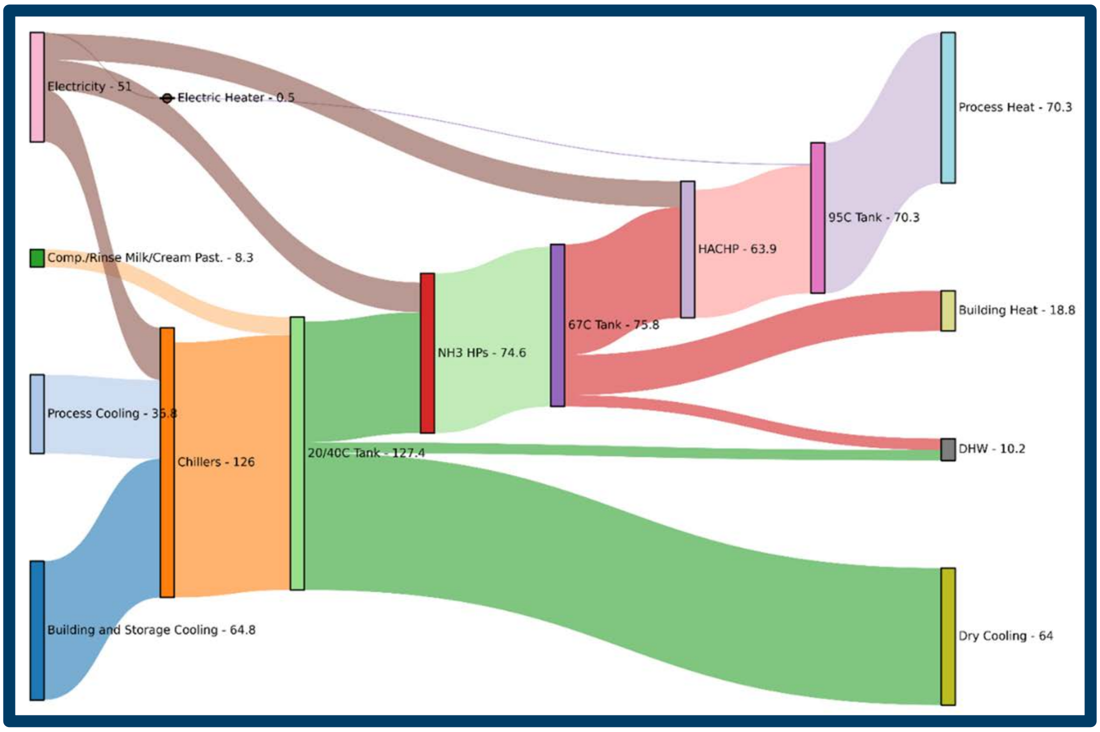

Report

Integrated technologies based on heat pumps, thermal energy storage and smart control systems

Activity 2: The potential for starting and developing a business for integrated technology based on heat pumps, thermal energy storage and smart control systems in order to enable the decarbonization in Romania

Author(s):

August Brækken, Sigurd Sannan

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Client:

Bucharest University of Economic Studies (ASE Bucuresti)

SINTEF Energy Research
Postal address:

7465 Trondheim, Norway

Switchboard: +47 45456000

energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

Report

Integrated technologies based on heat pumps, thermal energy storage and smart control systems

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AUTHOR(S) August Brækken, Sigurd Sannan	
CLIENT Bucharest University of Economic Studies (ASE Bucuresti)	**CLIENT'S REFERENCE** Professor PhD. Adrian Dumitru Tantau
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SUMMARY

An overview of integrated technologies based on heat pumps, thermal energy storage and smart control systems is provided. Heat pumps are devices that transfer thermal energy from low-temperature to high-temperature areas, consuming a small amount of electricity in the process. Their working principles, heat sources, working fluids, and applications are discussed. Heat sources include ambient air, ground, seawater, and waste heat. Natural working fluids like hydrocarbons, ammonia and CO_2 are recommended for their environmental advantages. Thermal energy storage is discussed, using water tanks, phase change materials, and boreholes. Examples of integrated heat pump systems in Norway are presented, including two dairies and one local heating network for a new neighbourhood.

PREPARED BY Sigurd Sannan	SIGNATURE Sigurd Sannan
CHECKED BY Mette Bugge	SIGNATURE Mette Bugge Mette Bugge (28. sep. 2023 11:40 GMT+2)
APPROVED BY Petter Egil Røkke	SIGNATURE Petter E. Røkke

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APPENDICES

No appendices

1 Introduction

In order to combat climate change, the EU is aiming to cut greenhouse gas emissions by 55% by 2030 (compared to 1990) and become climate neutral by 2050 [1]. As of 2020, more than 75% of the energy demands for heating and cooling in the EU are covered by fossil fuels [2]. At the same time, heating and cooling processes are rarely integrated, meaning that excess heat from cooling processes usually goes to waste. This shows the need for integrated renewable heating and cooling solutions in Europe, and the transition must be quick in order to reach our goals.

Integrated heating and cooling systems based on heat pumps, thermal energy storage, and smart control systems can be the renewable energy solution that Europe needs. Heat pumps can utilize heat from the ambient or from waste heat and upgrade this heat to reach the necessary temperature levels. The only external energy needed is a small amount of electricity for the compressor, which makes heat pumps highly efficient and an environmentally friendly option. In combination with heat pumps, it is very useful to implement thermal energy storage (TES) solutions to bridge the short-term differences in energy supply and demand.

The aim of this report is to provide detailed information on the operation of heat pumps, potential heat sources and working fluids, and various TES solutions. Examples of applications of these technologies will be given, further highlighting their potential and benefits.

2 Heat pumps

2.1 What is a heat pump?

In simple terms, a heat pump is a device that moves thermal energy from a location with lower temperature to a location with higher temperature, consuming a small amount of electricity in the process. Figure 1 shows a simple sketch of a vapor-compression cycle, which is the most common cycle for heat pumps. The working fluid (or refrigerant) is the medium used to transport heat through the heat pump. The working fluid is in a liquid state when it enters the evaporator (a). The evaporator is a heat exchanger where heat is transferred from the heat source to the working fluid, causing the working fluid to evaporate (at constant temperature). Here, the working fluid must have a lower temperature than the heat source (typically around 5 K), so that heat transfer occurs.

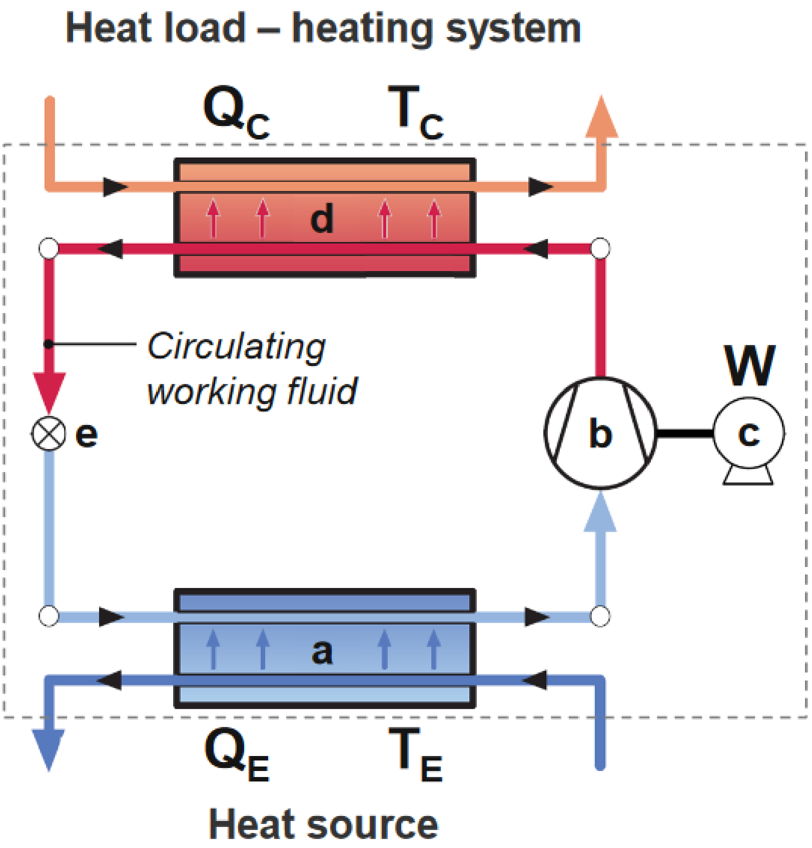


Figure 1: The basic setup for a heat pump, with an evaporator (a), compressor (b), compressor motor (c), condenser (d) and expansion valve (e) [3].

Subsequently, after leaving the evaporator, the working fluid (in vapor form) enters the compressor (b), where it is compressed to a higher temperature and pressure. In this step external energy is added to the process in the form of electricity for the compressor motor (c). Next, the gaseous working fluid enters the condenser (d), which is a heat exchanger between the working fluid and the heating system (heat sink). Here, the working fluid has a higher temperature than the heating system (around 5 K), so that heat is transferred to the heating system. The working fluid condenses in the process, again at constant temperature. The purpose of the compressor is to raise the temperature of the working fluid above the heating system temperature, so that heat is transferred in the desired direction. The next, and final step of the cycle is the expansion valve (e), where the pressure is reduced so that the temperature of the working fluid decreases back to the evaporator level.

A heat pump can also be used for cooling purposes by connecting the evaporator to the cooling system, i.e., using the cooling system as a heat source in the heat pump. In fact, traditional air conditioners and refrigerators are based on vapor-compression cycles, with opposite operation to heat pumps.

The efficiency of a heat pump is expressed using the Coefficient of Performance (COP). In heating mode, the COP is defined as

$$COP_{HP} = Q_C/W,$$

where Q_C is the heating capacity of the heat pump (the heat supply from the condenser) and W is the electricity input to operate the heat pump. This is mainly the electricity for the compressor but could also include a small amount of power for fans and pumps. The electricity needed for the compressor is usually small compared to the heating capacity, and most heat pumps therefore have a COP significantly higher than 1, typically in the range 2-5.

Since the electrical energy supplied to the compressor is converted into heat, the capacity of the condenser can be calculated by adding the capacity of the evaporator to the compressor power while accounting for any compressor losses. Thus, more heat is transferred out from the condenser than the heat removed by the evaporator, that is

$$Q_C = Q_E + W \cdot (1 - \xi),$$

where Q_E is the cooling capacity of the heat pump (the cooling capacity of the evaporator) and ξ is the heat loss from the compressor, as a fraction of the compressor power. The compressor losses are usually small and can often be ignored in simplified evaluations.

Like for the heating COP of the heat pump, the COP in the cooling mode is expressed as

$$COP_{REF} = Q_E/W.$$

Since Q_C is larger than Q_E, the COP of the heat pump's heating mode is higher than the COP of the cooling mode. If compressor losses are ignored, we have

$$COP_{HP} = COP_{REF} + 1.$$

The COP of a heat pump depends on several factors, including the temperature of the heat source and the heat sink. A large difference between these two temperature levels means that the heat pump must provide a large temperature lift, which reduces the COP of the heat pump due to the higher compressor power needed.

This is a description of a simple one-stage heat pump. Heat pumps often have additional components to enhance their performance in specific applications. One example is using a sub-cooler after the condenser to extract more heat from the (liquid) working fluid. This heat is at a lower temperature than the condensation temperature and could therefore be used for preheating in the heating system. On the other hand, if the working fluid is sufficiently superheated after the compressor (temperature is higher than saturation temperature), a de-superheater could be used to extract heat at a higher temperature than the condensation temperature. This could for example be used for heating of domestic hot water (DHW).

Another example is using an internal heat exchanger, or suction gas heat exchanger, to transfer heat from the working fluid after the condenser to the suction gas before the compressor. This increases the efficiency of the compressor and reduces the risk of compressor failure. It also increases the temperature of the gas after the compressor, i.e., the discharge gas temperature. For most heat pumps, internal heat exchangers increase the COP. However, internal heat exchangers should not be used with ammonia as the working fluid since this already gives very high discharge gas temperatures.

Heat pumps can also have multiple stages and compression steps, or be a combination of cycles with different working fluids, etc. This will make the presented operation and relations more complex, but the basic operating principles remain. In addition, there are also alternatives to the vapor-compression cycles used in most heat pumps. Most notably, this includes vapor-absorption heat pumps and hybrid absorption-compression heat pumps (HACHP).

2.2 Heat sources

Heat pumps can utilize a wide variety of heat sources. For heating of buildings, the prevailing practice involves employing ambient heat sources such as the surrounding air, bedrock, and seawater. It is also possible to utilize waste heat, for example from ventilation air or grey water. In industrial applications, when waste heat is available, but its temperature is too low for direct use, it can be upgraded. A heat pump is then used to increase the temperature and improve the quality of the heat.

2.2.1 Ambient air

Air-to-air heat pumps utilizing ambient air is the most common type of heat pumps in residential buildings. This means that both the heat source and the heating system are connected to the heat pump by an air stream. Furthermore, there are also air-source heat pumps that utilize the ambient air and transfer heat to a hydronic heating system, commonly referred to as an air-water heat pump. Air-source heat pumps are relatively simple and therefore offer a cost-effective alternative compared to using other heat sources. During the heating season, low outdoor temperatures lead to reduced heating capacities for air-source heat pumps, and thus reduced COPs. It can therefore be beneficial to use a heat source that has a more stable temperature throughout the year.

2.2.2 Seawater

Seawater is a commonly used heat source for large heat pumps in Norway, due to the country's long coastline. The variation in seawater temperature is much smaller than the variation in ambient air temperature, with seawater temperatures in Norway typically ranging between 3 and 15 °C. In addition, there is a delay of 2-4 months between the peak of the air temperature and the seawater temperature. This means that the seawater temperature reaches its peak in the autumn and early winter, which is beneficial since the heat source temperature is rising during the early part of the heating season. This, in turn, leads to higher COPs for the heat pumps.

In addition, due to the relatively low seawater temperatures, it is often possible to use the seawater for free cooling in the summer without having to run the heat pump. The seawater inlet for the heat pump should be at a depth of at least 20 m to achieve a more stable seawater temperature and to reduce fouling/growing and debris that could clog the pipes. Filters are also needed to prevent objects and particles entering the pipes.

Figure 2 shows different types of heat pump systems using seawater as the heat source. In direct systems (A), seawater is circulating directly through the evaporator. Due to the salt content of seawater, the evaporator must then be made of a corrosion resistant material, usually titanium. The evaporator should also be frost protected. It is more common to have an indirect system with a dedicated seawater heat exchanger (B or C), so that a secondary brine circuit is circulating through the evaporator. In solution B, seawater is pumped through a heat exchanger, which then must be resistant to frost and corrosion. Solution C uses tube bundle heat exchangers where brine circulates through plastic tubes that are submerged in the seawater. This means that dirty seawater will not enter the system at all, but it is still necessary with regular cleaning of the heat exchangers to reduce growth and ensure optimal operation. It is also possible to use horizontal pipes buried in the seabed, in a similar manner to a horizontal ground source heat pump using soil as the heat source. The main disadvantage of an indirect system is that the evaporation temperature will be somewhat lower than in a direct system.

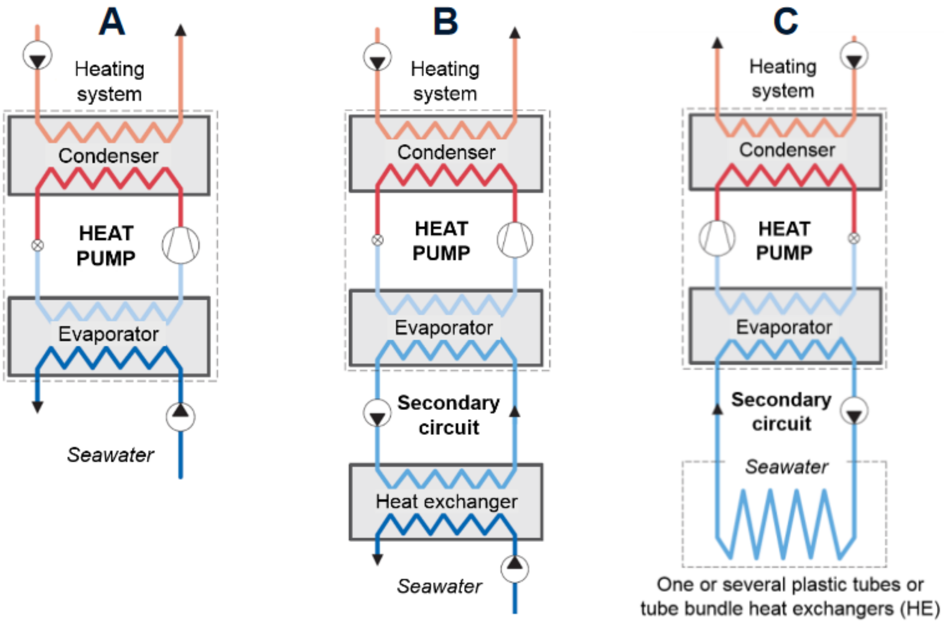


Figure 2: Types of direct and indirect seawater heat pump systems [4].

Correspondingly to seawater heat pumps, it is also possible to use freshwater as a heat source for heat pumps. This could be lake water or river water. These sources also have a relatively stable temperature throughout the year compared to ambient air. However, since freshwater has a higher freezing point than seawater, the risk of freezing during the winter increases significantly. There are also challenges related to fouling and growing, but one advantage is that freshwater typically is much less corrosive than seawater.

2.2.3 Ground

Ground source heat pumps (GSHPs) can use bedrock, the soil, or groundwater as a heat source. These heat pumps have water or brine (anti-freeze fluid) circulating on the heat source side, and typically water on the heat system side.

Bedrock is the most common heat source for GSHPs in Norway. The system uses vertical boreholes with a depth of 100-300 m and a diameter of 100-150 mm where the brine circulates in plastic pipes, exchanging heat with the bedrock. The boreholes are typically filled with a grout designed to enhance heat transfer with the ground. The system can have many boreholes, depending on the capacity of the heat pump and the desired heat exchange. At depths below around 15 m, the ground temperature is largely unchanged throughout the year. In Norway, this is typically between 2 and 10 °C. Thus, the heat source has a relatively high temperature during the heating season, leading to a higher COP for the heat pump. These temperatures could also be suitable for free cooling in the summer. One advantage of borehole systems is that they can be used for borehole thermal energy storage (BTES) for heating and cooling of buildings. This is described further in Section 3.4.

Another type of GSHP uses the soil as a heat source, usually with horizontal heat exchanger pipes in the top layer of the ground, at a depth around 80 to 150 cm. The heat in the soil is largely from solar radiation, and there are much larger seasonal temperature variations than in a vertical borehole system.

Lastly, one could use groundwater as a heat source. Groundwater is naturally occurring water that is found in gravel, sand or cracks in the bedrock. In Norway, it has a stable temperature of 2-8 °C throughout the year, meaning that it could also be utilised for free cooling. However, because groundwater flows through the ground, it cannot be used for thermal energy storage.

2.2.4 Other heat sources

For heat pumps in district heating systems, one potential heat source is sewage (black water) which has a temperature of 5-15 °C. There are significant challenges related to fouling, clogging and corrosion for black water, and it is therefore crucial to have proper filters and regular cleaning of the heat exchangers. It is also possible to use an indirect system design where the sewage heat exchanger is integrated in the sewage tunnel, in which case no cleaning is required.

Greywater is wastewater from showers, washing machines, swimming pools, etc. Typically, greywater has a high temperature of 20-30 °C and can therefore be a very good heat source for heat pumps. One common application is using greywater as a heat source to heat water for swimming pools or DHW for large apartment buildings. Once again, regular cleaning is important to avoid fouling and clogging.

Exhaust air in ventilation systems can be used as a heat source for heat pumps, with its relatively high temperature of 18-25 °C. For buildings with balanced ventilation, the exhaust air should first go through a heat recovery heat exchanger before being used in the heat pump, and it will therefore have a lower temperature. A higher efficiency heat recovery unit will lead to lower air temperature and lower efficiency of the heat pump.

In industry, there are several types of waste heat streams that could be useful heat sources for heat pumps. This could be water that has been used for cooling or heating and that is no longer at a useful temperature level. It could also be condensate from steam that has been used for heating purposes. Using these waste streams as heat sources to help deliver more heating or cooling can significantly reduce the need for external energy supply and therefore substantially reduce costs for industries. High temperature heat pumps could even be used to produce steam and therefore replace steam boilers.

2.3 Working fluids

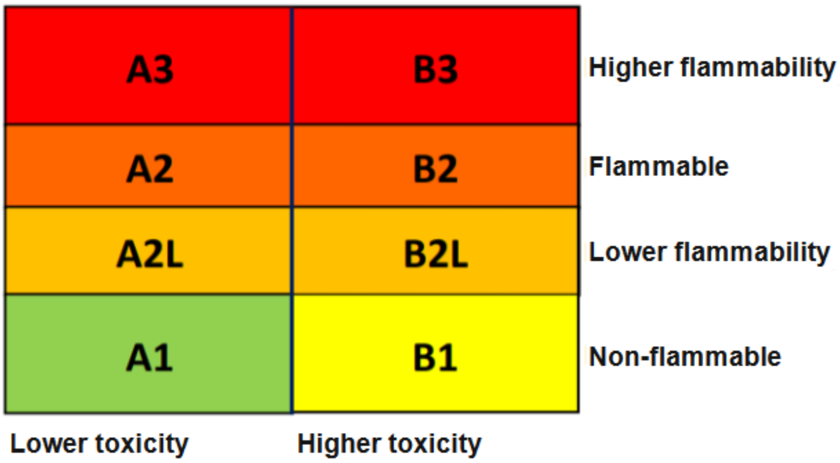
As noted previously, the purpose of the working fluid is to transfer heat from the heat source to the heating system. Thus, it is crucial that the working fluid evaporates and condenses at suitable temperatures and pressures.

Throughout most of the 20th century, the heat pump market was dominated by synthetic working fluids in the form of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). However, as these were found to deplete the ozone layer, they have been phased out following the Montreal protocol in 1987. Hydrofluorocarbons (HFCs) were then introduced as new synthetic working fluids, and these remain the most common working fluids to this day. However, HFCs are currently being phased out due to their high global warming potential (GWP). This was addressed in the Kigali amendment to the Montreal protocol in 2016 and by the F-gas regulation in the EU in 2014 [5], [6].

Following the reduced use of HFCs, hydrofluoroolefins (HFOs) have been introduced, with the aim of producing synthetic working fluids with negligible global warming and ozone depletion potentials. However, there are several environmental concerns related to the use of HFOs. When HFOs decompose in the atmosphere, they form trifluoroacetic acid (TFA), which leads to the formation of TFA salt in water and in the ground. This salt can make its way into drinking water sources and is difficult to remove, and it can therefore have detrimental effects both for nature and human health [7]. Preliminary research has also reported that HFOs partially decompose to the potent greenhouse gas HFC-23 in the atmosphere [8], though another recent study does not support this claim [9]. The full extent of these concerns has not been confirmed, and further research is necessary. However, it is evident that we do not have sufficient understanding of the decomposition process of synthetic working fluids and its associated environmental implications.

Due to the concerns related to synthetic working fluids, SINTEF recommends using natural working fluids, including hydrocarbons, ammonia, or CO_2. These have no ozone depletion potential and negligible global warming potential. Natural working fluids have in fact been used since the 1930s but were overtaken by the synthetic working fluids that had fewer operational challenges and safety concerns. Following the phasing out of HFCs, the investigation and use of natural working fluids has been increasing in recent years. Since these working fluids are derived from natural sources, we can be confident that they will not pose any unforeseen environmental consequences. Therefore, we can rely on their suitability for use in the future as well.

Many natural working fluids are toxic and/or flammable, and additional safety precautions are therefore needed when using them. All working fluids can be given a safety classification according to EN 378:2016 and ISO 817, shown in Figure 3. The working fluid is given letter A or B depending on toxicity, and a number between 1 and 3 for flammability. HFCs have classification A1, meaning they have low toxicity and are non-flammable. HFOs are slightly flammable and classified as A2L.



A3	B3	Higher flammability
A2	B2	Flammable
A2L	B2L	Lower flammability
A1	B1	Non-flammable
Lower toxicity	Higher toxicity	

Figure 3: Safety classification for working fluids [10].

Several different hydrocarbons can be used as working fluids in heat pumps. It is particularly common to use propane (R290), as well as butane (R600). All hydrocarbons are highly flammable and have safety classification A3. Necessary safety equipment includes an ATEX approved compressor, gas detectors and alarm system, and an independent emergency ventilation system. In order to restrict the working fluid charge, which refers to the quantity of refrigerant in each unit, the utilization of hydrocarbons in very large heat pumps is limited. Propane heat pumps can deliver heat at up to 65 °C, while butane can be used at higher temperatures than this.

Ammonia (R717) is a working fluid that gives high performance and has one of the highest theoretical COPs, also when compared to HFCs. Ammonia has a safety classification of B2L due to its high toxicity, and additional safety measures are therefore needed. These measures include using a gas-tight machinery room, gas detectors and alarm system, an independent ventilation system, and an ammonia scrubber or filter in case of leakage. Ammonia is also corrosive, which means that the heat pump must be made of steel or aluminium instead of copper. Ammonia heat pumps have high discharge gas temperatures out from the compressor, which can lead to decomposition of the working fluid, compressor failure and leakages. There are several measures that can limit the discharge gas temperature, for example de-superheaters, using condensers and evaporators with large heat exchanger surfaces, or using compressors with integrated cooling. Ammonia heat pumps can deliver heat at up to 50 °C with standard equipment and up to 90 °C if special equipment is used.

Another important natural working fluid is CO_2 (R744). The research done at SINTEF and NTNU has been central in reviving the use of CO_2 as a working fluid in the 1980s, with Gustav Lorentzen as the main contributor. CO_2 has, by definition, a GWP equal to 1. It also has a safety classification of A1, but an emergency ventilation system is still needed due to risk of suffocation at large emissions. CO_2 heat pumps are operated with very high pressures, which could give additional safety concerns in certain applications.

Compared to other working fluids, CO_2 has a very low critical temperature at 31.1 °C. At temperatures above this, CO_2 will be in a supercritical state, which is neither liquid nor gas. Most applications of CO_2 use a transcritical cycle, meaning the CO_2 will be supercritical in parts of the cycle. In such an application, the CO_2 does not condense when releasing heat to the heat sink, and the "condenser" is called the "gas cooler" in this case. Due to the absence of condensation, the temperature of the CO_2 decreases as it passes through the gas cooler, resulting in what is known as temperature glide. It is beneficial to have a small temperature difference between the two mediums throughout the whole heat exchanger. This means that CO_2 can be especially useful when the heat sink needs a large temperature increase, for example for heating of DHW from 5 to 70 °C, as shown in Figure 4. A standard transcritical cycle can deliver heat at up to 90 °C.

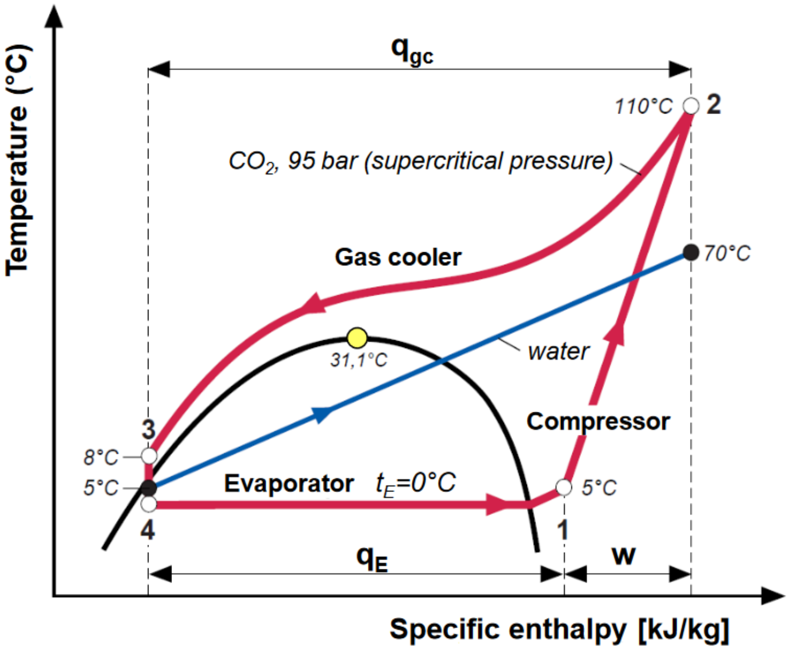


Figure 4: The temperature glide in a CO_2 heat pump when heating water from 5 to 70 °C [10].

Water (R718) can also be used as a working fluid, especially in high-temperature heat pumps. Water has a very high critical temperature (374 °C) and can therefore be used to produce steam or water at similarly high temperatures. It is a safe working fluid with its safety classification of A1. However, steam has a very low density, which means that the compressors of these heat pumps must be very large. In steam-producing heat pumps, it is also possible to use an open system where the working fluid goes directly into the heating system, provided that the heating system does not contaminate the working fluid. This eliminates the need for a condenser and increases the heat pump's COP.

In addition, there is limited use of several other working fluids, for example helium (R704). Enerin has developed an ultra-high-temperature heat pump using helium as the working fluid. With current technology, their heat pumps can supply temperatures up to around 200 °C [11].

3 Thermal energy storage

3.1 What is thermal energy storage?

Thermal energy storage (TES) is the storage of thermal energy, either heat or cold, in order to utilize the stored energy later. TES can be achieved through a temperature change (sensible heat) or a phase change (latent heat). In general, TES is used when there is a mismatch between the generation and the demand for thermal energy. One example is heat from waste incineration used for district heating, where the production of waste heat is close to constant throughout the day, while the heating demands are typically higher during the day. The use of TES to move energy use from periods with high demand to periods with low demand is called load shifting, illustrated in Figure 5.

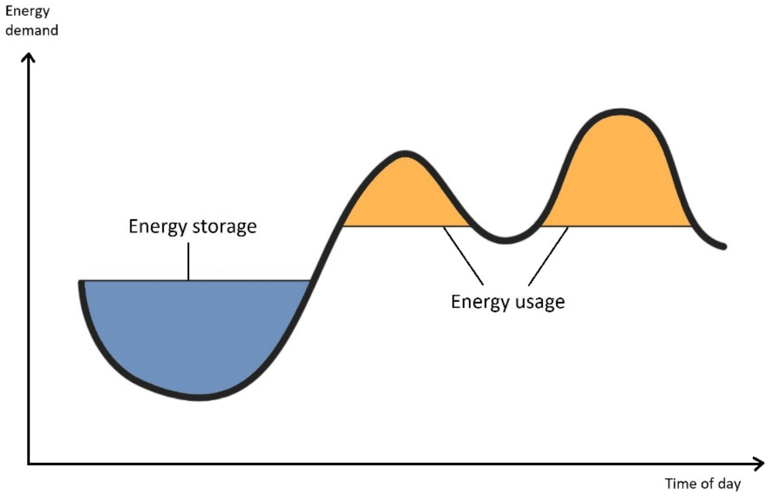


Figure 5: Illustration of load shifting. The storage unit is charged at times of low demand and discharged at high demand.

3.2 Water

The most commonly used TES is sensible heat in water tanks, e.g., tanks for DHW heating in residential homes. Water as a storage medium is readily available, cheap, safe and chemically stable. Water also has a relatively high specific heat capacity, meaning that it can store a large amount of energy per degree of temperature change. Water tanks are frequently used for storing heat but can also be used for cooling applications. Due to heat losses, water tanks are not suitable for long term energy storage, and they are therefore mainly used for storing energy on a day-to-day, or potentially week-to-week, basis.

3.3 Phase change materials

Instead of using sensible heat storage, one can also store thermal energy as latent heat using phase changes. The change between the liquid and solid phases is usually used. A traditional example of latent energy storage is using ice for cold storage. In recent years, there has been significant development and research related to the use of other phase change materials (PCMs), particularly paraffins and salt hydrates. Latent heat storage usually has a higher storage capacity than sensible heat, and a smaller tank volume is therefore needed to store the same amount of energy. In addition, phase changes occur at a near-constant temperature, which is beneficial for many applications. The lower temperature of the storage medium also leads to lower heat losses.

3.4 Boreholes

As mentioned in Section 2.2.3, vertical boreholes can be used for long-term thermal energy storage. In the summer, the boreholes are used as a heat sink for the cooling system, meaning that heat is dumped to the boreholes, increasing the temperature of the ground throughout the summer period. In the heating season, heat is extracted from the boreholes. To enhance the thermal energy storage in the ground, the boreholes should be relatively close together, typically around 6-8 m apart. It is important that the annual heat flow to and from the boreholes is similar, in order to achieve a stable average ground temperature over time.

BTES is often used in combination with heat pumps, as the temperature of the ground usually does not get high enough for direct heating. This alternating use of the boreholes as a heat source and heat sink means that the ground temperatures are lower in the cooling season and higher in the heating season, leading to more efficient use of the heat pump. Due to stable low ground temperatures, the boreholes can often be used directly for free cooling without using a heat pump. They could also potentially be used directly in low-temperature heating systems, or for preheating to reduce the use of the main heating source.

4 Examples of applications

4.1 Tine dairy in Bergen

This section is based on a scientific paper [12] and a conference paper [13]. Tine is the largest dairy product cooperative in Norway. Their dairy in Bergen was commissioned in 2018 and put into operation in 2019. It has an innovative integrated heat pump system providing cooling and heating at all temperature levels required for the production process, making it the world's first dairy designed to have all the heating demands covered by heat pumps. The dairy has a size of 20,000 m^2 and a projected annual production of 43.4 million litres, with the main part being liquid milk. 6000 m^2 of photovoltaic (PV) panels are installed on the roof to cover parts of the electricity demand.

Traditional dairies have separate systems for covering the heating and cooling demands. This is typically done using fossil-fuelled boilers for production of steam or hot water, as well as electric chillers. Using separate systems means that the waste heat that is removed in the cooling processes is usually not taken advantage of, even though there are heating demands present. Figure 6 shows the innovative heat pump system implemented at the dairy in Bergen. Here, the cooling and heating processes have been integrated by using a series of heat pumps to remove heat from the cooling processes (left) and upgrading this heat to higher temperature levels to cover the heating demands (right).

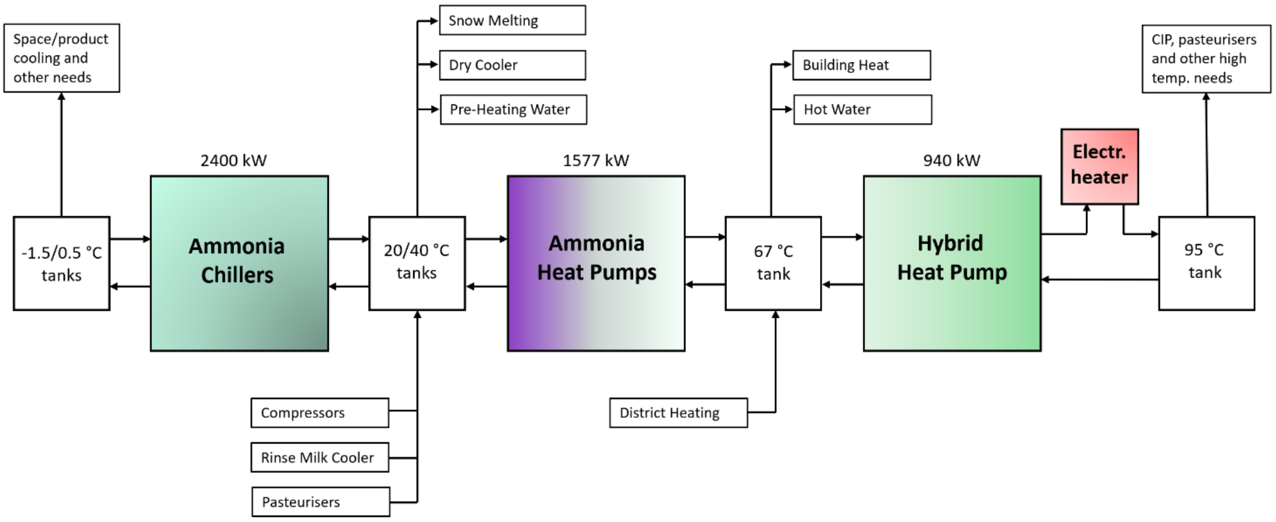


Figure 6: Integrated energy system with heat pumps and thermal energy storages in the Tine Bergen dairy [12].

The system consists of three ammonia chillers (total of 2,400 kW), two ammonia heat pumps (total of 1,577 kW) and one hybrid heat pump (940 kW). This is a hybrid absorption-compression heat pump, which uses a mixture of ammonia and water as the working fluid. It was delivered by Hybrid Energy in Norway. The hybrid heat pump is a high-temperature heat pump, delivering heat at 95 °C. The system also has six water tanks for thermal energy storage, one at each of the temperature levels. The storage tanks have a size of 60 m^3 at -1.5 °C and 0.5 °C, and 130 m^3 at the higher temperature levels. The tanks are used to decouple the heat sources and heat sinks and even out the fluctuations in heat supply and demand. At times of high demand, the system can be supported by a dry cooler, district heating, and an electric heater.

Operational data from the dairy have been analysed for one winter week in February 2020 and one summer week in June 2021. The Sankey diagrams in Figure 7 and Figure 8 show total energy flows from the heat sources on the left to the heat sinks on the right for the winter and summer weeks, respectively. Low measurement resolution and measurement uncertainties lead to some deviations between the energy flow to and from each component. In the winter week, most of the heating demands were covered by the waste heat from the cooling processes. There was good agreement between the heat supply and heat demands, and most surpluses and deficits were covered by the thermal energy storages. The district heating, electric heater, and dry cooler were therefore used to a small degree. This shows that the energy system is well designed with sufficient capacities for the heat pumps and energy storage tanks. The external energy consumption was 38% lower than in a traditional dairy system.

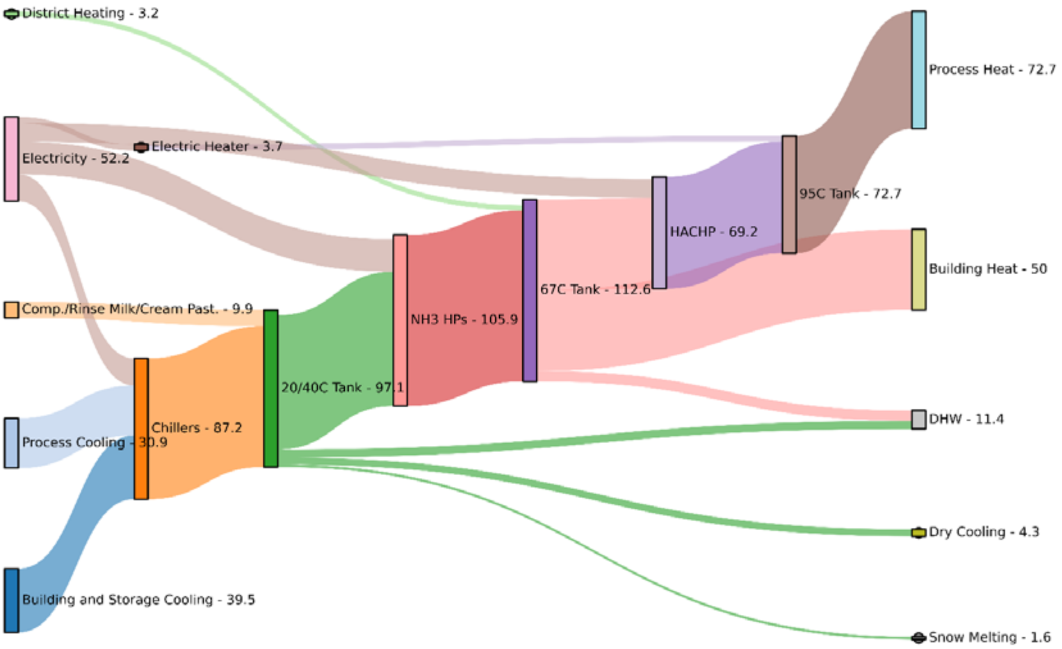


Figure 7: Sankey diagram showing energy flows in the dairy (MWh) for the winter week [12].

In the summer week, most of the heating demands are still covered by heat recovered from the cooling processes. However, the building heating demands are significantly smaller than in the winter, while the building cooling demands are much larger. Consequently, a mismatch arises between the heat supply and demand, leading to a frequent usage of the dry cooler to remove the excess heat. Overall, the system can handle the changing energy demands in the summer by increasing the use of the ammonia chillers and the dry cooler. Thus, the system is also properly designed for summer operation.

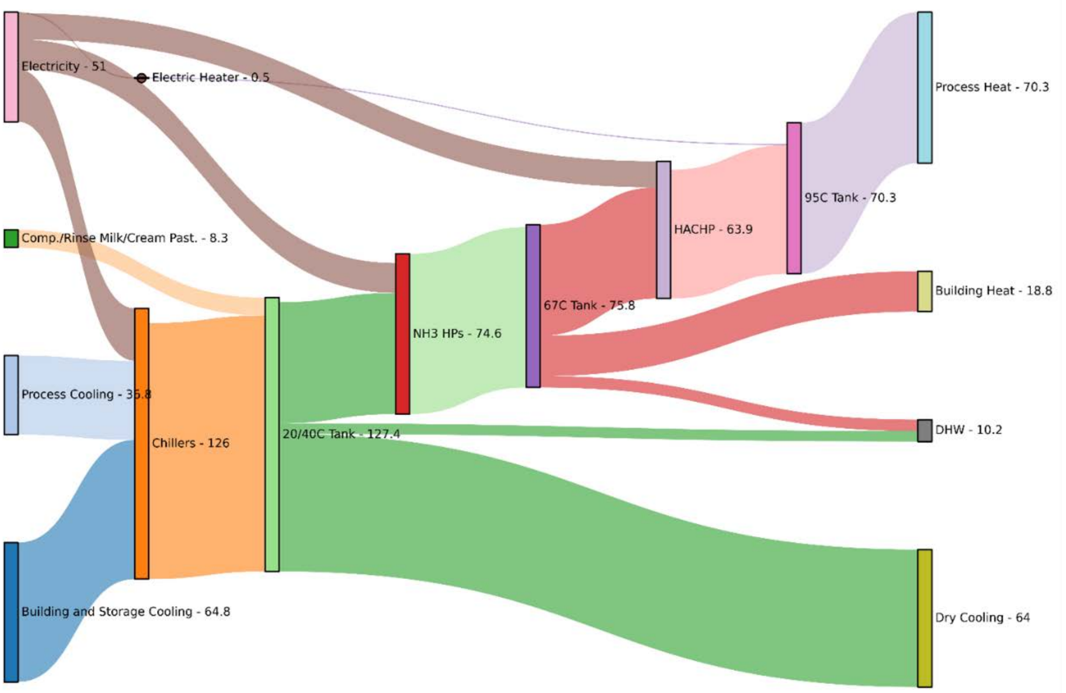


Figure 8: Sankey diagram showing energy flows in the dairy (MWh) for the summer week [13].

All the chiller and heat pump units were found to have high COPs between 4 and 6 during both winter and summer operation. Considering the combined heating and cooling output provided by the heat pumps in relation to the consumed electricity, the overall COP for the dairy process was calculated to be 4.1 for both winter and summer. These results point to a well operating heat pump system, demonstrating the potential for use of heat pumps and thermal energy storage in dairies.

4.2 Tine dairy in Trondheim

Tine also has a dairy in Trondheim, Norway, where they have implemented another innovative pilot heat pump system to deliver cooling and heating for the production processes. This system has been analysed in a conference paper [14]. The dairy in Trondheim has an annual milk production of 75 million litres, and it has similar demands to the Tine Bergen dairy, with a need for simultaneous cooling and heating. The heat pump system utilises heat from the cooling process in order to produce hot water up to 115 °C.

Figure 9 shows the pilot heat pump system installed in the Tine Trondheim dairy. The system consists of four ammonia chillers (total 2,700 kW), a transcritical CO_2 heat pump (160 kW) and a propane-butane cascade high temperature heat pump (HTHP). The ammonia chillers are used to produce ice water at 0.5 °C, which can be stored in a 300 m^3 ice water storage tank. Both the CO_2 heat pump and the HTHP use return water from the ice water production as a heat source, producing hot water for cleaning (75 °C) and for the production process (115 °C), respectively. The propane-butane HTHP has a low temperature cycle with propane and a high temperature cycle with butane. Such a cascade system enables large temperature lifts of more than 100 K, which is needed when using the ice water return as the heat source. Additional heat is supplied using a 3000-kW electric heater, with district heating and an oil-fired boiler as backup.

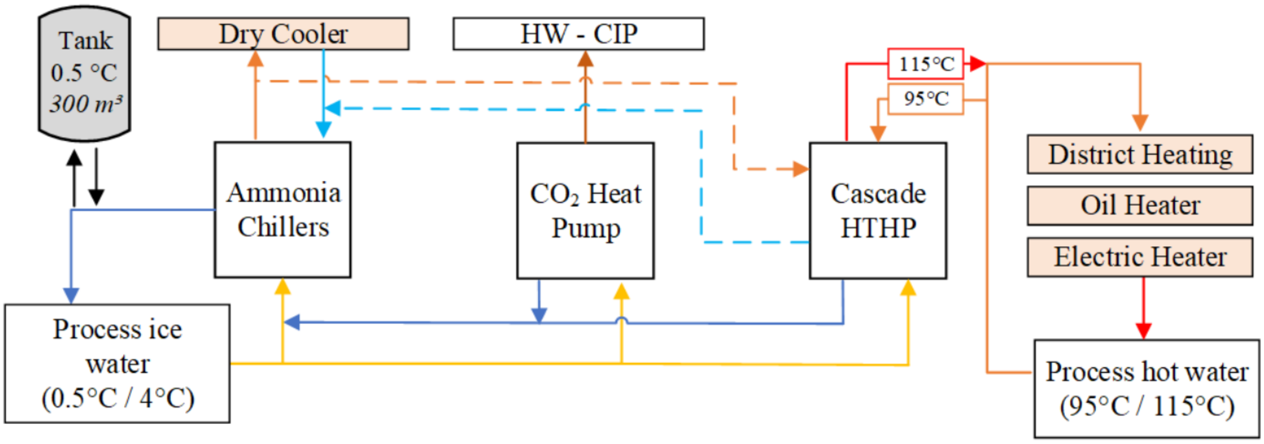


Figure 9: Pilot heat pump system in the Tine Trondheim dairy [14].

The operation of the system was analysed for a summer week in August 2021, focusing on the innovative cascade HTHP and excluding the heating and cooling demands for buildings and storage facilities. During this week, the dairy had a large variation in both the heating and cooling demands, with large peaks during the workweek and low demand during the weekend. It is worth noting that as this is a small pilot heat pump system, the HTHP system covered only a small part of the total process heating and cooling demands. The HTHP had a heat delivery up to 282 kW, while the process heating demand was up to 1565 kW. Similarly, the HTHP delivered cooling up to 134 kW, with a process cooling demand up to 1015 kW.

Taking into account both the delivered heating and cooling, the propane-butane cascade heat pump achieved a combined COP between 2.6 and 4.1, with an average value of 3.4. The heating COP is 1.8-2.9 with an average of 2.5. The temperature lift was between 88 K and 108 K, when using the ice water as the heat source. Considering the large temperature lift required, the propane-butane cascade HTHP achieves high COPs. In the future, an additional connection between the dry cooler circuit and the HTHP is planned, enabling the utilisation of higher temperature waste heat at 10-20 °C. This would lead to a temperature lift in the range of 60-80 K and a heating COP around 3-4. Overall, these results show the potential for full implementation of such a heat pump system to cover a larger part of the dairy's heating and cooling demands.

4.3 District heating for Leangen, Trondheim

Heat pumps can be used in combination with district heating to upgrade low temperature waste heat and utilise it for heating of buildings. Such a case was evaluated for a new neighbourhood planned for Leangen in Trondheim, where waste heat is available from a local ice skating rink [15]. The development of the area is expected to take place between 2022 and 2042, with a final annual heating demand estimated to 12.1 GWh. Between August and April, there is waste heat available from the indoor ice skating rink, at a total of around 3 GWh annually. Ammonia chillers are used to cool the skating rink, with waste heat available at 30 °C. This could potentially be increased to 35 °C by increasing the condensation temperature for the chillers.

The temperature level of the local heating network was evaluated using one low-temperature (LT) case (40 °C) and one medium-temperature (MT) case (70 °C), shown in Figure 10. In the MT case, a centralised ammonia heat pump was used to lift the temperature of the waste heat (WH) to 70 °C. In the LT case, the waste heat could be utilised directly for space heating (SH), while domestic hot water (DHW) was produced using decentralised transcritical CO_2 heat pumps. Any remaining demand is covered by the primary district heating (DH) network.

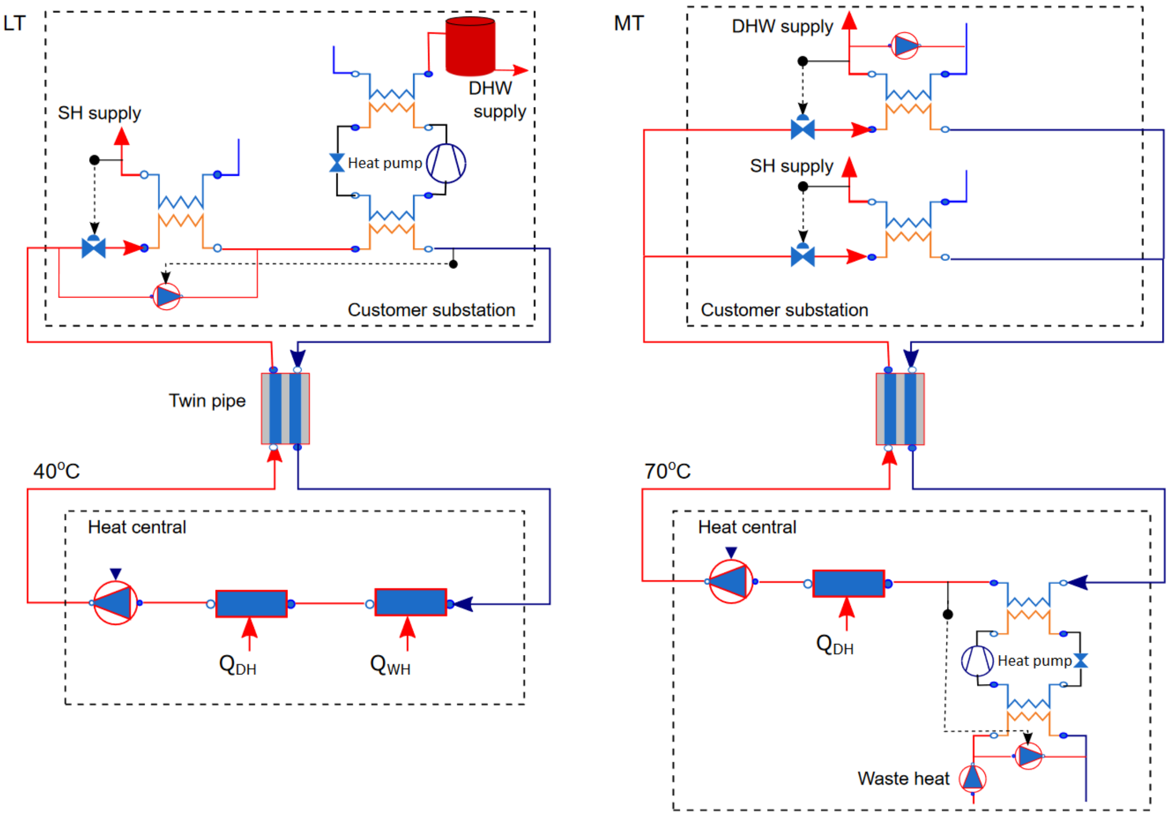


Figure 10: Heating networks for the low-temperature (LT) and medium-temperature (MT) cases [15].

Waste heat data from 2018 were used to analyse the two scenarios, evaluating waste heat temperatures of both 30 and 35 °C. The total waste heat available for this year was 3,078 MWh. The LT case could utilise 25% of the waste heat at a temperature of 30 °C, and 79% at a temperature of 35 °C. The MT case utilised 90% and 92% at WH temperatures of 30 and 35 °C, respectively. Thus, the waste heat temperature had a much larger impact on the waste heat utilisation in the LT case without a centralised heat pump. However, the increased waste heat temperature did lead to a significant decrease in the electricity use for the compressor in the MT case due to the smaller temperature lift needed.

In the MT scenario, the centralised heat pump is used to raise the temperature of the whole network for both space heating and DHW, even though space heating does not require 70 °C. This leads to a peak power demand that is up to 3.2 times higher than for the LT distribution. In the LT case, heat pumps are only used for DHW, which leads to a lower and more even power demand. However, the LT scenario has a much higher peak demand for district heating in the winter, especially at the lowest waste heat temperature.

Overall, the choice of supply temperature level for a local heating network depends on the temperature of the available waste heat, as well as the costs related to district heating and electricity use. If the waste heat temperature is high enough for direct utilisation, it could be beneficial to use a LT network with decentralised heat pumps for DHW production.

5 Conclusions

Integrated energy systems based on heat pumps, thermal energy storage, and smart control systems contribute to the decarbonization needed in all parts of the world due to climate change. In such thermal energy systems, heat pumps are core components that transfer thermal energy from low-temperature areas to high-temperature areas, consuming a small amount of electricity in the process. Heat pumps have become increasingly popular as efficient heating and cooling solutions in various applications.

The working principle of most heat pumps is based on the vapor-compression cycle, where a working fluid or refrigerant is used to transport heat. The process begins with the working fluid in a liquid state entering the evaporator, where heat is absorbed from the heat source, causing the fluid to evaporate. The vaporised fluid then enters the compressor, where it is compressed, raising its temperature and pressure. The high-pressure vapor then flows into the condenser, where heat is released to the heating system or heat sink, causing the fluid to condense back into a liquid state.

The efficiency of a heat pump is described using the Coefficient of Performance (COP), which is the ratio of the heating or cooling delivered to the electricity consumed. For heating applications, heat pumps typically have COPs ranging from 2 to 5, which indicates their energy efficiency.

Various heat sources can be utilized by heat pumps, including ambient air, the ground, seawater, waste heat from industrial processes, sewage, greywater, and exhaust air from ventilation systems. The choice of heat source depends on the specific application and availability of resources. Each heat source has its advantages and considerations.

The selection of working fluids is crucial for heat pump performance and environmental impact. Synthetic working fluids like hydrofluorocarbons (HFCs) have been commonly used, but their high global warming potential has led to their phase-out. Natural working fluids such as hydrocarbons, ammonia, and CO_2 are recommended due to their low environmental impact. These are suitable for different applications and operating conditions, and they can give similar or better performance than HFCs. Additional safety measures are required due to the flammability of hydrocarbons and the toxicity of ammonia.

Thermal energy storage (TES) plays a vital role in optimising heat pump systems. TES allows for the storage of thermal energy, either as sensible heat or through phase change materials. Water tanks are commonly used for short-term storage, while phase change materials like paraffins and salt hydrates offer higher storage capacities. Boreholes can be utilized for long-term thermal energy storage and are often combined with heat pumps for heating and cooling applications.

There are several examples of successful innovative heat pump systems installed in Norway, for example by the Tine dairy cooperative. Tine's dairy in Bergen has an integrated system utilizing a series of heat pumps, including ammonia chillers, ammonia heat pumps, and a hybrid absorption-compression heat pump. Thermal energy storage tanks are employed to balance heat supply and demand. This system effectively covers all heating demands using waste heat from cooling processes, resulting in significantly reduced external energy consumption compared to traditional systems. In Tine's dairy in Trondheim, another innovative pilot heat pump system has been installed, including a propane-butane cascade heat pump for high temperature demand. The system shows good performance and potential for full-scale installation.

Overall, heat pumps and thermal energy storage offer promising solutions for efficient heating and cooling applications, contributing to energy savings and environmental sustainability.

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