by district cooling. If the cooling demand is higher than the district heating, the amount of district heating determines the district cooling potential. A number of assumptions go with this variant. There is no specific network for cooling and there is the possibility of district cooling for every district heating. Of course, in reality this is not always possible and these demands are not necessarily in the same sector. Cooling with different cooling requirements, temperature requirements and geographical distributions are not taken into account. There is also no consideration of power at certain times or seasons, only energy use in general.
The second variant is also based on the district heating of the Energy Perspectives 2050+ scenario ZERO C. The coverage of the heating demand by district heating in percent is applied to the cooling demand in the different sectors. Thus, if 50% of the heating demand can be covered by district heating, 50% of the cooling demand can be covered by district cooling. Again, no account is taken of temperature requirements and geographical distribution.
The third variant is based on the VFS strategy and its potential for district heating with different energy sources. From the different values of the cooling and heating demand in the future in Annex 9.1, a heating/cooling ratio for the future is formed and this heating/cooling ratio is applied to the district heating potential with different heat sources. So, if the heating demand in the future is ten times higher than the cooling demand, the district heating value is also ten times higher than the district cooling value. It is very similar to the second variant, but with the heat sources and a different study of district heating. it also does not take into account the temperature requirements and the geographical distribution.

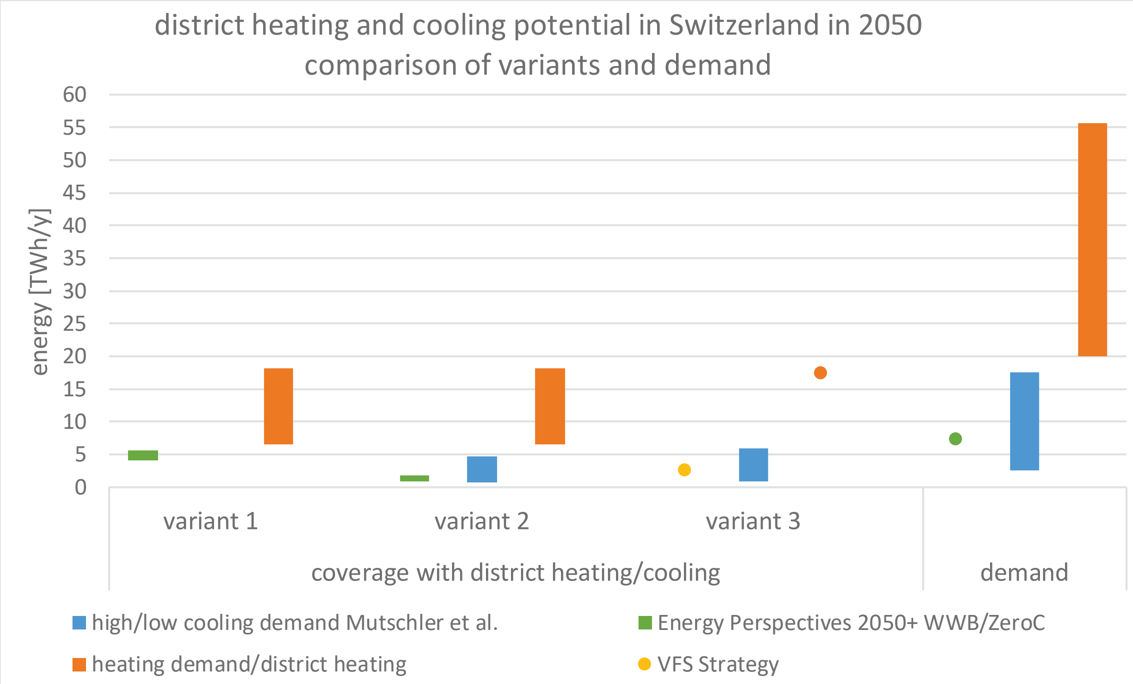

Figure 5: Estimation of district cooling and heating in 2050 in Switzerland comparison of different calculation variants and the heating and cooling demand in the future with different Energy Perspectives 2050+ scenarios WWB and Zero C, different cooling demand from Mutschler et al. and VFS Strategy [2,3,7].

The ranges of the results of these three calculations are shown in Figure 5. The green results are with data from Energy Perspectives 2050+ and the two scenarios WWB and ZERO C. The blue results are the calculations with different cooling demand from the study of Mutschler et al.[7]. The first variant could not be calculated as the data from Mutschler et al. did not have the distinction of the sectors. The yellow result is from VFS strategy. The orange results are the district heating of Energy perspectives 2050+ scenario WWB, ZERO C as well as VFS strategy and the heating demand of Energy perspectives 2050+ and Mutschler et al.
With the data of Energy Perspectives 2050+, the first variant with the most extreme conditions has the results of 5.58 TWh/y of district cooling with ZERO C and slightly less with WWB. The second variant has 1.88 TWh/y and the third variant with the VFS strategy 2.52 TWh/y. Compared to the cooling demand of the Energy Perspectives 2050+ of about 7.22 TWh/y this is a coverage of 26% to 35% and even 77% for the first variant. With the different cooling demands from Mutschler et al. which ranges from 2.5 TWh/y to 17.5 TWh/y, the district cooling in variant 2 ranges from 0.7 to 4.8 TWh/y and in the variant 3 from 0.9 to 6 TWh/y. As the cooling demand varies a lot, so does the district cooling potential. The coverage of the cooling demand with district cooling would be about 28% in variant 2 and 34% to 36% in variant 3.

In conclusion, it is expected that the demand for cooling will increase in the future, while the demand for heating will decrease due to improved efficiency. The cooling demand is and is expected to continually stay a lot lower compared to the heating demand, depending on the study. The district heating can cover approximately 30% of the heating demand according to studies. Data of district cooling potential is limited. An estimation of the district cooling potential results in about 0.7 to 6 TWh/y cooling demand covered by district cooling. The data varies a lot for the cooling demand and consequently does the district cooling potential. Compared to the district heating potential of 6.5 to 18.2 TWh/y the district cooling potential is lower to different extend depending on scenario. Nevertheless, there are various applications where district cooling can be included and even enhance efficiency, sustainability, and economics which will be discussed in the following chapters.

3 District Cooling Possibilities

Thermal networks transfer energy from a centralised heat generation system or another source of heating or cooling to various consumers in the surrounding area. They offer several advantages, such as enabling the use of heat generation systems that would be too expensive or technically unfeasible for small consumers. Waste heat from waste incineration plants, wastewater treatment plants, data centres, industry processes, as well as deep geothermal energy and groundwater, can usually only be used profitably in a network. If centralised generation occurs, the customer does not require their own heating system. Additionally, the network can continuously expand, both in terms of customers and suppliers. However, there are also drawbacks to using thermal networks. It is crucial that there is enough demand and acceptance for the network to be viable. Additionally, it is not universally available; demand and a suitable energy source must be in close proximity. The organization, planning, and construction of a thermal network are more complex, particularly in cities with building restrictions and numerous potential customers. A heating system is a long-term investment and may be more expensive than other options. Additionally, there is a certain level of dependency on the network operator [8,9].

Historically, district heating systems have focused on heating only, delivering heat from a central heating plant to decentralised customers at a high, directly usable temperature level. As district heating systems have evolved, the temperature level has also been lowered and the integration of different decentralised renewable energy sources and storage as well as the addition of cooling has taken place. The district networks can be divided into five generations [10]. The lowering of the network temperature allowed the integration of waste heat from cooling applications or even direct cooling applications in district heating networks. In recent years, fully decentralised 5th generation district heating and cooling networks (5GDHC) have been developed and built, where not only heating but also cooling is an integral part of the system [11]. A similar classification for district cooling networks has been made by Oystergaard et al. [12], ranging from simple source to consumer networks with refrigerants and minus temperatures in the first generation to fully integrated heating and cooling systems with higher temperatures, water based systems, multi-source and renewable cooling as well as different cooling technologies and storages in the fourth generation. The distinction between 5th generation district heating and cooling and 4th generation district cooling (4GDC) is not clearly defined and some networks are given as examples for both. In the case of 4GDC, examples are also given where waste heat from the cooling network is used for heating at the directly usable temperature level. The main criteria are the coupling of different sectors, especially of parallel heating and cooling demand, the integration of renewable energy and intelligent control.

Cold supply in a district network is usually associated with low temperature network. However, there are technologies using heat at elevated temperature in the network to drive cooling machines as desiccant and evaporative or ad-/absorption chillers [13]. These technologies can be combined with “hot”, earlier generation networks in order to provide cooling especially in grids where a surplus of summer heat is available (typically at waste or other incineration plants).

In Table 1 is an overview of the different coiling technologies and their energy sources, as well as their advantages and disadvantages. A main differentiation is done based on the network temperature, where “low” temperature summarizes all networks with a temperature not allowing direct use in the heating case and therefore decentralized heat pumps are needed. In “high” temperature networks all networks are summarized, which have a sufficient temperature level to directly supply heating need without decentralized heat pumps. The different cooling possibilities will be discussed in the following chapters.

Table 1: Overview of different network temperature, technologies and energy sources and the advantages and disadvantages.

Network Temp.	Technology	Energy source	Advantages	Disadvantages
Low	Direct cooling		- Low costs - Low effort - Saves electricity	- Not every application possible - Not everywhere possible - No use of waste heat
		Air	- Easy access	- Only for adequate temperatures
		Water (river, lake, groundwater)	- Consistent temperature - A lot of potential (in Switzerland)	- Investment costs - Regulations
		ground	- Consistent temperature - Regeneration of ground - Thermal storage	- Investment costs - Regulations (not everywhere possible) - Temperature level in summer to high for many applications
	Compression chiller		- High COP - Uncomplicated application - Combination with PV - Independent of temperature levels - Waste heat serves as source for heating applications	- Electricity need - Higher invest compared to direct cooling
		Air	- Easy access - Low investment costs	- Noise emissions - Lower COP with high temperature (for cooling)
		Water (river, lake, groundwater)	- Very high efficiency - Thermal storage	- Investment costs - Regulations
		ground	- High efficiency - Regeneration of ground heat in summer/ Thermal storage	- Investment costs - Regulations (not everywhere possible, no elevated temperatures)
High	Ab- / Adsorption chiller		- Less electricity consumption compared to compression cooling - Heat demand mainly in summer - Low operation costs (with low heat price)	- Lower COP (than compression chiller) - Needs high temperatures - Heat rejection at intermediate temperature level - Cost - Complexity - Not economical with less cooling demand / operation only in summer
		- Wood /other Biomass	- Additional heat demand in summer (in combination with CHP or waste wood)	- Limited wood sources - Cost
		- Waste heat	- Utilisation of waste heat in summer which is often wasted.	- Access needed - Cost
		- Solar heat	- Good correlation of demand and source	- Cost - Need of storage
		- Deep geothermal/ aquifer heat	- Creation of summer heat demand	- Investment costs - Clarifications of ground
	Compression chiller	- Wood /other Biomass	- Covering summer heating demand - Good correlation with PV - No heat rejection to air (no noise, less heat islands)	- Electricity as source - Lower COP than grid independent solutions
		- Wood /other Biomass	- Good correlation with PV	- Electricity as source

		- Waste heat - Solar heat - Deep geothermal/ aquifer heat	- No heat rejection to air (no noise, less heat islands)	- Lower COP than grid independent solutions - No need of summer heat
	Desiccant and evaporative cooling	- Wood /other Biomass - Waste heat - Solar heat - Deep geothermal/ aquifer heat	- Cooling and adjusting humidity - Waste heat utilisation	- Air duct needed - Other additional components

A distinction of district cooling cannot only be done based on the source of energy or the heating or cooling device, but also in terms of configurations of the construction and modes of operation of the network itself. Different network types can be distinguished based on their topology. The radial network has only one flow path between the supplier and the consumer, while the ring network has two possible flow paths and the mesh network has two or more. Networks can also vary in the number of pipe systems they have. A 1-pipe system, for example, only has one pipe to the consumer and the fluid flows back into the environment, making it an open system. The 2-pipe system has a colder and a warmer pipe for a closed flow and return system. The 3-pipe system has two supply lines and one return line, with the two supplies at different temperature levels. The 4-pipe system is essentially two 2-pipe systems, each at a different temperature level. The planning of a 4-pipe system in the beginning has the advantage of less challenging installations, than expanding the network at later stage. As most applications in thermal district networks are for heating, the temperature level is usually high and supplies both space heating and hot water. Cooling is typically done separately individually or by use a 4-pipe network, with one pipe system dedicated to heating and hot water, and the other dedicated to cooling. Another possibility is a low-temperature network, which can be used for direct cooling in summer. However, additional devices are needed for heating in winter and the hot water. A network can also be classified based on its operating modes. Directional and non-directional networks differ in terms of fluid flow and feed pumps. In directional networks, the fluid flows in only one direction, and there is a central pump at the network operator. Non-directional networks have a feed pump for each recipient and can be operated in both directions. Unidirectional and bidirectional networks are differentiated based on energy flows. In a unidirectional network, energy flows from the heat source to the heat sinks, and vice versa in the case of cooling. In a bidirectional network, the consumer can act as both a heat source and a heat sink, allowing energy to flow in both directions. The operation mode can be variable or constant. In the variable operation mode, the network supply temperature is depending on the outside temperature. Therefore, the network temperature falls in summer and rises in winter. In the constant mode, the supply temperature stays the same through the year and can be useful for applications like hot water heating. [14,15]

3.1 Low temperature network

The temperature of a thermal network is an important parameter. High and low temperatures are distinguished, in some cases medium temperature is also a classification. High-temperature networks which are hotter than 60°C (or in some definitions above 90°C) as in the 3rd Generation of District Heating Networks (3GDH), can provide heat for direct heating and hot water heating. Thermal networks above 90°C are mainly for industrial consumers (2GDH or 3GDH). Medium-temperature networks in some classification systems range between 60°C and 90°C. Low temperature networks are thermal networks with a temperature below 60°C and belong to 4GDHN. They can be used for heating and pre-heating in the range from 30°C to 60°C. Water with a temperature of 20°C to 30°C can be used for pre-heating, cooling applications, or for heating with the help of additional heat pumps. The network with a temperature of 0°C to 20°C (5GDHC) can be used for direct cooling or, with an additional heat pump, for heating. Lower temperatures are preferred in newer grids as they result in fewer losses and non-insulated and therefore less expensive pipes due to closer temperature to the environment. Additionally, a wider range of consumers and a high cooling requirement can be covered with lower temperatures in the network [10,15,16]. On the other hand, they may require larger flow rates, pipe diameters and increased pumping costs due to small temperature difference in flow and return. Typically, a heat pump is installed at the consumer's location to raise or lower the temperature as needed. [13] The network can be used bidirectionally for cooling and heating, and it enables direct or “free” cooling.

There are also networks for cooling applications only and these cooling networks can be classified into three temperature groups: networks with water temperatures of 4 to 7 or 15°C, ice-water systems with 0°C, and brine-ice mixtures at -1°C. The network temperature may also be higher depending on the required temperature, such as for data centres. [14]

3.1.1 Direct cooling

Direct or “free” cooling is a method of cooling that minimises energy consumption and costs by utilising low ambient temperatures in the air, ground or water only with heat exchangers. However, some energy is required for the fans, pumps and control systems. Water, particularly from deep lakes or ground water with constant low temperatures, is ideal for direct cooling. The potential for heating and cooling using Swiss lakes and rivers is high, exceeding demand in most areas except for some large cities. However, economics and legal requirements, as well as differing interests limit the utilization of this potential. Nevertheless, it is possible to make the thermal utilization of water bodies both economically and ecologically sustainable, allowing for further exploitation of this potential. [17]

There are numerous examples of direct cooling with **water**, such as the GenieLacNations network established in Geneva in 2016. This network draws water from Lake Geneva at a depth of 37 metres, with a temperature ranging between 6°C and 10°C. The pumping station adjusts the amount of water pumped according to demand. The process begins with filtration of the water, followed by the addition of chlorine. The treated water is then stored in a temporary reservoir before being distributed through the network to the buildings. Within the buildings, decentralised heat pumps and heat exchangers utilise the lake water for direct cooling during summer and heating during winter. Finally, the water is either returned to the lake or the river or repurposed for irrigation. It has an installed heating capacity of 4.3 MW and a cooling capacity of 16.2 MW. The network spans 6 kilometres and provides cold and heat to 840’000 m^2 of energy reference area [18,19]. Due to the success of the GenieLacNations, Geneva further expands its lake water district heating and cooling networks with several open and closed Grid. Also Lake Zurich is extensively used for district cooling. The EWZ has built several lake water networks including the Escherwiese, Fraumünster and Falkenstrasse [20] networks. In the mountains, lake water is used for direct cooling in St. Moritz. In Webermühle Neuenhof, river water is used for heating. Groundwater can also be used for direct cooling, as seen in examples such as Jardins de la Pâla in Bulle and the Moesa health centre in Roveredo.
The Tech Cluster Zug project demonstrates the feasibility of using multiple energy sources and grids. The area is heated using energy from both groundwater and lake water. Three heating networks have been installed, one with a temperature of 70°C for existing buildings, another with a temperature of 45°C for new buildings, and a cooling network with a temperature of 12°C. These temperatures are maintained by heat pumps. In summer, the groundwater system can be used for direct cooling. Any waste heat generated is stored in the groundwater. [21]

The last example shows, that in 5GDHCN in **ground based sources** as aquifers or borehole fields become seasonal storages, which are cooled down by the heating demand in winter and regenerated by waste heat from cooling. After the heating period, the temperature in such ground based seasonal storages are below typical ground temperatures 8-15°C and can therefore be used for direct cooling for most applications. However, if a significant regeneration must be achieved, the storage temperatures and therefore the network temperatures increase during the cooling period in summer, up to about 35 °C [22,23]. In these cases, direct cooling for building climatization in not possible anymore and an active integration with compression chillers is needed (next chapter). For some applications as server cooling or data centers, direct cooling can still be possible.
As an example, the Suurstoffi areal has a large geothermal borehole field. This new area in Rotkreuz was constructed until 2020 and has a low-temperature network for heating and cooling that connects all the buildings. The development comprises of flats, administration buildings, a restaurant, and a school, with a total energy reference area of 172’421 m^2. The network is powered by approximately 400 geothermal boreholes, which serve as a source and thermal energy store. During winter, heat pumps provide decentralised heating in the individual buildings. The total thermal output installed is 6.7 MW and the system has a cooling capacity of 2.3 MW. During summer, the waste heat from the buildings is channelled into the ground through the geothermal boreholes, resulting in the area being cooled by direct cooling. The cooling capacity requirement is 2.364 GWh per year and the heating energy requirement 10.6 GWh per year. An air-to-water heat pump has been installed to cover the peak output. The flow pipe has a temperature range of 25°C to 8°C and the cold conductor has a temperature range of 17°C to 4°C. The average temperature in the ground is 12°C. To further regenerate the geothermal

boreholes, 9’487 m^2 of PVT collectors have been installed. Additional PV systems supply electricity for the area and the heat pumps. [18]
Several heating networks in Switzerland use geothermal energy for heating and cooling, such as the Richti area in Wallisellen, the BaseLink area in Allschwil, the D4 Business Village in Lucerne, the EPFL building in Lausanne, the Friesenberg anergy network, and the Visp-West anergy network. [18,21]

Direct cooling with **air** is possible, but it depends on the outside temperature, which can fluctuate strongly and vary by location. This method is less commonly used in grids because it usually requires additional heat pumps or chillers. However, some individual systems rely solely on direct cooling. In Switzerland, data centres have great potential for direct cooling with outside air, provided that the required temperature is not too low (below 18°C) [24]. For instance, Swisscom's data centre in Wankdorf cools the air in the server room from 36°C-42°C to 26°C-32°C using direct cooling. Some of the heat is fed into the heating network in Bern, while the rest is released into the environment. If the external temperature is below 21°C, the recooler will cool normally using ambient air. However, if the temperature is above 21°C, the dry cooler will switch to the humid mode. In this mode, collected rainwater is used to cool the hot air through evaporation. [25]

Not only lakes and groundwater can be used for cooling, but also **snow**. However, no such systems are built Switzerland due to insufficient snow availability in the areas with significant cooling demand in the midlands or southern Switzerland. In Sweden, a cooling network that utilizes snow for cooling purposes has been established. In 2000, a cooling network with a snow reservoir was put into operation in Sundsvall. The snow is stored in a reservoir with a volume of 60’000 square metres, which is covered with a layer of wood chips for insulation. Artificial snow is added using snow machines if there is not enough natural snow. The meltwater at 0°C is filtered and heated to 10°C via heat exchangers before being fed back into the reservoir. On the other side of the heat exchanger, water is cooled from 12°C to 7°C, which cools the hospital. The cooling capacity is 1’500 kW and is regulated by the flow rate of the melt water. [26]

3.1.2 Compression Chiller

Depending on the main sources and storage technology the temperatures in low temperature (5GDHC) grids may rise above comfortable indoor air temperatures. In these cases, or when cooling needs at low temperatures are present, direct cooling is not possible anymore and an active cooling with compression chillers has to be installed. Compression chillers operate on the same principle as heat pumps, but instead of making use of the heating on the condenser side, the cooling on the evaporator side is utilized. Both the chiller and heat pump require only a fraction of the total energy transferred in the form of electrical energy. Some devices can operate in reverse, functioning as a heating device in winter and a cooling device in summer [14]. There are different types of refrigerants used in refrigeration machines. These can be classified as natural refrigerants, synthetic refrigerants that are stable in air, and synthetic refrigerants that are not stable in air. When selecting refrigerants, factors such as cooling capacity, temperature level, toxicity, flammability and environmental impact including global warming potential and ozone depletion potential are considered. [27]

A typical case, where compression chillers are needed to provide cooling in combination with low temperature grids are **soil/borehole** based networks. The undisturbed soil temperature of shallow geothermal boreholes is in the range of 12-15 °C. During heat extraction the operation temperature drops and during cold extraction or regeneration the operation temperature rises, and can reach temperatures over 30 °C [28]. In these cases, compression chillers are needed to provide a temperature level adequate for the cooling of buildings (depending on the distributions system about 18°C or lower). An example of geothermal energy utilisation is the anergy network in the Hönggerberg campus of ETH Zurich. It is a 5GDHC network for heating and cooling of the campus. The network was partially launched in 2013 and has since been expanded. It comprises of three underground storage tanks with a total of 431 geothermal boreholes, each 200 metres deep. As of 2019, there were five control centres that supplied heating and cooling to 14 buildings. An additional centre and three more geothermal borehole storages are currently in the planning stage. The heating capacity installed is 8 MW, and the cooling

capacity is 6 MW. The heating energy requirement is 28 GWh per year, and the cooling requirement 26 GWh per year. The hot water-bearing conductor has a temperature range of 8°C to 22°C, and the cold pipe is four Kelvin lower. In Mai it is the aim to have temperatures at 8°C/4°C and in September at 22°C/18°C. Heat pumps and heat exchangers are used in the centres to meet the heating and cooling requirements. The cold produced can be utilised directly for another process within the same centre. The waste heat is fed into the anergy network and stored in boreholes. During summer, the stored heat is used to increase the efficiency of heat production in winter. Conversely, heat extraction during winter cools the network, leading to more efficient cooling utilisation in summer. [18,29]
Additional examples include the Frauenfeld Cantonal Hospital, which operates four circuits for heating and cooling using geothermal boreholes, heat pumps, chillers and a gas-fired combined heat and power plant. One circuit with a temperature of 35°C is used for space heating in newer buildings, while the second circuit with 90°C heats the existing buildings and hot water. The hospital also has a 6°C cooling circuit for process cooling and a 16°C cooling circuit for air conditioning. Zurich Airport is another example, having installed energy piles for heating and cooling purposes. [21]

The temperatures at depth in the lake or groundwater remain consistently low throughout the year, typically around 10 to 12°C. This allows for direct cooling, which consumes less electricity. Only for special cooling applications, which are operated at low temperatures additional compression chillers are needed. In shallow lakes or rivers, the increase of temperature during summer is more pronounces. There are various examples of lake water networks in Zürich using Lake water as a source for compression chillers. The largest is the Escherwiese network [20], which collects lake water at a depth of approx. 12 metres and then produces 2.8 GWh of heat and 2.6 GWh of cooling in a control centre with a combined heating and cooling machine. 0.9 GWh of the cooling requirement can be provided via direct cooling, the rest has to be produced with the cooling machine. The network supplies the hotel, office and residential buildings.
Additional examples of district heating and cooling networks include the Aarau district network and the Kellermann AG plant in Ellikon an der Thur. Both of these systems use groundwater for heating and cooling. The district network in Aarau was constructed in 2014 by Eniwa and mainly utilizes groundwater from a depth of 18 to 35 meters. The groundwater temperatures range from 10°C to 12.5°C and are raised to the required temperatures in winter using heat pumps. Waste heat from the waste incineration plant and wastewater treatment plant is added into the network to support the heating system. The district network in Ellikon an der Thur utilises groundwater for both heating of the buildings and cooling of food. The cooling system has a power of 1 MW and serves for heating and cooling. [21]

For individual systems the heat sink (or “cold source”) is often **ambient air**. Cooling with outside air remains advantageous due to its availability and ease of implementation. However, with great applications, a large air heat exchangers is needed, which requires a significant amount of electricity and causes noise emissions. Furthermore, the waste heat is released into the air and not utilized further, making it less suitable for a heating or cooling network. While individual units are simpler, a network is often not cost-effective. [27]

3.2 High temperature network

The use of a high temperature network enables the utilization of high temperature waste heat. In most cases, a central energy station or additional installation is not required to meet the heating demand of the consumer, which includes space heating and hot water. If there is a cooling demand, an ab- or adsorption heat pump can be installed to provide cooling and utilize the waste heat during the summer. [13]

3.2.1 Ad-/Absorption Chiller

Ad- and absorption chillers differ from other chillers as they use heat rather than electricity as their main source of power. In these chillers, the refrigerant is not evaporated by pressure differences induced by electric compressor, but from partial pressure difference caused by concentrated solutions. Heat can be used to evaporate a solvent and produce this concentrated solution. Absorption chillers typically use ammonia or lithium bromide solutions with water as the absorbent. Adsorption chillers function similarly to absorption chillers, except that the refrigerant is adsorbed on a solid surface rather than absorbed in a liquid.
Adsorption and absorption chillers use thermal energy to cool, resulting in low electricity consumption and potentially low operating costs. However, these machines do have some disadvantages, such as requiring a constant heat supply at an elevated temperature level. In order to cool down the concentrated solution, such chillers need to reject large amounts of energy at an intermediate temperature level. Therefore, in most of the cases, large air to water heat exchangers are needed to operate ad- or absorption chillers. Additionally, this chiller may not be necessary as a heating system during winter months since a heat supply is already available through the heat supply. Therefore, the cooling demand must be high enough or the chiller must also be required for cooling during winter in order for it to be financially viable. [14]

All **waste heat** with a sufficiently high temperature can be used for cooling through ad- and absorption chillers. This waste heat is typically inexpensive for the heat consumer, and the system allows the heat supplier to provide heat for use in the summer. Waste heat from waste incineration plants is the largest source for district heating networks in Switzerland. However, waste heat is not often utilised for additional cooling. An example of utilisation is the Bern railway station cooling network, which uses absorption chillers to provide cooling to Bern railway station, the SBB data centre, the University of Bern, and other SBB facilities and buildings. The network was continuously built and expanded between 2001 and 2007, and the absorption chillers are operated with waste heat from the waste incineration plant in Bern. In summer, the band load can be covered with a total output of 1’680 kW, which corresponds to 60% of the total output. Piston chillers are used for peak coverage and the band load in winter, and two buffer storage tanks are also installed. The cooling supply is at a temperature of 6°C, and the return is at 12°C. Additional heat pumps are installed in each building. When the outside temperature drops below 12°C, hybrid coolers release heat directly into the environment. In 2003, the commercial cooling systems were supplied with a total of 6.19 GWh of cooling via the cooling network. An additional pipe system at a temperature of 27°C serves as a recooling network for the commercial cooling systems and this network supplied additional 1.46 GWh. [30]
The Meret Oppenheim tower, located near Basel railway station, utilises an absorption chiller during high outside temperatures. It is powered by district heating from the waste incineration plant and the IWB wood-fired power station. During lower outside temperatures direct cooling is employed and electrically operated chillers are used if necessary. [31]

Solar heat can be used as a source for ad- or absorption chillers. Another cooling option with solar energy is provided by PV systems in combination with chillers. In winter, solar collectors can support the heating system and heat water, increasing the system's economic efficiency. However, for smaller systems, the use of solar collectors and ad- or absorption chillers is not cost-effective, especially with few operating hours in summer. [32]
The use of absorption chillers with solar collectors for cooling in thermal networks is not yet widely adopted. Nonetheless, there are some isolated pilot projects, such as the Migros-Genossenschafts-Bund project on Limmatplatz in Zurich [33]. The project covers an area of 10’000 m^2 and includes flats,

offices, a restaurant and a warehouse. The installed absorption chiller has a cooling capacity of 46 kW at 16/9°C. The system operates using a solar system with vacuum tube collectors with an area of 108 m^2, generating temperatures ranging from 75°C to 100°C. The waste heat is recovered using a hybrid heat recovery system and then released into the ambient air with a hybrid recooler. During winter, the solar system and absorption chiller provide heating. An additional example is the refrigeration system at the Pictet & Cie bank in Geneva, which has three absorption chillers with a total cooling capacity of 210 kW installed. [34]

All sources with high enough temperatures can be considered heat sources. **Wood and other biomass** can be burnt, and the resulting heat can be used for ad- or absorption chillers to provide cooling. However, using these materials solely for cooling purposes is questionable as wood resources are limited. However, biomass CHP plants are often operated throughout the year, due to constant fed in tariffs. Therefor a surplus of heat can be available in summer. The CHP plant of the Migros Lucerne Cooperative is an example of this application. It supplies heating, cooling, and electricity for the company premises and neighbouring properties. Waste wood is completely burned in the combustion chamber to heat steam to 420°C and 35 bar in the high-pressure water-tube steam boiler. Additional recirculation gas is used to regulate the combustion chamber temperature, maximize CO burnout, and reduce nitrogen oxides. The reducing agent urea is also injected for this purpose. The generator produces 500 kW of electrical power using the steam. The steam is then channelled into the steam boiler at reduced pressure to heat water in the steam-hot water converter. This provides hot water and heats the Migros buildings and the local heating network in Dierikon in the Lucerne region. The stores are cooled with a temperature of -6°C to -1°C in the cold brine system using an absorption refrigeration system with an output of 800 to 1'200 kW and a heat supply at a temperature level of 95°C. [35]

Deep geothermal energy or **deep aquifers**, ranging from 500 m to several kilometres, can reach temperatures as high as 200°C. However, the costs and efforts associated with drilling such deep boreholes make it economically feasible only when there is sufficient heat demand [21]. Currently, there are plants and heating networks that utilise deep geothermal energy to provide heat, such as the Riehen heating network, which uses water at a temperature of 65°C. Other examples of geothermal power plants include the Rittershoffen and Zurich Triemli plants. The Rittershoffen plant has geothermal boreholes that reach 2.5 kilometres into the earth and supply heat at 170°C. Similarly, the Zurich Triemli plant has geothermal boreholes that are up to 2.7 kilometres deep and supply heat at a temperature of 97°C. All three plants are used for heat generation, either for space heating or for process heat. Theoretically, it is also possible to use absorption chillers with these sources to provide cooling. [36]

3.2.2 Desiccant and evaporative cooling

Desiccant and evaporative cooling is an open circuit system using water as a refrigerant. The warm, humid outside air enters the slowly rotating sorption wheel, where moisture is removed from the air by adsorption, slightly heating it. The air is then cooled by the heat exchanger and the desired temperature and humidity of the supply air are determined by humidification. The air extracted from the room is humidified to the saturation point, which significantly cools it down. It then absorbs heat from the outside air through the heat exchanger. An external heat source further heats the extracted air. This heat can be provided by a solar thermal system, district heating, or a separate heating system. Finally, the heated air passes through the sorption wheel, absorbs moisture from the adsorption medium, and therefore dehumidifies it. [14] There are also systems that use liquid sorption, where the sorbent absorbs water and then circulates. Desiccant and evaporative cooling systems can adjust both temperature and humidity and use waste heat, but they require an air channel and additional components. [32]

3.2.3 Compression chillers

Compression chiller can not only be used for providing cold or heat, but for both in combination. The waste heat from the cooling process on the one side is directed into the heat network. This way cooling processes in the network region can be used to support high temperature networks. As the network operates at a high, directly usable temperature level, an additional cooling network is needed to distribute the cold. This application therefore needs a 4 pipe distribution system. Such systems can be combined with various sources to provide the remaining heating or cooling demand during periods with unbalanced loads. For instance, in Neuhausen am Rheinfall a local heating network utilises wastewater from the Röti wastewater treatment plant to supply the consumers with heat and cold, with the aid of three connected heat pumps in the energy centre. This network was commissioned in November 2018. The heat pumps have a combined output of 15 MW and provide heat to 130 buildings. The produced cold is also supplied to customers with cooling requirements. The wastewater initially has a temperature of 10°C to 25°C and is then raised to the required temperature level. The network is 5.6 kilometres long in total and is still being expanded. In the near future, 100 more buildings may join the energy network. [37]

An international example, which feed the waste heat from the cooling process into a high temperature network is the system in Høje Taastrup in Denmark. This system was implemented in 2016 and provides cooling for 70 individual consumers. The plant includes a connection of three compressors and connects the cooling network of a large wholesale market with the consumers. Two compressors heat the water to 75°C for the heating system and at the other side cools water to 8°C for the district cooling system. The third set of compressors further lower the temperature to -8°C. the cold supply capacity of this system is 2 MW and the heating capacity 2.3 MW. [12]

3.3 Energy Storage

Various methods exist for storing energy in a heating or cooling network. Thermal energy storages can be categorised as either low-temperature or use-temperature storages. Use-temperature heat storages store energy at the temperature level required, while low-temperature heat storages store heat at a lower temperature and require a heat pump to rise the water to the required temperature level. Low-temperature storage tanks have lower energy losses due to the smaller temperature difference to the surroundings. For cooling applications the use temperature is the low-temperature storage.
A distinction can be made between short-term storage and seasonal storage. Short-term storage systems are designed for one to several days, while seasonal storage systems are designed to store energy for later in the year. Most storage technologies can be used for both seasonal and short-term storage, although the size and temperature parameters may differ. Heat storage systems have various parameters including cost, service life, temperature level, storage capacity, storage losses and safety to consider. [38]

Thermal storages can be installed in a cooling or heating system, with or without district cooling. The thermal storages offer several advantages, including flexibility in the network and temporal decoupling of production and demand. During peaks of thermal energy demand, the reservoir can be emptied and filled during valleys. Especially the cooling demand can change quickly and often during and between days as the amount of cooling depends heavily on solar radiation. The peaks being covered by the storage means that the heat or cooling production does not need to be designed for the same capacity, or at most, an additional machine does not need to be installed. This can result in lower purchasing and operating costs, as the heat or cold can be produced during times of less expensive conditions. Installing a seasonal storage system can even store heat for the winter or cold for the summer, which positively affects the system's efficiency. However, investing in storage may not always be worthwhile, depending on the size and technology. Additionally, storage requires space and planning effort for the network. Energy loss cannot be avoided for most storage applications. [39]

Three categories of heat and cold storage systems are available. The sensible thermal energy storage, the latent thermal energy storage and the thermochemical thermal energy storage.

3.3.1 Sensible thermal energy storage

Sensible heat storage devices are commonly used for heat storage, utilizing the heat storage capacity of the medium by change its temperature. Water is typically used as the storage medium due to its affordability, simplicity, well-known properties, and good thermal characteristics. When used as short-term storage tanks, these sensitive heat reservoirs are typically small, ranging from 10 to 100 m^2, and have low heat losses. The seasonal reservoirs are typically between 10’000 and 100’000 m^2 or more in size and are mostly aquifer, borehole or pit reservoirs. They have significant heat losses that depend on the operating temperature. Chilled water storages generally have operating temperatures between 3 and 6°C. In cooling applications, they get commonly used for short term storages to store generated cold through a day and night. The cooling capacity is proportional to the temperature difference between the returning water and the stored water and is normally about 7 to 9°C. As the ambient temperature is typically higher than the storage temperature, the environment can influence the efficiency of the storage. The sensible thermal energy storages are less expensive and more easy to scale upwards than latent heat storages, but due to less storage density require more space. [39,40]

In the category of sensible thermal energy storage exist different types of storages. **Borehole** thermal energy storages (BTES) utilise the earth to store energy. The large volume of soil provides a significant thermal capacity. If the storage gets dual use in winter and summer for heat source and heat sink, no losses are observed over the year. Boreholes have a lifespan of 50 years and can represent a significant investment, particularly for large fields. Drilling for boreholes may be restricted in certain areas due to groundwater or unfavourable soil conditions.

Aquifer thermal energy storages (ATES) have a large storage volume and operate in a similar way as BTES. Storage losses are minimal throughout the year, except when operated at high temperatures. Depending on the depth, the soil environment may already have a useful temperature. Groundwater reservoirs are suitable for large installations with low investment costs. However, they require complex geological investigations and the installation of an aquifer thermal energy storage is not feasible in all locations due to certain conditions that the aquifer must meet, such as high water permeability, high density of surrounding strata and low flow velocities. Additionally, regulations dictate that the water cannot be heated above 3 K difference in Switzerland. The storage requires minimal surface area as it is located underground. By 2018 more than 2'800 ATES were globally operating and 99% of them operate below 25°C. One of the largest ATES system is located in Arlanda, Sweden and provides heating and cooling to the Arlanda airport. It has a volume of 200'000'000 m^3 and provides 9 GWh cooling with a temperature of 3-6°C.

ATES and BTES are suitable for seasonal storages for heating and cooling combinations due to their storage volume. They are cooled down by the heating demand in winter and regenerated by waste heat from cooling in summer. After the heating period, the temperature in such ground based seasonal storages are below typical ground temperatures of 8-15°C and can therefore be used for direct cooling for most applications. If a significant regeneration must be achieved, the storage temperatures and therefore the network temperatures increase during the cooling period, up to about 35°C [22,23].

Similar to ATES **underground cavities or caverns** can be used as TES. In Stockholm, Sweden is a large district heating and cooling system installed. Additionally, a natural rock cavern in Hornsberg gets used as cold storage. It has a volume of 55'000 m^3 and a power of 55 MW and 0.4 GWh capacity. The storage covers daily peak of district cooling loads and is charged during nighttime to about 5°C. Sweden commonly uses cold water for cold storages, except the previously mentioned example of Sundsvall.

3.3.2 Latent thermal energy storage

Latent heat storages store energy by causing a phase change in the storage medium, which can be a transition from solid to liquid or to vapour. Another possibility is a restructuring of grid structures in a solid. The most commonly used latent heat storage system is the ice storage system. It is important to operate the latent heat storage units at the phase change temperature, which requires tuning the grid accordingly or using an intermediate unit. They typically have a higher energy density that enables them to store more energy. Additionally, the temperature difference during the phase change is minimal, resulting in a more efficient heat exchange. However, these storage devices are generally more expensive.

Ice storages are a common type of latent heat storages for cooling, but they can also get used for heating. When heat is removed from water at 0°C, the temperature remains constant until ice forms. When heat is added again, the ice melts and provides cold during the melting process and heat during the freezing process. These reservoirs are especially useful for district cooling and managing peak loads. Ice storage tanks have a lifespan of 30 to 50 years and are among the most cost-effective types of latent heat storage tanks. [38,39]

A variety of different types of ice storages were developed. The **ice harvesters** produce sheet ice, tube ice or ice cubes on vertical heat transfer surfaces. The ice is harvested by melting the bond between the ice and the surface and the ice drops into the storage tank below. In this tank, the water circulates through the piles of ice and gets cooled down. **Encapsulated Ice storages** contain small plastic containers like balls or lenses which are filled with water in the storage tank. A water/glycol solution flows through the tank and around the containers and freezes the water in these containers. During the discharge process, the warm fluid flows though the tank and melts the water in the containers and cools down. The ice-on-coil storage comes with two variants, the external and internal melt. In the **internal melt ice-on-coil storage**, a secondary coolant solution mostly with ethylene glycol and water circulates through tubes or coils submerges in water filled tanks. During charging, the cooled solution in the tubes causes ice to build on the outer surface of the coil in the tank. The discharge melts this ice again by flowing warm water through the tubes. The **external melt ice-on-coil storage** works similar. The liquid refrigerant flows inside the coils causing the ice to form on the outside surface of the coil in the water tank. In the discharging process, the ice is melted from the outside by circulating the water through the tank. The **ice slurry** is a dynamic ice storage. Small particles of ice within a solution of glycol and water are produced ending in a mixture that can be pumped. Usually heat exchanger separate the storage tank with the slurry mix and the cooling load distribution loop. The ice particles in the glycol/water mixture in the tank are generated by a cooled evaporating refrigerant solution flowing through tubes. The small size of the particles results in better heat transfer. [40,41]

An example of a large district cooling system with different cold storages is in Paris. It is a district cooling system with 6 cross linked cool generation plans with a total capacity of 215 MW. Three additional cold storage systems got implemented. The first one is a sensible cold storage in “La Tour Maubourg” with a capacity of 90 MWh. It is a 13’000 m^3 tank which is divided into 13 equal compartments, one is always empty. At the two other locations “Opera” and “Les Halles” are six ice storages installed. The two in “Opera” have a capacity of 20 MWh and one is an internal and one an external melting storage. The four storages in “Les Halles” have a combined capacity of 30 MWh. The main usage of the ice storages is to reduce the network temperatures from 4 to 2°C and thus transport a higher load through the existing system. Additionally, they serve as a backup in case of a chiller failing and also as reserve to cover peak loads. They get used for storing cold energy from the night through the day and operate the chillers in a more efficient way. [42]

Phase change material (PCM) for district cooling other than ice are rarely installed except for applications at research and development level. A Swedish example is a cooling system for an office building in Gothenburg. The cooling system is coupled with a salt hydrate PCM for daily storage with a volume of 7 m^3 and a cooling capacity of 99 kWh. Another example of the use of salt-hydrate is the University College of Bergen in Norway. This cooling system has a cold storage made of four tanks of 57 m^3 volume with encapsulated PCM based on salt-hydrate. The storage capacity is 11.3 MWh and has an output of 1.4 MW at temperatures of 4-18°C [43]. Other materials in research or already cancelled research for cold storages in research were paraffin Wax slurries, eutectic salts, triple point carbon dioxide, paraffin and gas hydrates. [41,44]

3.3.3 Chemical thermal energy storage

Thermochemical heat storages absorb energy through endothermic reactions and release it through exothermic reactions. This is typically accomplished through sorption, absorption or adsorption. Heat is released during the ad- or absorption process, and the substance is regenerated and stores this heat when heat is added. However, it can also occur through a reversible chemical reaction. Thermochemical heat storages can achieve higher storage densities than water and can provide energy after cooling down. Thermochemical storage tanks have minimal losses as the heat is typically stored at ambient temperature, preserving the potential. However, cooling losses persist. This storages are more used for heat storages and not yet implemented in district networks or for cold storages. [38,39,43]

4 Case study Losone

The previous chapters have shown that the demand for cooling in areas with thermal networks will rise considerably, although the demand for heating will still significantly exceed the demand for cooling on average. 5GDHC networks provide a solution to meet both, heating and cooling requirements. This technology has become established in recent years and numerous examples have been realised in Switzerland. However, there are many existing networks that are operated at a high temperature and, for various reasons, many networks are still planned as high-temperature networks with flow temperatures above 60°C. In areas with high-temperature grids, there are some examples which use heat from the grid to operate ad- or absorption chillers. However, these examples are built in networks with excess heat in summer and exclusively for larger cooling consumers. There are also examples where larger heat pumps/chillers condense at an elevated temperature level in hot grids and at the same time, cover a cooling demand.

In the next section, this approach is applied to the example DH grid of Losone. In the analysis, decentralised chillers are used to cover the cooling requirements of individual buildings, thereby covering part of the summer heating requirements and thus reducing the consumption of wood. This new approach is compared to solar thermal heat production in summer combined with ad-, absorption chillers and independent air compression chillers.

The software Polysun [45] was used to simulate various cooling configurations for the district heating network in Losone. Energie Rinnovabili Losone SA constructed the network in 2015 to replace individual oil heating systems, and it is heated by a wood chip power plant. The network spans approximately 3 kilometres and distributes heat at 85C to industrial, public and residential buildings. A detailed description of the network is given by Toffanin et al. [46]
The following chapters describe and compare different cooling configurations, including variations with and without connection to the heating network and different cooling technologies. All of these configurations get simulated with different variations of the size of the solar field and storage as well as cooling demand.

4.1 Implementation in Polysun

The heating network in the Polysun simulation is primarily heated by a 2.4 kW wood boiler, with an additional wood boiler of 1.2 kW for higher demands. An oil boiler with a 4 kW capacity is also installed for peak loads. The network includes a 60'000 litre hot water storage tank. The grid is strongly simplified, and the demand is simulated using only two types of buildings differentiated by the heating distribution in the buildings. These basic building types are then scaled with the Polysun "flow multiplicator" component in order to meet the demand of the network. The floor heating is installed in 200 houses and each requires about 10'000 kWh for SH and 3'200 kWh for DHW per year. Additional 200 houses are equipped with radiators and each requires about 30'000 kWh for SH and 3'200 kWh for DHW per year. For the variation of the cooling demand an additional building with 10'000 kWh of cooling demand per year was added and scaled by using the "flow multiplicator" component. This representation of heating and cooling demands in separate buildings simplified the implementation and variation of a cooling demand in Polysun [22], but neglects interactions of heating and cooling.

Figure 6 shows a system diagram as an example. The diagram displays the heating systems, including the boilers, water storage, thermal solar field, and additional water storage on the left. On the right, at the top and bottom, are the houses with their heating demand and hot water storages. In the middle, there is the cooling demand and the installed cooling device.

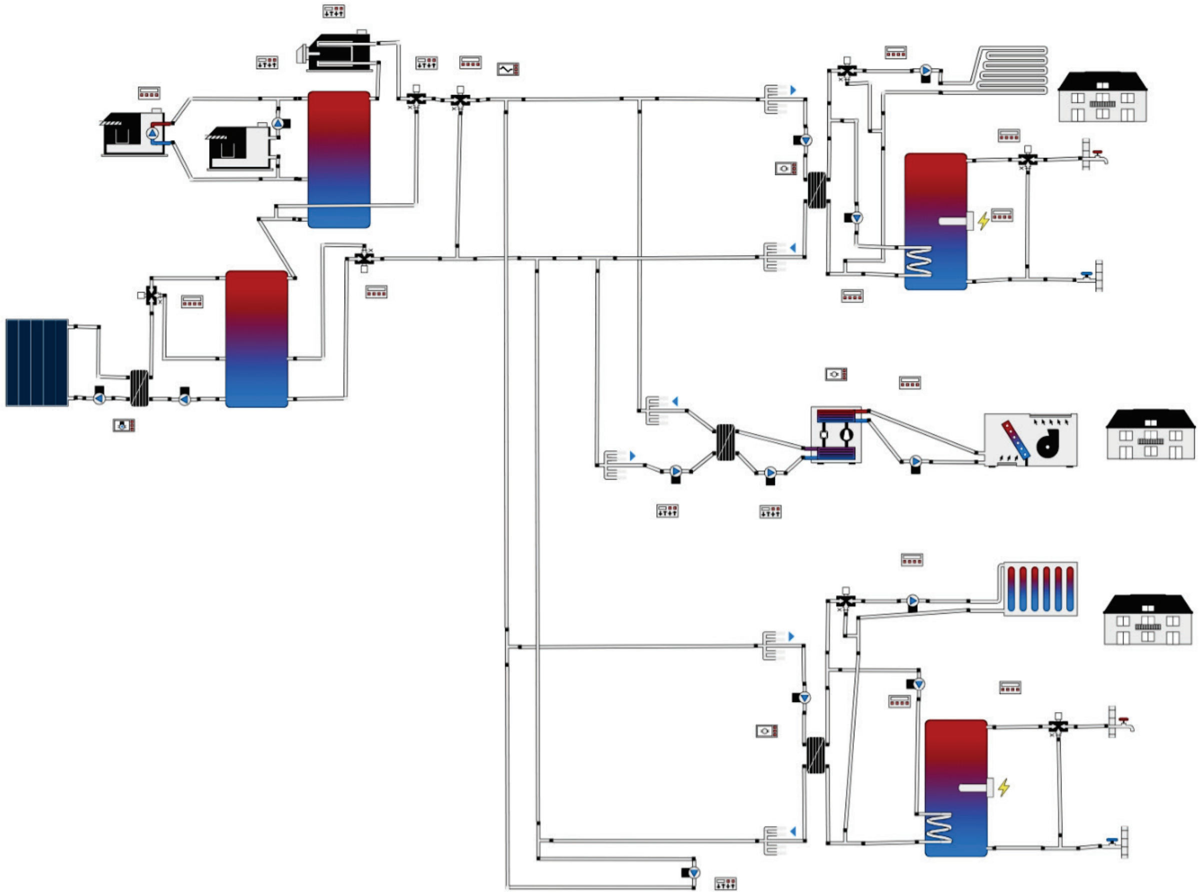

Figure 6: System diagram of the configuration with district heating, solar thermal system and compression chiller connected to the network.

Five cooling configurations were implemented. The first configuration simulated the network without a solar field, and the cooling demand was met by each house separately using a 15 kW compression chiller. There was no storage for the solar heat. The second configuration is similar to the first one but included a thermal solar field in the network with corresponding storage. The third configuration covers the cooling demand using a 15 kW absorption chiller connected to the heating network and also a solar thermal system. The fourth configuration replaces the absorption chiller with a 15 kW water to water compression chiller with connection to the network. The last configuration uses a compression chiller connected to the district heating network as well, but with a photovoltaic system and solar heat storage instead of a thermal solar field.
An overview of the different configurations:

1. District heating + compression chiller without network
2. District heating + solar thermal system and storage + compression chiller without network
3. District heating + solar thermal system and storage + absorption chiller
4. District heating + solar thermal system and storage + compression chiller
5. District heating + photovoltaic system and storage + compression chiller

The solar thermal system is connected to an additional water storage. The volume of this storage is adapted to the size of the solar field. The solar field size (thermal and photovoltaic) and the storage varies from 500 m^2 to 2'000 m^2 and 100'000 litres to 400'000 litres, respectively. Due to a limited availability of suitable roofs or other areas for solar installations no larger systems were analysed. The cooling demand also changes in different variants from 25x10'000 kWh per year for 25 houses with a cooling demand of 10’000 kWh to 100x10’000 kWh per year. Therefore, in every system configuration the following nine variants in Table 2 get simulated.

Table 2: overview of the variations of the solar field sizes and the cooling demands carried out.

	500 m^2 solar field, 100’000 litre storage	1’000 m^2 solar field, 200’000 litre storage	2’000 m^2 solar field, 400’000 litre storage
25x10’000 kWh/y cooling demand	x	x	x
50x10’000 kWh/y cooling demand	x	x	x
100x10’000 kWh/y cooling demand	x	x	x

4.2 Simulation results

The analysis of the Polysun simulation of the district heating network in Losone with different cooling configurations included nine variations of the size of the solar field and cooling demand. Figure 7 shows the energy contributions divided into different energy sources for three different solar system sizes and cooling demands. The diagrams start at 10’000 MWh/y for better visibility. Below 10’000 MWh/y the energy source is wood.

For a solar field of 500m^2 and 25x10MWh/y cooling demand, as well as 1000m^2 and 50x10MWh/y, all configurations require almost the same amount of energy, about 13’100 to 13’300 MWh/y, except for the configuration with the absorption chiller, which requires over 13’500 and almost 14’000 MWh/y. The configuration with an absorption chiller requires the highest energy consumption in general, ranging from 13’500 to 14’600 MWh per year. The variation with a 2000m^2 solar field and 100x10MWh/y cooling demand requires more energy per year over all configurations. The configurations that utilise a compression chiller without the network require 13’400 MWh per year, while the configurations that use a compression chiller at the network require approximately 13’650 to 13’750 MWh per year. However, up to 1’140 MWh (without electricity) and 1’540 MWh (with electricity) per year consist of “free energy” fed into the gris from the cooling of the building.
Wood is the most used energy source, with a consumption ranging from 10’900 to almost 13’000 MWh/y. Oil consumption is also in the same range for all configurations and variants at 450 to 630 MWh/y. As expected, thermal solar field energy usage is higher for larger sizes. The solar field in the configuration with the compression chiller without network produces more energy than the other two. The solar fields vary in size and energy production. The smallest system with 500m^2 produces approximately 300 MWh/y in all configurations. The medium-sized system with 1000m^2 produces between 560 and 500 MWh/y. The largest system with 2000m^2 produces between 900 and 740 MWh/y, and the smaller amount when equipped with a compression chiller with a network connection. The two configurations with a compression chiller at the district heating network have additional waste heat from the buildings and the compression chiller. The configurations do not differ in the amount of waste heat produced as they are controlled by the cooling needs. However, as the cooling demand increases, so does the waste heat, ranging from 290 to 570 and 1’140 MWh/y without the electricity. Additionally, electricity consumption increases with a rise in cooling demand. The electricity consumption of configurations with compression chiller and network connection ranges from 160 to 400 MWh/y. The electricity consumption of compression chiller without network and absorption chiller ranges from 140 to 340 MWh/y. The configuration with a photovoltaic system of the same size as the solar thermal fields produces additional electricity ranging from 170 to 330 and 660 MWh/y with different sizes, which is used for the operation of the chillers and fed into the grid as it is higher, than the electricity used for the chillers.

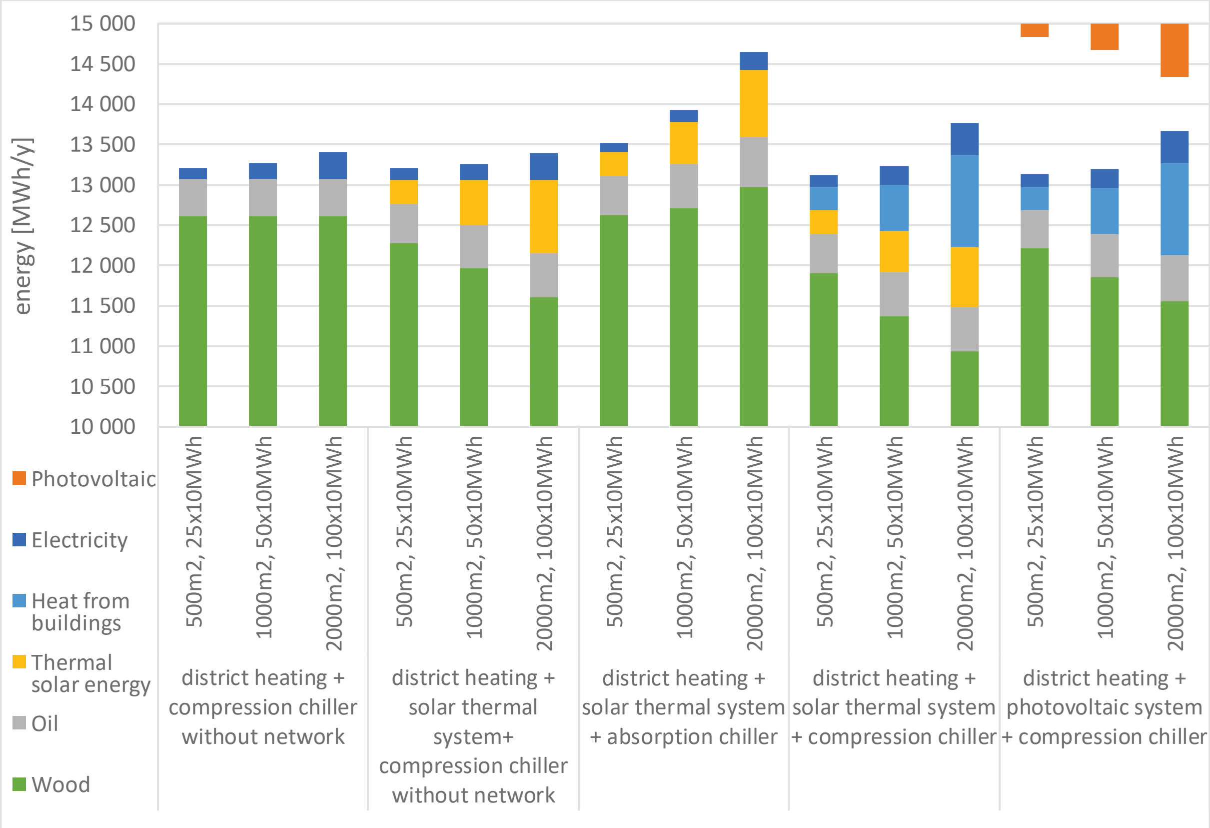

Figure 7: comparison of the energy consumption and energy sources of different configurations and the variants of 500, 1000 and 2000m^2 solar field and 25x, 50x and 100x10MWh/y cooling demand (y axis starting at 10'000 MWh/y).

Figure 8 shows the variations with the largest solar fields of 2000m^2 and 100x10MWh cooling demand with energy consumption divided into its sources over one year for all different configurations. As expected, the highest energy consumption occurs during winter when space heating is required. During the summer months, the network is heated to the same temperature due to the hot water demand in the buildings. Configurations that incorporate thermal solar fields require less wood during summertime, while those that use a compression chiller connected to the network can operate with little to no wood at all in summer as they feed in the waste heat of the cooling process. However, the configuration with the absorption chiller has the highest energy and wood consumption during the summer. Additionally, all configurations experience an increase in electricity consumption and thermal as well as photovoltaic system production during the summer season.

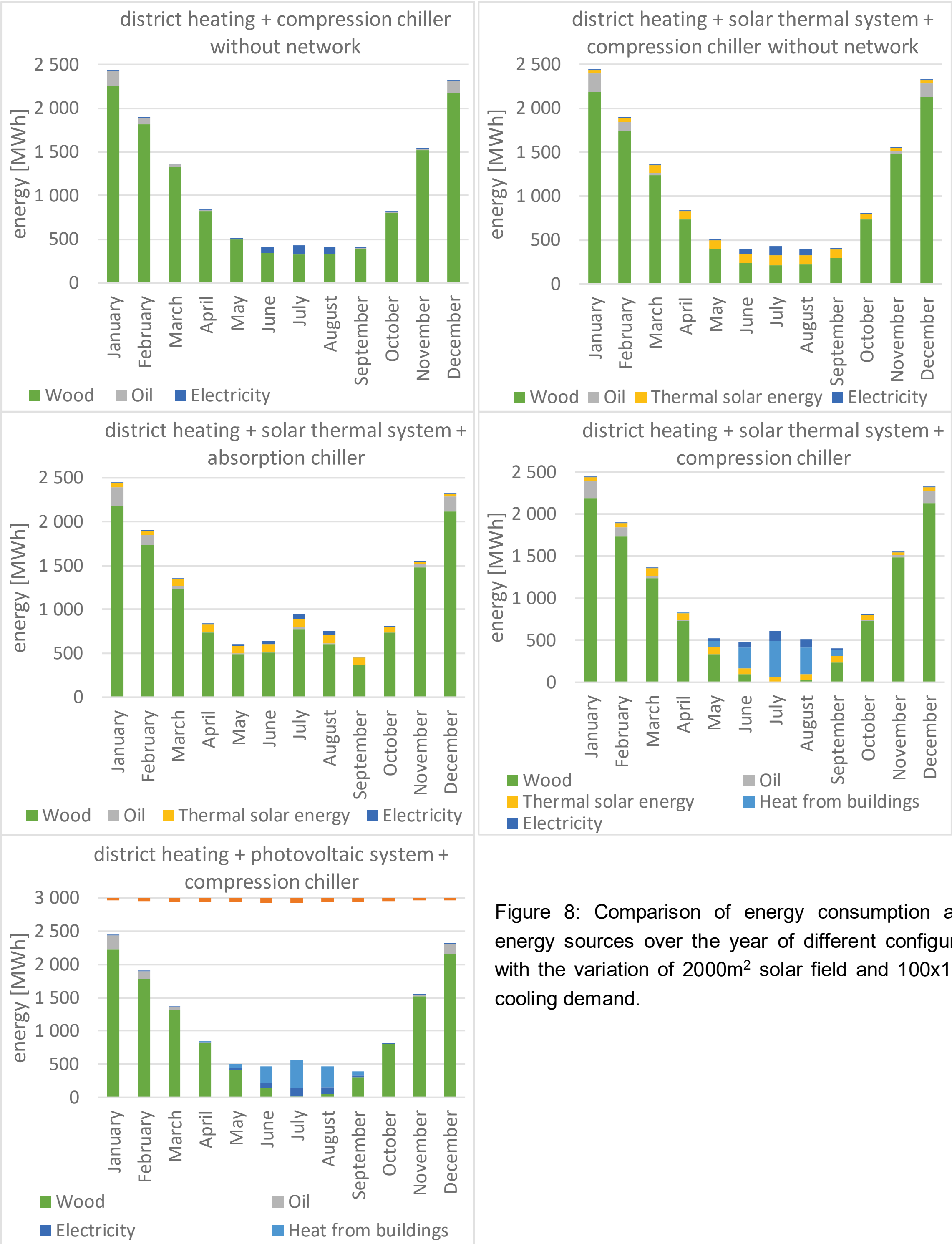

Figure 8: Comparison of energy consumption and its energy sources over the year of different configurations with the variation of 2000m^2 solar field and 100x10MWh cooling demand.

In conclusion, the use of different cooling configurations results in varying energy source requirements during the summer season. The solar field complements the wood boilers in each simulation, resulting in reduced consumption. The size of the solar field directly affects the extent of this effect. Conversely, the absorption chiller increases the demand for wood during summer due to the use of heat from the wood boiler for cooling. The waste heat from the compression chiller can also be used to support the wood boiler in heating the network during summer. However, connecting the compression chiller to the network results in increased electricity consumption during summer compared to when it is not connected. There is a correlation between cooling demand and energy consumption. With higher cooling demand resulting in greater energy consumption overall and a larger impact on the compression chiller's ability to support network heating with waste heat.
More diagrams are shown in the appendix 9.2.

5 Conclusions

Despite a general trend of increasing cooling demand for residential buildings in the future due to climate change, the predictions for cooling demand in Switzerland vary widely depending on the scenario and data source. Forecasts for total cooling demand range from a slight decrease due to efficiency measures in the dominant service sector to a strong increase to 17.5 GWh, still excluding industrial process cooling.

One possibility for Switzerland to reach the net-zero goal is to expand its district heating systems to cover about 30% of the heating demand. Based on these projections, the estimated potential for cooling in district heating areas is in the range of 0.7 to 6 TWh/y with higher variations if extreme scenarios are considered. Although this is significantly lower than the potential for district heating, which is 6.5 to 18 TWh/y, solutions are needed to meet this growing demand. There are different ways of meeting cooling demand within DH systems, depending on the energy source and network temperatures.

Modern 5GDHC networks operating at low temperatures have been installed in several locations in Switzerland. In such systems, the network serves as a common source for decentralised heat pumps to meet heating demand. The heating application lowers the temperature of the network and can be used for cooling applications and vice versa. Coupled with deep lake water, 5GDHC networks can provide a low network temperature all year round and enable direct cooling for most cooling applications. Coupled with other sources such as surface water, geothermal probes or wastewater treatment plants, network temperatures rise in summer to the point, where active cooling with compression chillers is required for most cooling applications. However, in many cases decentralised heat pumps can operate in reverse mode and no additional equipment is required to provide cooling at the required temperature level. As low temperature differences between flow and return result in elevated flowrates and pipe diameters, this technology is only suitable for newly built networks at locations with suitable sources like lakes, sewage plants, borehole fields or groundwater.

On the other hand, there are more than one thousand existing DH systems in Switzerland operated at high temperatures. The potential of various high temperature waste heat sources as waste incineration plants are not harvested yet and network based on such sources are still constructed/expanded. In combination with high temperature networks, ad- or absorption heat pump can be installed to cover cooling demands, making use of excess heat to drive the chillers. Also for this technology various examples were constructed in Switzerland. Ad- and absorption cooling is mainly suitable for large installations due to its complexity and cost. Another option is to use compression chillers, which condensate into a high temperature grid. This integration has a lower efficiency than the use of outside air for cooling. But, the summer heat demand of the network can be covered. Even though there are only little examples of this integration, saving fuel in summer becomes more and more interesting especially in combination with biomass networks, as this resource gets sparse. This option was analysed based on an exemplary real district heating system and compared to other options.

The simulation programme Polysun was used to simulate different district cooling configurations for the district heating network in Losone. The network operates at a high temperature of 85°C and is mainly fuelled by wood. The integration of decentralised compression chillers had a similar effect as the integration of solar thermal installations. However, the electricity consumption of these chillers is about 50% higher than that of individual air compression chillers due to the higher condensation temperature. As the compression chiller in the Polysun program is not designed for these high temperatures, the electrical energy use might not be as accurate as the compression chiller without connection to the network, so this effect might be even higher. On the other hand, when solar thermal collectors are replaced by PV systems, the solar electricity production exceeds the additional electricity consumption of the chillers by far. If absorption chillers are used, less electricity is consumed, but wood consumption increases despite the higher efficiency of the solar thermal collectors.

It may be concluded, that for new DHC systems with elevated cooling demands, the concept of 5GDHC is a well suited and already established principle to provide heating as well as cooling for the connected buildings. For existing high temperature networks, the integration of compression chillers that provide cooling with a lowered efficiency, but support the grid during summer operation, may be an attractive solution in comparison to other technologies such as solar thermal in combination with grid independent compression chillers or with ad-/absorption chillers.

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7 List of figures and tables

8 Abbreviations

- DHC: district heating and cooling
- DH: district heating
- DC: district cooling
- 1GDHN: first generation district heating network
- 1GDCN: first generation district cooling network
- VAC: ventilation and air conditioning
- VFS: Verbund Fernwärme Schweiz
- WWB: weiter wie bisher (business as usual)
- COP: coefficient of performance
- PV: photovoltaic
- CHP: combined heat and power
- BTES: borehole thermal energy storage
- ATES: aquifer thermal energy storage
- TTES: tank thermal energy storage
- PTES: pit thermal energy storage
- PCM: phase change material
- SH: space heating
- DHW: domestic hot water

9 Appendix

9.1 Cooling and heating demand, district heating collection and calculation

Table 3: cooling demand today and in future from different studies.

cooling						
Today		Future		Sector		source
8.1 TWh/y	15.2 kWh/m^2/y	10.2 TWh/y	17.9 kWh/m^2/y	CH, without industry	diff. Cooling measure	[47]
1.1 TWh/y	2.5 kWh/m^2/y	1.9 TWh/y	3 kWh/m^2/y	CH, without industry	diff. Cooling measure	
	6.5 kWh/m^2/y		16.8 kWh/m^2/y	old building	diff. Cooling measure	[22]
	0.4 kWh/m^2/y		2.6 kWh/m^2/y	old building	diff. Cooling measure	
	25.9 kWh/m^2/y		34.6 kWh/m^2/y	low-energy building	diff. Cooling measure	
	0.6 kWh/m^2/y		1.7 kWh/m^2/y	low-energy building	diff. Cooling measure	
	16.6 kWh/m^2/y		30.5 kWh/m^2/y	office	diff. Isolation	[48]
	7 kWh/m^2/y		16.6 kWh/m^2/y	office	diff. isolation	
0.9 TWh/y		6 TWh/y		service	diff. Scenario	[49]
TWh/y		4 TWh/y		service	diff. scenario	
8 TWh/y		7.22 TWh/y		CH	VAC	[2]
1.1 TWh/y		1.11 TWh/y		industry	cooling	
0.83 TWh/y		1.67 TWh/y		residential	VAC	
5.8 TWh/y		4.2 TWh/y		service	Only electricity	
1 TWh/y	15 kWh/m^2/y	2.3 TWh/y	22 kWh/m^2/y	residential	diff. Scenario	[7]
		1.1 TWh/y	16 kWh/m^2/y	residential	diff. Scenario	
0.2 TWh/y	20 kWh/m^2/y	0.9 TWh/y	25 kWh/m^2/y	office	diff. Scenario	
		0.4 TWh/y	16 kWh/m^2/y	office	diff. Scenario	
0.5 TWh/y		1.1 TWh/y		service	diff. Scenario	
		1 TWh/y		service	diff. Scenario	
1.7 TWh/y		4.3 TWh/y		total	diff. Scenario	
		2.5 TWh/y		total	diff. Scenario	
		17.5 TWh/y		total	Extreme scenario	
1.7 TWh/y				CH	Space cooling	[6]
3.5 TWh/y				CH	process cooling	
6.2 TWh/y				CH	VAC	
0.42 TWh/y				residential	Space cooling	
3.6 TWh/y				service	VAC	
2.8 TWh/y				service	Process cooling	
1.4 TWh/y				industry	VAC	
0.7 TWh/y				industry	Process cooling	
5.75 TWh/y				buildings	VAC	
4.8 TWh/y		6.4 TWh/y		air conditioning	diff. Scenario	[5]
		7.7 TWh/y		air conditioning	diff. Scenario	
8.1 TWh/y		7.4 TWh/y		VAC	diff. Scenario	
		9.6 TWh/y		VAC	diff. Scenario	
		9.5 TWh/y		CH	diff. Scenario	[4]
		11.5 TWh/y		CH	diff. Scenario	
		1.2 TWh/y		residential		
		7 TWh/y		service	diff. Scenario	
		8.8 TWh/y		service	diff. Scenario	
		1 TWh/y		industry		
2.4 TWh/y		2.8 TWh/y		buildings		[50]
		17.5 TWh/y			EMPA	
3.2 TWh/y				residential	electricity	[51]
3.2 TWh/y				service	electricity	
1.6 TWh/y				industry	electricity	
8 TWh/y				total	electricity	

Table 4: heating demand today and in future from different studies.

heating										
Today				Future				Sector		source
		140	kWh/m^2/y			120	kWh/m^2/y	old building		[22]
		9.9	kWh/m^2/y			6.8	kWh/m^2/y	low-energy building		
		108	kWh/m^2/y			78	kWh/m^2/y	residential	diff. Isolation	[48]
		25	kWh/m^2/y			17	kWh/m^2/y	residential	diff. Isolation	
		78	kWh/m^2/y			53	kWh/m^2/y	office	diff. Isolation	
		22	kWh/m^2/y			11	kWh/m^2/y	office	diff. Isolation	
		49	kWh/m^2/y			31	kWh/m^2/y	SFH, new		[2]
		35	kWh/m^2/y			22	kWh/m^2/y	MFH, new		
		75	kWh/m^2/y			49	kWh/m^2/y	SFH, renovated		
		60	kWh/m^2/y			34	kWh/m^2/y	MFH, renovated		
64.4	TWh/y	total		45	TWh/y	total		CH	space heating	
12.2	TWh/y	76.6		10.6	TWh/y	55.56		CH	hot water	
4.44	TWh/y			1.11	TWh/y			industry	space heating, hw	
22.2	TWh/y			17	TWh/y			industry	Process heat	
42	TWh/y	total		32	TWh/y	total		residential	space heating	
9	TWh/y	51		7.8	TWh/y	39.8		residential	hot water	
21	TWh/y			8.6	TWh/y			service	space heating	
		59	kWh/m^2/y			58	kWh/m^2/y	office	diff. Scenario	[7]
						51	kWh/m^2/y	office	diff. Scenario	
		38	kWh/m^2/y			38	kWh/m^2/y	residential	diff. Scenario	
						32	kWh/m^2/y	residential	diff. Scenario	
				20	TWh/y			total	diff. Scenario	
				25	TWh/y			total	Diff. Scenario	
55.7	TWh/y		total					CH	Space heating	
13	TWh/y		68.7					CH	hot water	
24.8	TWh/y							CH	process heat	
93.5								CH	total	
45.63	TWh/y							residential	space heat, hw	
								service	space heat, hw	
19.63	TWh/y	0.9	TWh/y						/ process heat	
								industry	space heat, hw	
3.37	TWh/y	22.4	TWh/y						/ process heat	
68.7	TWh/y							buildings	space heat, hw	
		140	kWh/m^2/y					old building		[9]
		220	kWh/m^2/y					old building		
		70	kWh/m^2/y					old building		
		110	kWh/m^2/y					old building		
		50	kWh/m^2/y					new building MuKEn		
		60	kWh/m^2/y					new building MuKEn		
		30	kWh/m^2/y					Minergie		
		40	kWh/m^2/y					Minergie		
63.7	TWh/y			50.5	TWh/y			CH	space heating	[5]
				53.3	TWh/y			CH	space heating	
11.1	TWh/y			11.1	TWh/y			CH	hot water	
				10.5	TWh/y			CH	hot water	
100	TWh/y			80	TWh/y			CH	total	[4]
				90	TWh/y			CH	total	
				60	TWh/y			CH	space heating, hw	
				20	TWh/y			CH	process heat	
				25	TWh/y			CH	process heat	

Table 5: district heating today and the potential in the future from different studies.

District heating									
Potential		Today		Future 2050					source
87TWh/y	LTDH						Total Demand	Current	[52]
58TWh/y	1.8TWh/y						Demand in DHN		
66%									
54TWh/y	LTDH						Total Demand	SwissRes szenario	
33TWh/y	23TWh/y						Demand in DHN	Energy Saving by	
60%								building retrofit	
43TWh/y	LTDH						Total Demand	SEST Szenario 50%	
23TWh/y	18TWh/y						Demand in DHN	heat Demand	
53%								reduction	
5TWh/y								Currently connected	
Potential share of heating demand in a district heating network (different marginal cost)									
3%		1.1%		9.7%					[2]
32%							SHF	ZERO Basis	
17%		4.5%		31%			SHF		
66%							MFH	ZERO Basis	
57%		3.7%	1.4TWh/y	16.3%	1.4TWh/y	WWB	service		
83%				32.6%	2.8TWh/y	ZERO C	service		
				23.5%	2.8TWh/y	ZERO Basis	service		
65%		8%	1.8TWh/y	10.7%	1.9TWh/y	WWB	industry		
83%				11.5%	2.08TWh/y	ZERO C	industry		
				23.5%	1.9TWh/y	ZERO Basis	industry		
		5.1%	2.5TWh/y	6.4%	2.6TWh/y	WWB	residential		
				23.1%	9.2TWh/y	ZERO C	residential		
				15%	6.4TWh/y	ZERO Basis	residential		
23%		8.5%	6.5TWh/y	9.8%	6.5TWh/y	WWB	total		
56%				26.1%	18.2TWh/y	ZERO C	total		
				22.6%	15TWh/y	ZERO Basis	total		
5.7TWh/y					3.6TWh/y		waste treatment plant	residential, service and industry	[3]
3.6TWh/y							direct waste heat utilisation industry	(without process heat)	
12.2TWh/y					1.9TWh/y		ground water		
7.7TWh/y					1.9TWh/y		wastewater treatment plant		
97TWh/y					5.1TWh/y		lakes		
21.3TWh/y					1.8TWh/y		rivers		
20.5TWh/y					1.7TWh/y		wood		
70TWh/y					1.3TWh/y		geothermal energy		
238TWh/y				38%	17.3TWh/y		total		
			5.9TWh/y				total		[6]
				5%			residential	diff. Variant	[4]
				25%			residential	diff. Variant	
				9%			service	diff. Variant	
				42%			service	diff. Variant	
				8%	6TWh/y		total	diff. Variant	
				27%	22TWh/y		total	diff. Variant	
2.1TWh/y					1.2TWh/y		lakes	cooling	
					1.7TWh/y		lakes	cooling	
					25TWh/y		geothermal energy	cooling	
					30TWh/y		geothermal energy	cooling	

Table 6: calculations of district cooling potential with three different variants.

variant 1 district cooling Energy Perspectives2050+							
cooling demand	district heating potential ZERO C	coverage ZERO C		district heating potential WWB	coverage WWB		
1.67TWh/y	9.2TWh/y	1.67TWh/y	100%	2.55TWh/y	1.67TWh/y	100%	residential
4.2TWh/y	2.8TWh/y	2.8TWh/y	66.7%	1.4TWh/y	1.4TWh/y	33.3%	service
1.11TWh/y	2.08TWh/y	1.11TWh/y	100%	1.53TWh/y	1.11TWh/y	100%	industry
7.22TWh/y	18.2TWh/y	5.58TWh/y	77.29%	6.5TWh/y	4.18TWh/y	57.9%	total

variant 2 district cooling Energy Perspectives2050+				
coverage	district heating			district cooling
32.6%	2.8TWh/y	ZERO C	service	1.37TWh/y
11.5%	2.08TWh/y	ZERO C	industry	0.13TWh/y
23.1%	9.2TWh/y	ZERO C	residential	0.39TWh/y
26.1%	18.2TWh/y	ZERO C	total	1.88TWh/y
16.3%	1.4TWh/y	WWB	service	0.68TWh/y
10.7%	1.9TWh/y	WWB	industry	0.12TWh/y
6.4%	2.6TWh/y	WWB	residential	0.11TWh/y
13%	6.5TWh/y	WWB	total	0.91TWh/y
26.1%	18.2TWh/y	ZERO C / lowest cooling demand scenario	total	0.68TWh/y
26.1%	18.2TWh/y	ZERO C / £ highest cooling demand scenario	total	4.79TWh/y

variant 3 district cooling VFS Strategy				
	District cooling			
District heating	average	low cooling demand scenario	high cooling demand scenario	
3.6TWh/y	0.52TWh/y	0.18TWh/y	1.24TWh/y	waste treatment plant
1.9TWh/y	0.28TWh/y	0.09TWh/y	0.66TWh/y	ground water
1.9TWh/y	0.28TWh/y	0.09TWh/y	0.66TWh/y	wastewater treatment plant
5.1TWh/y	0.74TWh/y	0.25TWh/y	1.76TWh/y	lakes
1.8TWh/y	0.26TWh/y	0.09TWh/y	0.62TWh/y	rivers
1.7TWh/y	0.25TWh/y	0.08TWh/y	0.59TWh/y	wood
1.3TWh/y	0.19TWh/y	0.06TWh/y	0.45TWh/y	geothermal energy
17.3TWh/y	2.52TWh/y	0.85TWh/y	5.98TWh/y	total
	34.15%	34.15%	34.15%	coverage
	50.66TWh/y	50.66TWh/y	50.66TWh/y	heating
	7.384TWh/y	2.5TWh/y	17.5TWh/y	cooling
	0.1457	0.0493	0.3454	cooling/heating ratio

9.2 Polysun simulation results

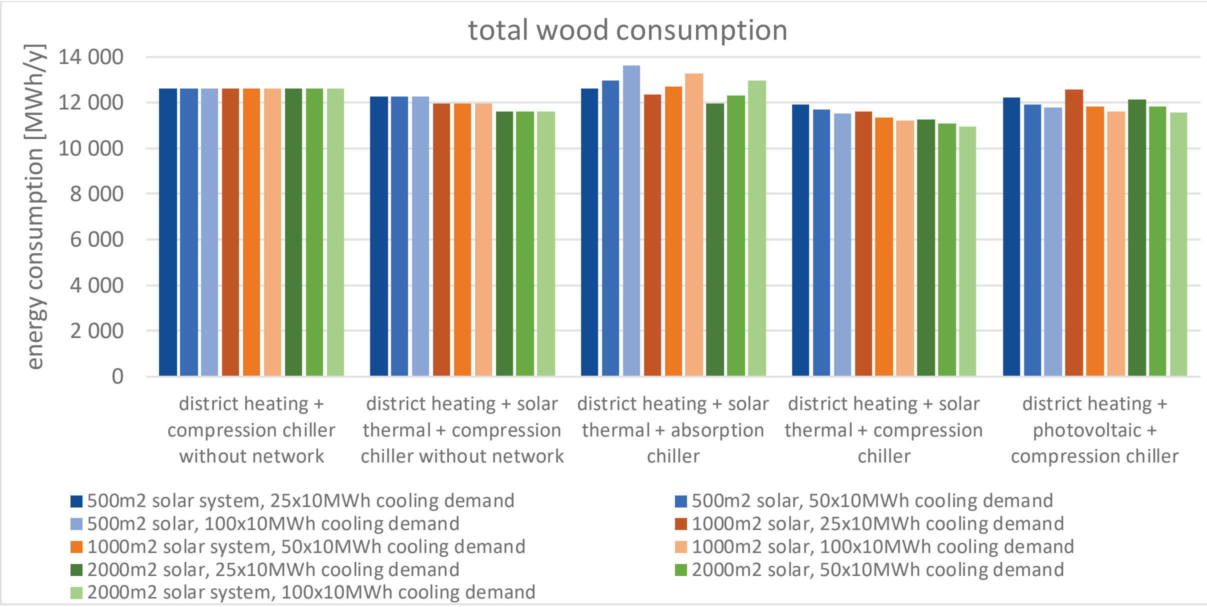

Figure 9: total wood consumption of all configurations and all variations.

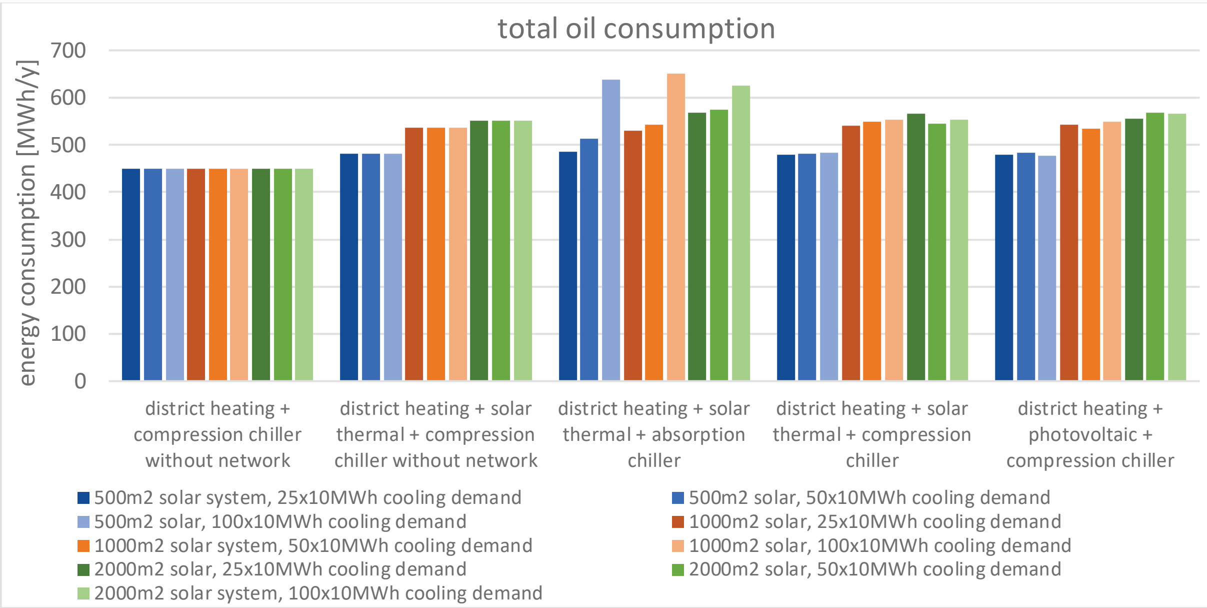

Figure 10: total oil consumption of all configurations and all variations.

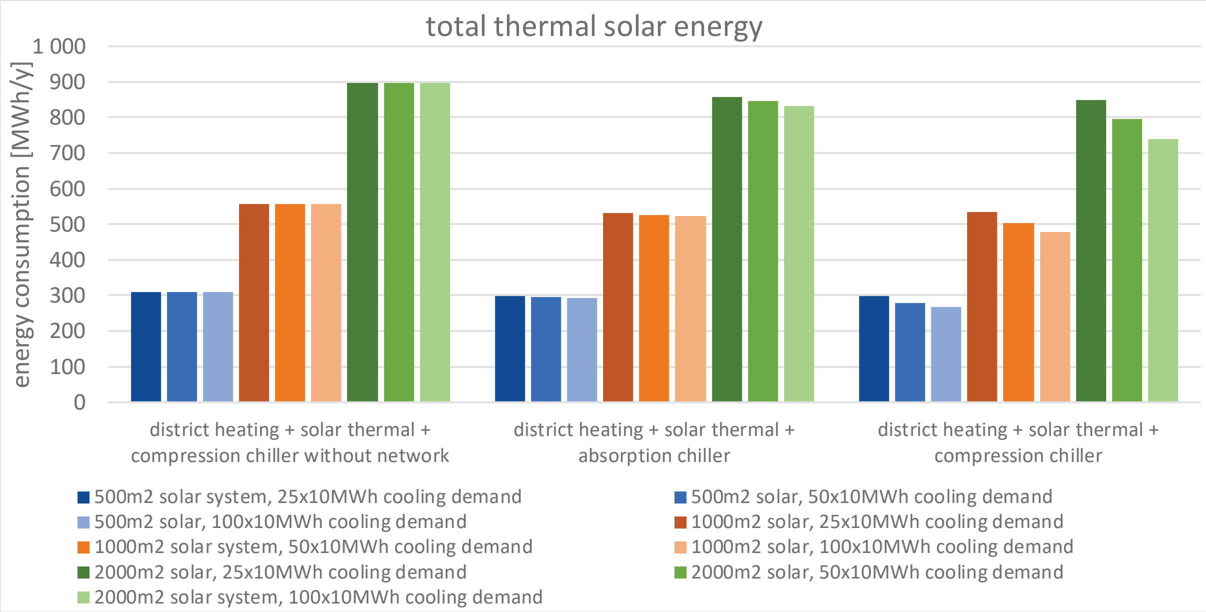

Figure 11: total thermal solar energy to the system of three configurations and all variations.

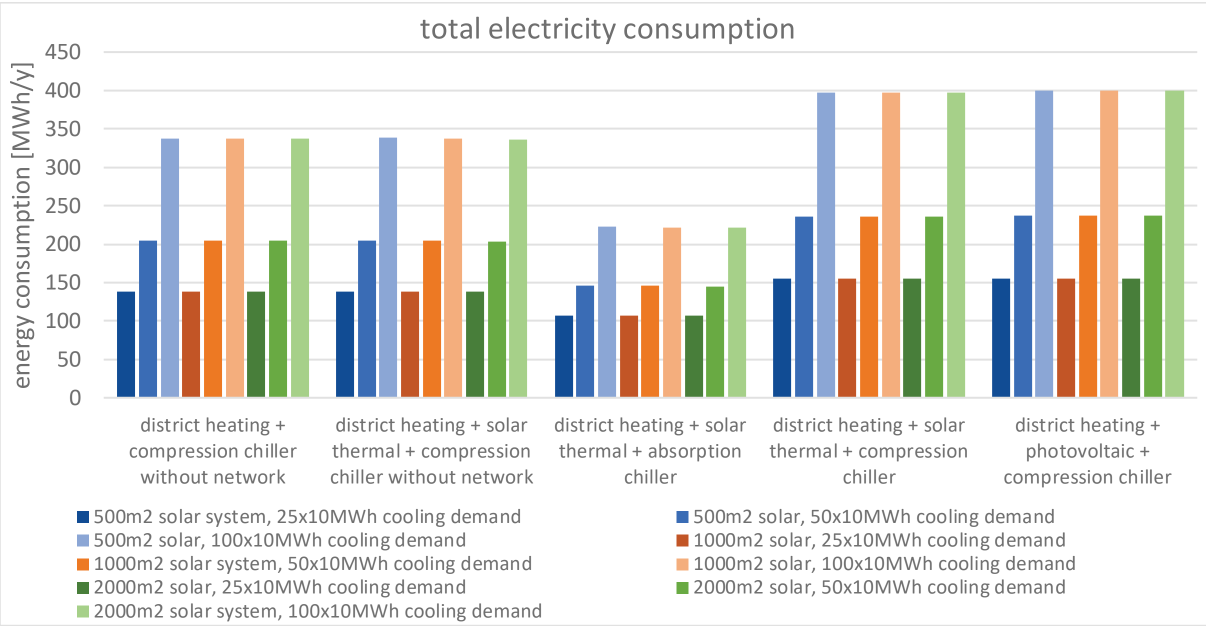

Figure 12: total electricity consumption of all configurations and all variations.

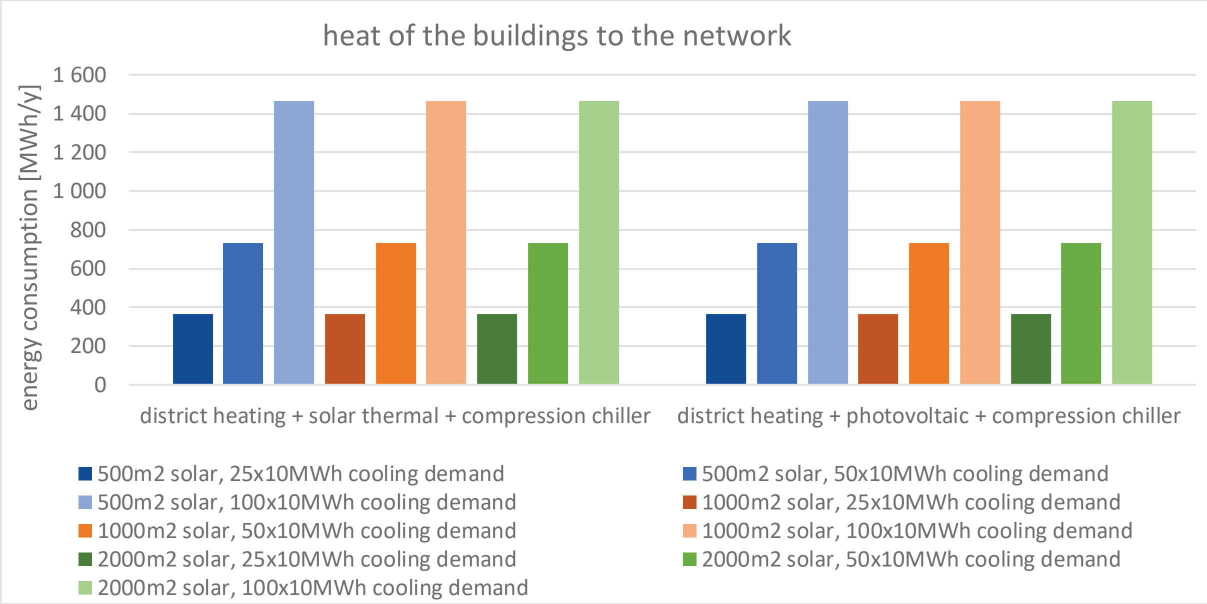

Figure 13: total waste heat from cooling with compression chiller to the network of two configurations and all variations.