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4DHC technology guide

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About HeatNet NWE

This document has been developed as part of the HeatNet NWE project, which is part-funded through the Interreg NWE programme and aims to increase the uptake of 4DHC networks across North-West Europe. As part of this project, the partners are developing the HeatNet Model, which will help the public sector to begin implementing 4DHC networks, and the Transition Roadmaps, which will outline the partners' experience in developing six district heating pilots across North-West Europe. The HeatNet Guide to Financing is also currently being developed and will give a broad overview of the various sources available to finance district heating schemes.

For further information on these reports and on the HeatNet NWE project, please visit www.guidetodistrictheating.eu.

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Executive summary

This technology guide aims to help stakeholders involved in 4th generation district heating and cooling (4DHC) projects to understand the different sustainable technologies for the development of future-proof and efficient 4DHC networks. This guide gives a short overview and explains advantages and disadvantages of different sources and network technologies on both system and component level. It helps readers to understand why and when to select a certain technology and at what conditions.

The guide starts with the basics of 4DHC and includes different technology options such as low temperature waste heat recovery systems, solar thermal systems, heat pumps, geothermal systems, cascading systems, combined heating and cooling systems, distributed systems with prosumers, etc. It also explains the operational aspects of each technology option. Furthermore, the guide shows the different components of a 4DHC network and how they can be designed and integrated efficiently in the network. It helps readers to develop a basic understanding of what a 4DHC network is and how it operates.

This guide also includes information on how to connect a 4DHC network with traditional district heating systems and how to convert existing district heating into a 4DHC network. Furthermore, it summarizes the future of 4DHC networks with the holistic view of an entire energy system and the benefits of integrating 4DHC with other utility networks such as electricity grids, gas grids, etc.

The development of this guide was led by the Building Physics group of Ghent University, with input from various HeatNet partners.

Introduction

The target group of this guide consists of local governments/municipalities and local politicians. Therefore, the aim is not to develop a detailed guide but a simple and easy to understand overview of the different technologies. This section provides the basics of traditional and 4th generation district heating and cooling (4DHC) systems.

What is DHC?

District heating and cooling systems consist of pipe networks between the buildings of a city and one or more centralized heating/cooling plants to supply heat/cold efficiently. They provide the flexibility to improve/change the heat/cold source easily. They allow the use of combined heat and power (CHP) plants, waste-to-energy plants and various other industrial surplus heat/cold as well as several renewable energy sources to supply heat/cold to the grid. Therefore, DHC systems have an important role to play in future energy systems, which can provide sustainable and green energy to the cities [1]. Figure 1 shows the basic layout of a district heating/cooling network.

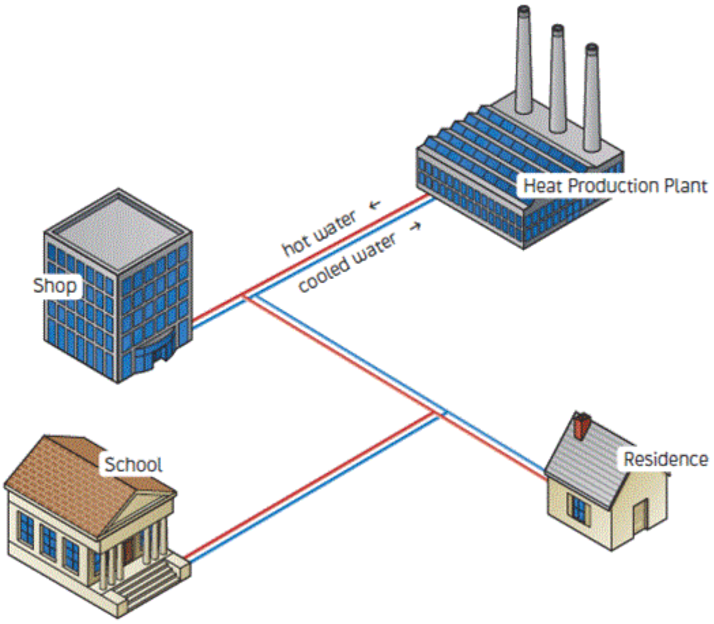


Figure 1: District heating / cooling system [2]

Why 4DHC?

DHC systems are constantly further developed and improved by reducing distribution losses, increasing energy efficiency and by integrating different energy systems and storage solutions. It started with providing steam through pipes in concrete ducts and evolved into pressurized hot water distribution through pipes. The supply and return temperatures of the networks are reduced drastically to improve energy efficiency as we reach 4DHC systems. Most of the actual DH networks are either 2nd or 3rd generation systems. 3rd generation district heating systems have various drawbacks such as high network operating temperatures, high distribution losses, inability to utilize low temperature waste heat and renewable energy sources, one way heat supply, non-integration of heating and cooling networks, etc. and hence need to be further developed to move towards future-proof sustainable energy systems [1]. Unlike the first three generations, the development of 4DHC involves meeting the challenge of more energy efficient buildings as well as being an integrated part of the operation of smart energy systems, i.e. integrated smart electricity, gas and thermal grids. Figure 2 shows the evolution of district heating and cooling (DHC) systems.

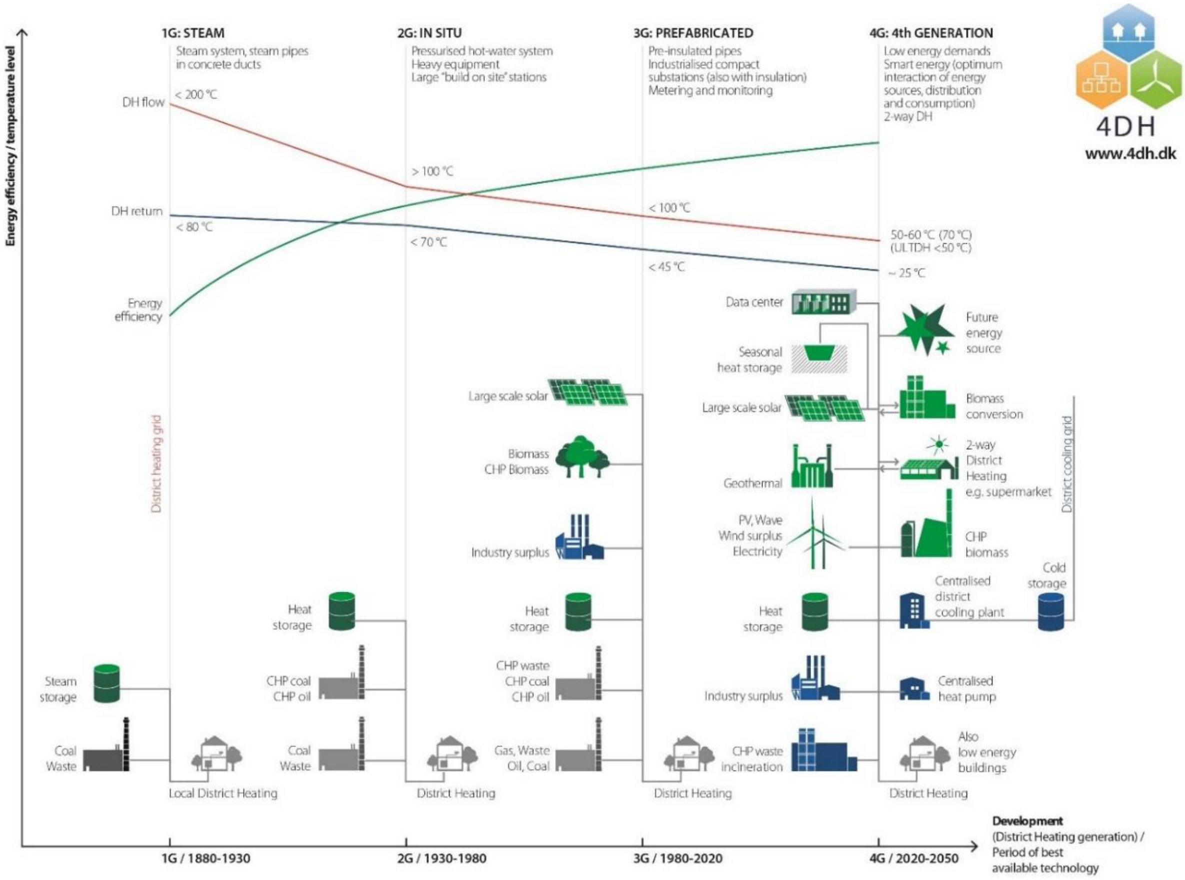


Figure 2: Evolution of district heating and cooling (DHC) systems [1]

About 4DHC

Lund et al., 2014 [1] defined the concept of 4th Generation District Heating (4DH), including the relations to district cooling and the concept of smart energy and smart thermal grids. They aim to decrease grid losses, exploit synergies and thereby increase the efficiency of low-temperature production units in the system. The key aspects of 4DHC system include:

- Ability to supply low-temperature heat for space heating and domestic hot water to both existing and new buildings
- Ability to distribute heat in networks with low grid losses
- Ability to recycle heat from low temperature waste heat and integrate renewable heat sources such as solar and geothermal heat
- Ability to be an integrated energy system (synergy with other grids)
- Ability to ensure sustainable planning, cost and motivational structure in relation to operation as well as to investments

Benefits of 4DHC

The deduction of supply and return temperatures in the distribution networks will bring extra benefits to the heat supply part of the system in addition to the network benefits. These supply part benefits can be higher power-to-heat ratios in steam CHP plants, higher heat recovery from flue gas condensation, higher coefficients of performance in heat pumps, higher utilisation of geothermal and industrial heat sources with low temperatures, higher conversion efficiencies in central solar collector fields and higher capacities in thermal energy storage if it can be charged to a temperature above the ordinary supply temperature [1]. Moreover, the benefits extend to a reduced risk of scalding at water leakages, less thermal expansion of steel pipes leading to less risk of low cycle fatigue, less risk of boiling in the distribution pipes and the possibility to use pipe materials other than steel. Network benefits can be lower distribution heat losses, utilization of low-grade waste heat, integration of renewable energy sources, combination of district heating and cooling and two-way heat supply.

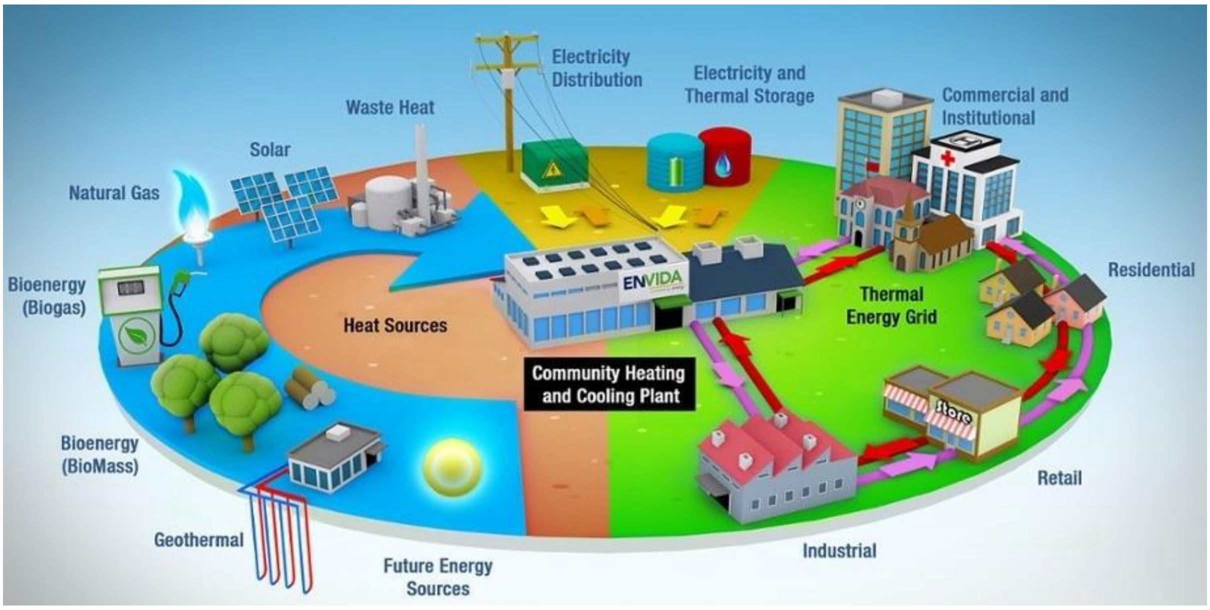


Figure 3: Concept of a 4th generation district heating and cooling (4DHC) system [3]

4DHC Systems: Technology Options

4th generation district heating and cooling (4DHC) generally involves different low-grade heat sources and different network design options. The technology options can be divided in technology options with different sources, different network design and different system combinations.

4DHC systems can utilize low grade waste heat sources such as data centres, heat/cold from rivers and low-grade industrial waste heat. In case of high temperature needs, the heat can be upgraded using a heat pump or electric boilers. It can also be suitable for renewable sources such as solar, geothermal and biomass. These are examples of different technology options by source.

4DHC systems can supply either only heat or a combination of heat and cold within a single network. Also, the system can include users that can feed heat into the network, so-called prosumers. Examples of prosumers are industries with waste heat, houses with rooftop solar thermal panels and anyone supplying extra heat into the network. The network might comprise a sub-network which can operate in a different temperature range than the main network. These are examples of different technology options based on network design.

4DHC systems can comprise different combinations such as systems using low temperature geothermal/solar energy together with a heat pump to provide high temperature heat or using heat from geothermal/solar energy to provide cooling by using absorption machines. These are examples of different technology options based on system combinations. This section provides an insight in the different technologies and includes a case study.

Low temperature waste heat

Low temperature waste heat can range from temperatures as low as 15-20°C and can still be used to provide heating in combination with heat pumps. The following three sources have a high potential to combine with district heating and cooling systems:

- Industrial waste heat
- Data centres
- Sewage water

Industrial waste heat

Industrial waste heat should be effectively utilized to provide sustainable heating, otherwise it is wasted and harmful to the environment. Moreover, the effective utilization of industrial waste heat and the adoption of thermally efficient practices are possible ways to improve industrial energy efficiency. During industrial processes such as drying, heating and combustion, waste heat is available in the forms of vapor, fume, exhaust and waste heat. It is discharged from furnaces, motors, refrigeration systems, boilers etc. without any further utilization. The temperature range of this waste heat varies with industrial processes, from as low as 30°C to more than 1000°C [4].

The low temperature heat source can be a local bakery, small-scale industries, supermarkets, etc. These should be mapped locally to find the potential to supply heat to the DH grid. The mapping of these sources and its types is important to design the potential recovery system. The details of heat mapping can be found in the guide to heat mapping.

Different types of waste heat recovery methods are used based on the temperature of the source and its form of availability. The most common types are:

- Heat pumps

- Organic rankine cycle (ORC) systems (Heat and electricity)
- Heat exchangers
    - Shell and tube type
    - Plate type
    - Non-metallic
- Absorption refrigeration
- Heat pipe systems

Heat pumps are the most preferred, because they transfer low-grade heat into high-grade heat by a compressor. However, the drawback of this technology is that external energy is needed to run the compressor. Organic rankine cycle uses organic substances with low boiling points and high vapour pressures as working fluid. This generates power and it has been shown that organic fluids allow the system to utilize low temperature waste heat. If the temperature of the source allows for this combination, ORC and heat pumps form a very effective combination.

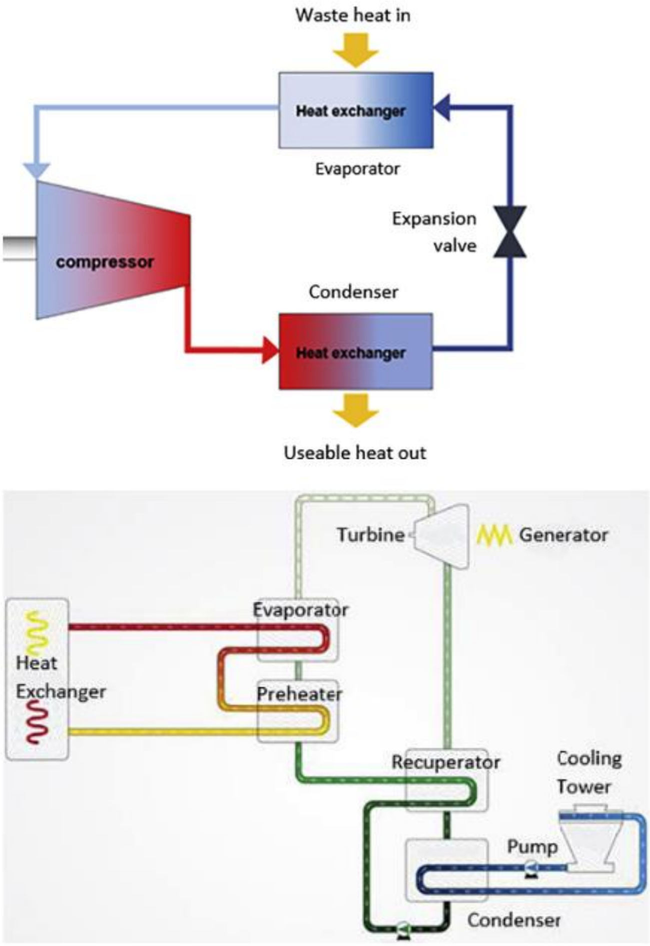


Figure 4: Waste heat recovery method – Heat Pump (left) and ORC system (right) [5]

Heat exchangers are used to transfer heat between two fluids. A solid wall separates the fluids to prevent mixing. Shell and tube exchangers have series of tubes which contain fluid that must be either heated or cooled. Another fluid flows over the tubes that are being heated or cooled, so that they provide heat or absorb the heat required. This type is generally used for high pressure applications. Plate heat exchangers have several thin metal plates that are stacked in parallel and formed into a hollow metallic shell. Each plate consists of different pressed patterns to control the fluid flow and produce turbulence for better heat transfer. The advantage of this type over shell and tube is that the fluids are exposed to a larger surface area per unit volume and hence present a large heat transfer coefficient. Absorption refrigeration is the process that uses a heat source to provide the energy needed to drive the cooling process [5].

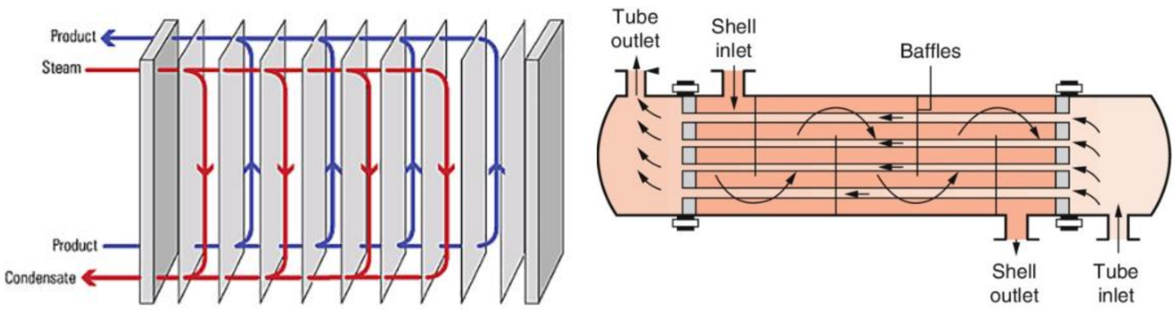


Figure 5: Waste heat recovery through heat exchangers – Plate type (left) and shell and tube type (right) [5]

A heat pipe transfers heat from one place to another with the help of condensation and vaporisation of a working fluid. It consists of a sealed container, a wick structure, and a working fluid [5].

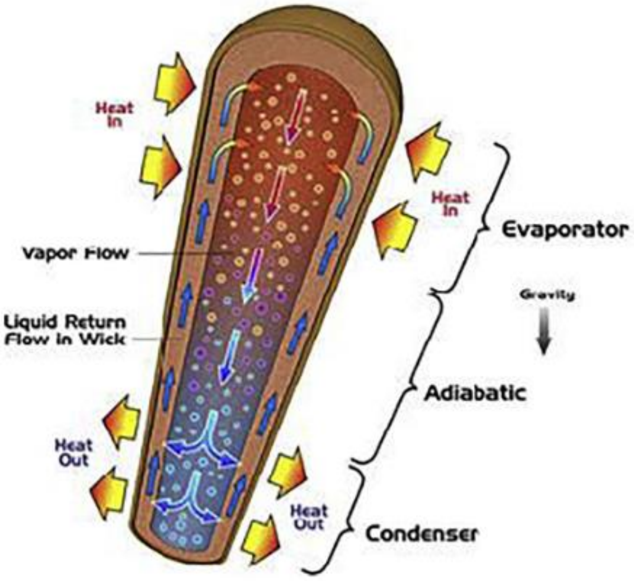
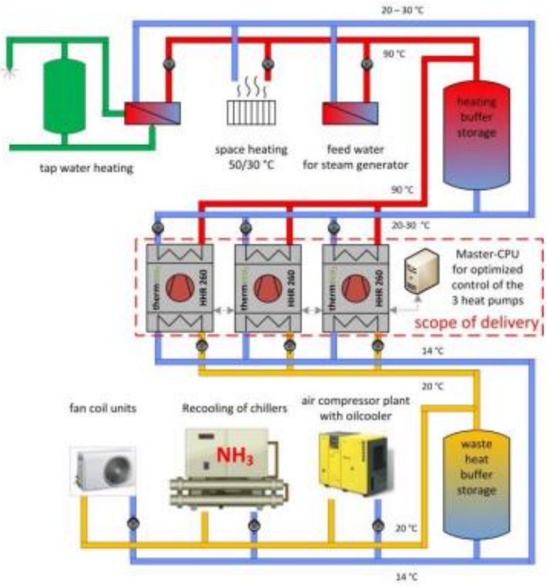


Figure 6: Waste heat recovery through heat pipe [5]

Some projects prove the feasibility of these solutions. A slaughterhouse in Switzerland [6] was fitted with heat pumps to provide heating and domestic hot water (DHW). Low temperature waste heat comes from an existing ammonia refrigeration machine, an oil-cooled air compressor plant and fan-coil units. Waste heat is collected in a waste heat buffer storage. The heat pumps deliver the required 90°C, with a capacity of 800 kW. The warm side of the heat pumps is also connected with a hot water buffer storage. Since the heat pump system needs very low space requirement, the entire system is built in a container system on the roof of the building. This



system results in a CO2 reduction of approximately 30% (510 tonnes of CO2 emissions), and 2,590 MWh from fossil fuels are saved.

Data centres

Data centres represent a futuristic market especially due to increased adoption of cloud usage. This market is expected to grow at a CAGR of 13% during the period 2019 to 2023 [7]. Therefore waste heat from data centres is attractive and can be a potential source for district heating and cooling systems. Data centres are fed with electrical energy, and their operation produces heat that is usually evacuated to the outdoor air. Data centres are typically cooled in one of the following ways:

- Direct free cooling
- Indirect free cooling
- Mechanical cooling

Air cooled data centres provide hot air at a temperature between 25°C to 40°C, while liquid cooling would allow capturing the waste heat at 50-60°C. In liquid cooling systems, the heat can be captured closer to the central processing units (CPUs) and other components, where operating temperatures are higher. Generally, the upper operating temperature limit for processors is 85°C. The higher temperature of the circulating liquid is due to more efficient heat transfer of liquid compared to air. In water-cooled systems, the circulating water temperature can be in some cases close to 60°C while still maintaining the component temperatures below the limits. It is found that water-cooled systems increase the processor performance by 33% compared to air-cooled systems. Waste heat could also be utilized in the chilled supply water, where the temperature level ranges between 10°C and 20°C. If mechanical cooling is used, the hot refrigerant at temperatures between 30°C and 60°C is obtained after cooling the data centre. However, additional electric energy is required in addition to power requirement of IT equipment and hence mechanical cooling should be avoided as much as possible [8].

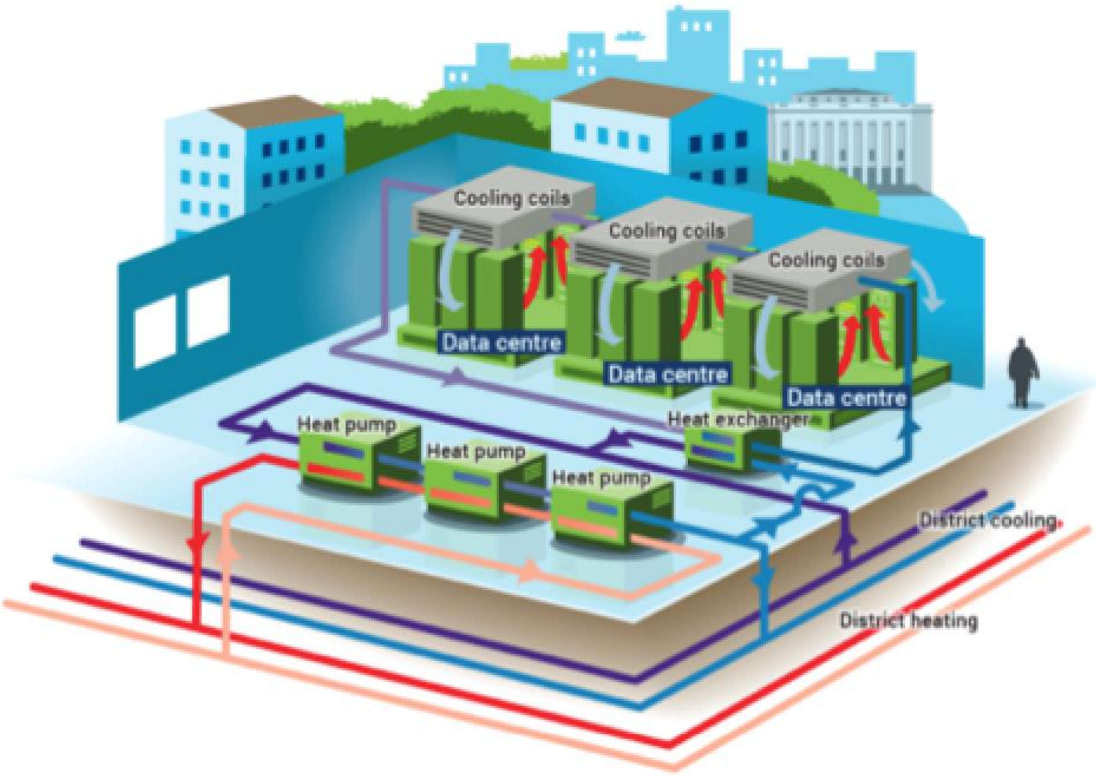


Figure 7: Connection of a data centre combined with heat pumps to district heating and cooling system [9]

A study [8] shows that 97% of the power consumption could be captured as waste heat. It also states that a 1 MW data centre operating at half of its nominal load could fulfil the heat demand for over 30,000 m^2 of non-domestic buildings annually. Another study estimates that a 1 MW data centre running at 30% utilization releases 3,700 MWh of waste heat to the environment. Stenberg [10] simulated a 3 MW data centre in Helsinki, Finland, and results show that utilizing waste heat will result in lifetime savings of millions of euros (with a lifetime of 20 years). The most cost-efficient system would be where a heat pump tops up the waste heat to 75°C and then this heat is sold to the district heating system. The investment costs for a heat pump to boost the temperature up to 75°C are €420,000 higher than in the reference case where the server room is cooled by free cooling and waste heat is not utilized. Moreover, the study suggests that the payback time of the cooling equipment investment would be less than 2 years.

The advantages of utilizing waste heat from a data centre are immense in terms of energy efficiency and environmental sustainability. It is also cost efficient and economically beneficial when coupled with heat pumps. However, there are challenges such as low temperature utilization technology, additional investment costs and producer-consumer problems. Generally, the problem is that it is hard to establish a link between the producer of waste heat (data centre) and the consumers that need thermal energy for heating. Establishing a contract between the producer, the grid owner and the consumer is challenging since the parties have different needs and requirements.

There are many projects with data centres providing thermal energy to heat buildings, swimming pools, etc. The following are some examples of data centres engaged in providing waste heat to district heating [8]:

Data centre operator	Location	IT load capacity	Cooling technology	Amount of waste heat available
Apple	Viborg, Denmark	Unknown (Floor area 166,000 m2)	District heating	Unknown
Bahnhof	Stockholm, Sweden	3 MW (21 MW under construction)	District heating	2.6 MW
CSC	Kajaani, Finland	2.4 MW	Other processes	Unknown
Telia company	Helsinki, Finland	24 MW	District heating	200 GWh/a
Telecity group	Helsinki, Finland	7 MW (2 MW reusing waste heat)	District heating	4500 block apartments + 500 detached houses
Tieto	Espoo, Finland	2 MW	District heating	30 GWh/a
Yandex	Mantsala, Finland	10 MW	District heating	20 GWh/a

Table 1: Data centre projects considering waste heat utilization [8]

With an ever-increasing demand for energy in data centres, district heating allows data centres not only to be cost-efficient but also to be smart and sustainable in fighting climate change.

Sewage water

Waste heat can be recovered on a large scale from sewage water. In Oslo, about 8% of the thermal energy required by district heating is obtained by recovering heat from the sewage system [11]. A similar system was installed near the Olympic village in Vancouver. In Switzerland, heat recovery from wastewater is a common system. For example, in the Bremgarten quarter in Bern about 60% of the heat demand is covered by heat pumps with thermal energy extracted from the treated water [11].

The first technology was built more than 20 years ago. Over 500 wastewater heat pumps are in operation worldwide and thermal ratings range from 10 kW to 20 MW. Studies effectuated in Switzerland and Germany show that 3 percent of all buildings could be supplied with heat (or cold) based on wastewater. The available ideal source temperatures are between 10 and 25°C all year around. Compared with other traditional energy sources for heat pumps (geothermal and ambient air), wastewater from local residential drainage systems has relatively high temperatures in the winter season. Temperatures below 10°C are very rare and therefore provide an excellent basis to combine with heat pumps [12]. Wastewater temperatures at the input of sewage treatment plant are shown in Figure 8.

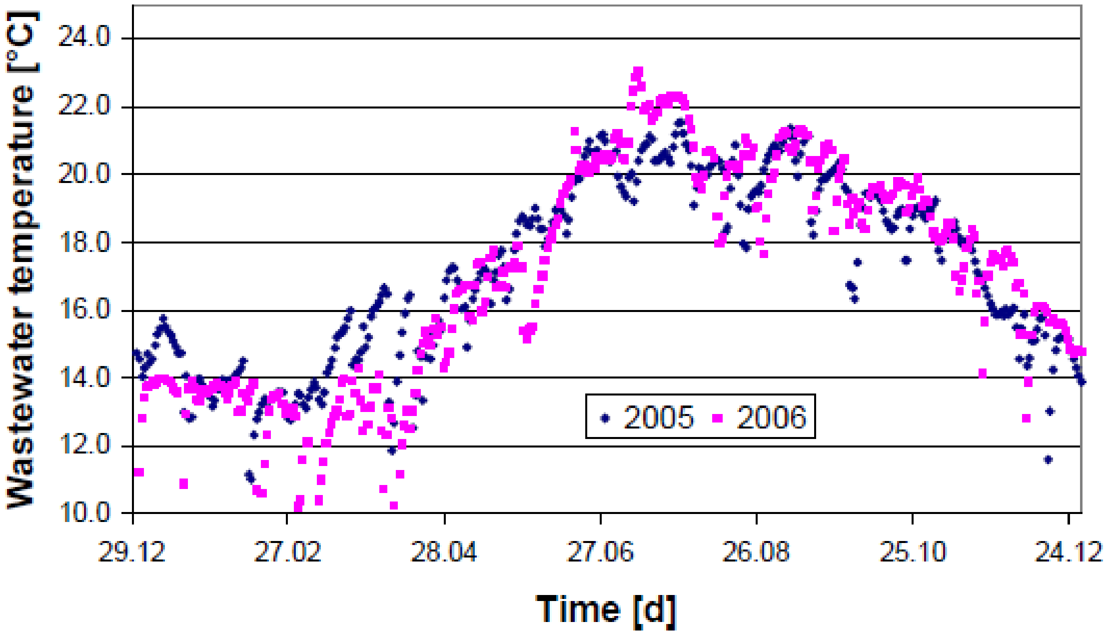


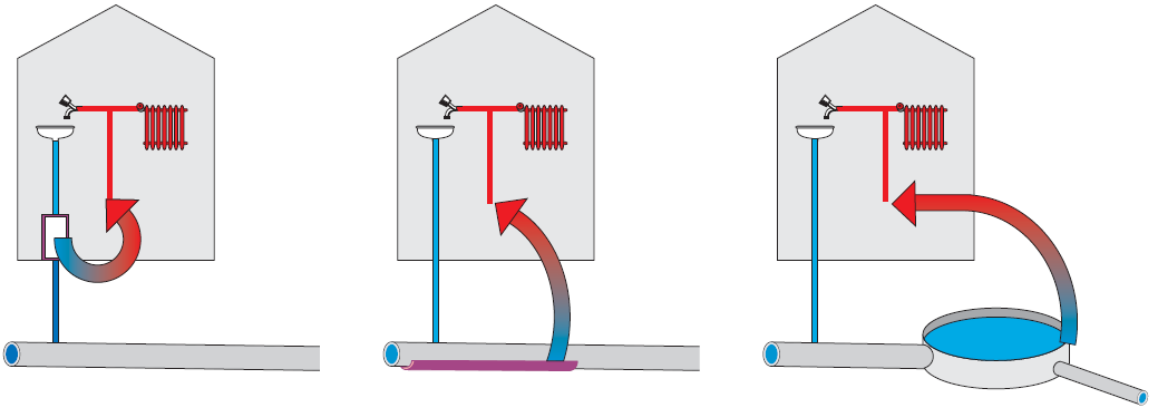
Figure 8: Wastewater temperatures at the input of the sewage treatment plant in Zurich [12]

Wastewater energy recovery can be divided into three categories depending on where the energy is extracted [12]:

- In-house energy recuperation
- Energy recovery from raw wastewater (sewers)
- Energy recovery from cleansed wastewater after sewage treatment plant

The in-house energy recovery method is practised in Switzerland in more than 200 installations: in industry, swimming pools, gymnasiums, hospitals and residential buildings. Tube-bundle heat exchangers are used for the constant quantities of wastewater. For non-constant wastewater flow, storage and filter systems with integrated spiral-tube heat exchangers are employed. Contamination of the heat exchangers is a challenge in this method. Some cases run smoothly, but some are de-commissioned due to problems.

There are some preconditions for the use of energy from raw wastewater directly. Since the efficiency of biological sewage treatment is temperature dependent, getting permission from the approval of operators is sometimes difficult. In Switzerland, the operating temperature in the sewage treatment process is 10°C. So the daily average temperature on the entry to sewage treatment plants should not be less. There are two different ways of energy from sewers: installing a heat exchanger on the sewer bed or an external heat exchanger with an upstream pump and filter installation [12].



Recovery in building
(from raw wastewater)

Recovery in sewer
(from raw wastewater)

Recovery in the wastewater
treatment plant (from cleansed wastewater)

Figure 9: Possibilities for energy recovery from wastewater [12]

The energy potential of cleansed wastewater is much higher than that of raw wastewater. Since the energy is utilized in the downstream of the sewage treatment plant, the wastewater can be cooled down much more than upstream. However, the large potential of this energy cannot be used in many locations since sewage plants are usually located outside the residential areas [12].

The wastewater treatment plant of Bern, Switzerland is designed for approximately 350,000 inhabitants and has a potential heat recovery of more than 30 MW. Currently, 1.4 MW is fed into a district heating system in the neighbouring quarter of Bremgarten. The Bremgarten heat collective sells a total of 5 GWh of heat per year and 60% of heat comes from wastewater. The measured annual COP of the wastewater heat pump system is 3 [12].

The cost of energy production from wastewater heating installations lies in a range of \$0.07 to \$0.22 per kWh [12]. Moreover, the economic viability of a wastewater heat system depends on three decisive factors:

- Traditional energy source price
- System size
- Heat density of its usage

The limitation of this technology lies in the fact that it is a finite source of energy. The available capacity is based on the use of water in buildings and is subjected to change based on behaviour. Therefore, the long-term development of wastewater quantities needs to be carefully analysed before installing any system of this type. Despite these variations/restrictions, the amount of energy available in wastewater is high. In Switzerland alone, approximately 2 TWh of heat used annually for space heating and domestic hot water is provided by wastewater [12].

Solar district heating

Solar district heating plants are large-scale solar thermal plants, which deliver heat through district heating systems. Solar thermal energy, along with district heating, plays an important role in decarbonizing the heat sector in Europe. Solar collectors and a heat transfer fluid transfer the absorbed solar heat to the district heating system. Since solar heat is available only in daytime and during sunshine hours, solar heating systems are usually combined with large storage systems. Moreover, this system needs to have additional backup systems or must be oversized to ensure that the demands are met during night-time/winter with the help of storage. In Europe, currently 200 solar DH plants with a capacity of more than 700 kW are installed [13].

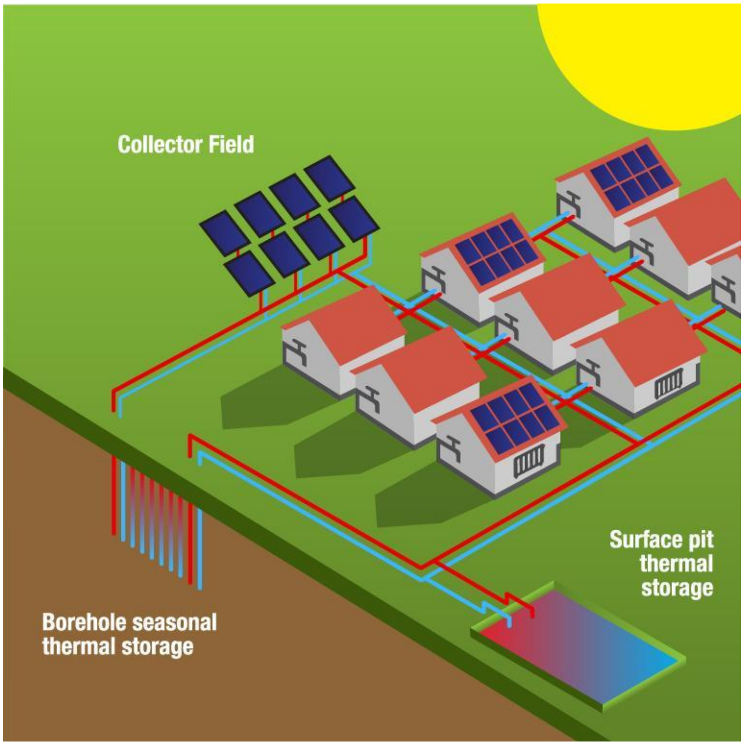


Figure 10: Solar district heating with centralized, decentralized solar collectors and heat storage [14]

Components

- Solar collectors
- District heating system
- Heat storage tanks
- Backup systems

Generally, flat plate solar collectors are used. Concentrated collectors can generate high temperature heat, but are usually used for electricity generation or other high temperature applications. Ground mounted solar collectors are the cheapest solution unless the price for land is very high (> 50 EUR/m^2). Roof mounted solar collectors are interesting solutions on large new buildings or buildings with large flat roof areas. Large scale solar systems can convert 40% to 60% of the available radiation with an annual production yield higher than 400 kWh/m^{2}y. The efficiency might change depending on slope, azimuth, operating temperatures and seasonal variations [13].

Some aspects to consider for the development of solar systems:

- Supply and return temperature of the DH system
- Daily and seasonal heat load profiles
- Interaction with existing sources
- Land availability and cost

Denmark is the pioneer in solar DH systems. Data for solar DH systems in Denmark is available from the Solvarme website. As of October 2016, there is 1 million m2 of total installed surface in 85 solar DH systems. The largest plant in the world has been built at the end of 2016, with 156,000 m2 of collector surface and a nominal peak power of 110 MW [13].

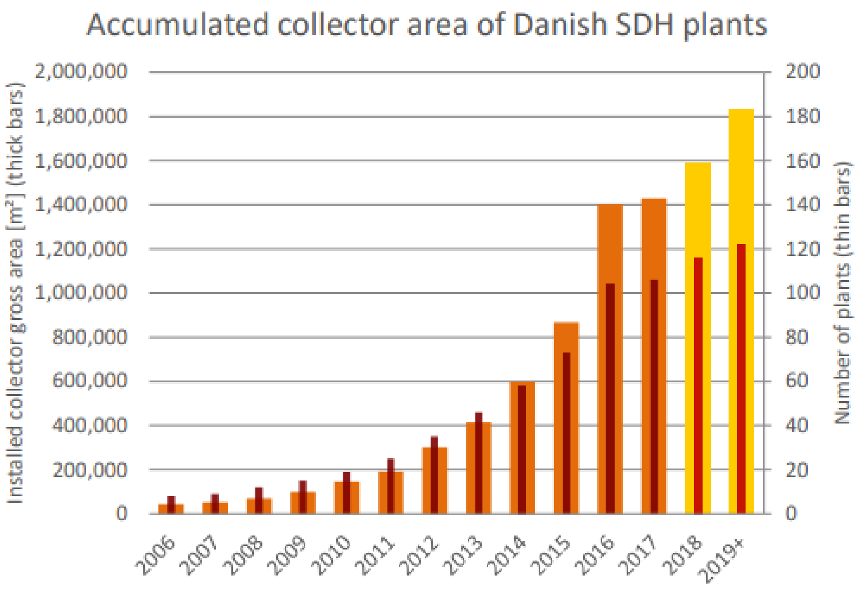


Figure 11: Solar district heating in Denmark [13]

All systems show annual specific productions between 400 and 500 kWh/m^{2}y. Efficiency can decrease due to fouling or glass transparency deterioration over the years. The correlation between the available radiation and the specific heat production appears quite linear. The average monthly efficiency in summer months is between 40% to 50%. The efficiency drops significantly in autumn and in winter months. The reason may be lower outdoor temperatures and a higher share of diffuse radiation. For this reason, huge seasonal storage is required.

In Denmark, large scale DH systems have been installed in several communities; e.g. in Dronninglund, a solar field with an area of 35,000 m2 with 50% solar fraction or in Marstal, a 3300 m^2 of solar collector with 55% solar fraction. A study compared the centralized and distributed solar collectors. In buildings, 6 m^2 of solar collector and 500 L storage is considered in 32 detached houses. The specific investment cost for the distributed system ranges from 1412 EUR/kW to 2119 EUR/kW. For central systems, the cost ranges from 309 EUR/kW to 918 EUR/kW. For the same investment cost, the solar fraction of distributed solar collector is 4% and the centralized solar collector achieves from 10% to 21% with different operating temperatures and costs. Centralized systems seem to favour lower heat production cost. Low distribution temperatures further decrease the cost. In centralized systems, storage size can be easily scaled depending on the collector size. Centralized systems result in a low payback period and seem to have a viable business case.

Advantages

- CO2 free energy source
- Local availability – Reduction of energy import

Disadvantages

- High investment cost
- Large space is needed
- Seasonal storage/backup systems needed to cover 100 percent demand. It is often not beneficial to cover 100 percent of demand with solar.

Case study

Figure 12 illustrates the solar DH system with seasonal storage pit in Gram (Denmark) [15]. The maximum heat load is 10 MW$_{th}$ and the heat production is 20 GWh/y. The district heating network has a length of 21 km.

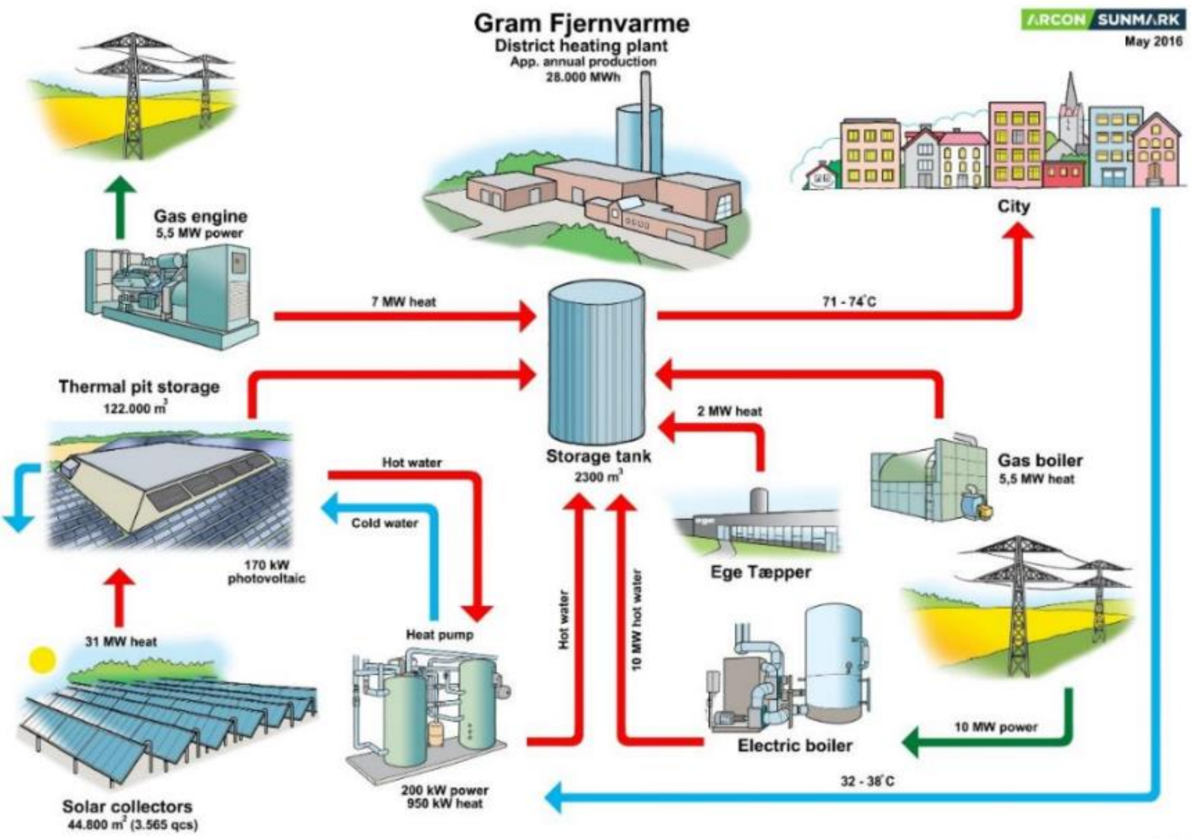


Figure 12: Gram solar district heating with seasonal thermal storage [15]

This system has flexible production and a seasonal storage pit:

- 44,000 m^2 solar thermal panels (62%)
- 10 MW electric boiler (14%)
- 5 MW_e / 6 MW_{th} CHP gas engine (9%)
- 5.5 MW gas boiler (7%)
- 900 kW heat pump (5%)
- 2 MW industrial surplus heat (3%)
- 122,000 m^3 seasonal thermal storage pit (8500 MWh_{th})

The use of seasonal storage pits allows shifting the delivery of solar heat from periods with higher production and lower demand to the heating season. Gram's neighbouring town, Vojens, has the world's largest thermal storage pit with a capacity of 200,000 m^3. These systems have proved to be very efficient to increase flexibility in DH, allowing an increase in solar fraction and integrating electricity from intermittent renewable sources.

Heat pumps

Heat pump technology is generally used to boost the temperature of the fluid. It works by moving heat from a low temperature area to a high temperature area. The heat source can be ambient heat, ground, water source or exhaust/waste heat. The most commonly used heat pumps are compressor and absorption heat pumps. The energy to operate compressor heat pumps can be delivered by an electric motor or a combustion engine.

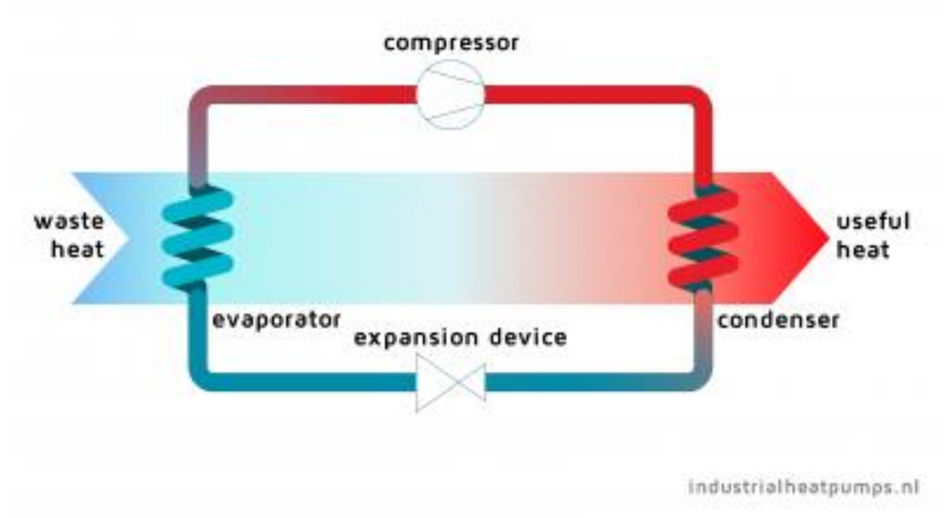


Figure 13: Compressor heat pump [16]

An absorption heat pump is operated by high temperature heat instead of electricity. The drive energy required for absorption heat pumps can come from different energy sources in the form of high temperature heat.

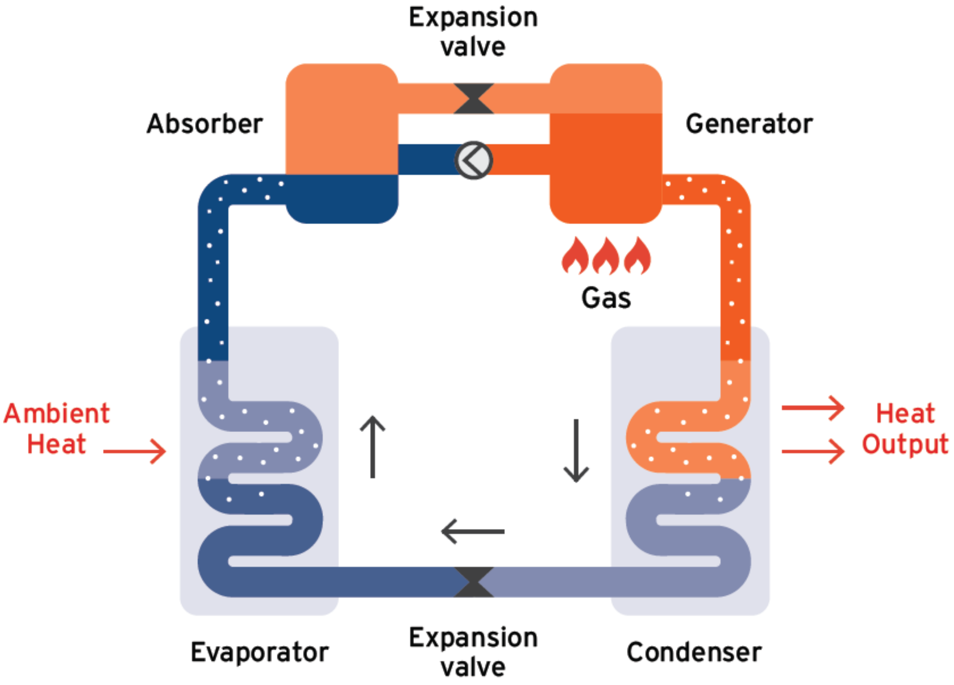


Figure 14: Absorption heat pump [17]

Components

The main components of compressor heat pumps are the compressor, the expansion valve, the evaporator and the condenser. They work following the same principle as a refrigerator. The working fluid circulates through the four main components. In the evaporator, the working fluid evaporates because of heating and then the vapor is compressed to a high pressure and temperature. The hot vapor is condensed and the heat is released in the condenser. The fluid is then expanded in the expansion valve and enters the evaporator for the fresh cycle. Different working fluids are available and can be used based on the specific application. However, CO2 and ammonia are the most commonly used refrigerants for high capacity heat pumps. CO2 based heat pumps can operate with temperatures up to 90°C, an ammonia-based system can operate up to 100°C. However, prices are more or less the same for both system types [18].

Absorption heat pumps use thermal energy instead of mechanical energy. This system uses liquids or salt to absorb vapor. The most commonly used working fluids are

- water and lithium bromide
- ammonia and water

The main difference with compressor heat pumps is that the evaporated ammonia is not compressed to a high pressure in a compressor, but is instead absorbed into water. A low power pump then increases the solution up to a high pressure. As the ammonia now needs to be removed from the water, a heat source boils the ammonia out of the water. These heat pumps can deliver up to 94°C, although in practice, it should not exceed 85 to 87°C. The typical supply temperature is around 80°C. The typical capacity is about 1 – 10 MW [18].

COP

The COP of compressor heat pumps [18] is estimated to be:

- CO_2 refrigerant: 2.8 – 3.5
- Ammonia refrigerant: 3.6 – 4.5

The COP of absorption heat pumps is estimated to be:

- Water and lithium bromide refrigerant: 1.7

Cost

The investment cost of compressor heat pumps is estimated to be [18]:

- CO2 refrigerant: 0.5 – 0.8 M€ per MW heat output
- Ammonia refrigerant: 0.45 – 0.85 M€ per MW heat output

The investment cost of absorption heat pumps is estimated to be [18]:

- Water and lithium bromide refrigerant: 0.35 – 0.5 M€ per MW heat output

Compressor heat pumps can deliver high efficiency, but the investment cost is higher per produced heat. Absorption heat pumps need lower investment cost per produced heat but will deliver low efficiency.

Advantages

- Low running costs
- Less maintenance
- Safer than combustion-based systems
- Reduced CO_2 emissions
- Provide cooling during summer
- Long life span

Disadvantages

- High upfront costs
- External energy is required
- Cold weather can damage the system

Case study

The case study [19] describes the Drammen district heating system with deep sea water as a source. The municipality of Drammen, in the capital area of Norway, has over 63,000 inhabitants. The Drammen system takes advantage of the low prices for electricity in Norway and is operational since 2010. Three heat pump units use the 8°C deep sea water to deliver heat at a temperature of 90°C. The plant has a COP of over 3. Ammonia is used as a refrigerant, which outperforms other synthetic refrigerants and eliminates the global warming potential as well. The heat pumps provide 85% of the district heating demand, the rest is being covered by oil boilers. This plant reduces 15,000 t/a of CO2 emissions and saves up to 6.7 million litres of fuel per year.

Technical details of the application

Heating capacity: 13.2 MW

COP: 3,05

Refrigerant: R717

Heating source: River water in at 8°C, out at 4°C

Supplied temperature: 90°C flow, return at 60°C (Hot water)

Figure 15: Heat pumps in Drammen district heating [19]

Geothermal district heating

Geothermal district heating is defined as the use of one or more production fields as sources of heat to provide thermal energy to a group of buildings. Using geothermal technology, heat from the underground can be extracted and utilized through a heat exchanger. Depending on the obtained temperature, it can be used directly or can be coupled with heat pumps. A typical system for geothermal district heating consists of:

- Heat production – well fields
    - Production well
    - Reinjection well
    - Peaking station
- Transmission/distribution system
- Central pumping station, and in-building equipment
    - Heat exchangers
    - Circulation pumps
- Heat pumps (optional)

The hot water/brine is obtained through the production well, the heat can be extracted using a heat exchanger. The cooled water/brine is fed back into the injection well. Systems can vary from small (0.5 to 2 MWth) to large capacities (up to 50 MWth). Some modern district heating systems utilize shallow geothermal resources assisted by large heat pumps. Many geothermal district heating systems are based on areas of hot sedimentary basins, and on the doublet concept of heat extraction. Modern doublet designs include two wells drilled in deviation from a single drilling pad. Hole spacing is designed to secure a minimum of 20-year life span before the production well cools down. Common depths for geothermal wells are between 2,000 m and 3,500 m. Geothermal district cooling is poorly developed in Europe with merely 30 MWth installed capacity [20].

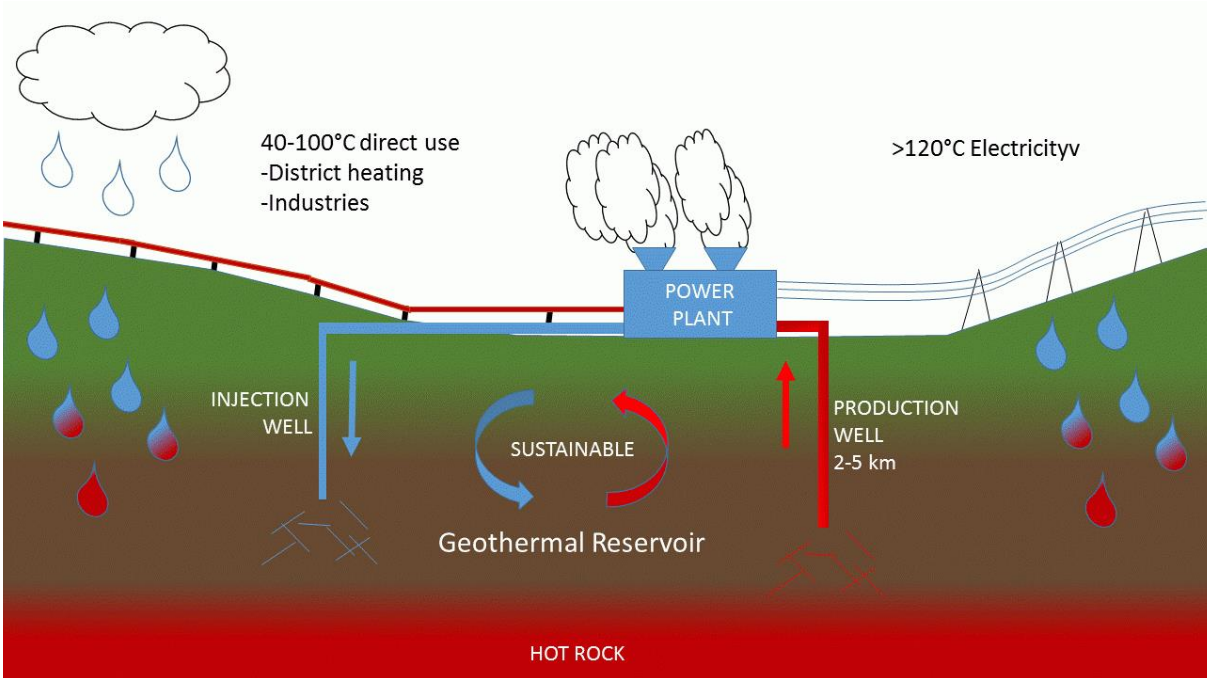


Figure 16: Schematic of a geothermal system [21]

Cost

The specific investment cost for this system can be estimated around 1.6 M€/MW [18].

Advantages

- Efficient system
- Free energy source with reduced CO2 emissions

Disadvantages

- High investment cost
- Pollutants in the geothermal water
- Limitation of energy source availability
- Risk of earthquake

Case study

The case study [15] describes the smart DHC system in Paris-Saclay. It has a heating capacity of 37 MW and cooling capacity of 10 MW. The heat and cold production are 40 and 10 GWh/y respectively. It has a network of 10 km. This system has two geothermal drills at 700 m depth with a temperature of 30°C. It also has 7 semi-centralized heat pump stations and natural gas boilers. The DHC system is composed of 4 different sub-systems:

- One geothermal network
- One medium temperature network: 30°C - 15°C feeding the heat pumps

- 7 hot water networks 63 - 45°C (from heat pump stations to buildings)
- 7 cold water networks 6 - 12°C (from heat pump stations to buildings)

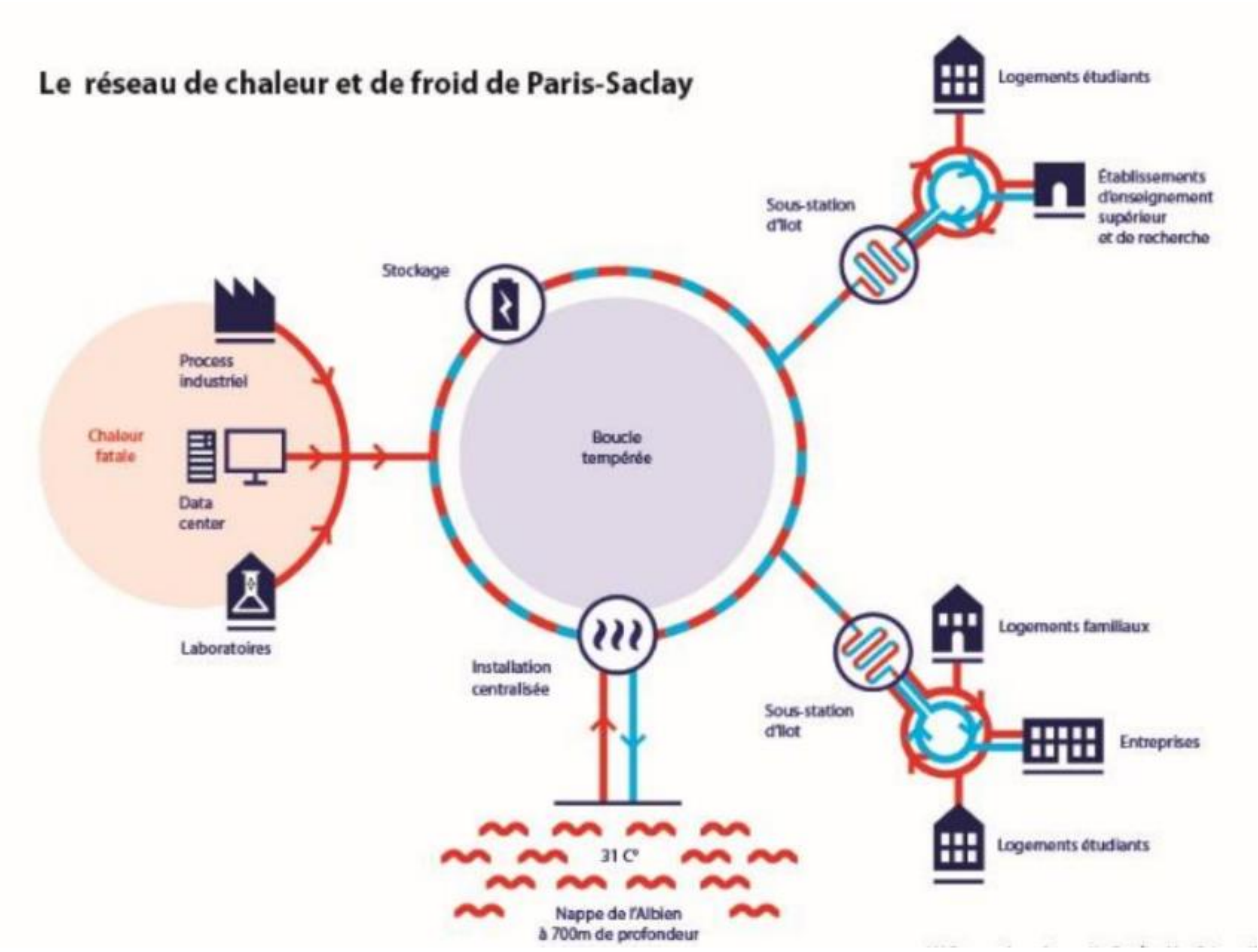


Figure 17: Smart district heating and cooling grid with geothermal wells and heat pumps [15]

District cooling networks

District cooling systems work the same as district heating systems, but chilled water is distributed instead of hot water. District cooling is normally used for space cooling in buildings. Alternatively, individual cooling devices could be used. They are normally purchased at low cost but have high operating costs due to their low energy efficiency. On the other hand, district cooling has a high investment cost but low operating cost. Therefore, at a particular volume of cold demand, the overall cost of district cooling will become cheaper than individual cooling.

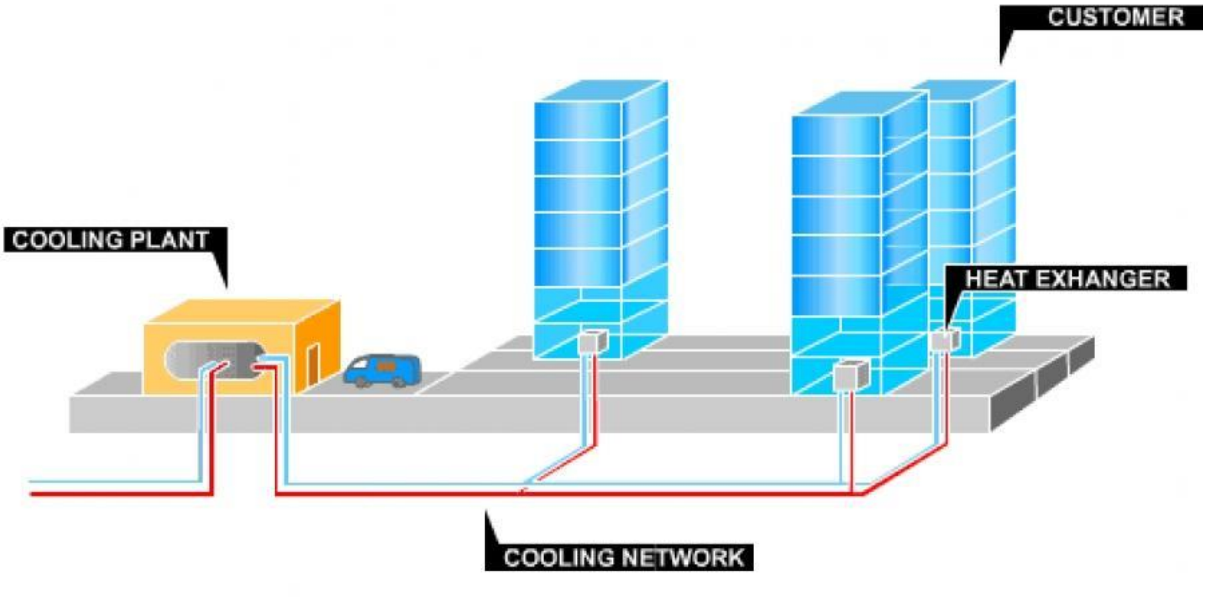


Figure 18: District cooling network with cooling plant, heat exchanger and customer [22]

Cold sources

Cold sources can be sea water, lake water, river water, ground source water or the ambient air. If source temperature is not sufficient to cover district cooling, it is combined with vapor compression or absorption chillers. These chillers can generate additional cooling during the warmer months.

- Free cooling – sea water, lake water etc.
- Waste cold – LNG terminal etc.
- Vapor compression / absorption / electrical chillers
- Cooling tower – evaporative cooling with air
- Heat pumps – ground / air / water source

Components

- Absorption cooling machines
- Heat pumps

To increase the efficiency and reliability, the cooling sources are often combined with various kind of storage solutions such as:

- Seasonal storage
- Night-to-day storage

Seasonal storage allows storing of free cooling in winter to be used during the summer period. The night-to-day facility is used for storage during night-time to use cold during the daytime. Compared with a traditional air conditioning system, district cooling network:

- consumes 35% less electricity
- emits 50% less CO2
- is 50% more energy efficient
- consumes 65% less water

Advantages

- Annual maintenance costs are much lower than with conventional air conditioning systems
- Lifetime can be twice compared to air chilled systems
- Same system can be reversed for space heating in winter
- No external energy required

Disadvantages

- High capital cost compared to chillers

Case study

This case study describes the district cooling network in Milan, Italy [23]. It is based around the Tecnocity CHP in the Bicocca area of Milan. The district cooling network uses absorption chillers and electric chillers with a total power of 17.5 MW. Typically, residential buildings in Milan do not have centralised cooling systems, limiting the possibility to expand. However, big tertiary buildings with centralised cooling can be targeted.

Cascading networks

The return line of a high temperature network can be used as supply side for a low temperature secondary network. This type of network design is called cascading network. Many renewable sources can be combined to provide sustainable heating. Figure 19 shows a cascading network with solar thermal system, heat pump, CHP and storage. The heat pump and solar thermal system preheat the return water from 30°C to 80°C. Then, the CHP boosts the water temperature from 80°C to 120°C. It is then combined with the industrial waste heat to provide old buildings with 90°C. The return temperature of 50°C is used to heat buildings with low temperature demand. The return line of 30°C is fed back to the cycle for preheating.

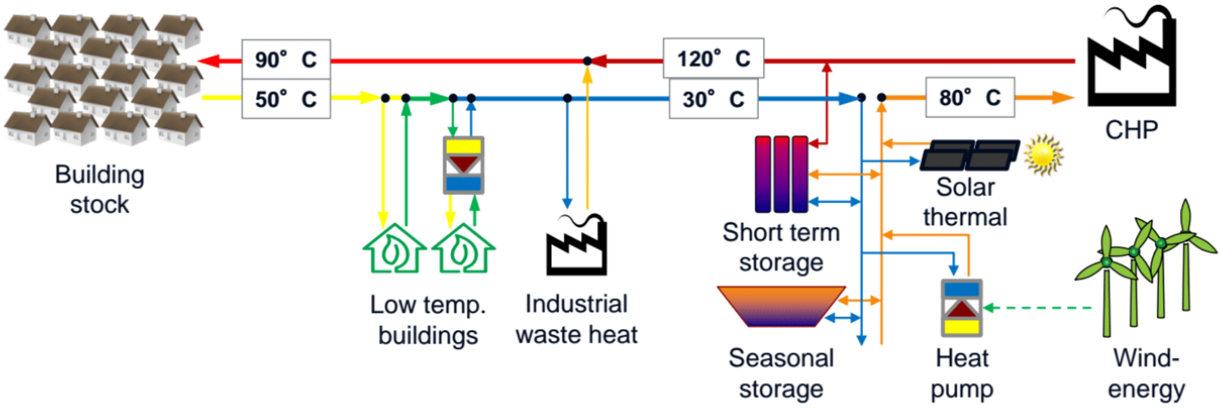


Figure 19: Cascading network (Online source)

Different options are possible to connect buildings, building clusters or neighbourhoods with each other in a heat cascade. Using the return of high temperature clusters as a supply for low temperature clusters can be done either indirectly through the return line of the network or directly through an interconnection of the buildings. Figure 20 presents the options for a direct or indirect cascading connection of a high and low temperature cluster. Some of these options have been realized, some cases are actually being researched. Standard heating systems are often implemented regardless of the building type and year of construction due to investment costs. Consequently, the temperature level required is often similar in different building types and ages. Hence, it is not possible to interconnect buildings without any action. Different measures like thermal retrofitting, radiators exchange and hydraulic balance is implemented to reduce the temperature levels [24].

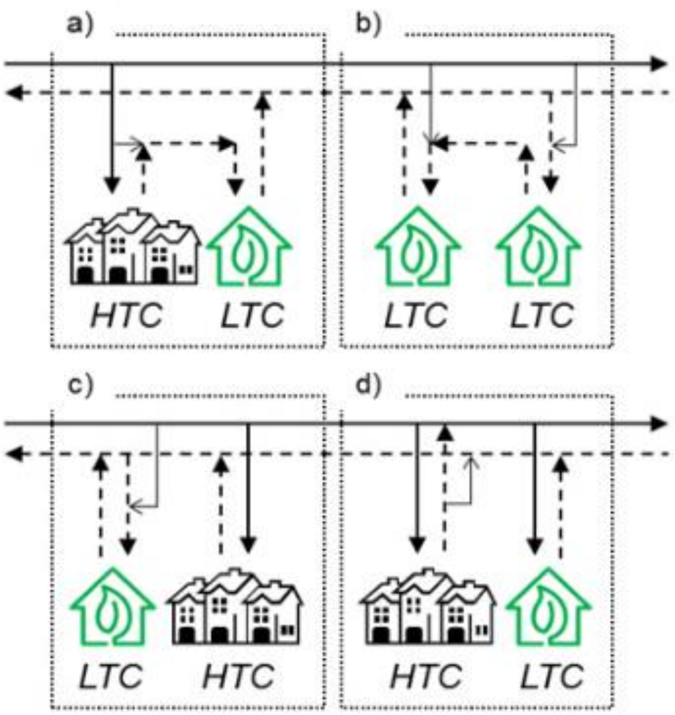


Figure 20: Options for direct or indirect connection of high and low temperature customers, a) direct use of HT-return b) double cascade: indirect use of HT-consumer c) indirect use of HT return via return line d) indirect use via the supply line of the network [24]

Advantages

- High utilization of low temperature return line
- High energy efficiency
- High energy output

Disadvantages

- Complicated design and complex planning required
- High investment cost
- It is not easy to find HT and LT buildings nearby

Case study

This case study describes a district heating network [24] in the city of Vienna. The meshed ring network is divided into a primary network to which all supply units are connected, and in numerous secondary networks. The primary network has a pipeline length of about 560 km. The flow temperature is controlled between 95°C and 160°C, according to the outside temperature. The secondary networks (around 630 km) are supplied by the primary network and operated between 63°C and 95°C. Five apartment blocks of the secondary network are connected via a transformer station.

Cold district heating networks

Cold district heating (CDH) networks [11] aim to combine the advantages of a centralized energy distribution system with low heat losses in energy supply. This is achieved by providing very low temperature water (10-25°C) through the centralized supply, which is then heated up by decentralized heat pumps. This is also suitable for district cooling since the cold water is circulated through the pipes. Advantages of this system are the possibility to use low cost pipe materials and a significant reduction of insulation thickness. This type is sometimes referred to as 5G district heating systems.

The temperature of a hot pipe has a range between 12°C and 20°C, while the cold pipe has 8°C to 16°C. If there is a demand, the circulation pump of the building extracts water from the hot pipe, uses it in a heat pump to reach the temperature suitable to provide heating and then discharges the cooled water to the cold line. If there is a cooling demand, the reverse occurs. The system requires a complex regulation of both the energy supply network and user substations. It also requires two pipes but can provide both heating and cooling.

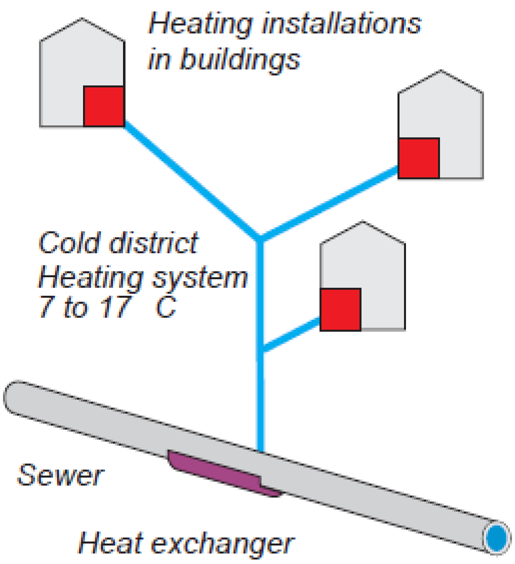


Figure 21: Cold district heating system [12]

A traditional 60°C district heating system requires 11% more primary energy than CDH networks, while a 90°C plant requires 112% more primary energy. The estimated thermal losses of the CDH plant in Hamburg are 2%, while the estimated thermal losses are 19% and 25% respectively if the same amount of energy is delivered through the district heating network at 60 or 90°C. Depending on the temperature, insulation can be avoided. The design is often based on a recommended value for specific pressure loss in the main lines. The pipe diameter is determined by the flow rate required to match total peak power. In CDH, a different temperature drop is possible depending on the cold-water source. The flow rate is also influenced by the COP of the heat pumps. COP varies with the cold water source and user temperature requirements. Compared to a traditional district heating network of 20-degree temperature drop and 15% heat loss, CDH requires a higher flow rate when the allowable temperature drop in the cold ring is under 10°C. It should also be considered that the CDH can supply both heat and cold. CDH requires an additional heat exchanger for cold water production, with a substation containing heat pumps, storage tanks and back-up systems. The substations require a larger spaced compared to traditional district heating systems. Therefore it is difficult to install CDH for existing buildings [11].

Traditional district heating systems are not suitable for integration with cold district heating networks, since their high temperature operation makes it difficult to connect with renewables. Moreover, the energy flux is mono directional, from the central plant to the users, and cannot be reversed. CDH systems are the way to utilize renewables and create synergy with other grids, which makes it a smart system. In CDH, the heat source can be integrated locally from different potential sources. It is also possible to integrate domestic hot water production with solar thermal or hybrid PV-T panels which can provide both electric and thermal power [11].

CDH networks also provide users the possibility of returning heat and/or cold to the district heating ring. This enables bidirectional exchange, requiring (high cost) smart meters and efficient control to manage prosumers. CDH can provide a smart system by connecting with thermal and electric via heat pumps and storage. In the future, even methane boilers could be added to the system [11].

Existing cold district heating networks *[11]*

Switzerland: The Furka railway tunnel has a drained water outflow of 5400 L/min at about 16°C, which is piped to the nearby village of Oberwald. The thermal energy extracted from this drained water, using individual heat pumps, supplies heat to 177 apartments and a sports centre, with an installed capacity of 960 kWth.

Germany: Within the national funded project EnVisaGe, the heat demand of the small district of Wüstenrot (6800 inhabitants) is covered with a cold water grid using low temperature heat from the ground surface geothermal system with decentralized heat pumps. The system includes heat storage as well.

In the town of Aurich (40,000 inhabitants), 1200 cubic meters of wastewater in the range of 25-35 °C are generated each day during the local dairy production process. A 2 km long cold ring circulates this wastewater. The users with heat pumps were tapping this heat, almost 80% of the total heating energy peak demand, cooling down the water by about 10°C.

In Troisdorf, a 5 km pipeline with individual heat pumps supplies heat to 100 houses. In Hamburg, 700 housing units a heated with a temperature level of 10 °C.

Italy: In the town of Berlingo, a geothermal source with 11-15 °C is sent to the heat pumps to produce hot and cold water simultaneously. Based on a pilot plant, a similar plant is being constructed in the town of Sale Marasino with 300 kW_{th} capacity. The heat source is a nearby lake.

Netherlands: The city of The Hague developed a district heating concept with sea water as a source, combined with heat pumps and a heat exchanger. In summer, sea water temperature reaches 11°C and only the heat exchanger is used. In winter, when the sea water temperature drops below 4°C, an ammonia heat pump is used to heat it up to 10°C and feed the water in the district heating network ring. It is then further heated up by individual heat pumps in the building side.

Combined district heating and cooling systems

Combined district heating and cooling systems provide heating and cooling together. These can be achieved with the following options:

- 2 pipe systems
- 3 pipe systems
- 4 pipe systems

2 pipe systems require heat pumps at the building side to provide heating and cooling together. Cold district heating is an example of 2 pipe district heating and cooling systems. A 3-pipe system has one hot supply pipe,

one cold supply pipe and a common return line for both the hot and cold supply line. A 4-pipe system contains a separate supply and return line for both heating and cooling.

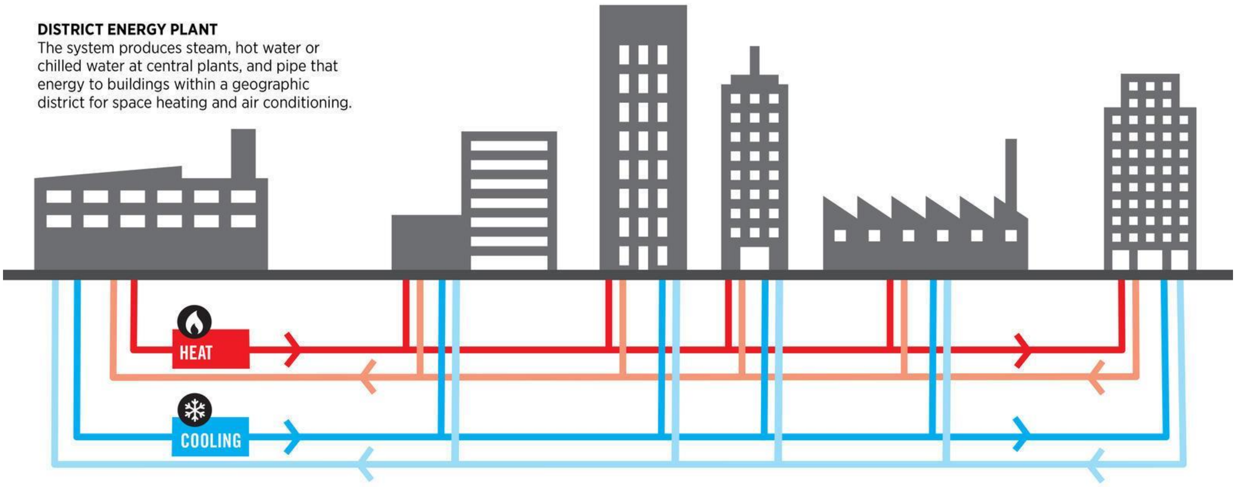


Figure 22: Combined district heating and cooling with 4 pipe system [25]

Combi-systems

This system type provides different possible combinations of technologies. The most commonly used technology with low temperature sources is heat pumps. These can be combined with any low temperature source to boost temperatures. Some of the possible combinations are:

- Industrial waste with heat pumps
- Solar thermal collector with heat pumps
- Geothermal system with heat pumps
- Solar collectors, heat pumps and CHP
- Solar collector, geothermal systems and heat pumps
- Solar / geothermal systems with absorption chiller to provide cooling

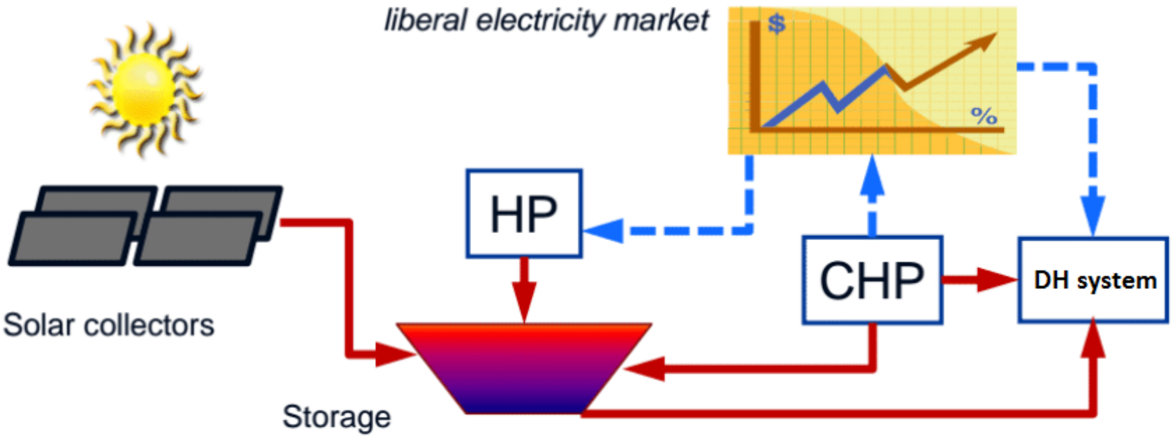


Figure 23: Example of a combi-systems with CHP, solar collectors and heat pumps (Online source)

Technology used: HeatNet pilots

This section provides an overview of the different technologies used by the six HeatNet pilots. It also provides the details of network temperature levels and storage.

Aberdeen pilot

The Aberdeen pilot uses gas boilers as a heat source, with a capacity of 800 kW and a maximum network temperature of 90°C. Single type steel pipes are used in the network, designed to withstand 10 bar pressure. The designed supply and return temperatures of the network are 70°C and 40°C respectively.

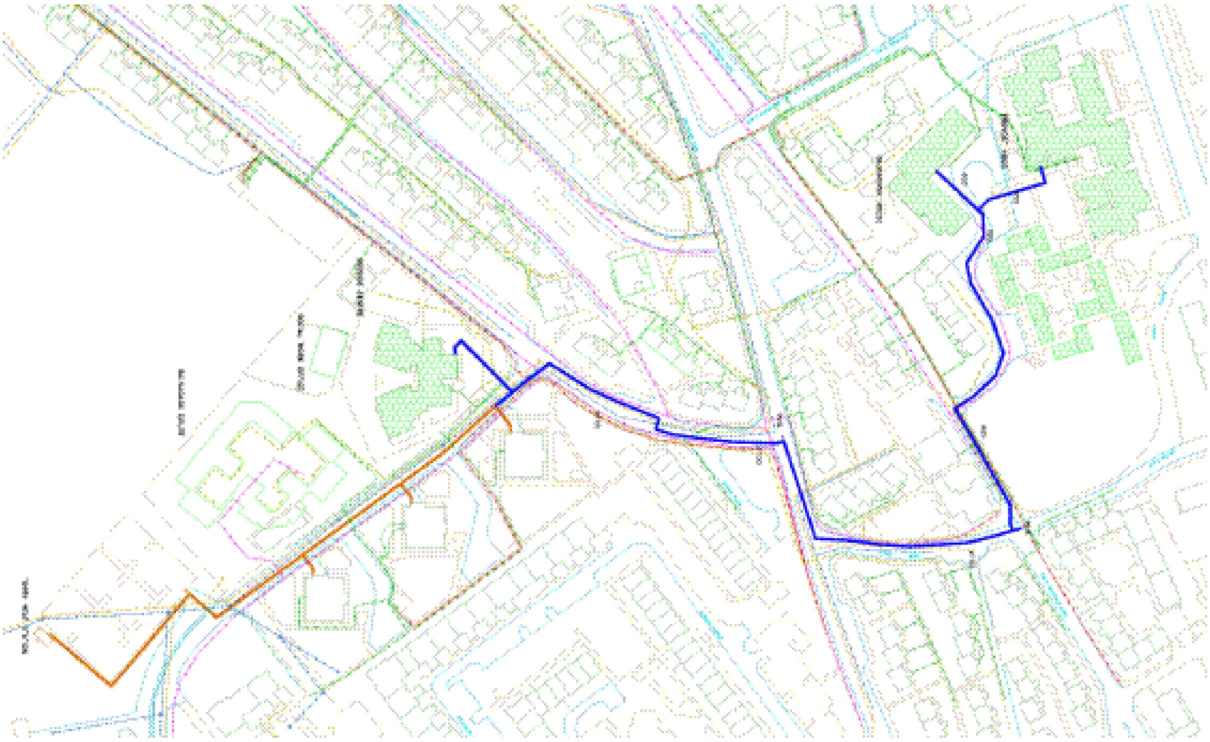


Figure 24: Schematic of the distribution network of the Aberdeen pilot

Boulogne-sur-Mer pilot

Five heat sources are used to provide heat in the Boulogne-sur-Mer pilot:

- Gas – 22 MW
- Waste incineration – 1.2 MW
- Heat pump – 3 x 750 kW
- Biomass – 3.5 MW
- CHP – 1 MW

Twin steel pipes are used to distribute the heat in the network, designed to withstand a 16 bar network pressure. The designed supply and return temperatures are 85°C and 65°C respectively. An instantaneous substation is used with a data monitoring system.

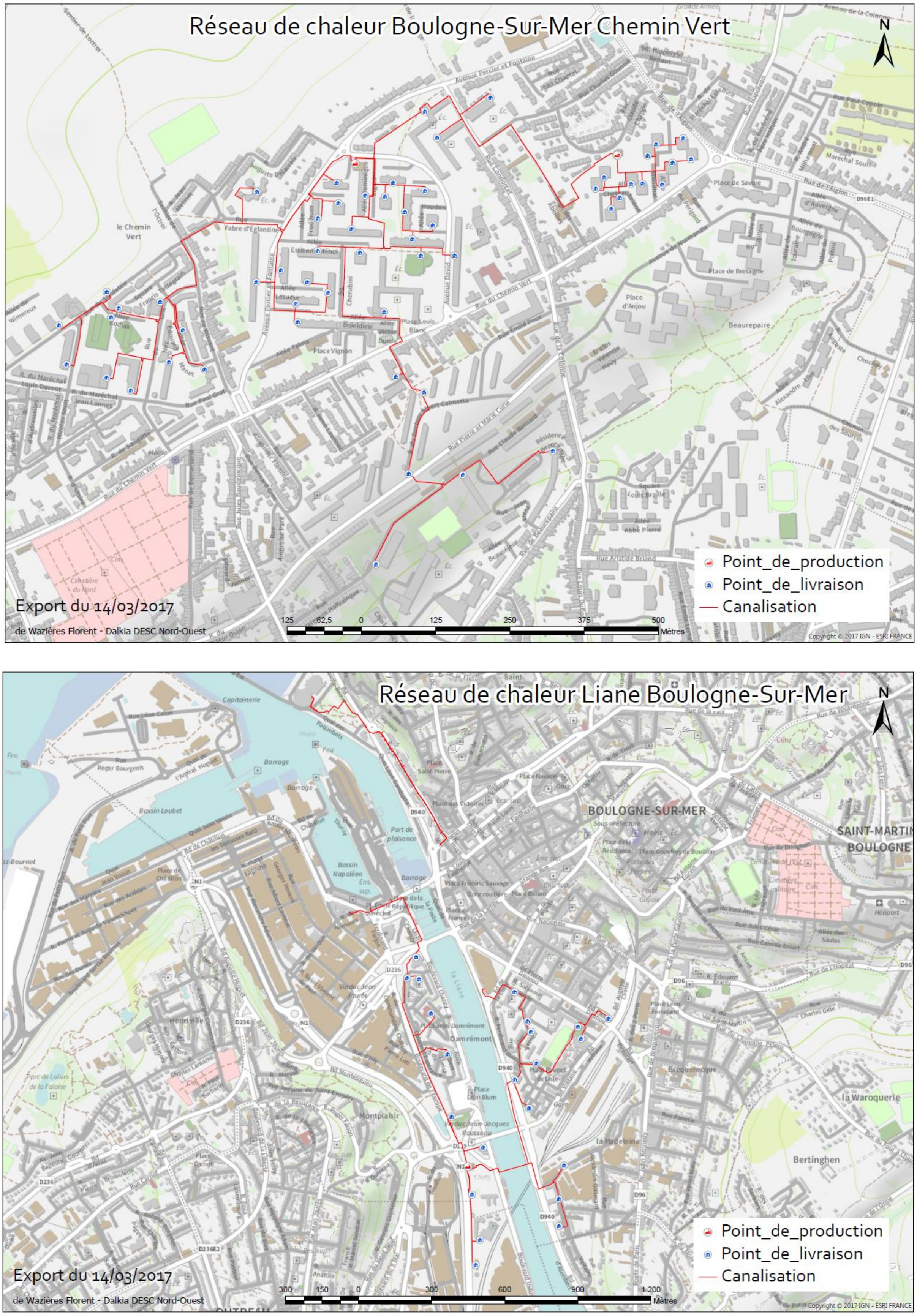


Figure 25: Schematic of a DHC network in the Boulogne-sur-Mer pilot

Kortrijk pilot

In the Kortrijk pilot a gas CHP with a capacity of 600 kW is currently used as a source. Future possible sources are a waste incineration plant, a data centre, heat pump and biomass CHP. A flexible single pipe is used in the distribution network, with supply and return temperatures of 55°C and 35°C respectively. The pilot has a hot water tank storage with a capacity of 2 cubic meter at 50°C. An instantaneous substation is used, with an average capacity between 100 kW and 250 kW.

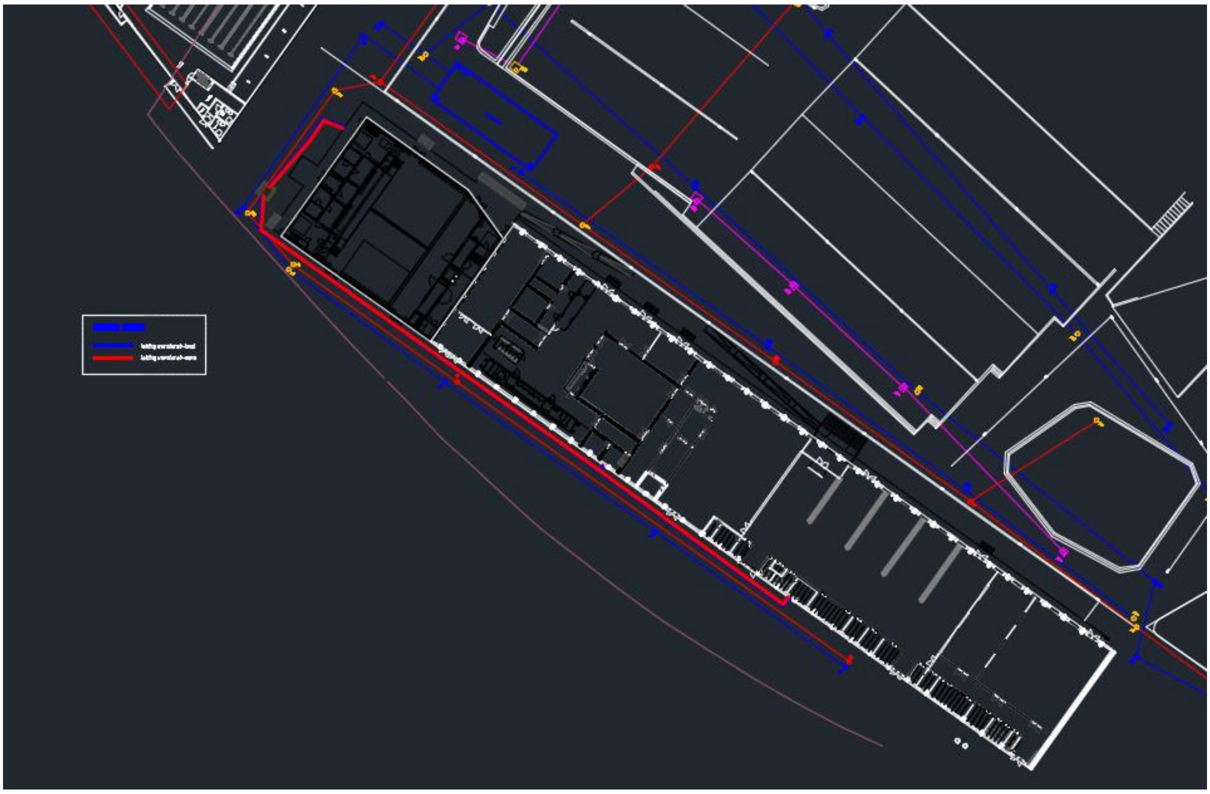


Figure 26: Schematic of a DH network in the Kortrijk pilot

Mijnwater pilot

The Mijnwater pilot has the following sources to provide heat to their network:

- Heat pump – 3.4 MW
- Energy exchange between buildings – 41% of energy can be exchanged
- Mine water reservoir – 6 MW

The backbone of the pilot consists of 3 single pre-insulated PE pipes; the clusters are connected with 2 single pre-insulated steel pipes, the dwellings are connected through 4 single pre-insulated PE pipes. The network has an operating pressure of 10 bar. The designed supply and return temperatures of the network are 28°C and 16°C respectively. It has a well storage with a capacity of 8 million cubic meters and a tank storage with a capacity of 68 cubic meters. An instantaneous substation is used, with a data monitoring system connected through a CISCO data network (mod-bus).

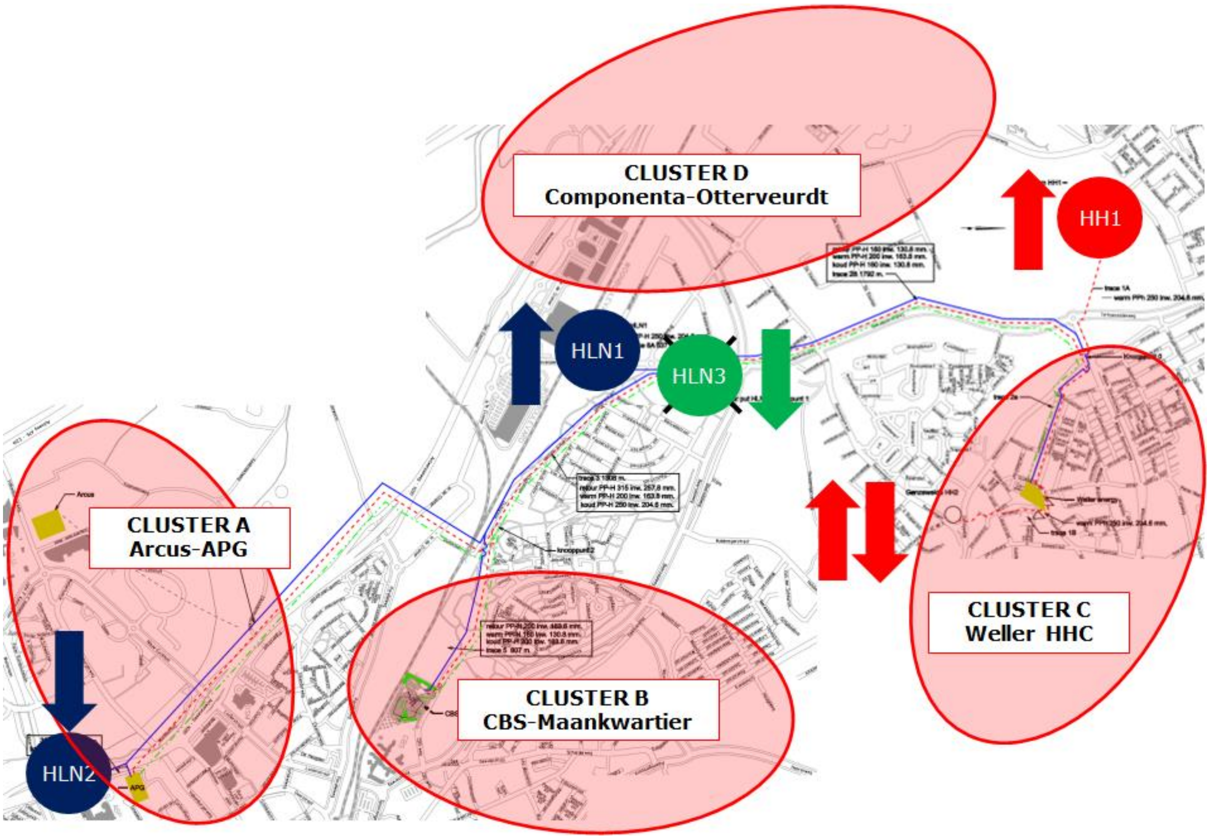


Figure 27: Schematic of the Mijnwater pilot with energy clusters and wells

Plymouth pilot

The Plymouth pilot uses the following heat sources to provide heat to their network:

- Gas – 500 kW
- Gas CHP – 1 MW
- Heat pump – 200 kW

The network uses single steel pipes, with supply and return temperatures of 70°C and 40°C respectively. It has a hot water tank storage with a capacity of 1040 kWh (phase 1) and 2080 kWh (phase 2).

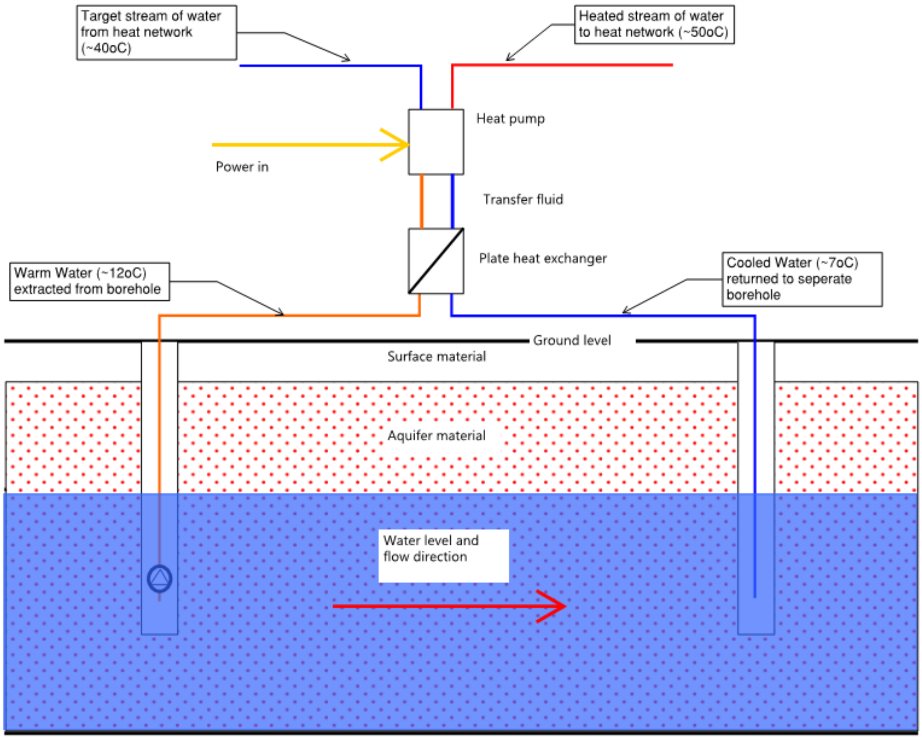


Figure 28: Technology used in the Plymouth pilot

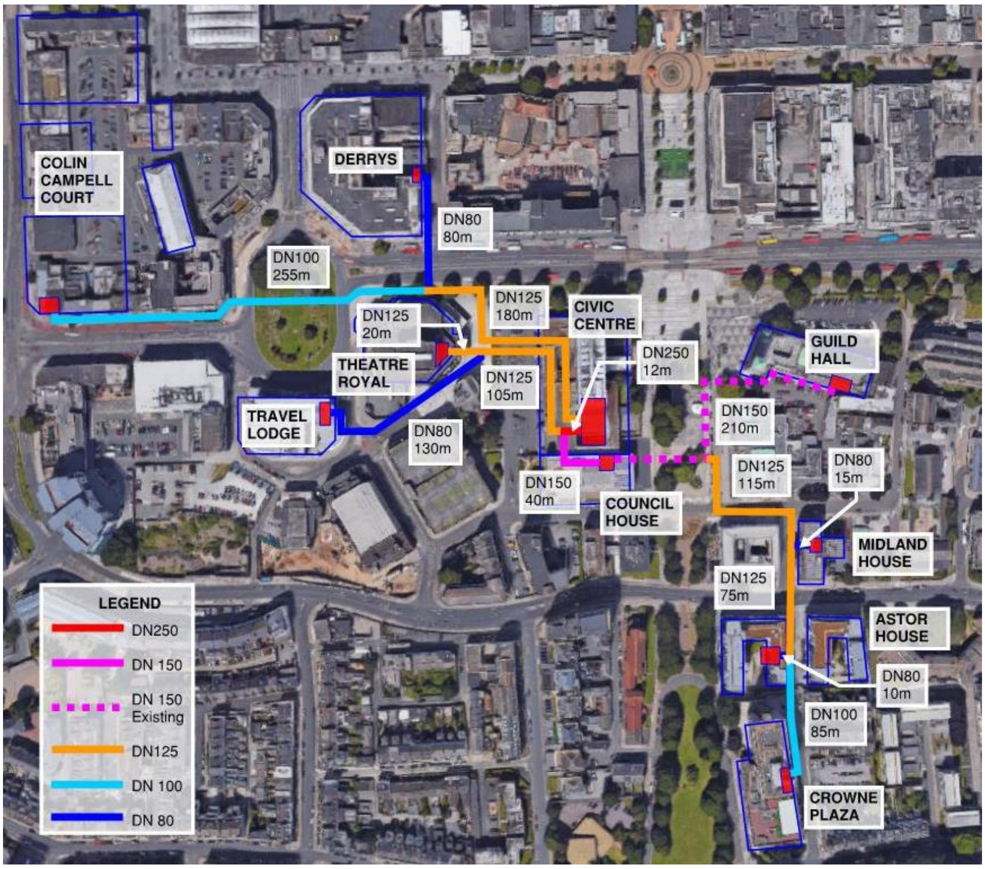


Figure 29: Schematic of the Plymouth pilot

South Dublin pilot

The South Dublin pilot has the following heat sources in its network:

- Heat pump – 0.4 MW
- Gas (Back-up and peak usage) – 0.6 MW
- Data centre – 4 MW

Single rigid steel pipes are used for pipelines larger than 300 mm and twin pipes are used for smaller distribution pipelines to decrease losses and costs. The designed supply and return temperatures of the network are 65°C and 40°C respectively. The pilot has a hot water tank storage with a capacity of 100 cubic meter. An instantaneous substation will be used in this pilot.

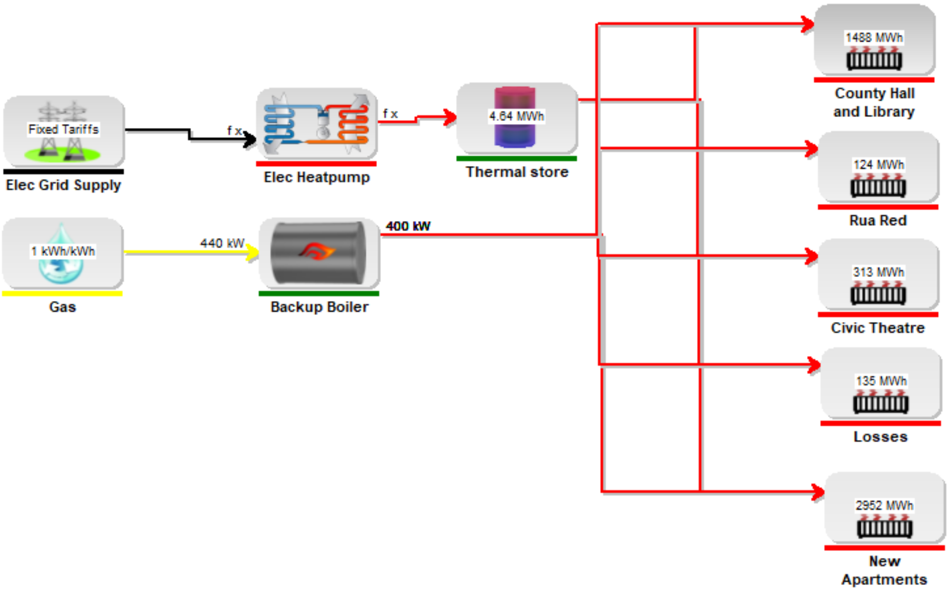


Figure 30: Technology used in the South Dublin pilot

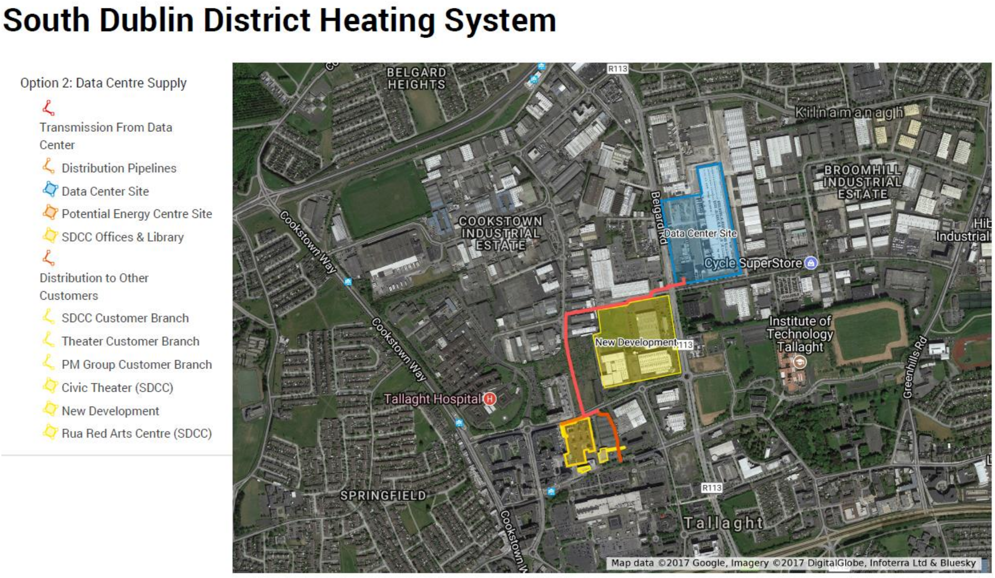


Figure 31: Schematic of the South Dublin pilot

4DHC components

This section summarizes the components of a 4DHC system.

Distribution pipes

The distribution pipes are mostly pre-insulated flexible pipes and possibly twin pipes. By using twin pipes with the supply pipe located at the isotherm equal to the return temperature, heat losses can be reduced and heat exchange between supply and return pipes can be eliminated. In order to reduce heat transfers caused by thermal radiation, the insulation materials may be improved by adding opacifiers [1].

The flow rate in the supply will be very low in summer. Therefore, the supply pipe heat loss may cool the water to a low temperature, which makes it impossible to provide heating of DHW in the buildings, at the end of the supply pipes. The supply pipes layout in a loop back to the heating plant or main parts of the grid is essential in order to avoid bypass to the return line. This opens the possibility to circulate enough warm water in the supply line to heat DHW in summer. The differential pressure between both pipes may even out at all places in the network, if the return pipe is also connected in a loop with the flow direction as the supply pipe [1].

Figure 32: Flexible 4DHC distribution pipes [26]

A triple-pipe configuration with one pipe available for recirculation reduces heat losses during summer. Single pipe, twin pipe and triple pipe configurations are suitable for 4DHC systems. 2 twin pipes can be used for 4 pipe systems. Flexible pipes allow a fast roll out of district heating systems.

Storage tanks

Seasonal heat storage refers to the long-term storage of heat. It helps to increase the share of solar systems in district heating systems. Underground storage of hot water is one of the more efficient and effective methods to store water. There are different methods of heat storage underground:

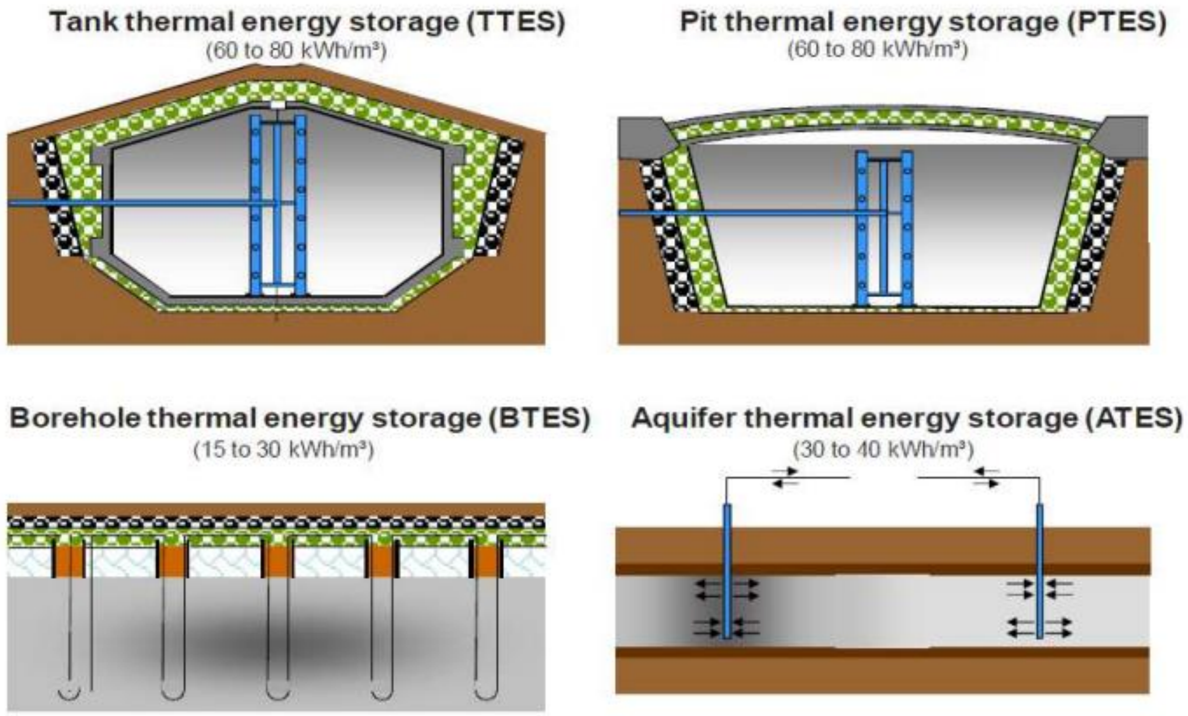


Figure 33: Seasonal storage tanks [27]

Tank thermal energy storage

This method uses hot water tanks made of concrete or steel under the ground. It is relatively expensive compared to other methods since steel/concrete is used for construction. However, it has the advantage that the hot water temperature is unaffected by local soil conditions.

Pit thermal energy storage

Pit storage means storing hot water in an opening in the ground by making it waterproof with a membrane. The pit can be covered with a floating and insulating lid. The bottom can be insulated or left without insulation if there is a large volume. The benefit of this system is that it is cheap and easy to install. The disadvantage of this system is that it is difficult to maintain it 100 percent watertight over many years. Moreover, heat loss can occur if it is not well insulated at the bottom.

Borehole thermal energy storage

In this method, heat and/or cold is/are stored in the underground using a borehole heat exchanger, consisting of U-loops installed in boreholes. The distance between the boreholes will be 2 to 3 meters. They are typically combined with heat pumps. This can also be used as a heat sink for cooling applications.

Aquifer thermal energy storage

This is constructed by using direct heat exchange in vertical wells. Aquifer thermal energy storage consists of one central well with several peripheral wells. It is typically used for low temperature applications in combination with heat pumps. One of the problems is the chemical composition of the water in the aquifer, which might lead to poor performance.

Both centralized and decentralized storage systems exist. They can be coupled with solar thermal systems to increase the solar fraction. It is also usually combined with heat pumps to provide flexibility.

Advantages:

- Provide flexibility to the energy system

Disadvantages:

- High investment cost
- Large volume is needed to reduce heat losses

Pumps

Pumps can be both centralized and decentralized. Booster pumps can also be used in the 4DHC networks. The most important pumps in a DH system are the main pumps at the heat source and the distribution pumps in larger systems. In a typical district heating system, pumps play an important role in many crucial applications such as the boiler shunt pump, lull heat pump, flow filter pump and water treatment system.

Monitoring systems

A monitoring system is used to record most of the network data and send the data wirelessly. Decentralised intelligent metering, in order to get a close link between the power and buildings energy, may be used for continuous commissioning and payments. This is enabled by gathering heat meter readings over short time intervals wirelessly. This also includes metering surplus heat sale from e.g. solar thermal from individual buildings to the grid as well as to motivate better cooling to consumers. More data provides us an option to predict future loads as accurate as possible [1].

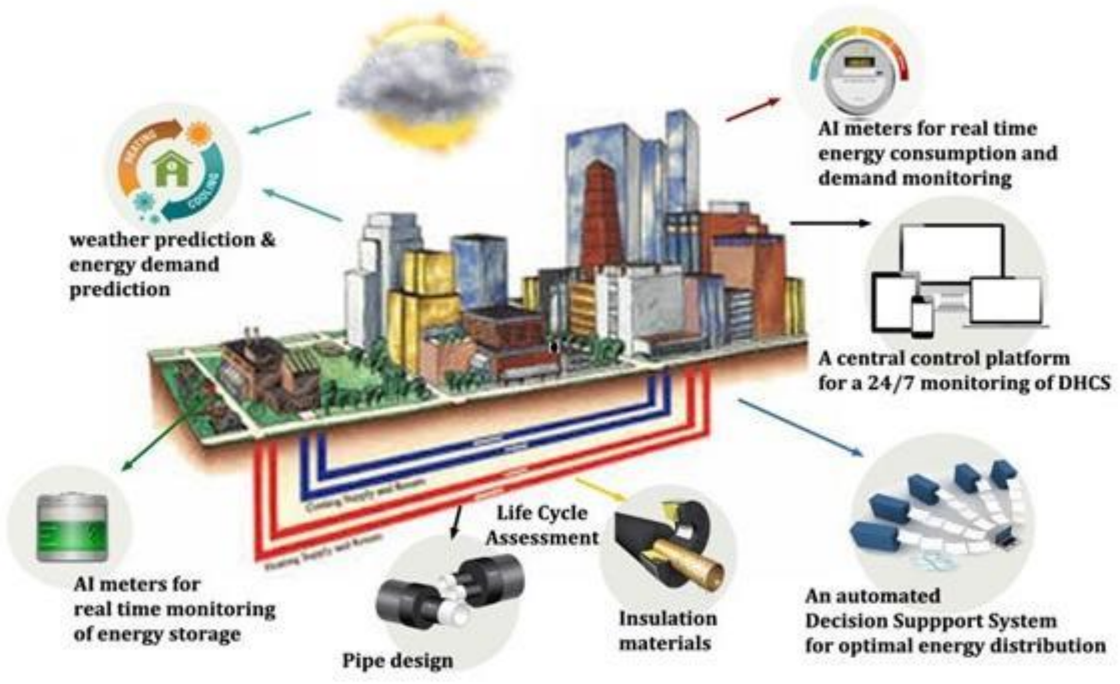


Figure 34: District heating monitoring system [28]

Conversion of existing DH into 4DHC

Changes that are needed for existing buildings to be connected to 4DHC depend on the energetic performance of the building. A 4DHC system uses low temperatures, therefore the climate system of the building should apply to this system. When using low temperatures, the insulating effect of the facade, roof and windows is very important.

A high temperature network has high energy losses due to the transportation of the energy and the temperature difference between the soil and the medium (water temperature). With a low temperature network, this difference is reduced and the energy loss decreases. Also, high temperatures are often not needed when choosing a low temperature delivery system in the building. However, the energy performance of the building becomes more important. As a result, the needed insulation of the facade will increase.

Low energy passive buildings are crucial when converting existing DH to 4DHC, and the insulation levels should be high. Therefore old buildings should be renovated prior to their connection with low temperature 4DHC.

Mijnwater has made calculations about the investment costs. Investment to connect an existing building to the 4DHC network = €15.000 + investment in adjustments for the building = €15.000. Compared to a sustainable upscale solution (e.g. solar panels), the expenses will turn out to be €60.000 per dwelling.

Future of DHC

Future district heating infrastructures should, however, not be designed for the present energy system but for the future system. One of the future challenges will be to integrate district heating with the electricity sector as well as the transport sector. In the following, future systems will be referred to as smart energy systems, i.e. energy systems in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them, in order to achieve an optimal solution for each individual sector as well as for the overall energy system. District heating will become an essential part of the future energy system and can provide the much-needed flexibility due to highly intermittent renewable energy sources.

Conclusion

Main benefits of 4DHC:

Since the supply temperature is low,

- low grade heat sources can be used;
- heat losses will be reduced;
- energy efficiency is high due to low heat loss;
- it is possible to use low cost pipe materials;
- a high lifetime of piping and other components is expected.

It can be integrated with other energy grids.

Challenges of 4DHC:

- Low temperature grids focus on future energy efficient buildings and the challenge with existing buildings should be addressed
- Lack of 4DHC standards

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