Chapter

District Heating and Cooling Systems

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Abstract

Decarbonisation of the energy sector is a crucial ambition towards meeting net-zero targets and achieving climate change mitigation. Heating and cooling accounts for over a third of UK greenhouse emissions and, thus, decarbonisation of this sector has attracted significant attention from a range of stakeholders, including energy system operators, manufacturers, research institutions and policy makers. Particularly, the role of district heating and cooling (DHC) systems will be critical, as these two energy vectors are central to our lives not only for comfort and daily activities, but also to facilitate productive workplaces and to run a variety of industrial processes. The optimal operation of DHC systems and the design of efficient strategies to produce heat and cold, store thermal energy, and meet heating and cooling demands, together with an increased integration of low carbon technologies and local renewable energy sources, are vital to reduce energy consumption and carbon emissions alike. This chapter reviews relevant aspects of DHC systems, their main elements, automatic control systems and optimal management.

Keywords: District heating and cooling systems, local energy systems, sustainable energy systems, renewable energy sources, thermal energy storage, heat transfer, heating demand, cooling demand, energy systems management

1. Introduction

From very early days, men and women learned to manipulate heat for their protection and survival. From the discovery of fire to the development of thermal systems in modern societies, the supply of thermal energy to meet heating and cooling demands has significantly improved, both in the efficiency of transport and the quality of the thermal energy available. As we face an unprecedented climate emergency threatening life in our planet, mitigation of global warming through the reduction of greenhouse gas emissions has become a crucial ambition. Due to the substantial amount of carbon emissions contributed by domestic and industrial heating, including space cooling, district heating and cooling (DHC) systems have recently attracted significant attention. With suitable operating regimes, inclusion of low carbon technologies and control strategies in place, a DHC system may be an integral solution for the reduction of energy consumption and carbon emissions while meeting local demand for heat and cold.

DHC systems use the infrastructure interconnecting dwellings, buildings or facilities within a city, district or neighbourhood to supply heating or cooling [1]. Using mainly water as the transport medium, heat and cold are distributed to meet demand for space heating and cooling, refrigeration, and water for domestic or industrial use.

A local energy system is an energy system led by a local authority or local organisations within a bounded geographical area (commonly a city) that aims to match local energy resources with the local energy demand [2, 3]. Therefore, a DHC system is considered a local energy system as it is limited to specific areas within a city, although it can extend to an entire municipality. In occasions a thermal system spans beyond municipal borders to incorporate thermal energy generation plants, such as Copenhagen's district heating system [3].

DHC systems supply a large share of the thermal energy demand in a local region. Therefore, considering them in regional plans for reaching net-zero targets is of importance. Although exploiting local energy resources could lead to DHC systems being part of energy islands [3, 4], they would be connected to national energy systems through electricity and gas grids. Thus, coordinated actions of national and local plans are required for a successful transition incorporating renewable energy sources (RESs).

The main components of a DHC system are shown in **Figure 1**: heating or cooling energy sources, distribution network components, customer installations including thermal loads and thermal energy storage (TES) systems.

1.1 Evolution of district heating and cooling systems

The first district heating system dates back to 1877, in New York, where 14 customers were connected to a network supplied by a single boiler fuelled by coal [5]. Subsequent systems developed elsewhere worked on the same principle. In general, they consisted of steam traps, expansion joints, and insulated steam pipes

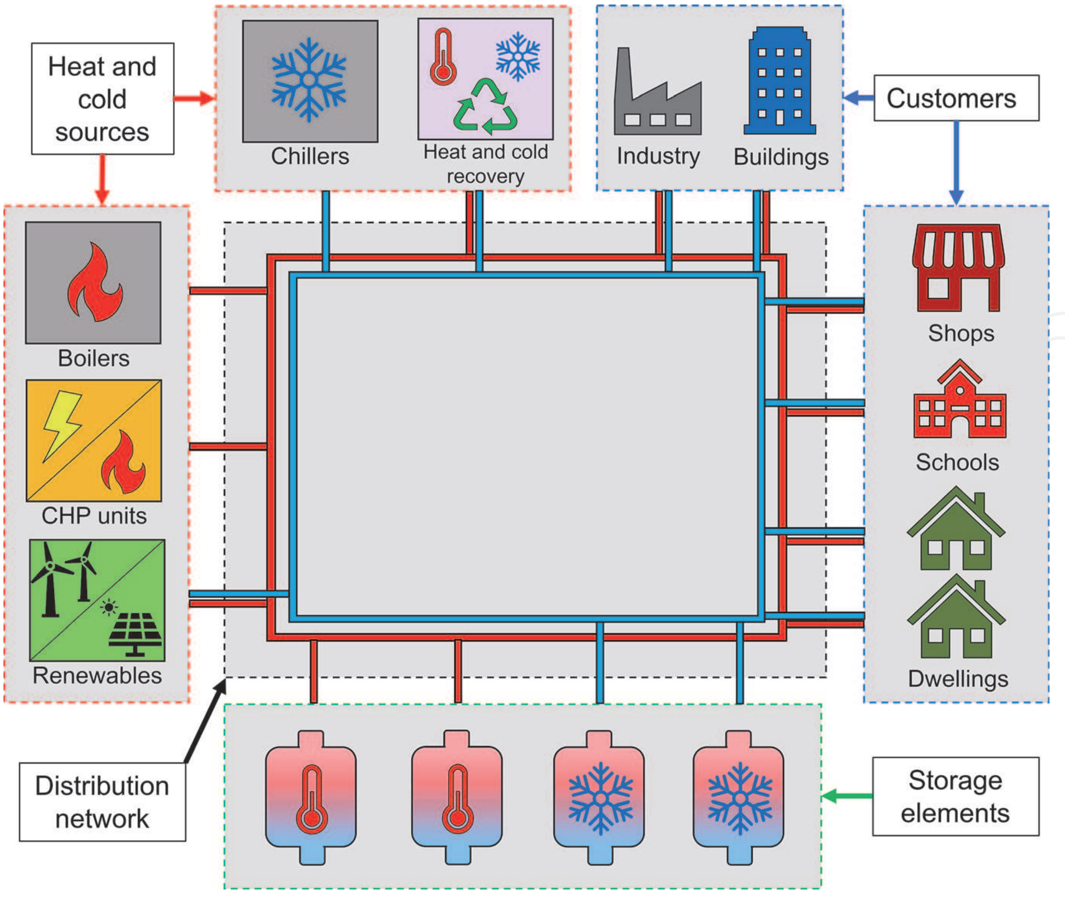

Figure 1.
Classification of components of a DHC system.

(supply and return), housed within underground concrete ducts transporting steam at high temperature and high pressure. Steam heat storage plant and combined heat and power (CHP) generation units driven by coal or oil were also incorporated, but their use was not extensive [6]. Steam district heating systems were highly inefficient due to the large heat losses resulting from operation at high temperatures. In addition, these systems were hazardous due to the risk of explosion. Steam district heating systems were the 1st generation of district heating (1GDH) systems, which dominated the market until the 1930s.

The 2nd generation of district heating (2GDH) systems replaced steam with pressurised liquid water at temperatures above 100°C, making the systems safer while reducing heat losses. Water pipes and water-based heat storage tanks were used. Large shell-and-tubes heat exchangers and large and heavy valves were also incorporated to the distribution network. The number of CHP units also increased, further integrating heating and electricity networks, while decreasing costs of energy production and emissions at the same time.

Although 2GDH systems were dominant until the 1970s and a few 1GDH and 2GDH systems remain operational, the 3rd generation of district heating (3GDH) systems is predominant nowadays. The distinctive feature of a 3GDH system is the use of heat interface units to provide an individual supply temperature control. Liquid water is still employed in the primary circuit; however, as the operating temperatures are below 100°C, heat losses and insulation requirements for pipelines are reduced. Large gas, biomass and waste CHP units replaced oil- and coal-driven units. Moreover, a range of distributed heat sources such as small CHP units, gas and electric boilers, solar collectors and heat pumps were incorporated, thereby integrating RESs as heat sources.

The development of district cooling systems followed a similar approach as district heating systems. Introduced in the 19th century, the 1st generation of district cooling (1GDC) systems were predominant until the 1960s. They consisted of centralised condensers and decentralised evaporators, with a refrigerant used as the transport medium. A solution of ammonia and saltwater was often used as the refrigerant. The 2nd generation of district cooling (2GDC) systems used chilled water as the distribution medium and adopted large mechanical chillers to produce cold. The 3rd generation of district cooling (3GDC) systems is dominant these days and grew in popularity in the 1990s. With a diversified cold supply consisting of absorption and mechanical chillers, modern cooling systems take advantage of local natural water resources, such as lakes or rivers, to obtain free cooling.

1.2 Modern district heating and cooling networks: an insight to Paris' system

According to the United Nations Environment Program, Paris is considered one of the "champion cities" for district energy use in the world [7]. With both large district heating and district cooling networks currently in operation, Paris is aiming to reduce its carbon emissions by 75% by 2050.

District heating was introduced in Paris in 1927 through a 1GDH system configuration based on steam. With 33% owned by the city, the Paris Urban Heating Company (CPCU) is still the only company operating under a concession contract. It currently serves 16 towns in the metropolitan area, supplying heat to ~500,000 households using a network of 475 km. Although steam is used as the main distribution medium, the network also includes smart operation control systems and several hot water loops (as those used in a 3GDH configuration). Due to their high distribution efficiency, hot water loops are preferred for areas under development in the city suburbs. These, in turn, help reduce peak demand on the steam network.

CPCU uses a wide range of heat sources. Three waste incinerators constitute the primary heat production units, which are supported by two CHP plants, several gas and coal boilers, and five fuel oil boilers. There are plans for replacing gas and coal boilers with waste and biomass-fired power plants by 2030 [8]. Currently, 50% of the energy consumed by the district heating network comes from RESs and energy recovery. As a result, the Paris district heating system is an important example of heat generation and supply from renewable energy.

Paris also has the most extensive 3GDC system in Europe. The cooling system has been operated by Climespace since 1991. It has an 83 km underground cooling network, which supplies chilled water to over 700 customers, including hotels, shopping centres, offices, state buildings, museums, and theatres. The system employs ten cooling energy production sites to produce ~480 GWh of cooling per year and it also features four cooling storage facilities [9]. What makes this system highly economic, operationally efficient and innovative is the incorporation of free cooling into the energy production process. Water from the Seine River is used as a large natural source of chilled water for the distribution network, reducing both costs and the environmental impact.

Paris' district heating and district cooling networks are monitored and operated by specialised personnel in real time through control centres to guarantee a consistent supply of heating and cooling. Both networks are constantly being extended, incorporating additional delivery stations to reduce the city's carbon footprint.

1.3 Modern district heating and cooling systems

1.3.1 The 4th generation district heating and district cooling systems

Existing 3GDH and 3GDC systems and their technologies are evolving to new systems. The 4th generation of district heating (4GDH) systems and the 4th generation of district cooling (4GDC) systems integrate RESs to ensure efficient and high-performance operation [6]. Although 4GDH and 4GDC systems are designed as individual networks, exploiting synergies between them is required to use energy efficiently, especially for recovering waste heating and cooling energy.

The expansion of heating and cooling distribution networks by integrating local RESs and exploiting the potential for recovering waste thermal energy from a wide range of customers' applications brings substantial benefits. Combined with a smart management of the systems and of the customers' installations, the overall efficiency of the thermal grid may be improved and the difference between supply and return temperatures reduced with respect to the ambient temperature. This temperature reduction could in turn help minimising thermal losses. Intelligent management includes 24-hour weather forecasting to estimate thermal demand and the use of load shedding and load shifting techniques to regulate it. Building insulation for energy conservation and the minimisation of health risks posed by the Legionella bacteria by eliminating domestic hot water (DHW) stores enables the reduction of water supply temperatures for space heating, space cooling and DHW production.

Thermal losses in the distribution network are one of the main concerns for future developments. In addition to a reduction of temperature in supply and return lines, achieving low thermal losses requires:

- Reducing pipe dimensions.

- Improving the insulation of pipelines using twin pipes.

- Implementing 3-pipe configuration in the distribution network to maintain a supply temperature at the periphery, avoiding bypassing the return line [10].

- Implementing a continuous metering system with fast wireless readings, enabling intelligent control of the network.

Decarbonisation of thermal networks involves the use of RESs and other low-carbon heating and cooling sources, which include CHP plants and efficient boilers, waste incineration plants, chillers and heat pumps. For local energy systems, the integration of energy resources available in close proximity is desirable. For a thermal network, these include free cooling from nearby natural water reservoirs and geothermal energy from low-temperature geothermal heating plants with efficiently operated heat pumps. Solar thermal plants can also be integrated into the network when combined with large-scale seasonal TES systems. Waste heat and cold from local industrial activity and commercial buildings represent a significant thermal resource. To this end, central thermal stores are used to recover waste thermal energy for a later dispatch.

Important benefits are obtained when operating thermal networks with supply and return temperatures near the ambient temperature. The capacity of a thermal network to take heating (or cooling) energy from a source is enhanced by lowering its return temperature (or raising it for cooling) since heat transfer is proportional to the temperature difference between the source and the network. For this reason, steam or fuel-driven CHP plants enhance their electricity production by enabling a further expansion of steam or flue gases without affecting the total heat recovered. Heat pumps, chillers and TES units are also sensible to temperature. A higher coefficient of performance (CoP) in vapour compression heat pumps and chillers is achieved by reducing the temperature difference between the heat source and heat sink since less work is required from the compressor. Charging and discharging temperatures limit the energy storage capacity of a TES unit. Since the discharge temperature is the return temperature in the network, lowering this temperature in TES units storing heat (or raising it for cold stores) can increase storage capacity. The design of smart energy systems aims to cope with the fluctuating nature of RESs. To achieve this, electricity, thermal and gas networks must be combined and their operation coordinated at a local and national level, providing optimal solutions at an individual level and as part of an integrated network. Coupling devices linking energy vectors, such as heat pumps, CHP plants and chillers, and the use of energy storage components play a crucial role in the operation of a local thermal network.

The large-scale integration of RESs involves a radical technological change and a paradigm shift from single-purpose organisations implementing undifferentiated solutions to multi-purpose organisations implementing differentiated solutions. Three main challenges have been identified:

- Deciding whether to have district heating and district cooling systems or individual thermal solutions.

- Establishing a trade-off between developing local heat production against implementing energy conservation measures.

- Motivating the integration of local RESs.

To address these challenges, it is necessary to develop planning and design tools and methodologies based on geographical information systems. On the other hand, implementing long-term marginal cost tariff policies and enabling access to loans and consultancy services to support customers are also relevant measures.

Although the technologies and policies for 3rd generation systems are in an early transition towards the 4th generation, encouraging results in research projects have been obtained when implementing the measures discussed previously [11]. Fourth generation systems are expected to dominate modern thermal systems in the future.

1.3.2 The 5th generation of district heating and cooling

Until the 4th generation, district heating and district cooling networks were treated as individual loops with limited interaction between them supplying either heat or cold to customers. The systems were unidirectional, with water flowing in one direction through the distribution network to meet thermal demands. However, in the last few years, a novel configuration using bidirectional networks has emerged. The 5th generation of district heating and cooling (5GDHC) systems integrate district heating and district cooling networks into a single distribution network [12–14], delivering either heating or cooling to a single facility by inverting the direction of the water flow in the consumer terminals. These systems reduce supply and return temperatures even further by using decentralised heat pumps. Benefits from 5GDHC systems include the reduction of thermal losses in the distribution grid, improved TES capacity, and an increased utilisation of heating and cooling generation plants and waste heat and cold sources. **Figure 2** shows a schematic comparison between 3rd and 4th generation district heating and district cooling systems and a 5GDHC system.

The characteristics of a 5GDHC system make of it a powerful and versatile solution to decarbonise thermal networks. For instance, bidirectionality of the flow produces different operational mass flow rates for different subsections of the distribution network. This feature enables to exploit synergies between buildings with different thermal demands, recovering waste heat or cold from some premises to supply others within the same cluster of buildings. Circular use of the energy may be achieved, where consumers become prosumers supplying the network. This could enable peer-to-peer energy transaction schemes to reduce energy costs. Bidirectionality also facilitates the integration of RESs and local thermal energy sources into the network.

Deployment of 5GDHC systems is challenging. Adding decentralised heat pumps to allow reduced working temperatures requires a significant capital investment and sophisticated control systems since the heat pumps are connected to the electricity grid. Reduction in temperatures also requires higher mass flow rates, for

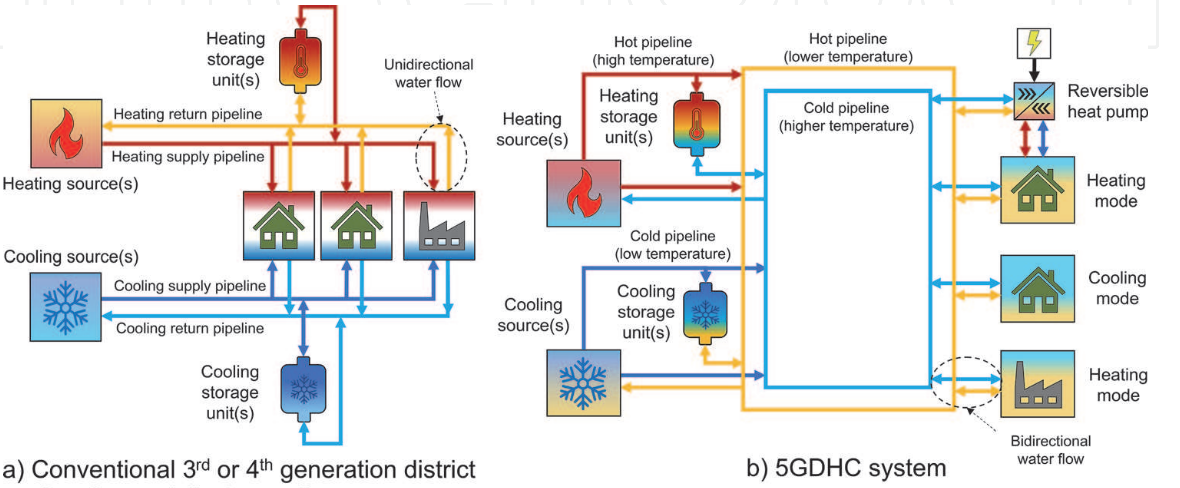

Figure 2.
Schematic comparison between 3rd or 4th generation district heating and district cooling systems with 5GDHC systems.

which extra pressure boost or larger diameter pipes would be required. Despite these challenges, there are 5GDHC systems in operation integrating RESs, including groundwater (e.g. ETH Campus Hönggerberg, Switzerland), seawater (e.g. Bergen University, Norway), or excess heat (e.g. Herleen, The Netherlands) [13, 14].

2. Thermal loads in energy transfer stations

Thermal energy flows in a DHC system can be considered as either supply or consumption flows. Supply flows are produced at the ends of the distribution network connected to the heat or cold sources. Conversely, consumption flows are generally associated with the customer ends or energy transfer stations (ETSs), which connect the customer's local installation to the distribution networks via heat exchangers or hydraulic separators.

Consumption flows are commonly referred to as thermal loads [15] and expressed in kilowatt [kW] or kilowatt-hour [kWh]. Thermal loads change with time and are specified as load profiles ranging from an annual, seasonal, monthly, weekly, daily, or even hourly basis [15, 16]. Weekly and daily thermal load profiles depend on the level of activity within the network which, in turn, depends on the energy consumption of each customer. Monthly and seasonal load profiles depend mainly on meteorological conditions. For instance, the demand for heating is high in winter, while cooling demand may dominate in summer. The definition of load profiles is critical for the optimal operation of DHC systems [17]. This will be briefly discussed in Section 6.

Within local customer installations, thermal loads are caused by three main energy consumption processes: space heating or space cooling, production of DHW, and industrial processes. Additionally, thermal losses in the distribution network represent a significant portion of the total thermal load.

2.1 Space heating and space cooling

Space heating and space cooling are used to condition the temperature inside a dwelling, building or facility to a uniform level which is different from the outdoors temperature. This may be achieved by placing radiators in each room or at specific locations inside a building. Alternatively, fan coil units distributed through a building regulate indoor temperature by varying the ventilation airflow temperature and mass flow rate [18]. Thermostats are included in key areas of a building when automatic systems are implemented to regulate temperature.

Lighting, the temperature of the water sources, or the insulation level affect the conditioning of indoor temperature within a building [19, 20]. The number of building occupants is also a major factor. For example, the energy consumption for space cooling in an office complex in the summer is higher during working hours than for the rest of the day. Meteorological conditions are particularly relevant for space heating and space cooling. Although these can lead to a higher heating or cooling consumption, they can also help to mitigate thermal losses due to the difference in indoor and outdoor temperatures. Solar radiation is especially beneficial for space heating during winter. Similarly, rainy or windy days lead to a lower cooling consumption in the summer.

2.2 Domestic hot water preparation

DHW refers to the water used for domestic purposes including cooking, sanitation and personal hygiene, where the final consuming elements are taps and showers. Thermal load due to DHW depends primarily on the specific temperature setpoint the water is heated to and the activity level of the customer.

In 3GDH and 4GDH systems, DHW preparation involves the use of water tanks and strict temperature control. To prevent the growth of Legionella, the bacteria causing Legionnaires' disease, temperature must be kept above 50°C [21]. In 5GDHC systems, this is challenging due to the low temperatures of operation. For this reason, heat pumps and electric heaters are used to locally raise temperature [22, 23], which increases the coupling between thermal and electrical networks.

2.3 Industrial thermal loads

Industrial loads can be attractive for DHC systems thanks to the diversity of thermal processes employed to manufacture and store products. The transport, electricity, pharmaceutics, and food sectors, and manufacturing processes such as machinery, textiles, chemicals, paper, metal, wood, rubber and plastic require heating and cooling [24, 25]. Although thermal loads in an industrial process may be affected by outdoor temperature and meteorological conditions, the determining factor to predict load profiles is the periodicity of activities within the process [24, 26].

Due to the economic and environmental benefits involved, the incorporation of industrial activity into DHC systems is increasing. In addition, the recovery of industrial waste heat and cold represents a major thermal energy resource that could be employed to meet the demands from other customers connected to the thermal network [25, 27]. Further discussion on this is provided in Section 3.

2.4 Thermal losses in the distribution network

Thermal losses modify the overall thermal load of a network. Several factors affect the amount of energy lost. The network's integrity is a major factor since cracks in distribution elements can leak water [6, 28]. It is thus essential to regularly monitor the network and to provide maintenance when required.

The amount of insulation and the geometry of pipes (i.e. diameter and length) influence the network's heat transfer to the surrounding ground [20, 28]. The reduction of operating temperatures in the latest generations of DHC systems aims to reduce thermal energy losses resulting from this heat transfer.

3. Heating and cooling sources

3.1 Boilers and burners

Depending on the heat source, boilers are classified as boilers supplied by fossil fuels, heat recovery boilers and electric boilers. Electric boilers (i.e. electric resistances immersed into water tanks) and small-scale fuel powered boilers are mainly used to produce hot water for space heating and DHW in dwellings, housing developments or offices complexes. Heat recovery and combustion boilers are extensively used in DHC systems and in industrial applications due to their wide range of capacities.

3.1.1 Fossil fuel fired boilers

Fossil fuel fired boilers consist of two separate flow channels to transfer heat from the fuel to water. Water is fed and circulated through the first channel. At the inlet ports of the second channel, fuel and air are fed and burnt to generate hot flue gases. These gases circulate through the second channel, transferring heat to the water at the points where both flow channels are linked.

Fossil fuel fired boilers may vary depending on the type of fuel used, the firing method, the field of application, the water circulation system, or the operating pressures [29]. However, they are classified mainly as hot water boilers and steam boilers. Steam boilers are more complex because of the separation process of the steam from liquid water. A schematic of a steam boiler is shown in **Figure 3**.

3.1.1.1 Economiser

An economiser consists of a heat exchanger where the feedwater temperature is initially raised, taking heat from the flue gases at the boiler exhaust. Flue gases at this point are at a lower temperature than in the furnace.

The economiser heat exchanger is found in both hot water and steam boilers. It is used to recover heat from the flue gases before they are released into the atmosphere, thereby increasing fuel utilisation.

3.1.1.2 Steam drum

Hot water boilers often feed water directly from the economiser to the tubes of the furnace, but in a steam boiler the preheated liquid water going out of the economiser can be passed to one or a set of steam drums. Within the steam drum, the fraction of water at liquid state is separated from the steam coming from the furnace, and it is fed back to the furnace through downcomers to be reheated.

3.1.1.3 Furnace

Most of the heat produced by fuel combustion is transferred to the water in the furnace, which can be configured in two different ways (see **Figure 4**). In fire-tube

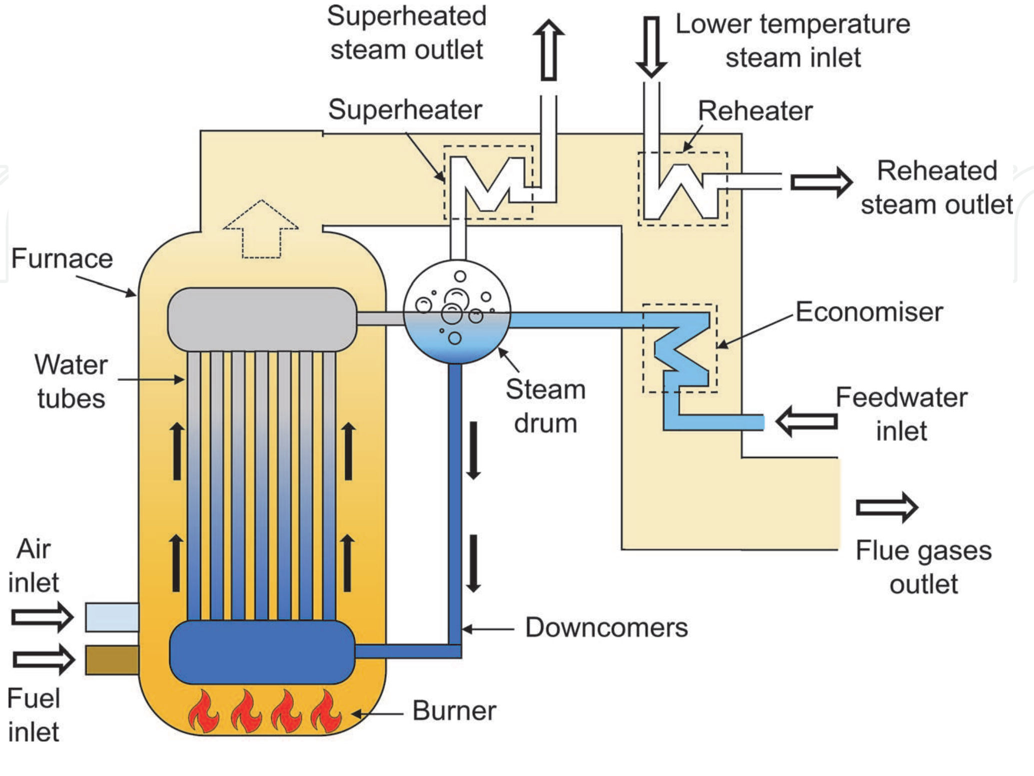

Figure 3.
General configuration of a steam boiler.

boilers (left), the flue gases flow through metal tubes placed within the water flow. Conversely, in water-tube boilers (right), water flows through an arrangement of vertical tubes between the flow of flue gases.

3.1.1.4 Superheater and reheater

These are exclusive to steam boilers. Heat exchangers are placed through the exhaust conduit to increase the steam temperature in several phases. Thus, they increase fuel utilisation by drawing heat from the flue gases. These heat exchangers can be used to superheat the steam exiting the furnace, or to reheat low temperature steam that has been cooled down by a process. In some configurations, superheaters may have their own combustion system to support the steam heating, which requires extra fuel consumption.

3.1.2 Heat recovery boilers

These work under the same principle of fossil fuel boilers. However, heat recovery boilers use the heat generated by burning the by-products of industrial processes instead of fossil fuel. For example, Kraft boilers used in the pulp and paper industry exploit the burning process of black liquor—a by-product of the pulp-making process [29, 30].

3.1.3 Waste heat recovery boilers

The waste heat recovery boiler is different from other boilers as it does not have a furnace. This boiler is powered by the heat generated from processes that would be wasted in normal conditions. This boiler is a fundamental part of CHP plants [31].

3.1.4 Operation and control of boilers

Boiler operation is monitored by a set of temperature, pressure and flow rate sensors. On–off and proportional-integral controllers are implemented to regulate internal variables. For combustion boilers, controllers and sensors are implemented for flow channels of both water and flue gases.

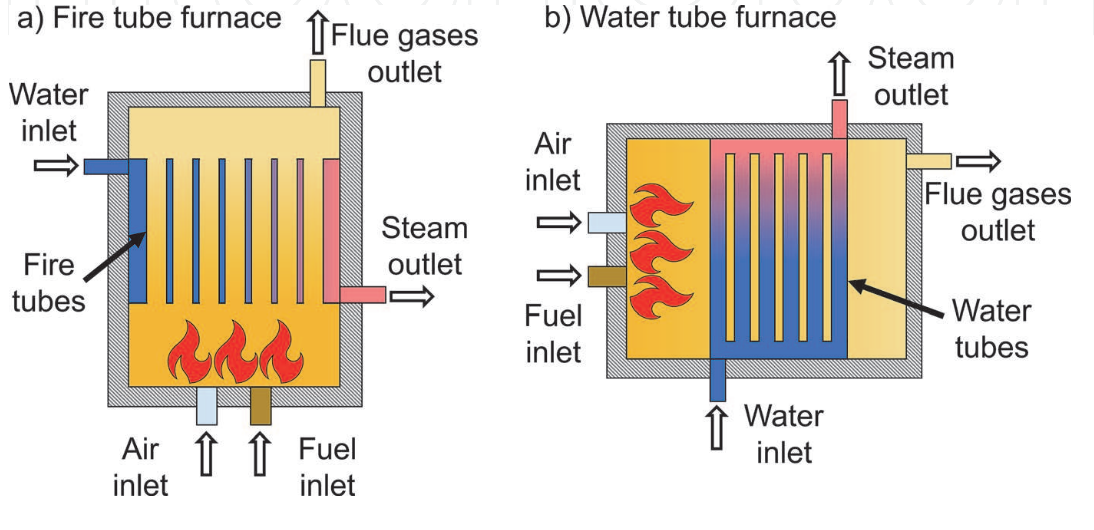

Figure 4.
Fire-tube and water-tube furnace configurations.

The fuel and air mass flow rates are responsible for the heat generation within the flue gases flow channels and thus the temperature and pressure in the furnace. Two control systems are implemented to regulate this operation: the burner management system and the firing rate control [32]. The burner management system supervises and limits the burner operation for safety, while the firing rate control regulates the fuel and air flows. The air inflow rate is regulated to achieve a desired air-to-fuel ratio, which guarantees the fuel is completely burnt while controlling sulphur and nitrogen oxides emissions [29].

The water flow channel is operated by the feedwater flow control system and, depending on the type of boiler, by the steam pressure or the fluid temperature maintenance system. The feedwater flow system is driven by the boiler feed pumps and, in some cases, by additional circulating pumps, which control the feedwater flow and fluid level. In hot water boilers, the outlet water temperature is maintained at a specific setpoint by varying the feedwater flow. However, the control of steam boilers is more complex. While the feedwater flow system keeps a constant water level in the drum, the pressure in the steam conduit is maintained by regulating the amount of fuel burnt and, thus, the steam flow produced.

Effective monitoring and control of the boiler operation are required to achieve an optimal performance, reduce losses, and draw the highest efficiency. The conventional definition of a fuel fired boiler's efficiency η_{boiler} is given by

$$\eta_{boiler} = \frac{Q_{heat}}{Q_{fuel}} = \frac{\left(Q_{fuel} - \text{losses}\right)}{Q_{fuel}} \quad (1)$$

where Q_{heat} is the total heat absorbed by water or steam considering losses, and Q_{fuel} is the heat added by the fuel—which can be approximated by the fuel's lower heating value or higher heating value.

3.2 Chillers

Chillers use the thermodynamic properties of refrigerant fluids to extract heat from water or air streams to produce cooling. Chillers are classified according to their refrigeration cycle.

3.2.1 Mechanical vapour compression chillers

Mechanical vapour compression chillers use mechanical power to drive a compressor. Although the compressor can obtain power from an engine or a turbine, the most popular power source is electricity. **Figure 5** shows the refrigeration cycle of a vapour compression chiller. Two main zones of operation are identified: the high-pressure and the low-pressure zones. At low pressure, the refrigerant boils at a low temperature in the evaporator, taking heat from the supply water or air stream. The supply stream temperature is decreased (sometimes below 3°C), producing cooling to feed a cooling network. On the other hand, the refrigerant vapour goes through the compressor, rising its pressure and, consequently, its dew-point temperature. The refrigerant vapour is then cooled down and condensed in the condenser by a secondary cooling stream with a temperature close to ambient temperature. This secondary stream takes heat subtracted from the refrigerant to a cooling tower or radiator to be released into the atmosphere. The refrigerant, now in a liquid state, reduces its pressure when passing through an expansion valve and goes to the evaporator, completing the cycle.

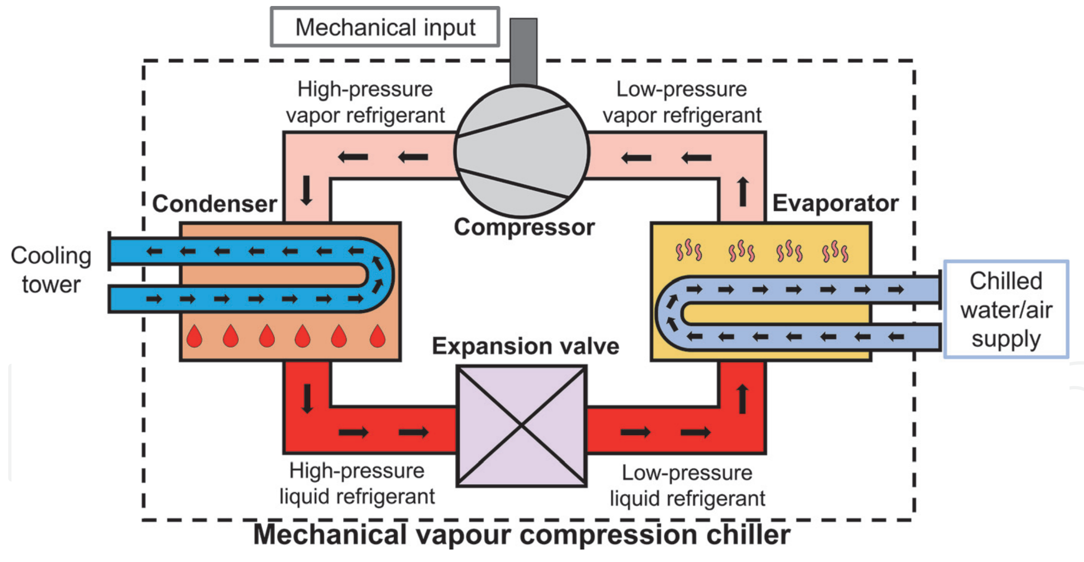

Figure 5.
Refrigeration cycle of a mechanical vapour compression chiller.

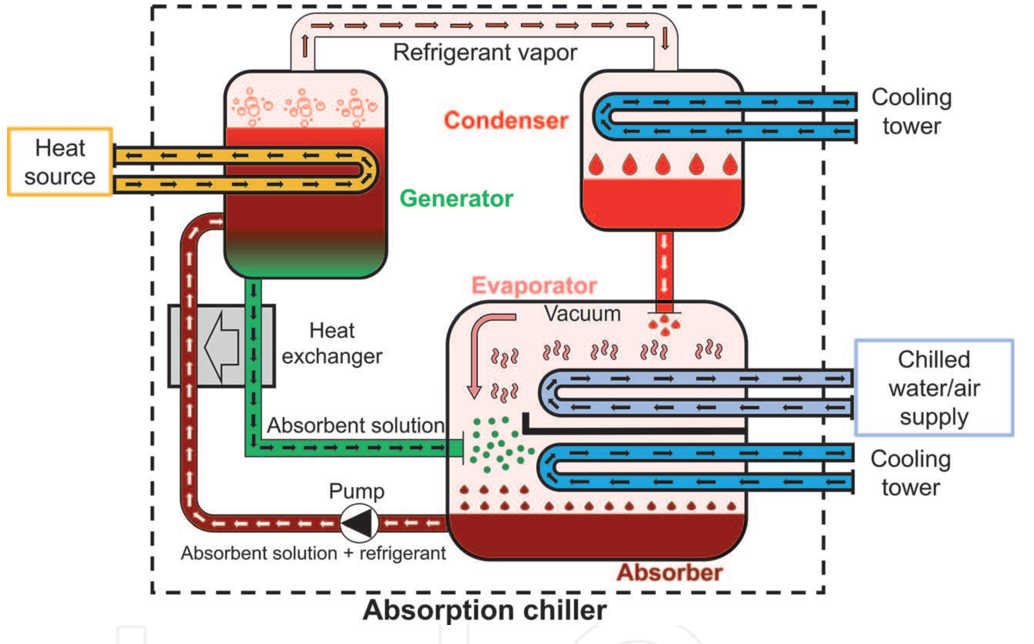

Figure 6.
Refrigeration cycle of a vapour absorption chiller.

3.2.2 Vapour absorption chillers

Unlike mechanical chillers, absorption chillers are driven by heat and do not employ a compressor or an expansion valve. Instead, they use two heat exchangers and an absorbent solution (e.g. lithium bromide) to modify the refrigerant's pressure.

Figure 6 illustrates the refrigeration cycle of an absorption chiller. This starts in the generator, which stores a mixture of a refrigerant and a concentrated absorbent solution. An external heat source heats the mixture up to the refrigerant's boiling temperature, separating the refrigerant vapour from the absorbent. The vapour goes to the condenser, where a secondary cooling stream extracts heat from the refrigerant to condense it. The condensed refrigerant and the absorbent solution from the generator enter the evaporator-absorber. Then, the refrigerant boils at a low temperature in the evaporator (due to close to vacuum conditions), producing cooling. This low-pressure condition results from the absorption process carried out

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in the absorber, where the absorbent strongly attracts the refrigerant vapour. Aided by a secondary stream, the absorbent-refrigerant mixture is condensed and pumped into the generator, completing the cycle. To increase efficiency, a heat exchanger is added between the streams of absorbent solution and absorbent-refrigerant mixture.

3.2.3 Vapour adsorption chillers

The refrigeration cycle of vapour adsorption chillers is characterised by the use of adsorbers, such as silica gel and activated carbon, which are solid substances that attract refrigerant vapour that sticks to their surface (i.e. adsorption).

Figure 7 shows a schematic of this kind of chillers. To achieve a continuous cycle, a minimum of two adsorbent beds are required, where one acts as an adsorber and the other as a desorber. The cycle starts with one of the beds already saturated with condensed refrigerant. The saturated bed is heated by an external heat source, desorbing the refrigerant by evaporation. A directional valve connects the bed with the condenser, which, supported by an external stream, condenses the refrigerant. Once in a liquid state, the refrigerant goes through an expansion valve, reducing its pressure until a nearly vacuum condition exists in the evaporator. Within the evaporator, the refrigerant boils at low temperature, producing cooling. The refrigerant vapour is adsorbed by the second bed, connected to the evaporator by another directional valve, and cooled down by a secondary stream. The cycle is completed by inverting the directional valves and heating the second adsorbent bed.

3.2.4 Coefficient of performance

Chiller efficiency is measured by a dimensionless CoP, which is the ratio of useful energy output for cooling to the primary energy input [33, 34]. For electric chillers,

$$CoP_{elect} = \frac{Q_{cool}}{W_{elec}} \quad (2)$$

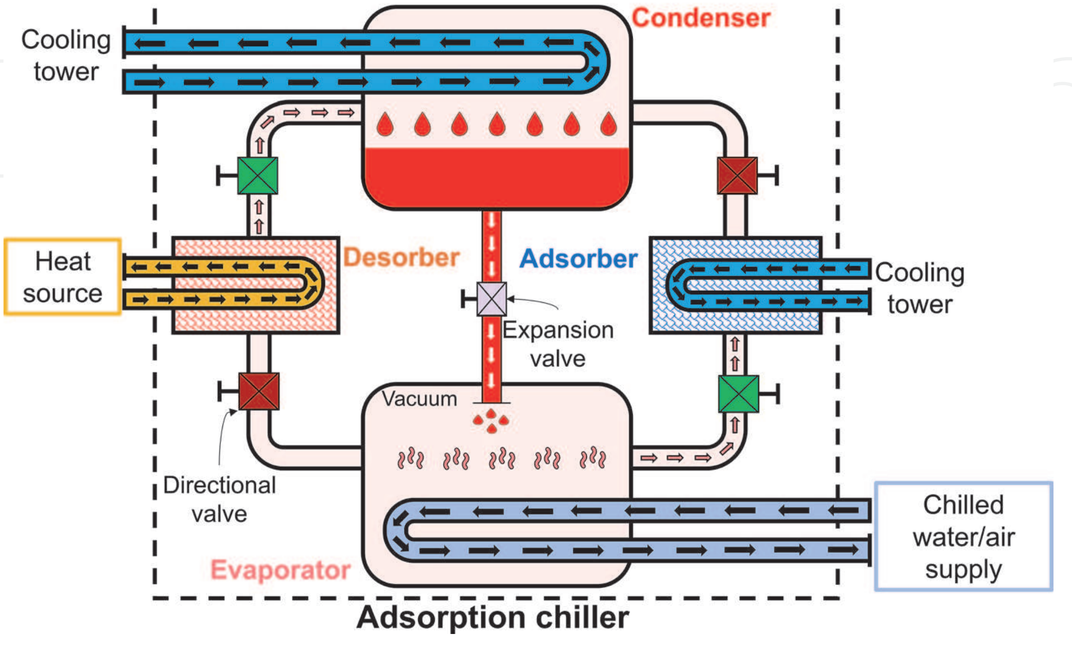

Figure 7.
Refrigeration cycle of a vapour adsorption chiller.

where Q_{cool} is the ratio of cooling rate capacity in the evaporator and W_{elec} is the electrical power input to the compressor. For absorption and adsorption chillers,

$$CoP_{abs/ads} = \frac{Q_{cool}}{Q_{in}} \tag{3}$$

where Q_{in} is the rate of heat input in the generator or desorber.

3.2.5 Refrigerant considerations

Before 1990, refrigerants were mainly produced from chlorofluorocarbons—ozone-depleting substances responsible for the "ozone hole". The Montreal Protocol, agreed in 1987, initiated a gradual phasing out of these substances for replacement with refrigerants with zero ozone-depleting potential [35]. In addition, the increasing concern on global warming led to the definition of the global warming potential (GWP) index, which is used to compare the effects of different greenhouse gases [36].

Refrigerants currently in use are classified as fluorocarbon and non-fluorocarbon refrigerants. Non-fluorocarbon refrigerants, such as ammonia, hydrocarbon, CO_2 and especially water have gained interest for their low GWP.

3.3 Co-generation and tri-generation power plants

3.3.1 Combined heat and power plants

Co-generation or CHP generation is the process of recovering the waste heat from electric power generation to produce steam or hot water. CHP plants are one of the main interfaces between electrical and thermal grids. Their configuration may vary, but waste heat recovery boilers are normally used. CHP plants can use an internal combustion engine or be based on a Brayton cycle (e.g. gas turbine), Rankine cycle, or a fuel cell [31, 37–39].

Figure 8 shows the configuration of a reciprocating engine CHP plant, which takes heat from the combustion gases and an engine block to generate hot water. Gas turbine CHP plants also take heat from exhaust gases, but steam is produced due to the high operating temperatures. In a Rankine cycle-based CHP plant, heat is recovered from the low-pressure steam in the condenser to generate hot water. The steam produced by a gas turbine CHP plant can be subsequently used in a Rankine cycle CHP plant to generate additional electricity. The integration of these thermodynamic cycles into a CHP plant is known as a combined cycle power plant [31, 37].

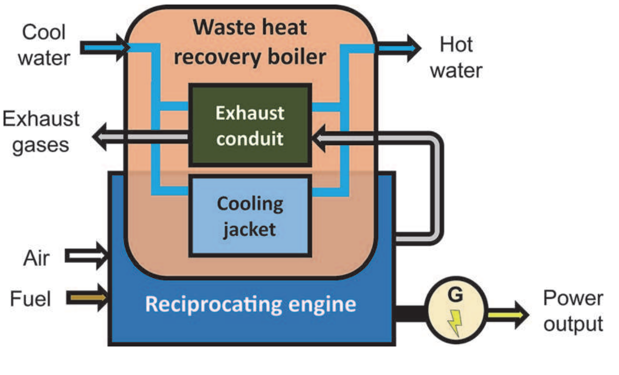

Figure 8.
Reciprocating engine co-generation plant.

Figure 9 illustrates the configuration of independent Brayton and Rankine cycle CHP plants.

In fuel cell-based CHP plants, instead of transforming thermal energy into mechanical energy to drive the shaft of a generator, fuel cells generate electrical power via an electrochemical reaction, which makes them more efficient. A schematic of a fuel cell stack working with hydrogen and oxygen is presented in **Figure 10**. Here, hydrogen (H_2) injected through the anode is separated into electrons and protons. Hydrogen protons travel through an electrolyte membrane to the cathode of an individual cell, where they combine with oxygen (O_2) and hydrogen electrons to produce water and heat. The electrical current produced by the flow of hydrogen electrons is forced through an electric circuit connecting anodes with cathodes of the fuel cells (i.e. current collector) to produce electrical power.

The operating temperature of a fuel cell may range from 80–1000°C depending on the electrolyte used [39]. Because of this, a cooling water system is required. Cooling water is circulated through the fuel cell stack, collecting heat and generating steam or hot water as a by-product of the process.

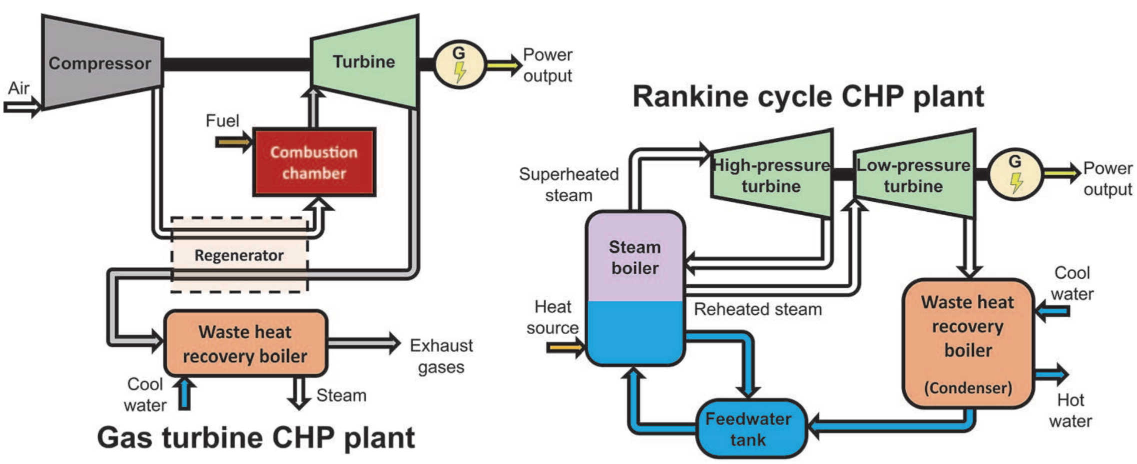

Figure 9.
Brayton and Rankine cycle co-generation plants.

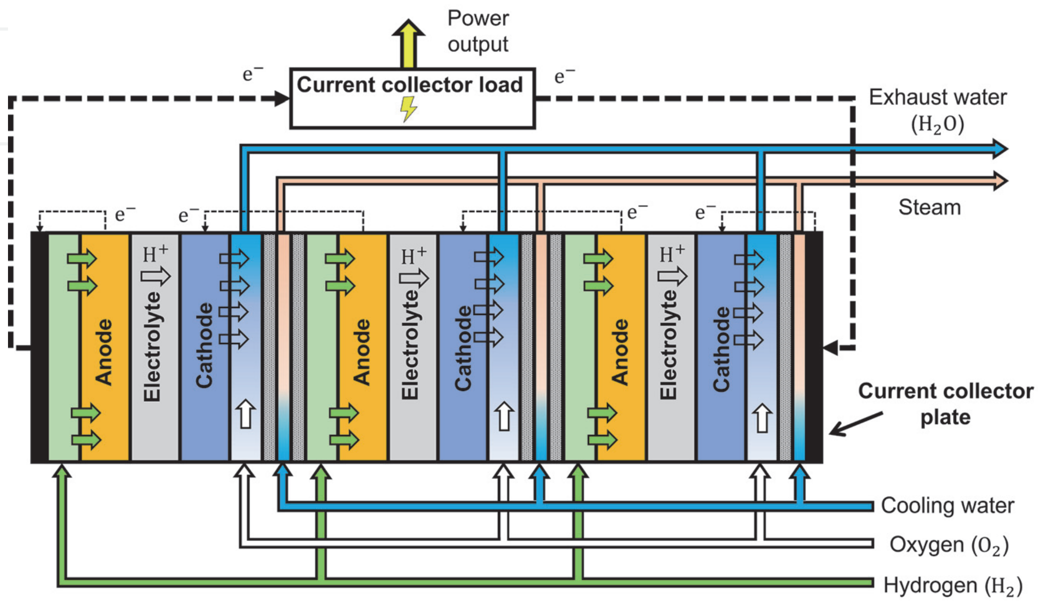

Figure 10.
Fuel cell-based co-generation plant.

3.3.2 Combined cooling, heat and power plants

A special case of co-generation is tri-generation, or combined cooling, heat and power (CCHP) generation. CCHP plants employ some electricity or heat generated by a CHP unit to produce chilled water. To this end, electrical or heat-driven chillers are used. Schematics illustrating the operation of CCHP plants are shown in **Figure 11**.

3.3.3 Control of co-generation power plants

Sensors and control loops are used in CHP plants to regulate their operation. Although the selection of control variables depends on the type of CHP plant, they may be either electrical power or heat-driven [40].

For electrical power led CHP plants, the control of electricity production is prioritised while heat is a by-product. The electrical power output is controlled and the water flow feeding the waste heat recovery boiler produces hot water at a specific temperature. Conversely, heat production is prioritised in heat led CHP plants, where the generated electricity is a by-product. A constant hot water flow at constant temperature is achieved in the waste heat recovery boiler by modifying the electrical power generation.

3.3.4 Performance indicators of co-generation and tri-generation power plants

In a co-generation power plant, the total input energy E_{in} is transformed into electrical energy W_{elec} and heating energy Q_{heat}. Performance of this process can be described in terms of electrical efficiency η_{elec} and thermal efficiency η_{th}:

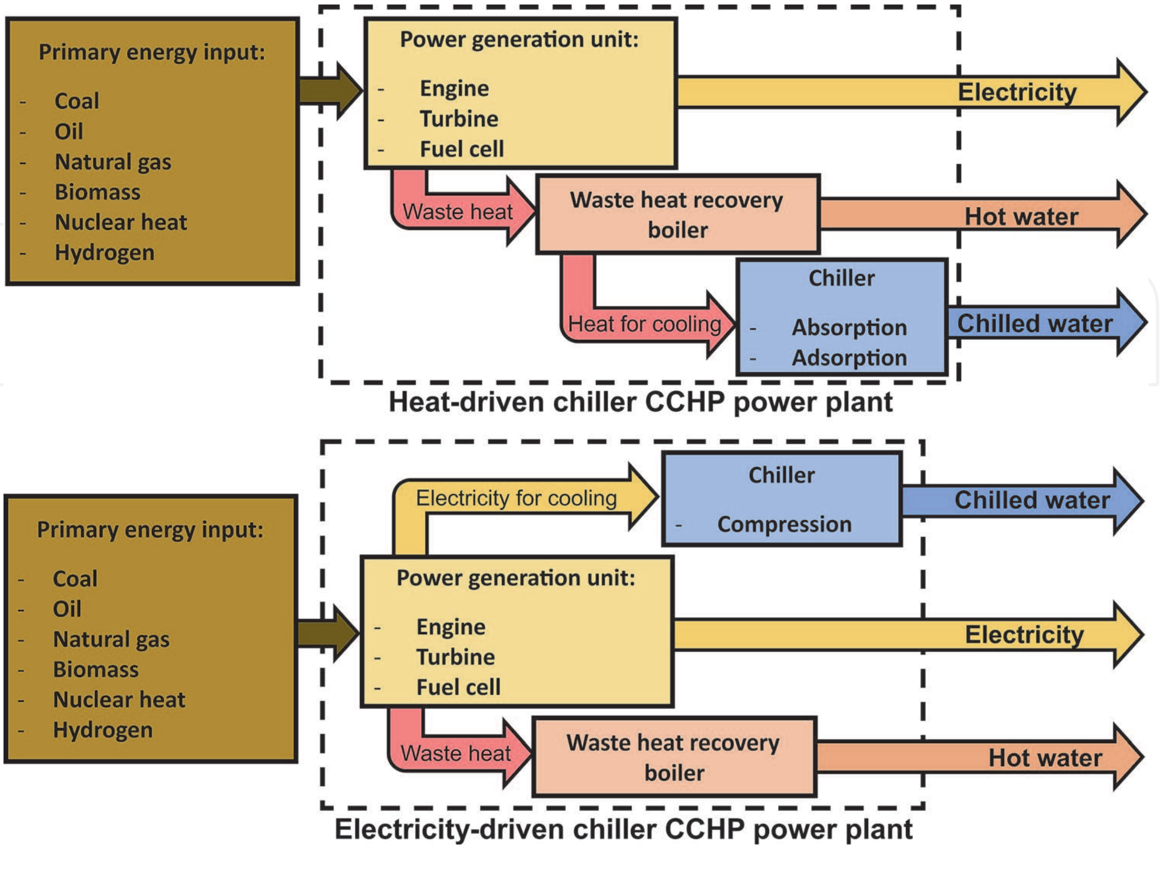

Figure 11.
Operation of tri-generation power plants.

$$\eta_{elect} = \frac{W_{elec}}{E_{in}}, \eta_{th} = \frac{Q_{heat}}{E_{in}} \tag{4}$$

The overall co-generation performance is normally quantified in primary energy savings (PES) achieved in comparison to the independent generation of electricity and heat [41, 42]. Although PES calculation may depend on national legislation [41], a direct calculation based on electrical and thermal efficiencies is given by

$$\text{PES}_{CHP} = \left(1 - \frac{1}{\eta_{elec,CHP}/\eta_{elec,SP} + \eta_{th,CHP}/\eta_{th,SP}}\right) \times 100 \tag{5}$$

where $\eta_{elec,CHP}$ and $\eta_{th,CHP}$ are the electrical and thermal efficiencies of the CHP plant, and $\eta_{elec,SP}$ and $\eta_{th,SP}$ the efficiencies for sperate production of electricity and heat.

Similarly, the performance of tri-generation plants is described by the cooling efficiencies of tri-generation $\eta_{cool,CCHP}$ and separate cooling production $\eta_{cool,SP}$:

$$\text{PES}_{CCHP} = \left(1 - \frac{1}{\eta_{elect,CCHP}/\eta_{elec,SP} + \eta_{th,CCHP}/\eta_{th,SP} + \eta_{cool,CCHP}/\eta_{cool,SP}}\right) \times 100 \tag{6}$$

where $\eta_{cool,CCHP}$ and $\eta_{cool,SP}$ depend on the type of chiller included in the CCHP plant (i.e. electrical, absorption or adsorption chiller). Effectively, the cooling efficiency of a CCHP plant is the product of the chiller's CoP and the electrical or thermal efficiency of the CHP unit. The calculations of $\eta_{cool,CCHP}$ and $\eta_{cool,SP}$ are given by

$$\eta_{cool,CCHP,elec} = CoP_{elec,CHP} \times \eta_{elec,CHP}, \ \eta_{cool,CCHP,abs/ads} = CoP_{abs/ads,CHP} \times \eta_{th,CHP} \tag{7}$$

$$\eta_{cool,SP,\ elec} = CoP_{elec,SP} \times \eta_{elec,SP}, \ \eta_{cool,SP,abs/ads} = CoP_{abs/ads,SP} \times \eta_{th,SP} \tag{8}$$

where subscripts $_{elec}$ and $_{abs/ads}$ denote the type of chiller.

3.4 Renewable energy sources and waste thermal energy recovery

3.4.1 Renewable electricity

Heating and cooling accounted for 49% of the total global energy consumption by the end of 2018, with an estimated 2% of this energy supplied by electricity from renewables [43]. RESs have gained importance in power production over the last decade, accounting for 27% of the global power generation in 2019 and 90% of the global power capacity increase in 2020. Although hydropower is still dominant, wind and solar photovoltaic (PV) are currently the leading technologies in growth.

Integrating electricity from RESs into thermal networks is aided by electric boilers and chillers. Another technology widely used is the electric heat pump—an essential component in new generations of DHC. Heat pumps work under the same operation principle as chillers and are either compression, absorption, or adsorption-based technologies. The main difference between a heat pump and a chiller is the ability of heat pumps to supply both cooling and heating. This is achieved by reversing the cycle in vapour compression chillers (see **Figure 5**) or exchanging the streams in the evaporator and condenser in absorption and adsorption chillers (**Figures 6** and 7). Thus, heat pumps may supply heating during winter and cooling during summer.

3.4.2 Geothermal heat and deep lake water cooling

The soil and local natural water reservoirs are important sources of thermal energy for heating and cooling. DHC systems can exploit existing local resources to significantly reduce electricity and gas consumption from national grids to drive boilers and chillers.

The heat produced at the Earth's core from nuclear reactions flows towards the surface, causing the ground temperature to vary with depth at an approximately constant rate of 30°C/km. This geothermal heat is exploited by extracting hot water from aquifers or using heat pumps to obtain heat from the shallow depth soil.

Although large power plants can use high temperature groundwater reservoirs to supply electricity to national grids, groundwater at temperatures below 100°C can be used for direct heating in local networks [44]. Heat exchangers are employed to subtract heat from the groundwater stream before it is reinjected to the ground.

For direct soil heat extraction or "geo-exchange", ground source heat pumps are used [45]. These consist of an electric heat pump connected to a water-filled pipe circuit buried into the ground to work as a heat exchanger between the soil and a water stream. Near the surface, the soil temperature varies significantly from season to season, but it remains relatively constant below 10 m [46]. Considering the ground temperature is higher than the outdoor temperature during winter and lower over the summer, the reversed operation capability of heat pumps is ideal to supply heating or cooling depending on the season of the year. These systems have proven to be suitable for heating cities and small communities in Denmark [47, 48].

Deep lake water cooling is the term adopted to identify the use of deep lakes, rivers or oceans to obtain free cooling from natural water bodies. Like groundwater systems, deep lake water cooling is achieved through a close or open heat transfer, using either heat exchangers or subtracting water directly from the bottom of the water bodies where the temperature is relatively constant. Examples include the district cooling systems in Paris and Ontario [9, 49].

3.4.3 Solar thermal systems

Unlike solar PV, solar thermal systems convert solar radiation directly into thermal energy. Solar collector panels (shown in **Figure 12**) are used to this end.

Based on the structure of the solar collector panel, solar collectors can be either flat-plate or evacuated tube collectors [50]. These panels are used to capture the solar radiation in a heat transfer medium, commonly water, which is displaced to a TES tank when the fluid reaches a temperature setpoint. The heat stored in the TES tank is later used for either heating or cooling purposes.

Solar thermal systems can be used together with solar PV cells to form solar hybrid photovoltaic-thermal (PV-T) collectors [50, 51]. Hybrid PV-T collectors are basically solar PV power plants which exploit the waste heat of solar PV generation. Thus, a solar hybrid PV-T collector is essentially a solar co-generation plant.

3.4.4 Waste thermal energy recovery and renewables integration through thermal energy storage

Thermal energy demand may be in a wide range of supplying temperatures. For example, power generation or industrial processes require heat from high-temperature fluids but generate significant waste heat. This differs from space heating or heat-driven refrigeration systems. The temperature difference between processes produces a thermal spectrum of energy use [52]. By adopting a cascaded heat supply system, an efficient use of the available thermal energy can be planned,

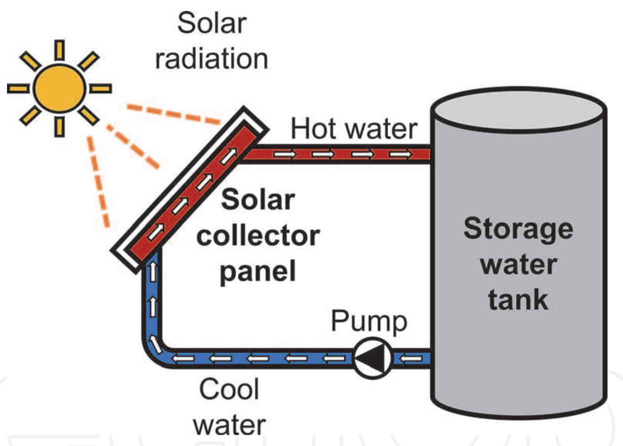

Figure 12.
Solar collector system.

where the waste thermal energy generated by a high-temperature range application can be recovered to supply other applications in a lower temperature range.

Industrial and commercial waste heat is an underutilised thermal energy resource with an enormous potential for DHC systems [53]. However, it is necessary to account for the temporary or geographical mismatch between waste thermal energy release and its demand. TES technologies are employed to this end, becoming crucial components when integrating recovered waste heat into thermal networks [54].

The use of TES elements is also important for the integration of RESs. Their intermittent nature is clearly exhibited in solar thermal systems, for which TES tanks are needed to collect as much energy as possible from the source while it is available. A further discussion on the different TES technologies can be found in Section 5.

4. Heating and cooling distribution technology

Distribution of heating and cooling from thermal energy sources to the final consumer can be achieved in a variety of manners. The distribution network and the ETS connecting a dwelling or installation are normally adapted to the needs of a customer and the availability of the sources. The different components and topologies of these two elements of DHC systems are revised next.

4.1 Distribution network

4.1.1 Pressure systems

The distribution network of a DHC system consists of an arrangement of underground pre-insulated pipelines filled with a heat transfer fluid (HTF). Although the vast majority use water as the HTF, CO_2-based DHC systems have been investigated [55, 56]. The distribution of thermal energy throughout the network involves a series of pressure systems to pump and effectively manage the thermal–hydraulic dynamics of the HTF.

The supply pressure system (SPS) is the primary system, which uses a pressure differential to move the HTF. It consists of several hydraulic pumps either centralised in a supply pressure station or distributed throughout the distribution network. A central supply pressure system (CSPS) is used for the HTF to provide a unidirectional flow path at each pipe segment of the network. Therefore, it is commonly adopted for networks with centralised thermal energy generation (CTEG) [57, 58]. Instead, a decentralised supply pressure system (DSPS) enables reversing the flow direction of the HTF. Two main DSPS configurations exist: a DSPS with distributed thermal energy generation (DTEG-DSPS) and a DSPS with distributed pumps at each ETS (ETS-DSPS) [10, 11, 59–63]. The flow paths for these systems are illustrated in **Figure 13**.

Most distribution networks are closed hydraulic circuits where the HTF follows a closed path in a confined space. Whenever the temperature of the HTF changes, the pressure of the whole network also changes. Expansion and pressurisation systems are used to avoid significant and potentially hazardous pressure changes [57, 58].

An expansion system contains several expansion vessels. These are filled with air or gas and HTF from the network, segregated by an expandable membrane to prevent them from mixing. The expansion system enables variations to the network's volume, where the distribution of thermal energy could be seen as a nearly isobaric process if the gas pressure does not significantly increase. The pressurisation system considers a mechanical pressurisation unit to guarantee a minimum pressure level in the network to prevent a phase change of the HTF at a low temperature.

4.1.2 Distribution network topologies

These refer to the pipe arrangement in a DHC system. Depending on the number of distribution lines, DHC systems can be one-pipe (1P), two-pipe (2P), three-pipe (3P) or four-pipe (4P) networks. In turn, these can be classified according to the configuration of the SPS and the directionality of the energy flow [64].

Conventional 3GDH and 3GDC systems are commonly 2P networks with a CSPS and a unidirectional thermal energy flow. Here, energy flow direction denotes the capacity of all ETSs to consume heating or cooling energy from the network. Systems with a bidirectional flow and a DSPS are instead associated with 5GDHC systems, where ETSs are active thermal energy producers or "prosumers" that supply and consume both heating and cooling. This results in a highly segmented network with different flow rates and temperatures at each pipe segment.

Open circuit networks without a return line are considered 1P networks. Here, the HTF is released directly to the environment instead of returning to the thermal energy source. Examples include networks directly supplied by rivers, lakes or geothermal water.

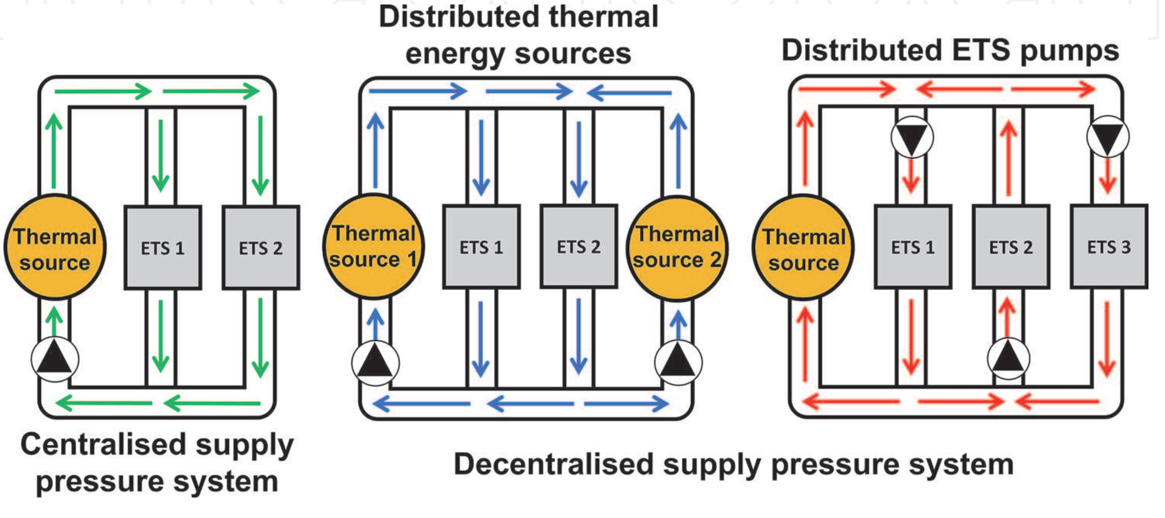

Figure 13.
Centralised and decentralised supply pressure systems.

Common return, recirculation and direct supply line connections are available for 3P networks, which aim to solve common problems with 2P networks. Common return line networks supply simultaneously heating and cooling through direct connections, incorporating a third line as a common return [65]. Recirculation of the supply line is necessary to guarantee a minimum supply temperature in 2P networks. To prevent significant thermal dissipation because of by-passing supply and return lines (due to their temperature difference), a direct recirculation line for the supply line is included [10, 11, 66, 67]. A direct supply line can be also added to 2P networks with operating temperatures close to ambient to supply heating or cooling with a higher or a lower temperature than in the other two pipelines [13, 64, 66].

4.2 Energy transfer stations

4.2.1 Station elements and connections

An ETS consists of two hydraulic circuits associated with the distribution network of the DHC system and the customers' installation. These circuits, primary and secondary, are linked via thermal–hydraulic couplers. The connections are either direct or indirect. An indirect connection is achieved by heat exchangers while a direct connection is obtained using hydraulic separators. Although direct connections are more efficient, indirect connections allow the primary and secondary sides to use a different HTF and prevent pollutants or the effects of damage or leakage to be transmitted from one side to the other [57].

Connections can be centralised or decentralised [22, 23]. In a centralised connection, a single heat transfer coupler is used. The thermal energy supplied from the primary to the secondary side is distributed through the customer's local installation. Decentralised connections use at least two heat transfer couplers: one for space heating or cooling and one for DHW.

ETSs may substantially differ in how thermal energy is subtracted from the distribution network. For ETS-DSPS networks, a local pump or a set of pumps creates a pressure differential to circulate HTF through the heat transfer couplers. Instead, for CSPS and DTEG-DSPS networks, a pressure boost is generated outside the ETS and control flow valves are placed at the inlet or outlet ports of the ETS. When a control flow valve opens, the pressure differential between the network's supply and return lines enables the HTF to flow. In bidirectional networks, this may require the use of a 3-way valve system to alternate between heating and cooling consumption [13]. Additionally, electric boilers, chillers and heat pumps may be used within the ETS to support the heating and cooling supply of a consumer.

A centralised ETS configuration for 3GDH systems is shown in **Figure 14** (left). This includes a central heat transfer coupling element for space heating and DHW production, a flow control valve in the outlet port, and a water tank for DHW on the secondary side. The diagram to the right shows an ETS-DSPS configuration typical of new generations of DHC systems. It includes a decentralised heat transfer connection for space heating or cooling and DHW, a heat pump and a 3-way valve system for flow reversal. Both ETSs include a heat meter to quantify thermal energy consumption.

4.2.2 Heat meters

Heat meters consist of temperature and flow sensors and an integration unit to calculate the thermal energy consumption of an ETS. The calculation is given by

$$E_{th} = \dot{V}\left(c_{p,sup}\rho_{sup}T_{sup} - c_{p,ret}\rho_{ret}T_{ret}\right)\Delta t \qquad (9)$$

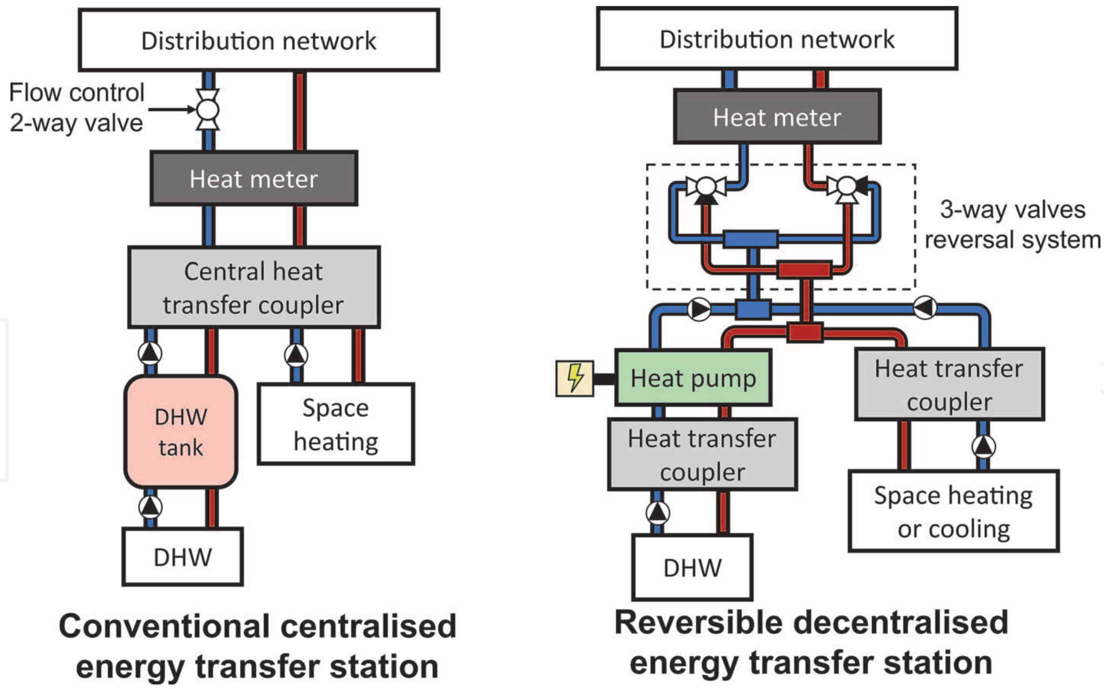

Figure 14.
Examples of energy transfer stations.

where the total thermal energy consumed E_{th} is obtained by integrating the heat flow difference between the supply and return lines at each time step Δt. In turn, such difference depends on the volumetric flow $\dot{V}$ passing through the ETS, the temperatures of the supply and return lines, T_{sup} and T_{ret}, and the specific heat value c_p and density ρ of the HTF corresponding to these temperatures [57, 58].

5. Thermal energy storage

An energy storage process can be considered in three stages: energy injection into the storage medium, energy holding and energy extraction, namely, charging, storing and discharging.

A wide variety of storage technologies have been developed. Their classification depends on the energy source (solar, geothermal, waste energy recovery), application (DHW, heating, cooling), location (centralised, distributed, underground, static, mobile), storage medium (air, water, soil, concrete, sand, salts), thermal energy collection system (active, passive), or the nature of thermal energy transfer couplers for charging or discharging storage devices (direct, indirect, both) [50, 54, 68–70].

5.1 Storage phenomena

5.1.1 Sensible heat storage systems

Sensible heat systems are based on the injection or extraction of heat into or from a storage medium to modify its enthalpy. Temperature levels are bounded to prevent a phase change of the medium. This enthalpy difference is called sensible heat.

The most common sensible heat TES units used in DHC systems are water-based [69]. They consist of insulated water tanks to prevent heat exchange between water and the environment during the storing stage and are used to store either heating or cooling energy.

The capacity of a medium to store thermal energy in the form of sensible heat is represented by its specific heat value c_p, which is the heat required to change the storage medium's temperature by 1°C per unit of mass. This relation is given by

$$\Delta H_{sens} = m_{st} c_p \Delta T_{st} \tag{10}$$

where a storage medium with a mass m_{st} exhibits a temperature difference ΔT_{st} resulting from a change in its enthalpy ΔH_{sens} [71].

5.1.2 Latent heat storage systems

Latent heat or phase change material (PCM) systems store more heat per unit of mass of the storage medium compared to sensible heat systems. Their application is widespread for cooling systems, where ice-liquid water storage is often used [69].

As in sensible heat systems, latent heat storage systems modify the enthalpy of the storage medium to store heat. As enthalpy changes by the addition or subtraction of heat, temperature of the medium also changes. This temperature variation stops at some point while the enthalpy keeps changing, resulting from a phase change of the medium. Such enthalpy difference at constant temperature is denominated latent heat, and it is reflected by a sudden change of the specific heat value of the medium.

Since latent heat storage systems consist of a two-phase storage medium, the enthalpy difference of the storage medium ΔH_{st} is equal to the addition of the sensible heat of both phases, namely ΔH_{sens}^{ph1} and ΔH_{sens}^{ph2}, and the latent heat H_{lat}:

$$\Delta H_{st} = \Delta H_{sens}^{ph1} + \Delta H_{sens}^{ph2} + H_{lat} \tag{11}$$

5.1.3 Thermochemical heat storage systems

These are classified depending on the phenomenon used for storage: chemical reactions and sorption processes. Through a reversible chemical reaction, a chemical is dissociated into and recombined from its components via endo and exothermic processes, storing and supplying heat accordingly. Absorption and adsorption bind a gas to an absorbent solution or a solid adsorber when heat is subtracted and release it when heat is added. These phenomena are represented by

$$R_1 + \text{Heat} \rightleftarrows R_2 + R_3 \tag{12}$$

where R_2 and R_3 are the gas and sorbent substance involved in sorption processes or the chemical products of a dissociative endothermic chemical reaction of R_1.

5.2 State-of-charge and storage efficiency

The total thermal energy H_{st} stored in a TES unit is estimated via temperature measurements at different points within the unit, discretising the storage volume in n nodes with an assumed uniformly distributed temperature [72, 73]:

$$H_{st} = \sum_{i=1}^{n} V_{st,i} \rho_i c_{p,i} T_{st,i} \tag{13}$$

This implies a summation of the internal energy of all nodes, where $V_{st,i}$ is the volume of the i-th node, $T_{st,i}$ the temperature measured in the node, and ρ_i and $c_{p,i}$ the density and the specific heat value of the storage medium at a temperature $T_{st,i}$.

Although H_{st} represents the total energy stored, only a portion of this energy can be used, limiting the storage capacity to minimum and maximum levels. The state-of-charge (SoC) is a dimensionless unit of the instantaneous available thermal energy in a TES unit, commonly given in percentage of maximum available energy or a value between 0 and 1 [74]. The SoC for a unit storing heating energy (SoC_{st}) is given by

$$SoC_{st} = \frac{H_{st} - H_{st}^{min}}{H_{st}^{cap}} = \frac{H_{st} - H_{st}^{min}}{H_{st}^{max} - H_{st}^{min}} \tag{14}$$

where H_{st} is the actual energy stored, H_{st}^{min} the minimum energy condition the unit can be discharged to, H_{st}^{max} the maximum energy condition the unit can be charged to, and H_{st}^{cap} the storage capacity of the unit. To calculate the SoC of a TES unit storing cooling energy, minimum and maximum energy terms are exchanged in (14).

Storing thermal energy entails an inherent energy loss. Thus, the performance of TES devices can be expressed in terms of the efficiency η_{st} of the energy storage process [69, 73]. For a generic TES unit storing heating energy, this is given by

$$\eta_{st} = \frac{H_{dis}}{H_{ch}} = \frac{H_{ch} - H_{loss}}{H_{ch}} \tag{15}$$

where H_{dis} is the energy subtracted during the discharging stage and H_{ch} the energy injected during the charging stage. The difference between the injected and subtracted energy is the energy loss H_{loss} during the storing stage.

6. Operation of district heating and cooling systems

6.1 Conventional control approach

DHC systems with CTEG and CSPS configurations are operated by a control system consisting of four cascaded control loops: the marginal pressure differential, supply temperature, flow, and thermal demand loops [57, 58, 67]. The marginal pressure differential control and the supply temperature control work in parallel at a network level, whereas the flow control and the thermal demand control operate at each ETS. **Figure 15** illustrates the four control loops in a conventional district heating system.

The marginal pressure differential control ensures the CSPS supplies enough differential pressure to meet the flow rate demand of HTF of all ETSs connected to the grid. It maintains a constant pressure differential between supply and return lines at the farthest point of the distribution network. The supply temperature control regulates the thermal energy flow feeding the distribution network from the generation plant to maintain a specific supply temperature setpoint. Thus, these two control loops ensure sufficient thermal energy is supplied to all ETSs in the network by feeding them with a flow rate of HTF at a constant temperature.

The flow control regulates the opening of the flow control valve to modify the flow rate of the HTF passing through the primary side of each ETS. As the HTF is fed at a constant temperature, its flow rate is directly proportional to the flow of

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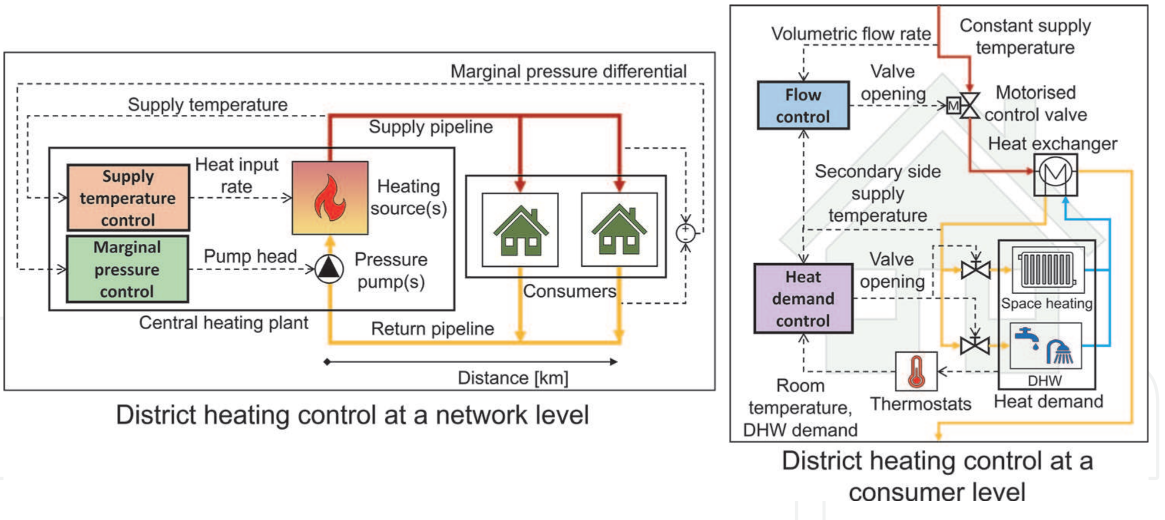

Figure 15.
Control of a conventional district heating system.

thermal energy entering the ETS. The control variable is selected depending on the type of thermal–hydraulic coupler used in each ETS. For ETSs working with heat exchangers, this is commonly the supply temperature at the secondary side [57, 58].

The thermal demand control is located at the lowest level of the cascaded control scheme, guaranteeing the thermal demand of each consumer is met according to the requirements for space heating, space cooling, DHW generation, or any other industrial or commercial process. As flow control guarantees a supply temperature of the ETS's secondary side, the requirements for thermal energy are regulated by the control of the final consuming elements within the consumer's premises (e.g. thermostatic radiator valves, flow control valves of DHW tanks, taps, showers).

6.2 Advanced control

Improvements to the conventional control approach previously discussed have been achieved. For instance, a supply temperature reset strategy to vary the supply temperature setpoint according to the ambient temperature increases the generation plant efficiency while decreasing thermal losses [57, 58]. Implementation of DSPS schemes, either DTEG-DSPS or ETS-DSPS, relieves the need for marginal pressure control [59–63]. In general, advanced control schemes have been a milestone for DHC systems as they mathematically optimise system operation through the coordinated management of thermal energy generation, storage, and distribution.

Advanced control schemes consider thermal load control as an additional element of a conventional control approach to optimise system operation [75]. Thermal load control is based on the operational flexibility of a thermal system and discussed next.

6.2.1 Operational flexibility

The stability of an energy network depends on the energy balance between supply and demand. This balance must be always fulfilled to prevent a deterioration of the system's performance. However, since the devices supplying and consuming thermal energy may cannot be operated as quickly or as frequently as the thermal energy demand changes, achieving energy balance is not easy. For example, the ramp-up or ramp-down of large thermal energy generation plants is slow, while the availability of RESs depends on weather conditions. Although some small-scale auxiliary devices can help maintain the energy balance, this comes at the expense of a higher utilisation of the different consuming or supplying devices in the network.

A definition of operational flexibility is provided in [75] as the ability to accelerate or delay the injection or extraction of energy into or from a system. For a thermal system, operational flexibility is mainly provided by energy storage elements. Although network pipelines and buildings have been used to provide flexibility [76, 77], the primary provision comes from TES units [78]. This concept is shown in **Figure 16**. TES units deal with the variations of thermal loads by storing thermal energy during periods when the supply is higher than demand and supplying this energy when the demand is higher than supply. The techniques to deal with load variations are known as load shaping [79].

6.2.2 Goals and challenges of advanced control

Advanced control focuses on the operational optimisation of a DHC system, which requires an optimal generation and distribution of thermal energy [75]. This entails:

- Selecting the most suitable generation method and prioritising energy dispatch from RESs against generation units fired by fossil fuels (thus supporting the decarbonisation of DHC systems).
- Implementing load shaping techniques to handle thermal load variations in the network and the intermittency of RESs.
- Decreasing operating temperatures in the distribution network to ambient temperature (or increasing for cooling) to reduce thermal losses.
- Provision of ancillary services by operating devices coupling electricity and thermal networks (i.e. CHP plants, electric boilers, compression chillers, heat pumps) to support balancing electrical energy generation and demand [80].

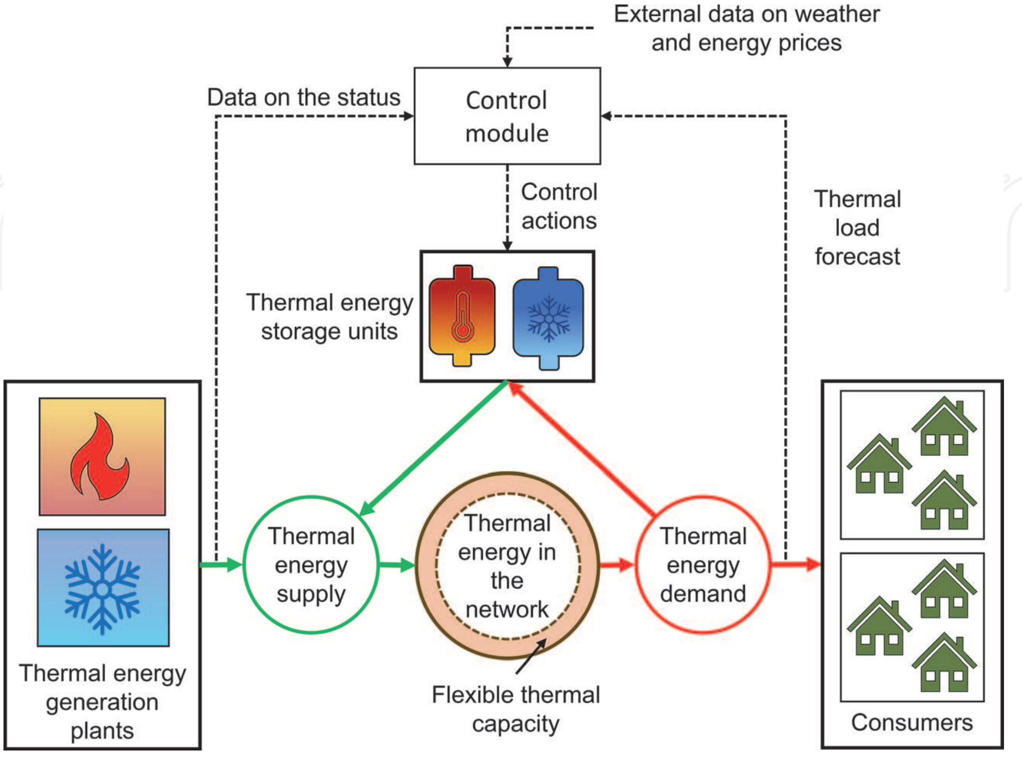

Figure 16.
Thermal load control based on operational flexibility.

The number of ETSs in DHC systems, the variability of thermal loads, thermal and electricity generation prices, and the complex dynamics in thermal networks constitute the main challenges preventing the adoption of advanced controls. DHC systems with several ETSs require many sensors to monitor and control the network's operation, increasing costs. Developing state estimators and new control strategies to reduce the amount of data may be key to relieve this challenge.

For an optimal operation of DHC systems, information on relevant operational variables is required. Temperatures and flow rates can be directly sensed and controlled. Still, the operation of thermal energy sources and TES units must be scheduled ahead for handling uncertainties on energy generation prices and thermal loads. Forecasts of prices and weather conditions, and models for determining the consumers' thermal loads are used to this end [81, 82].

The design of control systems requires a good understanding of the system's dynamics. Accurate and yet simple dynamic models of all the elements in the thermal networks are necessary, including generation plants, pipelines, storage units and thermal loads. These models can be used to reproduce the dynamic characteristics of the network (i.e. temperatures, pressures, flow rates, transport delays) and for quantifying the total operational flexibility available to operate the system [83–87].

6.2.3 Control configurations

Advanced control is categorised as central, distributed and hybrid control [75]. This classification depends on how the decision-making entities which operate the system are configured. In a central control topology, a centralised module interacts with all consumers, receiving online information of relevant operational variables. The central module combines this information with forecasts of system dynamics to generate and send control orders to optimise the operation of the system.

Distributed control, on the contrary, is based on multiple-decentralised modules operating the system. A multi-agent system architecture is commonly adopted [88, 89], where each agent may represent an element or a subsystem in the DHC network (e.g., producer, consumer, cluster of consumers, an energy storage plant). Agents communicate with each other, receiving information on the overall network conditions to optimise their operation locally.

Hybrid control integrates central and distributed control configurations. A central module optimises the operation of the entire system, tracing the conditions for an optimal thermal load in the network. This information is distributed to agents, which trade with each other to operate as close as possible to the optimal conditions [90].

6.2.4 Optimal operation

To guarantee an optimal operation of thermal networks, an optimisation process is performed in the short term by a central control module. This can be either an offline operational optimisation [91], or online model predictive control [92].

For DHC systems with distributed thermal energy sources, optimisation involves selecting energy sources to supply the network and quantify the best power output for each—known as unit commitment and economic dispatch, respectively [93, 94]. This should consider the flexibility provided by TES units to reduce costs [92].

Supply temperature control is a common practice to optimise system operation, aiming to reduce thermal losses in the network [91]. However, no specific control method has been firmly established for 5GDHC systems due to the highly variable working temperatures. A common approach bounding temperatures in the supply and return lines to maximum and minimum values has been adopted [12, 95].

7. Summary

In this chapter, DHC systems were described, including DHC system classification, technologies for thermal energy generation, distribution and energy storage, and topologies for distribution networks. In addition, the different components of thermal loads and the control strategies for the operation of a DHC system were reviewed.

The development and implementation of the latest generations of DHC systems is seen as an integral solution to satisfy local thermal energy demand. The potential of these systems to reduce carbon emissions by integrating local RESs and recovery of thermal energy from industrial and commercial activities, and an optimal energy generation and distribution represent a solid pathway to support the transition to sustainable local energy systems that many countries are aiming for.

The adoption of the thermal energy sources available locally, the increasingly complex dynamics resulting from implementing new topologies of ETSs and distribution networks, and the uncertainty in energy generation prices, local thermal loads variation, and intermittency of RESs make the optimal control of DHC systems highly challenging. Besides, the increasing number of coupling devices between the electricity grid and the local thermal networks requires a whole systems approach. A coordinated operation of local energy networks with different energy vectors and national energy systems is required, supporting each other in balancing energy supply and demand.

To deal with the challenges of implementing DHC systems, the development of mathematical models, analysis tools, forecasting methods, and the implementation of advanced controls are crucial to predict and study the dynamic interactions of the systems and to exploit the operational flexibility provided by TES units.

Abbreviations

5GDHC	5th generation of district heating and cooling
CCHP	Combined cooling, heat and power
CHP	Combined heat and power
CoP	Coefficient of performance
CSPS	Central supply pressure system
CTEG	Centralised thermal energy generation
DHC	District heating and cooling
DHW	Domestic hot water
DSPS	Decentralised supply pressure system
DTEG	Distributed thermal energy generation
ETS	Energy transfer station
GWP	Global warming potential
HTF	Heat transfer fluid
nGDC	n-th generation of district cooling
nGDH	n-th generation of district heating
PES	Primary energy savings
PV	Photovoltaic

PV-T	Photovoltaic-thermal
RES	Renewable energy source
SPS	Supply pressure system
TES	Thermal energy storage

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