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STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS AND MARKETS

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Contents

Abstract

This report is part of the Clean Energy Technology Observatory 2022 series on technologies and their integration into the energy system. It focuses on how district heating and cooling networks can be managed efficiently and how they can provide flexibility to the wider energy system. Frontrunner cases show that DHC networks can play a central role in future energy systems by offering flexibility to the power sector and by enabling a high integration of renewable energy sources. DHC networks can be a versatile asset for the wider energy system through the utilisation of certain technologies. For example, *advanced control technologies* make it possible to integrate multiple supply and demand points, optimise system efficiencies and maximise the use of renewables. *Thermal energy storage* technologies can cost-effectively store energy, making it possible to spread out the consumption of intermittent renewable production, while *combined heat and power* plants can be used to steer the production of both thermal energy and electricity towards both systems. The report describes the status of these technologies and shows the significant flexibility potential they can provide to the wider energy system.

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Executive summary

This report is part of the Clean Energy Technology Observatory 2022 series on technologies and their integration in the energy system. It focuses on how district heating and cooling (DHC) networks can be managed efficiently and how they can provide flexibility to the wider energy system. Frontrunner cases show that DHC networks can play a central role in future energy systems by offering flexibility to the power sector and by enabling a high integration of renewable energy sources (RES). DHC networks can be a versatile asset for the wider energy system through the utilisation of certain technologies. For example, *advanced control technologies* make it possible to integrate multiple supply and demand points, optimise system efficiencies and maximise the use of renewables. *Thermal energy storage* (TES) technologies can cost-effectively store energy, making it possible to spread out the consumption of intermittent RES production (i.e. solar and wind). *Large heat pumps* can use the surplus electricity to produce heat or cold, while *combined heat and power* (CHP) plants can be used to steer the production of both thermal energy and electricity towards both systems. Table 1 presents a SWOT analysis of these technologies, some of which are further explored in the report.

Smart and low-temperature DHC systems (often referred to as 4th generation DHC networks) expose the potential of interconnecting multiple energy supply sources and demand profiles. For example, these networks can efficiently reuse a higher share of waste heat and cold from sources like data centres, supermarkets, industry processes or wastewater. Furthermore, these systems can be an integrated part of the operation of smart energy systems, interconnecting the thermal, power and mobility sectors. The low supply temperatures make these systems more compatible with energy-efficient buildings. However, the control of conventional DHC networks, characterised by higher supply temperatures, can also offer valuable balancing services to the power sector and enable better optimization of the power generation plants.

DHC networks are not equally represented in all Member States and account for around 12% of the European Union's (EU's) total final heating and cooling demand. One of the key actions for a more integrated energy system, in the European Commission's Strategy for Energy System Integration, was therefore to "accelerate investment in smart, highly-efficient, renewables-based district heating and cooling networks"(1). The uptake of new DHC systems remains limited, but the climate mitigation needs and energy dependency concerns are triggering a growing interest.

Technology trends and opportunities for the EU:

- Digitalisation, big data and decreasing costs of certain technologies, make it easier to cost-effectively optimise the network operations while empowering the end-users. Smart meters (TRL 9), thermostats (TRL 9), and sensors (TRL 9) have all become much more intelligent and less expensive, enabling higher monitoring and control. At the same time, innovations such as artificial intelligence (AI) (TRL 3-6) and digital twins (TRL 3-7) make it possible to optimise the network based on real-time information. With the appropriate regulatory framework, new business models could appear, e.g. by incentivising end-users through demand response and thus reducing system costs and increasing the use of RES. Several challenges need to be addressed, including data security and privacy as well as questions about data ownership.
- TES is a key enabler for DHC networks enabling them to provide significant flexibility to the wider energy system. Short-term sensible TES solutions (e.g. storing heated water in a well-insulated tank) (TRL 9) are already commercially viable, and the longer-term TES solutions (TRL 5-8) using the same technology are gaining more traction. Latent (TRL 4-8) and thermochemical heat storage (TRL 1-6) have the potential to overcome some of the inherent limitations of the other TES technologies, as it offers the possibility of high energy density, high volume and high-temperature storage. The large or seasonal storage capacity of thermochemical storage systems, with very limited heat losses, makes it a potentially attractive option for future DHC systems. The solutions are, however, currently quite far from being commercially viable.

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1 European Commission's "EU strategy on energy system integration" [Website] Available: https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en

- Larger networks and system integration represent a great opportunity for the European Union's power and heating and cooling sectors. As the systems grow larger, for example in Copenhagen, Stockholm, and Helsinki, they have multiple thermal generation plants, which can offer great flexibility to the wider energy system. Advanced control and management of generators in multi-source systems can serve the same purpose as TES, except the energy is stored in the unburnt fuel.
- Reuse of waste heat, from industrial processes, data centres, wastewater, supermarkets, is a growing trend. Waste heat is sustainable and increasingly financially attractive to be reused for heat, cold and domestic hot water through the DHC system. For example, wastewater can be used as the heating source for heat pumps. There is an abundance of waste heat currently not being utilised across the EU and studies indicate this could meet most of the EU's space heating demand in the building sector (Heat Roadmap Europe, 2017). The evolvement of DHC systems with higher efficiencies and lower temperatures will make this solution even more efficient.

Table 1. SWOT summary of DHC and its control technologies.

Strengths	**Weaknesses**
• Provides relative inexpensive flexibility which enables the integration of variable renewable energy sources and the use of waste heat • Improves energy and resource efficiency • Supports sector coupling by integrating the electricity, heating, cooling, and transport sectors	• DHC networks are concentrated in a number of Member States, and it's close to non-existing in others, and account for just 12% of thermal energy consumption • Challenging to upgrade and construct DHC networks in densely built areas
Opportunities	**Threats**
• Value creation as it enables the utilisation of local and existing resources (e.g. waste heat and renewable energy) • The decreasing energy demand in buildings allows for lower-temperature networks and the integration of low-temperature renewables and waste heat • Synergies between various sectors and technologies • New business models valorising flexibility and thermal storage capacities	• A decreasing energy demand (due to energy renovations and behaviour changes) can be a risk to DHC investments • Cost-effectiveness of individual heating/cooling appliances • Limited competitiveness among DHC suppliers • Remaining questions on data security and privacy

Source: JRC compilation based on the analysis presented in this report

1 Introduction

Replacing fossil fuels with renewable energy sources (RES) is pivotal to achieving the EU's climate and energy targets set out in the European Green Deal (2). Traditionally, the district heating and cooling (DHC) and power sectors heavily relied on dispatchable generation capacity, meaning fossil-fuelled generation and cogeneration as well as nuclear power plants. The share of RES and waste heat in the systems is gradually increasing. In 2020, RES accounted for 23.1% of total energy use for heating and cooling and 37.5 % of the gross electricity consumption. However, the penetration of RES in heating and cooling differs significantly from country to country, from Sweden with 69% to Ireland with only 8%. Similarly, the RES in DHC systems alone, ranges from 2% in Poland to 68% in Lithuania (Toleikyte & Carlsson, 2021). The share of RES is expected to steadily increase, boosted by strengthened climate ambitions, improved competitiveness of RES technologies, as well as imminent energy security concerns.

Heating and cooling in buildings and industries account for half of the EU's energy consumption, with 75% still generated from fossil fuels. While district heating (DH) only represents 12% of the supply, the countries where this technology has been largely adopted (e.g. the Nordics) are among the best performers in decarbonising heating and cooling. In some EU Member States DH is well developed and central to their vision of a flexible, efficient and decarbonised energy system, while in others DH barely exists. Germany, Poland and the Nordic countries represent 68% (2018 data) of the EU's total DH final energy consumption (European Commission, 2022), while the use of DH in the Benelux and most south European countries is very limited. The DH final energy consumption across the EU.

District cooling (DC) is much less common in EU, with a total installed capacity of 7.74 (GW) and around 200 installations. Sweden represents 75% of the installed DC capacity (Pezzutto, et al., 2022). There is still a considerable untapped potential. DC systems not only allow more efficiency compared to individual solutions and access to sources such as waste heat, but they also help manage peak demands and therefore support electrification in other sectors, such as transport.

The EU aims to achieve a climate-neutral economy by 2050, with the intermediate target to reduce greenhouse gases by 55% by 2030. To speed up the reduction of gas consumption, the REPowerEU (3) plan recently proposed to increase the EU renewable energy target to 45%. A crucial element to achieve this is decarbonising the heating and cooling sector, where DHC plays a key role. As described in this report, DHC is one of the main infrastructures enabling higher use of RES and integration of different energy systems. The EU has established several strategies to facilitate the spread and improvement of DHC systems, including the EU strategy on energy system integration (4), the EU strategy on heating and cooling (5), and the Action plan on the digitalisation of the energy sector (6).

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2 European Commission "A European Green Deal" [Website] Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

3 European Commission "REPowerEU" [Website] Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

4 EU Energy System Integration Strategy, [COM(2020) 299 final]. Available: https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en

5 EU Heating and Cooling Strategy [COM(2016) 51]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en

6 Action plan on the digitalisation of the energy sector. Available: https://ec.europa.eu/info/news/action-plan-digitalisation-energy-sector-roadmap-launched-2021-jul-27_en

The EU has also developed a broad policy framework to facilitate the uptake of DHC and increase the share of RES in the thermal networks. The Energy Efficiency Directive (EED) ([7]) defines *efficient district heating and coolin*g (Art. 2) and requires Member States to conduct economic and geographic analyses to identify DHC potentials (Art. 14) ([8]). The Renewable Energy Directive (RED) sets out a target of an annual increase in the percentage of renewable heating and cooling (Art. 23) and sets an annual target for increasing the share of RES in DHC (Art. 24). RED also asks Member States to enable producers of energy from RES and from waste heat and cold to access DHC networks (also, Art. 24) ([9]). In addition, the European Performance of Buildings Directive (EPBD) ([10]) sets out several provisions to improve the efficiency of new and existing buildings, which is a prerequisite for lower-temperature DHC networks ([11]).

The EU has also enacted a number of strategic plans and platforms in which DHC is explored and supported. The European Strategic Energy Technology Plan ([12]) is advancing the deployment of low-carbon technologies, with, innovation platforms on renewable heating and cooling and smart networks for the energy transition, among others. Positive energy districts are one of many explored topics. The related European Partnership for Clean Energy Transition ([13]), co-supported by industry, public organisations, research and citizens' organisations, aims to accelerate the energy transition by enabling energy research and innovation on different levels. Focus areas of the multilateral partnership include renewables, DHC, energy storage and system integrations. Furthermore, the EU has launched a mission to have *100 climate-neutral and smart cities* by 2030. The Smart Cities Marketplace ([14]) supports this mission by offering knowledge, capacity-building support and facilitation of finance solutions for cities. Covenant of Mayors for Climate and Energy ([15]) brings together local and regional authorities, which commit to the EU's climate and energy objectives. Implements in European cities can use the platform to exchange experiences and views.

The EU also supports the uptake of smart and low-temperature DHC networks through research projects ([16]). Heat Roadmap Europe, THERMOS, COOL DH and 4DH are examples of projects looking at the potential of (ssmart) DHC systems, while STORM, TEMPO, OPTi and FLEXYNETS are examples of projects exploring intelligent control and optimisation strategies of DHC networks. OpenLAB, ARV, PROBONO, W.E.DISTRICT, and Syn.ikia are projects developing and testing innovative smart district solutions, in which DHC play a central role. Several projects focus on specific technologies, such as ReUseHeat on waste heat, SmartCHP on cogeneration, HEATLEAP looks at waste heat recovery through large heat pumps, while CREATE and COMTES focus on TES systems.

The DHC systems need to transform as traditional control strategies will no longer be able to effectively manage the increasingly complex heating and cooling supplies and more fragmented demand profiles. The DHC systems need to be intelligent and flexible to manage multiple generation sources, and enable the integration of RES, as well as waste heat from industries, supermarkets and data centres. Digitalisation and new technologies are making it possible to better control the temperatures and flows, enabling a higher integration of RES in the DHC system but also in the power and industry sectors.

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7 Energy Efficiency Directive [2018/2002, 2012/27/EU] Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

8 Efficient DHC is defined as systems using at least 50% RES, 50% waste heat, 75% cogenerated heat or 50% of a combination of such energy and heat

9 Renewable Energy Directive [2018/2001/EU, 2009/28/EC] Available: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

10 European Performance of Buildings Directive [2018/844/EU, 2010/31/EU] Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

11 A new report carried out for the European Commission provides a good overview of the policy framework for DHC, with a special focus on the RED recast (European Commission, 2022).

12 European Commission "Strategic Energy Technology Plan" [Website] Available: https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en

13 CETPartnership [Website] Available: https://cetpartnership.eu/

14 European Commission "Smart Cities Marketplace" [Website] Available: https://smart-cities-marketplace.ec.europa.eu/

15 Covenant of Mayors [Website] Available: https://www.eumayors.eu/en/

16 Many of the projects have received funding through the Horizon Europe and the LIFE programme.

How the management and control of DHC systems can help facilitate the introduction of intermittent RES and waste heat is discussed in this report. In contrast to oil and gas, intermittent RES only produce when the sun shines or the wind blows. This generates imbalances in the power and DHC systems, which if not managed, cause imbalances, inefficiencies and high costs. One underutilised source to mitigate these adverse effects lies in the DHC system, which can balance the system and offer relatively inexpensive storage solutions. Power-to-heat solutions, such as electric boilers and heat pumps, as well as combined heat and power (CHP), can unlock significant balancing services for the power sector. An integrated DHC system with advanced control can enable a large influx of RES and curtail the investments in additional power capacity of the electricity grids.

This first section outlines the concept of control of the thermal and power sectors, where we are now and how the systems are expected to evolve in the future. The second section describes the technology state of the art for five key sub-technologies, including Advanced control technologies (section 2.1), Thermal energy storage (section 2.2), and Combined heat and power (section 2.3).

1.1 Control of district heating and cooling networks

Management of the pressure, temperature and flow is needed to ensure a high efficiency of DHC systems and to enable a high share of variable RES. Traditionally, DHC networks have operated without any advanced control technologies. Conventional control is focusing on ensuring a sufficient supply and optimising the economic and environmental performance of the system (Schmidt, 2021). The ongoing transition towards a more complex system with a higher share of renewables and waste heat is requiring more sophisticated control strategies, to facilitate the more complex system efficiently. At the same time, digitalisation and technological innovations have made it a more advanced control possible, improving the reliability, sustainability and performance of the system (Schmidt, 2021).

The integration of different systems can enable potent synergies while increasing the necessity of control. The coupling of the DHC and power sectors can take place at different levels (i.e. national, centralised, and decentralised) in an energy system. This means that it can be provided through large heat generators feeding heat to thermal networks and then be delivered to the end users, or by small-scale power-to-heat technologies at the individual building level. The coupling is mainly enabled by the technologies using electricity to produce heat, those producing heat and power simultaneously, or even those producing electricity from heat, although the latter has a limited role in current energy systems. These two most relevant technology groups, representing the interface between thermal networks and the power system, are combined heat and power (CHP) and power-to-heat technologies (e.g. heat pumps and direct heaters).

The demand side can also be managed through various demand response strategies, which can be applied on both building and network levels. For example, buildings and thermal networks can act as energy buffers taking advantage of their thermal inertia. By doing so, they can provide passive storage and allow a certain degree of decoupling between supply and demand. As a result, they enable a more flexible operation of the generation technologies. The use of thermal inertia in buildings requires the involvement of individual consumers, while in thermal networks a more centralised control is sufficient. Thermal networks act as a natural demand aggregator bringing together the energy needs of multiple users. As a result, the DHC operator can act as a market player offering the energy and the balancing capacity to the electricity markets. The aggregation of individual power-to-heat consumers can also be activated for this purpose. However, the control required from the aggregator is much more complex than at the centralised level. Thermal energy storage (TES) is another potent flexibility source, which also can be applied on a centralised and decentralised level. It tends to be more cost effective to set up larger TES facilities, than to aggregate several small TES installations, as these installations allow larger load shifting capacities and for longer periods. In comparison with thermal inertia, TES offers the ability to shift demand over a longer time.

Waste heat from industrial processes can be a positive energy source for low-temperature DH networks, with a supply return of about 50-60C/25°C (Lund, et al., 2014). Depending on the level of temperature of the waste heat source and the level of temperature of the DHC network, whether the source will need an increase in temperature or not. For example, if the DH network works at 90°C and the waste heat is at 50°C this source is not directly useful. As waste heat is a place-fixed source of energy, the way to fix these situations is to increase the temperature with, for instance, heat pumps. In this case, a water loop will work with the waste energy source and with the evaporator of the heat pump and the DH network will use the condenser of the heat pump as an energy source.

Table 2 shows the main technologies and the role they can play on a centralised and decentralised level.

Table 2: Comparison of centralised and decentralised options.

Technology group	**Centralised**	**Decentralised**
Control of flexibility	One heat load pattern (thermal network) Easy aggregation of capacities to act as virtual power plants	Multiple heat load patterns (end consumers) Requires significant investments in digitalization to act as virtual power plants
Thermal energy storage	Larger capacities and storage periods Thermal network inertia Small buffers at consumer/neighbourhood level Building inertia depends on the system of the dwelling	Small buffers at consumer/neighbourhood level Building inertia depends on the system of the dwelling
Combined heat and power	Adaptive operation to heat and power requirements Larger overall efficiencies	Heat driven operation Overall performance determined by the amount of electricity that can be absorbed
Large heat pumps	Works best with low temp DHC More stable performance due to better quality heat sources (higher coefficient of performance) Used to upgrade low quality heat sources, such as certain waste heat sources	Works for any space heat application (performance subject to level of renovation of the building) Usually air-sourced. Coefficient of performance varies with outdoor air temperature

Source: JRC compilation based on previous studies.

Frontrunner cases illustrate how advanced control can bring real benefits to the local heating, cooling and power sectors. The below cases have mainly been derived from (European Commission, 2022), a report providing more detailed information and additional examples.

- The DHC network in Odense (DK) integrates several of the technologies discussed in this report. The DHC utilises multiple synergies across different sectors, such as data centres, power grids, thermal storage and large heat pumps. The DHC covers 97% of the heating demand in the city and the main sources are waste-fuelled CHP (34.5 %) and biomass (33.8 %). The CHP plants are coupled with sensible TES (water tank) to increase flexibility and optimise efficiency. The temperature of the TES is 95°C and has a storage capacity of 3.6 GWh, meaning it for example can dispatch 300 MW over 12 consecutive hours. Large heat pumps were integrated into the system to recover heat from other heat sources, such a large data centre of Odense. This is the largest project of waste heat recovery in Europe by the use of heat pumps, with a heating capacity of 44 MW.

- The DH facility in the city of Jelgava (LV), shows how it is possible to transform an old DH system and drastically reduce CO_2 emissions. The network provides heat to around 85% of the city's total consumption, which for a long time was achieved through gas-based boilers. However, in 2008 the whole DH system was revamped and two separate networks were interconnected. In addition, all heating plants were replaced by biomass CHP plants, achieving a decrease in CO_2 emissions by 70%.

- The DHC integration in the North-west of Scania (SE) is a great example of how system integration brings synergies. The DH systems in three small and medium-sized cities, Helsinborg, Landskrona and Lund, enable optimal heating production and balance between the cities. The heat provided by the networks is derived from the plant with the lowest production cost in real-time. Heating production stems mainly from waste heat and biomass-based generation.

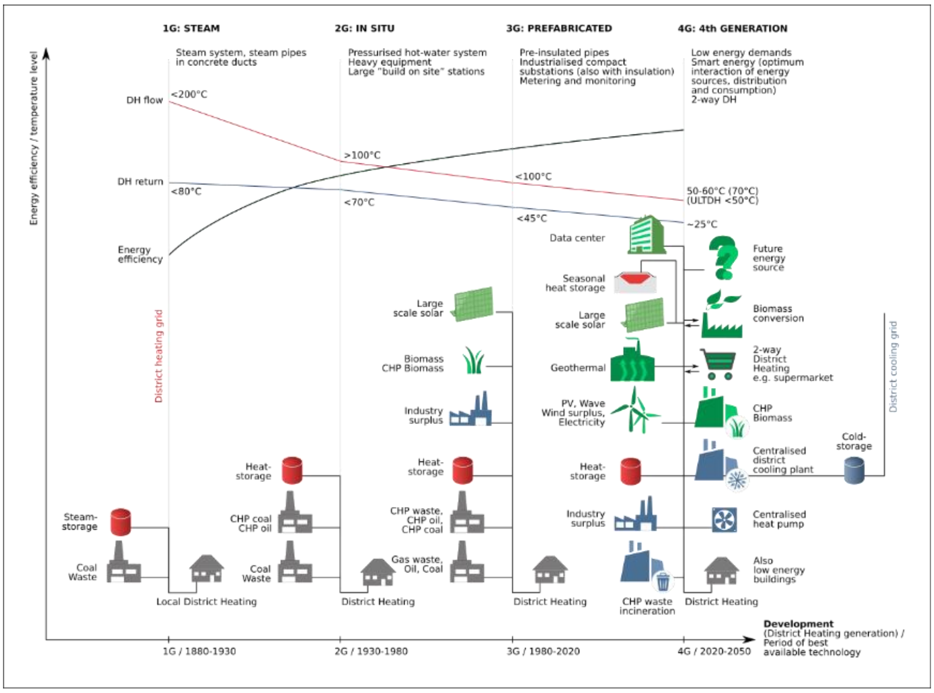
- The largest DC system is located in Paris (FR). The system used to cool the water of this DC network is a water/water set of chillers, which provide annually around 500 GWh of cooling energy. The source where the system can condense the heat is the Seine river. In addition, Paris is a good example of the implementation of RES and heat recovery installations for DH reaching a contribution of 50% taking into account heat recovery from a data centre, heat recovery from systems surrounding the city or a geothermal power plant.

1.2 District Heating and Cooling in the future

The frontrunner cases illustrate how DHC can play a key role in the EU's effort to decarbonise heating and cooling, and industry sectors. Furthermore, it can provide flexibility to the power sector, enabling a higher integration of variable RES and electric mobility, through advanced control and thermal storage solutions. The advanced control of DHC networks can also further help public authorities to support the climate targets, as it allows a certain level of steering of which heating and cooling resources are being deployed. In other words, with intelligent control techniques it is possible to maximise the usage of RES (Vandermeulen, et al., 2018). This section outlines some key trends and describes the role DHC can play in the future.

Advanced control is a prerequisite for effective system integration and cost-effective integration of RES. The future DHC networks won't all be homogenous but they will be characterised by advanced control systems, lower temperature and connections with the wider energy system. The optimal design of DHC systems depends on the neighbourhood characteristics (e.g. heating demand from buildings, and the existence of industries, data centres, and supermarkets), as well as the situation of the electricity grid. Figure 1 illustrates the evolvement of DHC systems from a simplistic high-heat inefficient system to a complex low-heat and highly efficient system.

Figure 1: 4th generation DHC system compared to predecessors



Source: Lund et al. 2014.

During the last decade, the concept of fourth-generation district heating (4GDH) has been used to describe advanced DH systems, characterised by lower temperatures and intelligent control technologies. Large heat sources for these systems include recycled heat from service sector/industrial processes having a considerable amount of residual heat, such as thermal power plants. Heat is also to a much larger extent obtained from RES. The overarching goal with these systems is to obtain fully decarbonised DH systems. These smart and low-temperature DH are becoming more common in urban areas, as lower temperatures enable higher efficiency in heat supply and allow the use of alternative and low-grade heat sources.

Low-temperature DH and the use of low-grade and renewable heat sources necessitate a larger role for digitalisation in heat networks. Compared to traditional networks, 4GDH networks are becoming increasingly complex, with added considerations including multiple heat production sources and end-users. 4GDH tends to be integrated with other energy sectors, like gas, electricity, or DC networks. Specifically, in combination with the addition of TES capacity, demand side management in DHC networks - i.e. adjusting the demand of energy to the actual production - is an enabling technology to increase variable RES. This kind of technology is often accompanied by other digital solutions, such as leak detection, predictive tool and smart controller on the demand side (DHC+ Technology Platform c/o Euroheat & Power , 2019).

While the 4GDH network is a natural evolution of its predecessor, the novel 5GDH is a new concept. DH networks have traditionally relied on centralized heat plants, which have converted the energy source and distributed useful thermal energy to the end-users. The idea with the 5GDH is to directly distribute the energy source to the end-users, who convert it to useful heat or cold through a local heat pump. The potential is considerably lower distribution losses and higher efficiencies (Gudmundsson & Thorsen, 2021).

The improved competitiveness of RES and waste heat, is another driver of change in DHC systems, in addition to digitalisation, energy policies and financial support schemes. Industry waste heat and low-grade renewable heat have not been adequately represented in DHC systems because it was cheaper to build fossil-based heat-only boilers than investing in power driven heat pumps to boost the temperature level of low grade heat sources. Now there is a paradigm shift, renewable power and the phase out of fossil fuels mean most of the traditional heat sources for existing DH systems are disappearing. This is pushing the industry to reinvent itself and innovate, not only to justify its existence in the future but also to make the rest of the energy system aware of the potential it has to support the future development of the energy system.

This paradigm shift, which is driving this development, is mainly characterised by:

1. Aggregated thermal demands are becoming a valuable commodity since it enables (1) load shifting for short to extended periods, (2) effective balancing services to the energy system, and (3) cost-effective development and utilization of low-grade thermal sources (e.g. waste heat).
2. Digitalisation in combination with optimization enable a higher utilization of resources, while reducing the cost of future RES-based energy systems.
3. Low-temperature heat sources, such as renewable and industrial waste heat, become central to ensure renewable powering of heat pumps.
4. In an electrified building thermal supply system, TES in combination with heat pumps and electric boilers, become a large energy battery, capable of utilizing considerable amounts of excess power generation in particularly favourable conditions for renewable power generation.
5. Multi-source and multi-fuel DHC systems offer the possibility of effective shifting between input energy supplies, which reduces energy dependencies of societies as well as provides exceptionally stable thermal energy costs for societies (Gudmundsson, 07.09.2022).

The following chapter describes and discusses some of the key technologies, and their technological maturity.

.

2 Technology State of the art and future developments and trends

This chapter describes three key technology groups, their status and potential and discusses how they contribute to increased control of DHC networks. The technology groups are (1) advanced control technologies, (2) thermal energy storage, and (3) combined heat and power.

2.1 Advanced control technologies

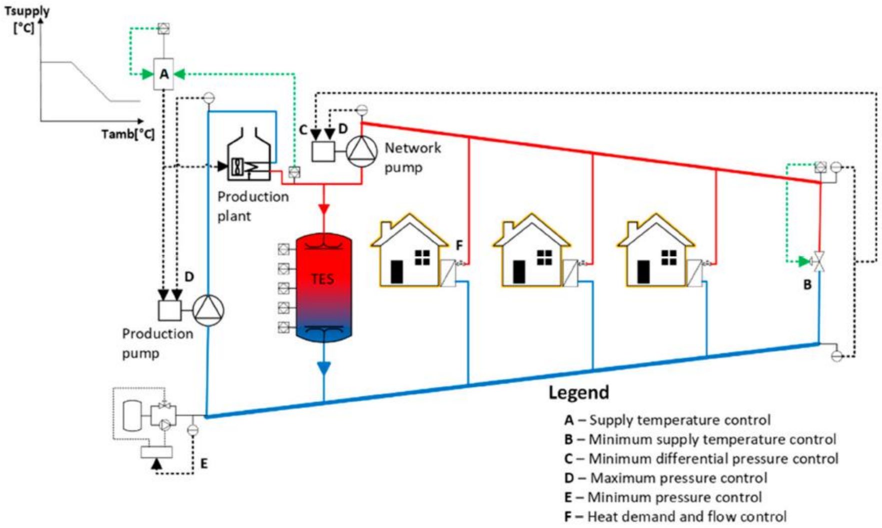
The recent trends in heat production in DHC, with an increase of renewables together with utilisation of waste heat from industries, make it less adjustable to thermal peak loads in the system. A high peak load is a problem because it (I) impacts the required system capacity, (II) increases cost as peak energy is more expensive, and (III) typically increases greenhouse gas emissions (GHG) as fossil fuels are often used to cover the peak load (Li, et al., 2021). New advanced control and management technologies make it possible to increase flexibility by better controlling the heating load (Frederiksen & Werner, 2013). In addition, new technologies have also made it easier to quickly adjust the heating demand in buildings and industries and by doing so also contribute to a more flexible system (e.g. through demand response (17)) (Romanchenko, et al., 2021). The management and control system of DHC and its interface technologies, large heat pumps, CHP, TES, and waste heat, can be utilised to balance the power grid and allow it to integrate a higher share of RES at a lower cost.

The management of traditional DHC networks comprises several decentralised control systems at the production and building levels, with limited interaction. Intelligent control and optimisation on a system level is still rather uncommon. The following section describes the classical and intelligent control technologies.

2.1.1.1 Classical control methods

Basic control strategies comprise the control of (A) supply temperature, (B) minimum supply temperature (also referred to as bypass control) (C) minimum differential pressure, (D) maximum pressure, (E) minimum pressure, and (F) the heat demand and flow, as shown Figure 2 (Buffa, et al., 2021). The DHC network is typically controlled on operator level (i.e. centrally) and at the sub-station level (i.e. distributed or neighbourhood level) (Vandermeulen, et al., 2018). In addition, new technologies make it possible to also control the energy demand on individual building level (Romanchenko, et al., 2021).

Figure 2: Basic control strategies in traditional DH systems.



Source: Buffa et. al. 2021.

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(17) Demand response is a solution to increase the system's adequacy and substantially reduce the need for investment in peaking generation, by shifting consumption away from times of high demand or using extra electricity if the grid is overloaded.

2.1.1.2 Intelligent control technologies

High-level of control is also a prerequisite for the forthcoming DHC systems, such as the 4GDHC as well as the ambient temperature alternative, commonly referred to as the 5GDHC, as they will need to enable a dynamic interaction with the wider system, absorb a higher share of intermittent RES and enable lower supply temperatures (or higher for district cooling) (Vandermeulen, et al., 2018). While conventional control methods use feedback loops and fixed parameters defined by an operator, intelligent control methods can learn and adjust throughout the process. Self-learning systems can optimize the control strategy during the operation. Intelligent control is a prerequisite for an effective low-temperature DHC system with multiple generation sources and fluctuating supply and demand.

Advanced management and control strategies can be described as the brain of the DHC system. Conventionally, the management of the DHC system was rather unsophisticated, with limited control abilities. The development of algorithms and technologies is rapidly growing to enhance the operation of the DHC system. One straightforward example is to model the district load forecasting based on certain indicators, such as weather and climate, indoor conditions, and building characteristics, which can enable an improvement of the design and operation of the system (Weiwu, et al., 2017). Another example is the *smart district heat network*, characterised by optimization of the heat load and intelligent control of the network (Grzegórska, et al., 2021). There is multiple heterogeneous advanced control strategies including model predictive control, mixed integer linear programming and multi-agent systems, which all have proven effective in reducing operational cost, energy consumption and peak loads (Buffa, et al., 2021).

Several EU projects have developed solutions for smart control of DHC networks. The STORM controller originated as a Horizon 2020 project and is now a market-ready product offering to reduce peak load and network temperatures. Their dynamic control solution builds on data-driven algorithms include an energy forecaster, operation optimization planner and demand side management tracker (Grzegórska, et al., 2021) (18). Another example is the Horizon 2020 project FLEXYNETS, a project integrating multiple generation sources by managing energy at different temperature levels and assuring optimized exergy exploitation (19).

Machine learning is a type of artificial intelligence allowing software to become more and more accurate by learning how something works and usually behaves. In DHC networks, machine learning is used to forecast the energy demand (20), which has the potential to allow for higher production flexibility that can be used to maximise the use of RES (Mbiydzenyuy, et al., 2021). In addition, the forecasting of energy demand is needed to manage the generation of on-site RES and the usage of storage systems in DHC networks (Saloux & Candanedo, 2018). Machine learning is a technology that keeps evolving, just as its applicability for management of DHC network. A recent paper outlines several barriers hampering the utilisation of machine learning in DH, including lack of data, data ownership regulations, unclear/unfavourable ground for new business models, lack of incentives for DH industry to change, diverse ownership structures of the networks and a lack of cross-disciplinary cooperation (Mbiydzenyuy, et al., 2021).

Artificial intelligence here refers to software automatically taking decisions based on available information. In a DHC network, the self-learning data-driven algorithms can, for example, optimise the performance of the system and increase the usage of RES, due to enabled capabilities such as forecasting the energy demand, detecting anomalies, predicting maintenance needs and improving the planning of DHC systems (Zdravkovic, et al., 2021). Several energy companies have applied artificial intelligence to optimise the performance of DHC (21).

These solutions can optimise the DHC operation and enable future systems to run more effectively and smoothly interact with the wider energy system.

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18 STORM District Energy Controller builds on scientific research carried out by VITO/EnergyVille, conducted in the Horizon 2020 project 'STORM – Self-organizing Thermal Operational Resource Management". https://stormcontroller.eu/en

19 Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS. A Horizon 2020 project. https://cordis.europa.eu/project/id/649820

20 It can also be used for other purposes, such as detecting anomalies in the system.

21 The examples include Vattenfall (in Gustavsberg, Sweden) and Leanheat (in Espoo, Finland).

2.1.1.3 Other supporting technologies

The control and management of DHC networks is not one single technology. Control of flexibility is a collective term for technologies contributing to more advanced control, which enables effective and flexible management of networks. These technologies include sensors, smart meters, thermostats, digital twins, artificial intelligence and machine learning. These technologies are all somewhat mature and most of them have been demonstrated in projects (22) and utilised in business models (23). The section below briefly describes their area of use and their current maturity level.

Sensors are a device that records a physical occurrence, such as heat load in a DHC network, and reports this data. In other words, sensors collect data on what is going on in the system. The data is a prerequisite for better monitoring and more advanced strategies. The information collected through sensors can be increased through the analysis of the data in combination with other information sources and data sets. While sensors are a very mature technology, innovations are trying to improve their usability and applicability. For example, Danish researchers are working to "develop intelligent, battery-less sensors (24) that communicate wirelessly to an autonomous cloud-based monitoring system", to reduce leakages and heat losses in DH systems (25). Possible areas for innovation include self-learning sensors, and improvement of the chip and wireless connections (26).

The *Smart meter* is a device recording the energy consumption of electricity, heat and cold in a building. It is a key technology in a smart grid/DHC system, as it can provide close to real-time feedback on energy consumption, and enable customers to engage in demand response models (i.e. shift consumption from peak demand periods). One EU directive (27) mandates the Member States to roll our smart meters for electricity and gas if its cost-beneficial to do so, and a report from 2020, estimates that by 2024 close to 225 million smart meters for electricity and 51 million for gas will be rolled out in the EU (European Commission, Directorate-General for Energy, Alaton, C., Tounquet, F., 2020). The EU also requires buildings connected to a DH network to be equipped with smart meter devices where feasible (28). While smart meters are primarily used for electricity consumption, it's applicability for DHC is clear. Smart meters provide a detailed record of the energy consumption of a building, which, for example, can be used to optimise the DHC temperature control at the production site (Bergsteinsson, et al., 2021).

Smart meters can also allow the end-users to access real-time information on energy usage and the share of RES at that specific point in time, which can increase awareness and more active participation. Smart meter is a mature technology with more than 200 million units installed in the EU (most for electricity). The main innovation potential lies in how smart meters and their data can be used to facilitate more effective energy systems and in new business models.

Digital twin (29) is a virtual representation of a physical system, with the capability of dynamically modelling all relevant components. The solution can, for example, be used when planning a DHC network as it can model the whole system performance and changes to it, such as improved energy performance of the buildings, integration of more variable RES, impact of future expansions of the system, or the behaviour and the impact of decentralised heat pumps and other future heat supply facilities. The digital twin solution can help the planner optimise the DHC network (30). Furthermore, the data in the digital twin can be updated real-time, giving the operator an up-to-date and accurate depiction of what is happening in the DHC.

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22 Examples include the H2020 projects STORM – Self-organizing Thermal Operational Resource Management, OPTiOptimisation of District Heating Cooling systems, and Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS.

23 Examples include Danfoss' Leanheat and SAM DISTRICT ENERGY and Gradyent.

24 The smart meters intend to they intend to rely on energy harvesting from the DH grid (temperature difference). As the communication they consider is sporadic capacitors may be sufficient for running the communication bursts.

25 Aarhus University "Smart sensors to provide real time data for optimized operation of the district heating grid" [Website] Available: https://ingenioer.au.dk/en/current/news/view/artikel/smart-sensors-to-provide-real-time-data-for-optimized-operation-of-the-district-heating-grid

26 Sentech. Future sensor technology: 21 expected trends. https://www.sentech.nl/en/rd-engineer/21-sensor-technology-future-trends/

27 2009/72/EC Electricity Directive and the 2009/73/EC Gas Directive

28 Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency (EED)

29 Other more elementary IT simulation and monitoring solutions are also used with a similar purpose.

30 Several business models use digital twins, including heatbeat and Gradyent.

2.1.2 Technology readiness level

This section outlines an indication of the technological readiness level (TRL) for the described sub-technologies. Please note the TRL can differ depending on the specific use of the technology and the numbers should only been seen as an indication of the technological readiness level.

Advanced management and control: No data available.

Machine learning/artificial intelligence: The TRL for energy-related AI ranges from 3 to 6. The topics assessed in the report (Quest, et al., 2022) are not directly linked to DHC control and management but they have similar characteristics. The energy-topics include energy consumption optimisation (TRL=6), consumer flexibility assessment (TRL=3), EV charging optimisation (TRL=4) and Battery charging control (TRL=4).

Digital twins: a recent study summarising the TRL of digital twins in different *Smart Cities and Urban Spaces* projects, concluded that the TRL level ranges from 3 to 7. The study also concludes that to reach its full potential several issues need to be addressed, including costs, information complexity, lack of standards and issues related to cybersecurity (Botín-Sanabria, et al., 2022).

Sensors: a mature technology which has been on the market for a considerable time, with a TRL of 9. Innovation tends to focus on new areas of applicability and ways to use the collected data.

Smart meters: a mature technology with around 200 million installations across the EU, with a TRL of 9.

Table 3: Indication of TRL of advanced control technologies

Technology/technology group	**TRL**
Machine learning/artificial intelligence	3-6
Digital twins	3-7
Sensors	9
Smart meters	9

Source: Compilation based on the above listed sources

2.1.3 Technology Cost – Present and Potential Future Trends

The sub-technologies described in this chapter are very diverse and difficult to fully describe. It is clear that the cost for several of these technologies are rapidly decreasing, while innovative and more effective solutions (e.g. to collect data, analyse data, automatize control) and new areas of applicability (waste heat, server halls, shopping centres etc.) are constantly explored.

Cost projection:

Sensors: between 2004 and 2018, the cost of sensors decreased by around two-thirds, to 0.38 Euro (31) (Microsoft, 2018). While no data is available, the market indicates there has been a steep increase in the cost of sensors and other smart technologies during 2021 and the beginning of 2022 (Gudmundsson, 07.09.2022).

Smart meters: The cost for a typical smart meter is estimated to be around €180 and €200, on average in the EU (32). While smart meters are not yet widespread in DHC systems in most countries, there are pilot projects showcasing its value to increase control (European Commission, 2022) (Bergsteinsson, et al., 2021). A recent report concluded the roll outs of smart DHC meters are only recorded in eight countries (33). In Iceland and Denmark, “the roll out is mainly driven by DHC-companies without any obligation to install smart meters”, where the installations enables an optimisation of the DHC system. Smart meter allows for better monitoring and understanding, as well as control of flow temperatures (European Commission, 2022).

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(31) The US Dollar ($) has been converted to Euro (€) according to the average exchange rate mid-2018, the time the report was launched, where 1 USD was worth 0.85839 EUR.

(32) European Commission, “Smart grids and meters” [Website] Available: https://energy.ec.europa.eu/topics/markets-and-consumers/smart-grids-and-meters_en

(33) Belgium, Denmark, Estonia, Finland, France, Lithuania, Poland and Iceland

Given the heterogeneity of advanced control and management technologies, it is difficult to estimate the installed capacity. However, it is safe to conclude that the market penetration of the most advanced controlling systems is still limited across the EU. The majority of business models and DHC operators exploiting these technologies are located in the Nordics and Benelux countries.

When the roll-out of smart meters is completed, the infrastructure will collect real-consumption data on heat usage in the majority of European household. In other words, the DHC utilities will receive an abundance of data on their customers' heat consumption. Currently, the majority of DHC utilities are not aware of how to use these data in the daily control and operation of the DHC network. They lack tools, methods and resources to discover the knowledge about the demand side captured in the data (e.g. size and timing of peak consumption for individual users, load profile characteristics, details on the temperature of return water). Indeed, research work on smart heat data is still in its infancy compared to the extensive work on smart electricity data.

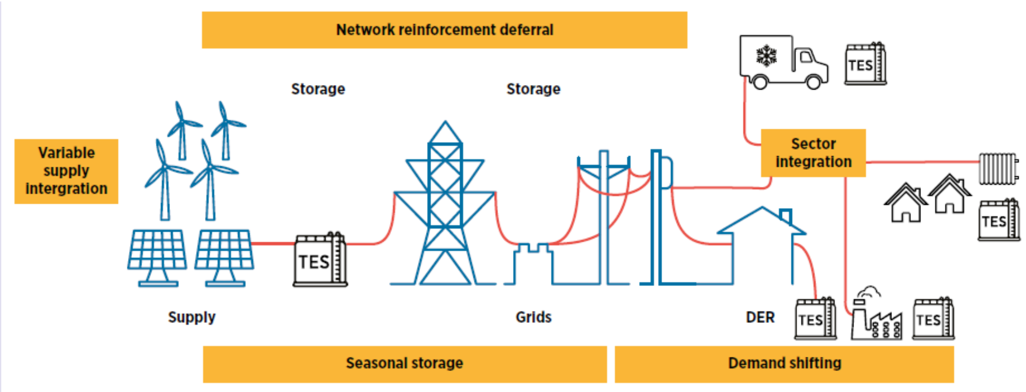
2.2 Thermal Energy Storage

TES technologies can contribute to a flexible DHC and power system, and thus enable the integration of a high share of variable RES. TES stores thermal energy so it can be used at a later time and by doing so offers a stress mitigating effect on the systems, which enables a higher integration of variable RES. Storing thermal energy in a medium, such as water, decouples the heating and cooling demand from the power generation and supply, which allows the DHC system to operate more effectively. Despite the fact they can play a key role in the EU's decarbonisation push, the potential has often been overlooked.

Coupling TES to DHC brings several benefits to the system. First, it enables peak shaving and enables a higher integration of variable RES. Second, TES offers relative inexpensive storage of energy, as thermal storage solutions are more cost-effective than electric alternatives and have a larger storage capacity. Third, it optimises the performance of the DHC system with both emission and cost reductions. It also allows for a reduced capacity increase due to more variable RES and newly connected customers (Guelpa & Verda, 2019). Fourth, an almost unique ability is some types of TES offer the possibility of seasonal storage. The surplus energy produced during the summer (e.g. by solar PV) can then be used to heat buildings in the winter. Fifth, TES increases the possibility to control the DHC and its interaction with industry and the power sector. TES makes it, for example, possible for CHP plants to produce electricity when the prices are higher. Sixth, TES can take on the role of an emergency supply for critical consumers if strategically located, e.g., at hospital premises. Finally, it provides a back-up to the system in the time of an undesired event, such as pump failure of leakages (Guelpa & Verda, 2019).

The deployment of large heat storage in DHC networks can provide considerable flexibility to the power grid. Large/seasonal TES will, in principle, be able to capture all the excess power generated by wind and solar power and store it for a longer time, days, weeks or even months. While large TES, can store thermal energy over a whole season, a more rapid charging and discharging cycle improves the effectiveness and cost-effectiveness of the system. In future RES-based energy system, the utilisation of large TES is important to make use of all the variable RES production. Further, direct connected water-based TES will have discharger capacities more or less equal to the pipe capacity connecting them, which implies a considerable discharge capacity. Figure 3 illustrates the basic idea of TES in a dynamic and integrated energy system.

Figure 3: Role of thermal energy storage in providing flexibility to DHC and power sectors. Note: DER = distributed energy resources.

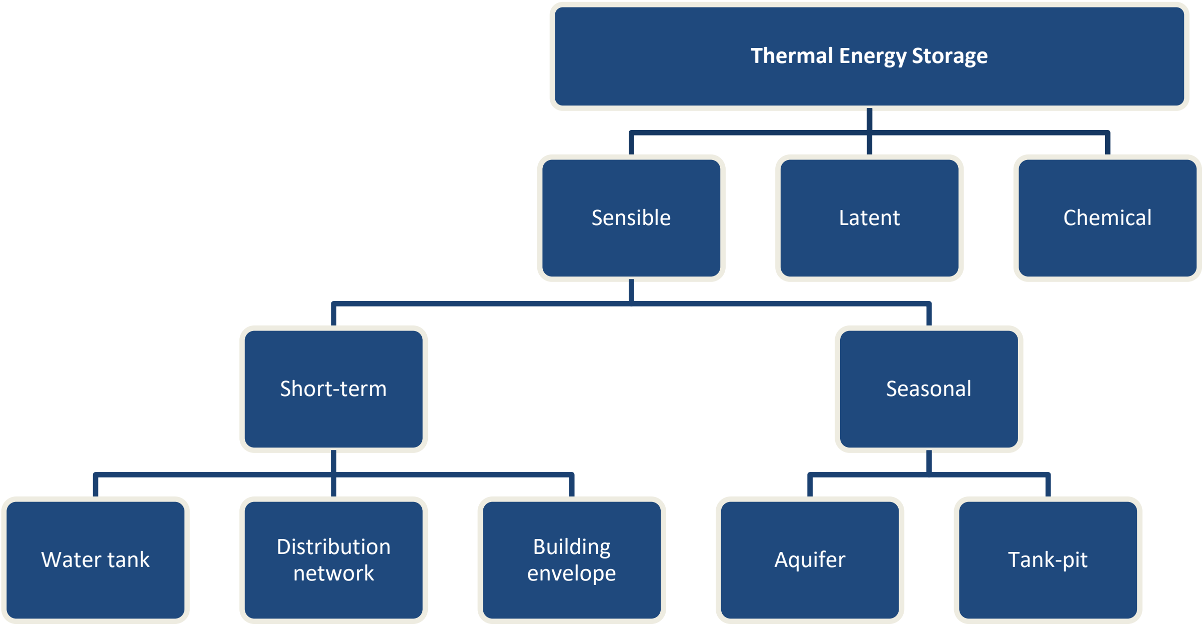


Source: IRENA, 2020.

The industry sector can also benefit from TES applications. The sector is characterised by its energy-intensive processes, where TES technologies can facilitate its wider electrification due to the wide temperature operating range in storage mediums. With TES technologies reaching over 500°C, such as chemical looping and solid state, the industrial sector can manage its energy demand by storing low-cost energy which later can be used for peak loads, while also guaranteeing high temperature supply for its processes (IRENA, 2020).

TES comprises several different technologies with various abilities and potentials. Figure 4 illustrates the most common TES categories and technologies. The three overarching categories are sensible, latent and chemical heat and cold storage.

Figure 4: Illustration of the common TES technologies. The illustration is a simplification and does only intend to depict the TES technologies discussed in this paper.

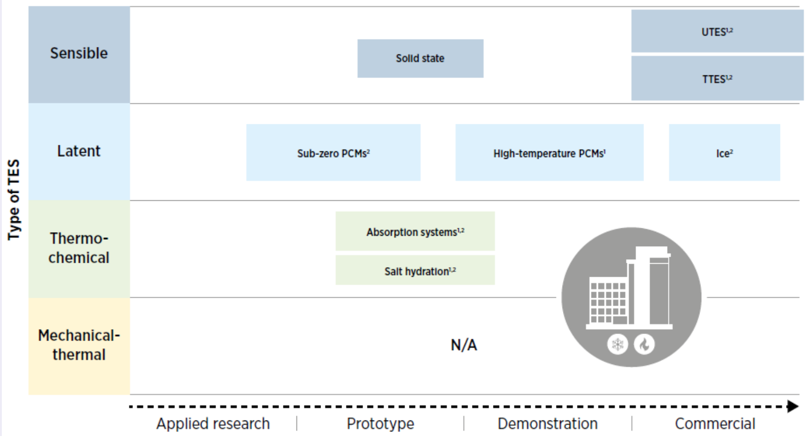


Source: JRC compilation

2.2.1 Technology readiness level

Figure 5 shows the commercial readiness of different TES technologies according to IRENA's classification. The sensible solutions (e.g. storing heat in water) are not particularly complicated technologies. Storing cold in ice is a commercially effective way to preserve cold. The more complicated technologies and materials, such as high-temperature phase changing materials (PCM) or salt hydrations, are not yet commercially viable solutions.

Figure 5: Commercial readiness of different TES solutions.



(1) UTES = underground thermal energy storage. TTES = Tank thermal energy storage.

Source: IRENA, 2020.

2.2.1.1 *Short and medium term sensible storage*

Sensible heat storage is the most widely used daily storage solution in DHC networks, with water primarily used as the storage medium. This is a mature and cost-effective technology with heat storage density compared to alternative solutions. Sensible storage tanks can be 50-100 times cheaper than electric storage (Hennessy, et al., 2019). This section will describe the status of three short-term sensible storage technologies; water tank, distribution network and building material. It will also describe two seasonal sensible storage technologies; tank and pit, and aquifer.

Distribution network. One sensible TES solution is simply to increase the temperature of the water flowing in the DH network pipes. By doing so, the distribution network itself becomes storage of thermal energy, which can be used to frontload the system. The storage capacity depends on the size and the possibility to control the temperatures of the network. This way of storing requires smart technologies to assure the full exploitation of the pipeline storage capacity and to guarantee the quality of the heat supply to consumers. As the temperature of the fluid increase, the pressure is going to increase because of the internal expansion of the fluid. Maximum admissible temperatures and pressures of the materials must be checked (Lund, 2018). Using the existing medium as a storage solution requires relatively small investments but the storage capacity often ranges from 1-3 hours depending on the size of the distribution pipeline. Studies have shown that a control strategy together with the inherent storage of DH systems can reduce system costs and mitigate daily peaks in the system (Kouhia, et al., 2019) (Basciotti, et al., 2011). The TRL is 9 (Guelpa & Verda, 2019) and while the innovation potential is limited, it's a proven technology that still is underutilised.

Building envelope. Another passive storage solution is to store heat in the DHC-connected building envelopes, as the materials of the buildings can act as thermal storage. This is particularly relevant for highly efficient buildings where thermal losses are limited. The storage capacity is likely ranging from 2-4 hours before comfort starts to be noticeably impacted. As with distributional water in DH systems, studies have shown that a control strategy together with the inherent storage of buildings can reduce peaks in the system (Guelpa, et al., 2018). The storage capacity depends on the building size, the properties of the materials and the allowable temperature ranges. The option of using the inertia of buildings requires more advanced digitalisation compared to the thermal network option since multiple buildings with different properties and heat loads must be coordinated. While distributional network storage is currently easier to exploit than building envelopes, the increased control abilities can make this solution more viable in the future.

Water tank. The most common storage technology is to store hot or cold water in an insulated tank. Large water tanks are quite common in DHC networks with the ability to store an abundance of electricity, waste heat or variable RES (e.g. solar collector) directly. Together with CHP and HP, water tank storage enables dynamic control of DHC and its interaction with the power sector. Central water tanks are typically designed for perhaps 10 hours and up to 24 hours of decoupling of heat demand from power generation in CHP plants. Some larger water tanks can store heat for a couple of weeks. The TRL is 9 and due to its cost-effectiveness, it is the most common storage solution in DHC networks. The ongoing innovation focuses on improving the insulation of the water tank, to prolong the storage's ability to keep the heat or cold (Sarbu & Sebarchievici, 2018).

Table 4: Indication of TRL of short and medium sensible TES technologies

Technology/technology group	**TRL**
Water tank	9
Distribution network	9
Building envelope	9

Source: Compilation based on the above listed sources

2.2.1.2 *Large scale/ seasonal sensible storage*

Long-term or seasonal sensible storage is the storage of heat or cold for longer periods than one day and up to several months. Seasonal storage technologies are rather well developed but their market penetration remains limited. Despite this, it has the potential to alleviate many of the issues and increase in variable RES and waste heat brings to the future DHC and power systems.

Tank and Pit Larger tanks and pits can also facilitate medium to long-term storage of thermal energy, preserving the heated or cooled water (or another medium). The main strength of large well-insulated tanks and pits is their vast capacity and directly useful temperature levels. Several barriers do exist such as limited space in urban dense areas and, in the case of pits, suitable geological conditions (Guelpa & Verda, 2019). One innovation potential is improved liner material, with the potential to keep higher temperatures in the pit (Peham, et al., 2022). Another innovation potential is to improve the economic feasibility of the technology, by investing in improvements to construction methods (Dahash, et al., 2021). The TRL is estimated to be 6-8 (BEIS, 2016) and 7 (Guelpa & Verda, 2019).

The trend is moving towards larger and larger pits, which can store thermal energy at a lower average cost. Especially in rural towns where there are few geographic limits for fields for solar panels. The development of pit TES has mainly taken place in Germany, Sweden and Denmark, due to many research projects and progressive DH owners. The largest pit TES is located in the Danish town of Vojens. The DH-connected pit holds 200 million litres of water and is powered by a 70,000 m^2 solar heating plant and CHP. Another Danish example is the Pit TES in Høje-Taastrup, outside Copenhagen, which holds 70 million litres of water. In contrast to most seasonal storage facilities, this TES will be charged and discharged several times per year. The application of this TES is not to store thermal energy over a season but to serve as flexible thermal batteries over shorter times, with the ability to store considerable amounts of variable RES. This TES technology has the potential to become more financially viable, as the higher number of charging cycles reduces the average cost of storing thermal energy (Gudmundsson, 07.09.2022).

Aquifer. One solution is to store heat and cold in the ground. Aquifer is an underground layer of rocks or gravel, completely saturated with water. Simply put, it is a natural reservoir of water. This TES technology uses the aquifer's natural geological formation as the storage medium and the groundwater used as the transfer fluid (Guelpa & Verda, 2019). The excess energy produced in the summer can increase the temperature of the aquifer groundwater and then be used for heating when it is cooler. It is also possible to store cold in the winter and use that for cooling in the summer. Aquifer TES can offer cost-effective (34) large-scale applications, making it a suitable match with DHC networks.

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34 The costs have been lower than 50 €/m^3 in some projects

Certain conditions must be suitable for this storage solution to be possible, including a minimal movement of the groundwater (Guelpa & Verda, 2019). Other conditions include operational temperature limitations that need to be considered (e.g. below 25C in countries like Denmark, Netherlands and Austria) or limitations on the temperature change of the aquifer (common in countries like Switzerland and France). Due to that Aquifer TES generally have certain temperature limitations, they are best fitted with low-quality waste heat and require a combination with a heat pump facility (Gudmundsson, 07.09.2022).

The technology has evolved over the last 40 years and is now an established technology with over 2800 installations worldwide. However, a large share of these (85%) installations is located in The Netherlands, with another 10% in Belgium, Denmark and Sweden (Fleuchaus, et al., 2018). The technology is mature and while geological barriers exist, the main barriers are rather social, legislative and market-oriented, including lack of knowledge, complicated permit rules and large upfront investments (Bloemendal, et al., 2016). One innovation potential is to improve site characterization, which can make the technology applicable in new areas (Hoekstra, et al., 2020). TRL is estimated to be 5-8 (BEIS, 2016) and 7 (Guelpa & Verda, 2019).

Table 5: Indication of TRL of short and large scale and seasonal TES technologies

Technology/technology group	**TRL**
Tank and pit - seasonal sensible storage (Guelpa & Verda, 2019)	7
Tank and pit - Seasonal sensible storage (BEIS)	6-8
Aquifer- seasonal sensible storage (Guelpa & Verda, 2019)	7
Aquifer - Seasonal sensible storage (BEIS)	5-8

Source: Compilation based on the above listed sources

2.2.1.3 Latent storage

Latent storage occurs when the phase of a material is changed, from solid to liquid or liquid to steam. These storage technologies have higher energy density than sensible storage alternatives, which means less storage volume is needed for equal energy stored. Furthermore, the heat losses are significantly lower than their sensible counterparts. However, the technological readiness of this option is currently lower than sensible heat storage (Guelpa & Verda, 2019). Phase-changing materials (PCMs) have different phase-changing temperatures, which make them applicable to various storage needs.

Latent storage can be coupled with DHC networks but the temperature need and PCM must be well planned and synchronised. Latent storage is more effective when the temperature differences are small. This makes it particularly suitable for DC, where the common technology of ice/water storage offers low cost and high latent heat (Guelpa & Verda, 2019). For DH networks, decentralized storage related to the building heating systems is generally more favourable than central storage solutions (Colella, et al., 2012). The narrow temperature range is also the main shortfall as other TES technologies are more economical when the temperature differences are larger.

The market penetration of latent heat remains limited (Guelpa & Verda, 2019). There is clear applicability in DC networks. Another main potential for latent storage is to provide short-term storage, e.g. to allow electric heating, and CHP to work more efficiently with the flexibility to adapt to price signals (BEIS, 2016).

The innovation needed for high-temperature composite-PCM need improving the thermal cycling stability, corrosion, and structural instability to avoid spillage. “The main focus of innovation is on novel integration systems that improve the charging/ discharging rate, and materials science research to improve component compatibility and reduce maintenance costs.” (IRENA, 2020). Sub-zero PCM is a cold storage technology using a mixture with a freezing temperature of lower than 0 degrees (e.g. water-based salt mixture).

The latent storage technologies have been estimated to have a TRL between 5 and 8 (BEIS, 2016), and 4 and 7 (Guelpa & Verda, 2019).

Table 6: Indication of TRL of latent TES technologies

Technology/technology group	**TRL**
Latent storage (Guelpa & Verda, 2019)	4-7
Latent storage (BEIS)	5-8

Source: Compilation based on the above listed sources

2.2.1.4 *Chemical storage*

Thermochemical heat storage has the potential to overcome some of the inherent limitations of the other TES technologies, as it offers the possibility of low energy density, high volume and high-temperature storage (BEIS, 2016). Furthermore, heat losses are low as the chemical-TES material is stored at ambient temperatures (Guelpa & Verda, 2019).

Chemical storage can be divided into two broad categories, (1) *chemical reversible reactions*, utilising endothermic reactions when excess heat is available (and the opposite when heat is required), and (2) *absorption and adsorption,* which occurs "when a gas bonds the surface of a solid, respectively creating (absorption) and not creating (adsorption) a new material'' (Guelpa & Verda, 2019).

One study suggests replacing the water in a DH system with thermo-chemical fluids, as the DHC system would then be able to utilise a larger share of available heat. The authors conclude the solution could extend the use of the DHC system (e.g. improves the feasibility of district networks even in areas of low-density demand.), enable longer distance transport as the losses are lower, and the possibility to store the energy with very small losses (Geyer, et al., 2017). Chemical storage solutions are currently far from being commercially viable but studies, like this, showcase the huge potential.

The chemical storage technologies have been estimated to have a TRL between 1 and 5 (BEIS, 2016), and 4 and 6 (Guelpa & Verda, 2019).

Table 7: Indication of TRL of chemical TES technologies

Technology/technology group	TRL
Chemical storage (Guelpa & Verda, 2019)	4-6
Chemical storage (BEIS, 2016)	1-5

Source: Compilation based on the above listed sources

2.2.2 Technology Cost – Present and Potential Future Trends

There are some different estimates of the future cost of the different TES technologies. This section compiled the estimates from (1) The European Commission's Study on long term projections of large-scale heating and cooling in the EU, (2) IRENA's Innovation outlook – Thermal Energy Storage, (3) Guelpa & Verda's paper Thermal energy storage in district heating and cooling systems: A review, (4) United Kingdom's Department for Business, Energy and Industrial Strategy (BEIS)'s paper Evidence Gathering: Thermal Energy Storage (TES) Technologies (BEIS, 2016), and (5) Danish Energy Agency's Technology Data for Energy Storage (Danish Energy Agency, 2018). It should be noted that the estimates vary greatly depending on several aspects, such as the size of the storage systems and the number of charging cycles.

Sensible storage

Cost per volume stored:

- One report estimate the cost to be 30–50 €/m3 for a short-term water tank and 30–500 €/m3 for a seasonal tank, pit and aquifer (Guelpa & Verda, 2019), while another report concludes the cost for tank TES to be 100–200 €/m3 for a tank above 2,000 m3 (Doczekal, 2019). Another report looking at tank TES estimate the cost at 441 €/m^3 for a (300 m^3 hot water tank), 140 €/m^3 (4,300 m^3 hot water tank) down to 111 €/m^3 (12,000 m^3 hot water tank) ([35]). The report concludes due to the high maturity of tank TES, the further cost reduction potential is limited (BEIS, 2016).
- BEIS compilation indicates the cost for an interseasonsal pit TES ranges between 30€/m^3 and 148€/m^3 (BEIS, 2016). The report concludes further improvements are connected to the material of the lining and quality of insulation, and that the cost could be decreased below €30/m^3 One Danish pit TES example has been able to provide heat storage at a cost between 32 €/m^3 to 64 €/m^3 (BEIS, 2016; Miedaner & Sørensen, 2015). Another report claims the cost is as low as 20 - 40 €/m^3 for pit TES above 50,000 m3 (Doczekal, 2019).

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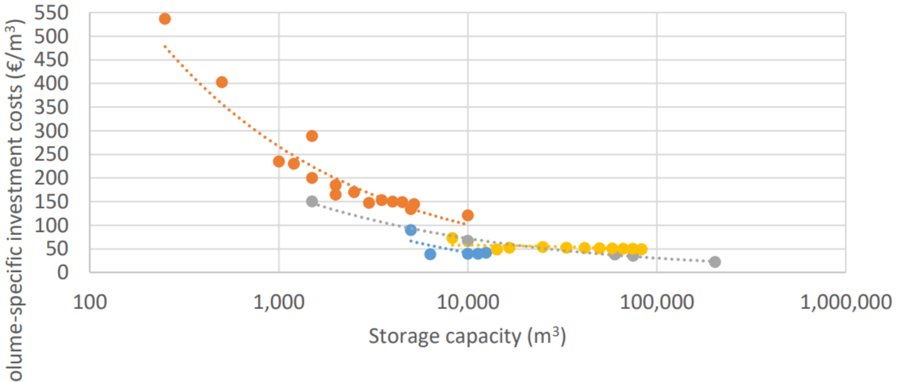
[35] The British Pound (£) has been converted to Euro (€) according to the average exchange rate in 2016, the time the report was launched, where 1 GBP = 1.2242 EUR.

- The cost for borehole TES is estimated at 14-60 €/m³, given the assumption, m³ = 15-30 kWh (BEIS, 2016).
- Aquifer TES is estimated to cost 25-40 €/m³ (BEIS, 2016). Another report estimates the cost as 50 - 60 €/m³ for aquifer TES above 10,000 m³ water equivalent (Doczekal, 2019).

Figure 6 shows the economies of scale of different sensible TES technologies, based on a compilation of the Horizon 2020 project Flexynets. Coupling TES with large DHC networks can help to improve the cost-effectiveness of sensible TES technologies.

Figure 6: A comparison of the economics of scale (on a volume basis) for different types of TES technologies



Source: Sveinbjörnsson, et al (Horizon 2020 project Flexynets). 2019.

Cost per thermal capacity stored:

- The current cost for sensible TES is estimated at 0.1-31 €/kWh, which is projected to evolve to 0.1-22 €/kWh by 2030, and 0.1-13 €/kWh by 2050, depending on longevity and local storage potential (IRENA, 2020). Other estimations say the cost for a large hot water tank is around 3 €/kWh capacity and is projected to remain constant until 2050.
- A projection from the Danish Energy Agency, looking at seasonal pit TES, concludes the current cost to be 0.58 €/kWh capacity, which is estimated to decrease to 0.54 €/kWh by 2030 and 0.47 €/kWh by 2050 (Danish Energy Agency, 2018). Another study concludes Danish examples have been able to provide heat storage at a price as low as 0.37 €/kWh (BEIS, 2016; Miedaner & Sørensen, 2015). However, the cost for kWh for seasonal storage greatly depends on the number of charging cycles, where two cycles instead of one will half the average cost.
- The cost for borehole TES is estimated between 0.4 €/kWh and 4.2€/kWh (BEIS, 2016).

Latent storage

The cost for latent storage technologies is estimated at 53-202 €/kWh, which is projected to decrease to 39-162 €/kWh by 2030, and 25-132 €/kWh by 2050, depending on longevity and local storage potential (IRENA, 2020). Compilation by another report estimates the cost between 50 €/kWh and 400 €/kWh (BEIS, 2016).

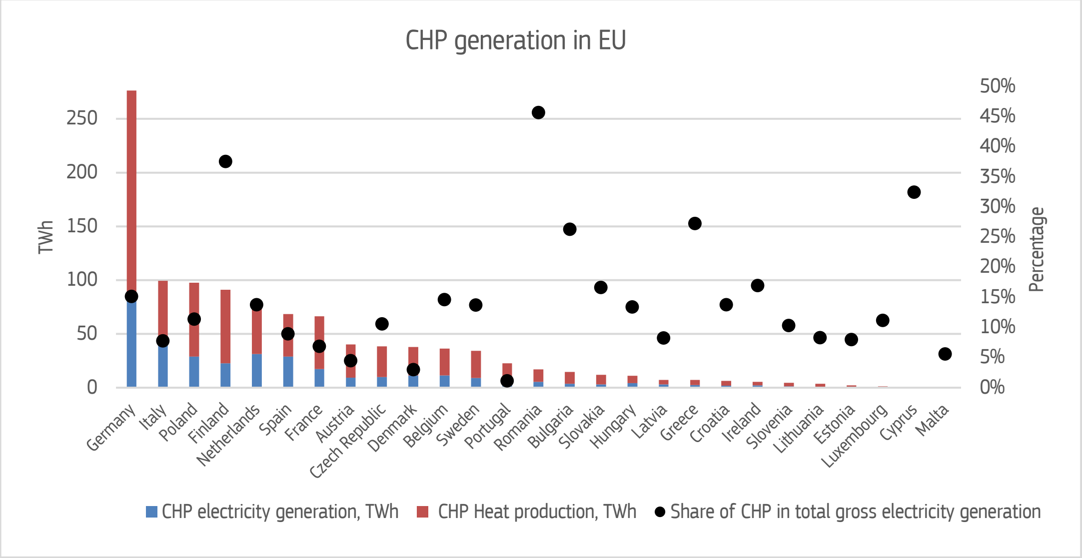
Chemical storage

The cost for chemical storage technologies is estimated at 13-132 €/kWh, which is projected to decrease to 13-105 €/kWh by 2030 (pilot cases), and 9-70 €/kWh by 2050 (IRENA, 2020).

2.3 Combined Heat and Power

CHP plants can be combustion-based units (e.g. internal combustion engines, gas turbines, steam cycles) or fuel cells, and generate power and heat simultaneously. Due to its combined production of heat and power, CHP may be seen as the adequate interface technology to guarantee an effective coupling between the heat and the power sectors. CHPs are currently the largest supplier of thermal energy in European DH networks (European Commission, 2016a). Figure 7 shows the CHP production in the EU as well as the CHP share of the electricity generation in each Member State.

Figure 7: CHP heat and electricity capacity in EU, 2018.



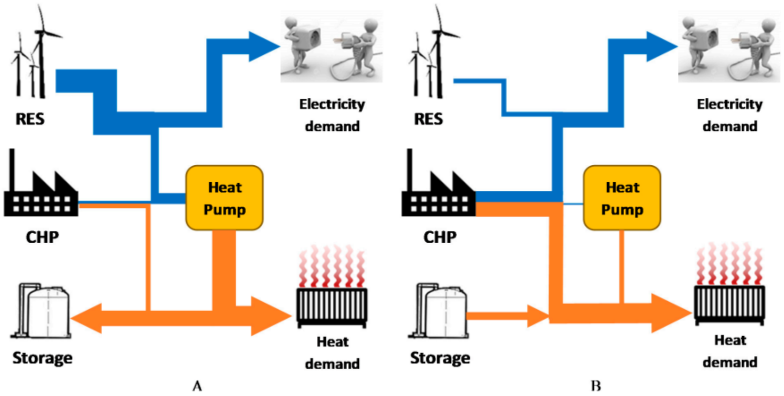
Source: Eurostat, Combined Heat and Power data

Cogeneration or CHP is the most used technology for energy generation in DHC networks. The technology is popular as it allows for producing heating and electricity simultaneously, which enables synergies between the DHC and power networks. During times of high share of RES generation, electricity from the power grid can be used, e.g. through heat pumps, to produce heat and feed into the DHC. Due to the varying nature of RES, the role of the CHP can be changed more towards being a balancing provider. This would apply as well to the operation of DHC heat pumps, which can also be operated within the balancing market. Simply put, CHP reduces production when there is a high influx of RES and increases its electricity production when there is a lack of renewable electricity in the power grid.

- In case of positive imbalance – demand lower than supply - CHP can offer downward reserves by decreasing electricity production, if not operating at minimum electrical load. This entails a decrease on heat production in the case of a backpressure turbine and a possible increase in heat production in the case of an extraction turbine.
- In case of negative imbalance – demand higher than supply – CHP can offer upward reserves by increasing electricity production, if not operating at maximum electrical load. This entails an increase in heat production in case of a backpressure turbine and a possible decrease in heat production in the case of an extraction turbine.

Figure 8 illustrates, in a simplified way, how the control of the DHC network and CHP can provide flexibility to the power grid. In times of high RES production, this fulfils the demand of the power grid while the surplus can be used through heat pumps for heating and cooling demand, or stored in TES. The CHP production remains limited. In the opposite situation with a limited RES production, CHP produced a high share of electricity and TES can be used to fulfil the remaining heating and cooling demand. Furthermore, control and management are crucial to optimise the use of CHP, as the heating and electricity demands fluctuate. The use of AI and related technologies is crucial in this regard as the complexity, of the needs of the power and DHC systems, makes it difficult to manually control.

Figure 8: DHC and power sector flexibility



Source: David, et al (Horizon 2020 project Heat Roadmap Europe). 2017

Control of CHP is needed to respond to variations in the electricity and heat demand in an efficient way. One control solution is to vary the power-to-heat ratio of CHPs, by adjusting the pressures in which the turbine(s) can operate. For example, electricity generation can be prioritized over heat generation by enabling total expansion of the steam. That is, by lowering the condenser pressure the steam can have a bigger expansion in the turbines, which leads to a higher production of electricity. Combining CHP with TES, to avoid heat losses, is another solution which has shown to have a “dramatic effect on the amount of available flexibility”. (Nuytten, et al., 2013).

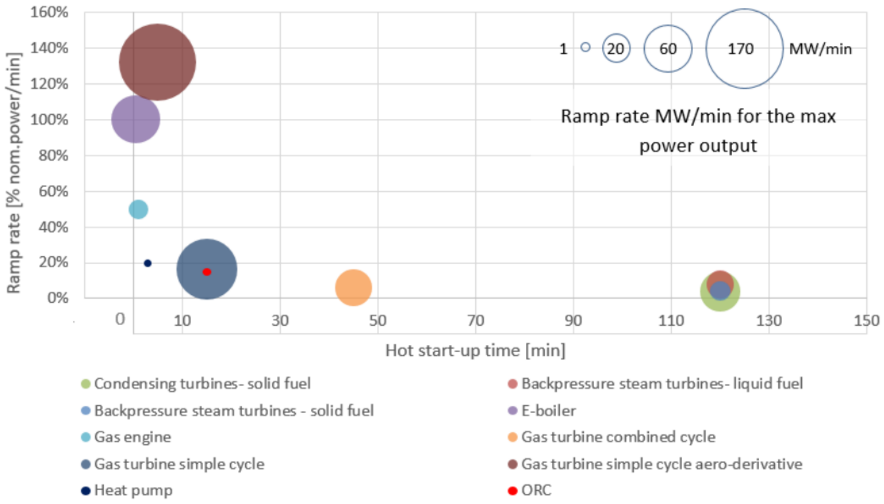
Another control option is the combination of dual technologies (interface technologies between heat and power) supplying thermal networks. A thermal network supplied by CHP can optimise the cost of heat generation based on variations in the electricity price. Large heat pumps can operate with low electricity prices, when CHP plants are not competitive in the electricity market because of cheap electricity generated by variable RES; instead, at times with higher electricity prices, power to heat operation is unfavourable and heat generation can be provided by CHP plants, which can also be competitive in the electricity market (Averfalk & Werner, 2020) (Levihn, 2017).

Due to its combined production of heat and power, and its ability to steep production in both directions, CHP may be seen as the suitable interface technology to guarantee an effective coupling between the sectors. However, studies have shown the heat requirements to be covered by CHP hinder flexibility, meaning since CHP are forced to operate due to heating requirements, there is no room for accommodating RES in the energy system (Jiménez Navarro, et al., 2018). For this reason, much focus in research is given to defining the optimal strategy for CHP plants to jointly dispatch heat and power (Zhou, et al., 2019) (Jimenez-Navarro, et al., 2020).

Most CHP systems operate following certain heat requirements. One example is given by the power and heat market in Copenhagen, Denmark, where the objective is to minimise the total marginal heat cost, calculated by subtracting the revenues of electricity sold in the day-ahead market. Power generation is determined by heat generation and restricted by constraints on the power-to-heat ratio. This ratio influences ramp up-rates and minimum output of the CHP plant, which in turn impacts its ability to provide flexibility to the power grid (Wang, You, Zong, Træholt, et al., 2019). These conditions have been proven very challenging for the quantification of CHP electric capacity that can be reserved for the provision of flexibility.

The capability of CHP to provide flexibility depends on aspects such as ramp-up rate (how quickly the power production/consumption can be altered depending on demand changes), operation range (a wider range allows the CHP to avoid shutdown) and start-up time (i.e. how fast the plant can provide heat and power on full load) (Salman, et al., 2021). Figure 9 shows the ramp-up rate for different heating technologies, developed by the Horizon 2020 project Magnitude (Pini, 2019). The technologies with short ramp-up and start-up times are more suited to provide flexibility with short notice.

Figure 9: Ramp rates for the largest power output in a relation to hot start-up time



Source: Pini (H2020 project Magnitude), 2019.

2.3.1 Technology readiness level

Conventional CHP is a commercially mature technology, with a TRL of 9. Despite its maturity, the control and flexibility of CHP are still underutilised in DHC and power markets. One report concludes "that to be more flexible and profitable, CHPs are expected to be able to operate in a larger load range with higher load-change rates and even operate in start/stop mode with full turndown and fast re-start at high-efficiency levels". The report also identified new technologies which can increase the flexibility in CHPs, such as electrolysers, fuel cells, pyrolysis and gasification (Salman, et al., 2021).

- Electrolysers and fuel cells, both elements in clean hydrogen production, which can replace fossil gas in CHP plants, have a TRL of 5-7 but can also be lower or higher depending on the exact technology and its applicability (IEA, 2020).
- Pyrolysis and gasification, different technological solutions to transform biomass or fossil fuels – have TRLs of 6–7 for heat and power production (Salman, 2020).

Table 8: Indication of TRL of CHP technologies

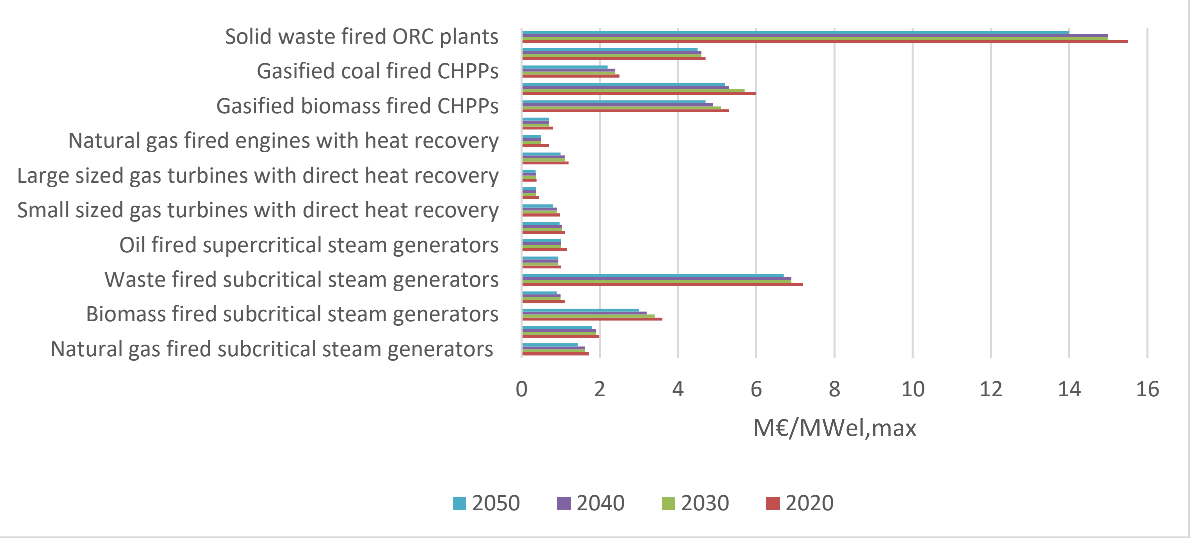
Technology/technology group	**TRL**
Combined Heat and Power	9
Electrolysers and fuel cells	6
Pyrolysis and gasification	6-7

Source: Compilation based on the above listed sources

2.3.2 Technology Cost – Present and Potential Future Trends

Depending on the heat source and the installation type, the initial investments and the cost associated with the use of the plant can be modified. Figure 10 shows the projected nominal cost (i.e. CAPEX) for different CHP technologies until 2050. The figure shows a rather modest decrease of cost of around 5-10% until 2050 for the different CHP technologies. The high maturity level of CHP technologies is one explanation for this.

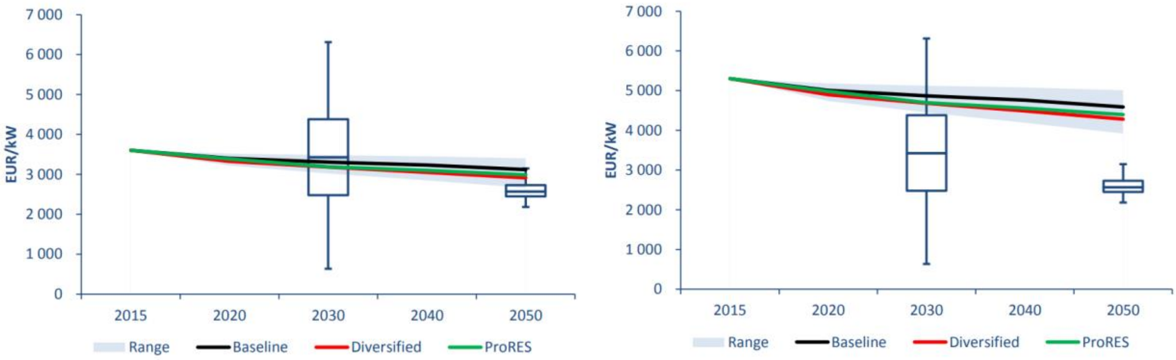
Figure 10: Nominal investments (CAPEX) for different CHP technologies 2020-2050



Source: European Commission, 2017.

Another report by the European Commission forecasts the CAPEX for biomass subcritical steam turbine CHP and gasified biomass CHP, as shows in Figure 11.

Figure 11: Capital investment cost trajectories of biomass subcritical steam turbine CHP (left) and gasified biomass CHP (right) in different global growth scenarios and varying learning rates



Source: Tsiropoulos, Tarvydas, & Zucker, 2018

The heat generation from CHP is expected to be stable until 2030, according to what the Member States report in their Comprehensive Assessments, as required by Article 14 of the Energy Efficiency Directive (2012/27/EU). The technical potential for flexible operation of CHP is not fully exploited partly due to the lack of viable business models for the operators.

3 Conclusion

There is growing attention to smart and low-temperature DHC networks. Frontrunner cases have demonstrated the many benefits that advanced control of DHC systems can bring. For example, a smart DHC network coupled with TES can provide vast flexibility service to the wider energy system, facilitating a smoother integration of solar and wind-produced energy, heat pumps and electric vehicles. Despite the potential and growing interest, the uptake of new systems remains limited. Several countries have indicated a plan to invest in DHC infrastructure ([36]) but the reality is still that the existence of DHC in the EU is centred to Member States in the North, Central and Easter parts of Europe.

The benefits of DHC systems become stronger when more advanced control technologies are applied and with lower temperatures of the system. The TRL of most of the control technologies indicate the possibility to effectively control very complex systems is already there. Technologies such as sensors, smart meters, AI and digital twins are already at an advanced stage and can be utilised to optimise the efficiency and flexibility of DHC networks. Low-temperature DHC systems, such as 4GDH, requires in some areas that the overall performance of the buildings is improved. District-level plans to upgrade the DHC network could effectively be coupled with plans to renovate buildings or with urban mobility strategies.

Advanced control is a prerequisite for effective system integration and cost-effective integration of RES. The future DHC networks won’t all be homogenous but they will be characterised by advanced control systems, lower temperatures and connections with the wider energy system. The optimal design of DHC systems depends on the neighbourhood characteristics (e.g. heating demand from buildings, and the existence of industries, data centres, and supermarkets), as well as the situation of the power grid. This is also shown in the actual implementation of smart DHC networks, where some focus more on large sensible TES (e.g. Denmark) while others focus on waste heat or district cooling (e.g. Sweden).

Technology trends and opportunities for the EU:

- Digitalisation, big data and decreasing costs for certain technologies, make it possible to optimise the network operations while empowering the end-users. Smart meters (TRL 9), thermostats (TRL 9), and sensors (TRL 9) are all becoming more intelligent and less expensive, enabling higher monitoring and control. At the same time, innovations such as AI (TRL 3-6) and digital twins (TRL 3-7) make it possible to optimise the network based on real-time information. With the appropriate regulatory framework, new business models could appear, e.g. by incentivising end-users through demand response and thus reducing system costs and increasing the use of renewable energy sources. Several challenges need to be addressed, including data security and privacy as well as remaining questions about data ownership.
- TES is a key enabler for district heating and cooling networks to be able to provide significant flexibility to the wider energy system. Short-term sensible TES solutions (e.g. storing heated water in a well-insulated tank) (TRL 9) are already commercially viable, and the longer-term TES solutions (TRL 5-8) using the same technology are gaining more traction. Latent (TRL 4-8) and thermochemical heat storage (TRL 1-6) have the potential to overcome some of the inherent limitations of the other TES technologies, as it offers the possibility of high energy density, high volume and high-temperature storage. The large or seasonal storage capacity of thermochemical storage systems, with very limited heat losses, makes it a potentially attractive option for future district heating and cooling systems. The solutions are, however, currently quite far from being commercially viable.
- Larger networks and system integration represent a great opportunity for the European Union’s power and heating and cooling sectors. As the systems grow larger, for example in Copenhagen, Stockholm, and Helsinki, they have multiple thermal generation plants, which can offer great flexibility to the wider energy system. Advanced control and management of generators in multi-source systems can serve the same purpose as TES, except the energy is stored in the unburnt fuel.

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[36] See Member States’ report in the Comprehensive Assessments, following the mandate of Article 14 of the Energy Efficiency Directive (2012/27/EU)

- Reuse of waste heat, from industrial processes, data centres, wastewater, supermarkets, is a growing trend. Waste heat is sustainable and increasingly financially attractive to be reused for heat, cold and domestic hot water through the district heating and cooling system. For example, wastewater can be used as the heating source for heat pumps. There is an abundance of waste heat currently not being utilised across the EU and studies indicate this could meet most of the EU's space heating demand in the building sector (Heat Roadmap Europe, 2017). The evolvement of DHC systems with higher efficiencies and lower temperatures will make this solution even more efficient.

This report will be updated in the coming years, including an analysis of the EU's competitiveness in the global market, value chain, and R&D. The next iteration intends to look closer at other sub-technologies contributing to a better management and operation of DHC systems, including large heat pumps and waste heat. The interconnection between DHC and the industry sector will also be explored.

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List of abbreviations and definitions

4GDH	4th generation district heating
5GDH	5th generation district heating
AI	Artificial intelligence
ATES	Aquifer thermal energy storage
CA	Comprehensive assessment
CHP	Combined heat and power (cogeneration is another term)
DC	District cooling
DH	District heating
DHC	District heating and cooling
DR	Demand response
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	The European Union
GHG	Greenhouse gases
HP	Heat pump
HRE	Heat Roadmap Europe
NECPs	National energy and climate plans
PV	Photovoltaics
PTES	Pit thermal energy storage
RED	Renewable Energy Directive
RES	Renewable energy sources
TES	Thermal energy storage
TTES	Tank thermal energy storage
UTES	Underground thermal energy storage
WH	Waste heat

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