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Smart Thermal Networks in the European Union

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Abstract

This report is part of the 2024 Clean Energy Technology Observatory series and is focusing on smart thermal networks within the European Union. It provides an overview of the current status, emerging trends, and the potential of this sector integration technology. Smart thermal networks represent a substantial opportunity for urban areas, functioning with increased efficiency and smarter control at lower flow temperatures. This enables the introduction of more renewable energy sources and waste heat, while also enhancing the flexibility of the system. As a result, smart thermal networks can serve as versatile assets, providing balancing services to the wider energy infrastructure.

An increasing number of district heating and cooling systems within the European Union are evolving into smart thermal networks. Many cities are channelling investments into the expansion and modernisation of their current infrastructures to meet anticipated future energy demands, which are increasingly dependent on variable renewable energy sources, like solar and wind power. Smart thermal networks incorporate a range of technologies, the majority of which are technologically advanced, such as intelligent control systems with sensors, utilisation of waste heat, high-efficiency cogeneration, large-scale heat pumps, and thermal energy storage systems. One of the most promising frontiers for innovation lies in digitalisation, which enables the smooth integration and management of energy flows. By promoting intelligent control and data exchange throughout the system, smart thermal networks can control their operations for optimal performance in the short and medium term. As a global frontrunner in this arena, Europe is well-equipped to spearhead the shift towards smart thermal networks, exemplifying their importance within the framework of carbon neutral and smart cities.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complex and multi-faceted character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognising the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), which runs the observatory, and Directorate-Generals Research and Innovation (RTD) and Energy (ENER) on the policy side. Its overall objectives are to:

– monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal;

– assess the competitiveness of the EU clean energy sector and its positioning in the global energy market;

– build on existing Commission studies, relevant information and knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020);

– communicate findings by publishing reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.[1]

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as a primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.[2]

The observatory produces a series of annual reports addressing the following topics:

Clean energy technology status, value chains and markets: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower and pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin, renewable hydrogen, solar fuels and wind;

Clean energy technology system integration: building-related technologies, digital infrastructure for smart energy systems, industrial and district heat and cooling management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport;

Foresight analysis for future clean energy technologies using weak signal analysis;

– clean energy outlooks: analysis and critical review;

– system modelling for clean energy technology scenarios;

– overall strategic analysis of clean energy technology sector.

More details are available on the CETO web pages.[3]

(1) https://setis.ec.europa.eu/what-set-plan_en.
(2) https://energy.ec.europa.eu/topics/research-and-technology/clean-energy-competitiveness_en.
(3) https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en.

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Executive Summary

This report is part of the Clean Energy Technology Observatory (CETO) 2024 series, featuring technologies and their integration and contribution to a clean energy system. It describes how *smart thermal networks*, operating more intelligently, efficiently and on lower temperatures than conventional district heating systems, can enable the integration of a higher share of renewable energy sources and become a versatile asset for the wider energy system by providing flexibility services. This report summarises the status, trends and potential of smart thermal networks as a sector integration technology.

Policy context

In an effort to cut carbon emissions and build for a carbon-neutral future, the European Union (EU) strives to decarbonise its heating and cooling systems, which constitute around half of the regions energy consumption. The EU has identified district heating and cooling (DHC) networks as an important element in the process of improving energy efficiency and reducing greenhouse gas emissions in urban areas.

EU has therefore enacted a number of directives, strategies and support schemes. Policy instruments, such as the Energy Efficiency Directive and the Renewable Energy Directive, mandate Member States to carry out heating and cooling assessments and require a certain increase of renewables into their thermal systems. The European Performance of Buildings Directive supports efficient building standards which go hand in hand with lower flow temperatures. Financial backing is provided, for example, through the Cohesion Policy Funds and InvestEU to support DHC expansions and improvements. Strategic efforts, including the European Strategic Energy Technology Plan and the European Partnership for Clean Energy Transition, also push for renewable energy in DHC. In parallel, there are a number of efforts boost digitalisation and energy smartness, for example through the new strategy “Europe Fit for the Digital Age”. The EU is also pursuing to have 100 climate-neutral and smart cities[4] by 2030, in which smart thermal networks will play a key role for a number of cities.

District heating and cooling in the EU

There are around 19 000 district heating networks in Europe[5]. As of 2022, the collective installed capacity of the district heating systems across Europe amounts to approximately 333 gigawatts thermal (Euroheat & Power, 2024). District heating, despite supplying just 13% of this demand, plays a pivotal role in the energy strategies of countries that excel in reducing carbon emissions, notably the Nordics. In certain EU Member States, it’s integral to the vision of achieving a flexible, efficient, and decarbonised energy system, whereas it is scarcely present in others. For instance, district heating satisfies a substantial portion of the heating needs in Denmark (66%) and Finland (45%) (Euroheat & Power, 2024). Moreover, Germany, Poland, and the Nordic countries accounted for 68% of the EU’s total district heating consumption in 2018 (Eurostat, 2022). In contrast, the adoption in the Benelux countries and most of Southern Europe remains so far limited.

District cooling is much less common in EU, with a total installed capacity of 7.74 gigawatts and around 200 installations (Pezzutto, et al., 2022). District cooling is experiencing gradual adoption and expansion across various regions in Europe beyond the leading countries of Sweden and France, which currently are accounting for around two-thirds of the total district cooling supplies in the EU (Euroheat & Power, 2024). District cooling is expected to play a more prominent role in the future.

The role of smart thermal networks

The term *smart thermal network* refers to an efficient heating infrastructure, distributing heating and cooling to multiple points of delivery within a district or a city. A smart thermal network is characterised by the use of intelligent control technologies and strategies to optimise the operation. Smart thermal network further strives for operation with low distribution temperatures for maximizing the potential for energy efficient integration of alternative energy sources. Smart thermal networks are generally characterised by a higher complexity in terms of numerous supply points which enables more flexibility in the system operation. In particular, combined with large-scale thermal energy storage, they can provide enormous flexibility and optimisation potential to the wider energy system.

Smart thermal networks enable invaluable sector-coupling synergies. Firstly, the infrastructure enables recuperation of waste heat. For example, the thermal network can recover waste heat from industrial processes or data centres, but also provide them with cooling services, a win-win exchange. Secondly, with power-to-heat technologies (especially combined heat and power, large heat pumps and electric boilers), excess electricity can

(4) https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en

(5) Including also non-EU countries such as Norway, Switzerland and the UK.

be stored as heat in the thermal network, for example in times of an abundance of sun or wind. With the same logic, when there is a shortage of electricity, production from combined heat and power can be steered towards producing more electricity while the thermal network uses the stored heat.

Technology state of art and futures trends

Most individual components of smart thermal networks have reached a high level of technological readiness (i.e. TRL of 8 or 9), including sensors and intelligent control systems, high-efficient cogeneration, large heat pumps and thermal energy storage technologies.

However, the integrated concept of smart thermal networks has considerable innovation potential left. There are local networks that have been incrementally built towards becoming smart thermal networks, although they still have quite some path to go before becoming truly smart. With the integration of machine learning/AI technologies, smart thermal networks have become much more intelligent and able to manage more complex systems. A considerable innovation potential lies with the digital and control elements of the thermal networks rather than with the physical networks themselves.

Another promising trend is to utilise a thermal energy storage as a virtual power battery to support power grids. The thermal energy storage is charged when there is an abundance of renewable energy and discharges to the district heating network when there is a scarcity of renewables, thus lowering the power demand. Depending on the size and number of cycles per year this approach has the potential to significantly outperform any power battery, both in terms of capacity and “power-to-power” efficiency.

The EU position and global competiveness

The EU is a global leader when it comes to smart thermal networks, with more networks operating at lower temperatures and with a higher share of renewables in the systems. The United States and most parts of China do not have the same track record of establishing district heating (and cooling) systems. While most production and installation is local when it comes to smart thermal networks (except software and digital applications), Europe has the opportunity to spearhead the transition to smart thermal networks and showcase their value in the low-carbon transition. This is, for example, evident in EU’s role as a global exporter of heat-exchange units. In 2023, the amount of heat-exchange units exported from the EU to a non-EU country increased by 11% compared to 2022, reaching almost EUR 2.4 billion.

Table 1 presents a SWOT analysis, illustrating the central strengths, weaknesses, opportunities, and threats for this sector-integrating technology in the European context.

Table 1: SWOT table of Smart Thermal Networks in the EU

Strengths	**Weaknesses**
Flexibility and storage: • Flexibility: smart thermal networks can provide flexibility to the wider energy system • Inexpensive storage: the integration of thermal energy storages can provide an inexpensive energy storage solution to the wider energy system Integration and efficiency • High efficiency: the networks can optimise the distribution and use of heat and cooling, reducing energy waste. • Economies of scale in renewable integration: district-wide systems can enable more efficient and cost-effective adoption of renewables due to the aggregated demand and investment. Energy security • Energy security: cities with thermal networks, with a considerable share of renewables, had on average more stable prices during the 2022 gas crisis	Infrastructure and cost • High initial costs: it can be challenging and expensive to upgrade and construct thermal networks in densely built areas System integration and distribution • Interoperability issues: need for compatibility among different systems and standards • Uneven geographical dispersion: the distribution of district heating and cooling networks is variable across the EU, with a strong presence in some Member States and almost none in others
Opportunities	**Threats**
Sustainability and resource opportunities • Local resource utilisation for value creation: smart thermal networks capitalise on local and existing resources, such as waste heat and renewables, adding value and promoting sustainability • Lower temperatures: the decreasing energy demand in buildings allows for lower temperature networks and the integration of low-temperature renewables and waste heat Market opportunities • Urbanisation: increasing urban populations create a demand for efficient and sustainable urban energy solutions • New business models: opportunity to valorise flexibility and thermal storage capacities	Market development challenges • Economic uncertainty: economic downturns can reduce investment in new technologies. • Energy market fluctuations: volatile energy prices can impact the cost-effectiveness. • Competition from other solutions: competition with established systems like natural gas networks or individual heat pumps could limit adoption Stakeholder and labour challenges • Stakeholder commitment: establishing a thermal network requires consensus among diverse stakeholders and long-term dedication from local authorities • Lack of skilled workers: shortage of construction workers in general and welders in particular Cybersecurity challenges • Cybersecurity risks: increased digitalisation raises the risk of cyber-attacks on energy infrastructure

Source: JRC compilation

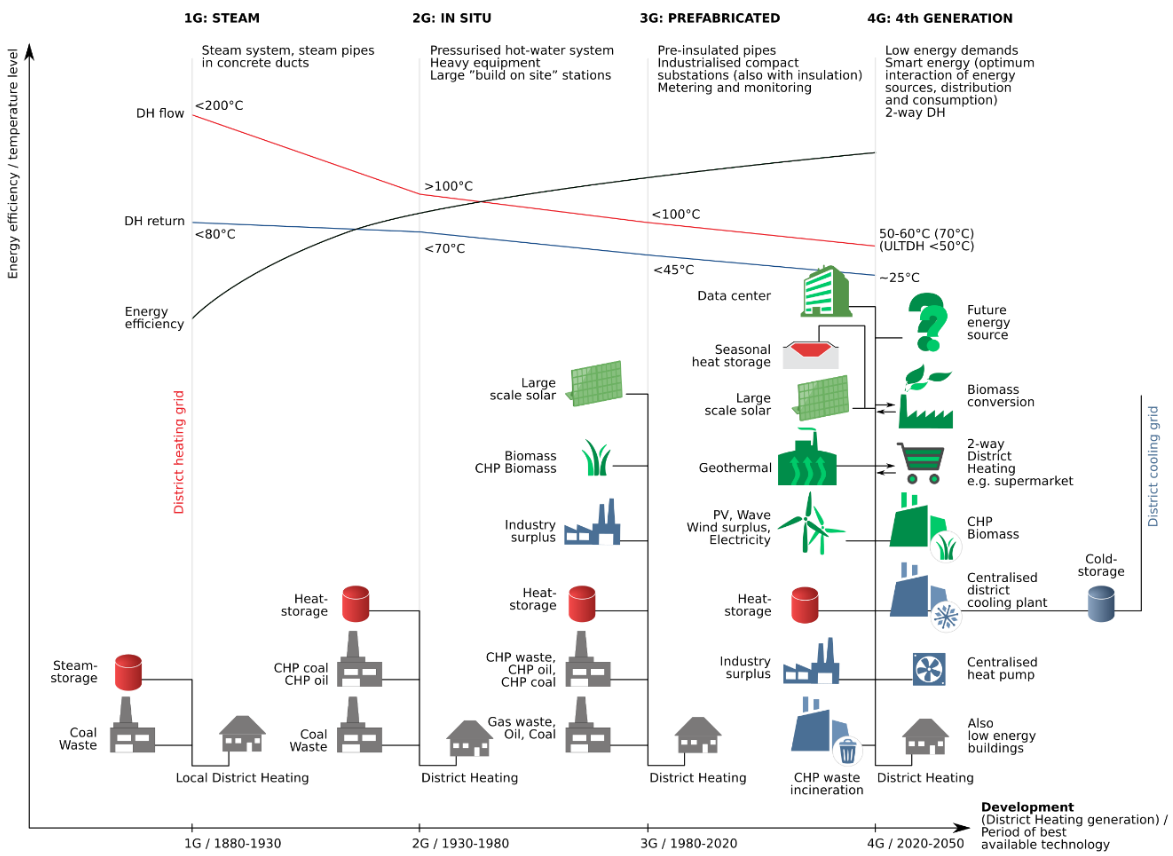
1. Introduction

The role of district heating and cooling (DHC) networks is slowly transforming. From simply ensuring a sufficient heat supply to becoming an active and dynamic part of the wider energy system. Traditionally, DHC networks heavily relied on dispatchable generation capacity, meaning fossil-fuelled generation and cogeneration. In the early stages of district heating (DH) development, fossil fuels were combusted, generating heat of up to 200"ºC, which was then distributed throughout cities via steam pipelines. The modern DHC networks, referred to as smart thermal networks in this report, operate with pressurised water at lower temperatures, a higher share of renewable energies (RES), and manage more complex systems with a multitude of supply and demand points. They utilise advanced control strategies and monitoring solutions (e.g., sensors and smart meters) to optimise the flow of heat or cold and integrate a higher share of RES efficiently.

The importance of smart thermal networks is growing as the share of RES is steadily increasing, reinforced by climate mitigation ambitions, improved competitiveness of clean energy technologies (e.g. solar and wind power), as well as imminent energy security concerns. This report provides an overview of the current status and trends of district heating and cooling networks and smart thermal networks in the European Union (EU).

Smart thermal network is a system integration technology that can help cities move towards carbon neutrality in a cost-effective way by offering the ability to utilise local low carbon resources as well as provide relatively inexpensive storage solutions. DHC networks can be an integrated part of the wider energy systems by providing flexibility, through interface technologies, like combined heat and power (CHP) and power-to-heat. Simply put, DHC networks can produce and store heat when there is an abundance of electricity and increase CHP's electricity production when there is a shortage of electricity generation (i.e. when its economical for the DHC or CHP operators to do so)[6]. The potential of this sectoral integration is larger when the system becomes smarter, more efficient and operates on a lower temperature.

Figure 1: 4th generation district heating and cooling system compared to predecessors.



Source: (Lund, et al., 2014).

(6) Advanced control and management of generators in multi-source systems can serve the same purpose as thermal energy storage, except the energy is stored in the unburnt fuel.

As illustrated in Figure 1, the operating temperatures of DHC networks have decreased over time, driven by the goal of reducing thermal distribution losses and increase the efficiency of the thermal generation. A key enabler for reducing the operating temperatures has been the decreased temperature demands of buildings, for example due to better insulated buildings, and the adoption of digital tools for optimising the system operation. Most networks, defined as smart thermal networks, operate on a low temperature for the majority of the year (i.e. not over 80°C)[7], making the integration of more RES technologies, like geothermal heat, waste heat, and heat pumps, more cost-effective. Increasing efficiencies and lowering the temperature of the networks enables faster integration of RES and waste heat. Growing investment in RES also increases the demand for smart thermal networks. Consequently, investments in RES and smart thermal networks are mutually reinforcing.

Furthermore, waste heat from industrial processes can be a positive energy source for low-temperature DH networks, with a supply of 50-60ºC with a return water temperature of 25ºC (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[8]. 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. For industry zones with multiple waste heat sources, a water loop can be used to recover the waste heat from various processes and deliver it to a central heat pump, which both cool down the water loop via the evaporator and delivers the waste heat at useful temperature to the DH system via the condenser of the heat pump. The waste heat collection water loop would avoid the need for a dedicated heat pump for each waste heat source.

The concept of a smart thermal network is identical to the one of a 4th generation district heating (4GDH) system. During the last decade, the concept has been used to describe advanced DH systems, characterised by lower temperatures and intelligent control technologies. The overarching goal of the 4GDH is to attain a fully decarbonised energy system.

Box 1: The transformation of DHC into smart thermal networks is characterised by several key features.

Aggregated demands: Aggregation of thermal demands are becoming valuable commodities because they enable:
- Load shifting for both short and extended periods.
- Effective balancing services for the energy system.
- Cost-effective development and utilisation of low-grade thermal sources, such as waste heat.

Digitalisation and optimisation: The use of digitalisation, in combination with optimisation, allows for a higher utilisation of resources while reducing the costs associated with future RES-based energy systems.
Low-temperature heat sources: Low-temperature heat sources, including renewables and waste heat, are central to ensuring high energy efficiency of heat pumps.
Electrified thermal supply: In an electrified thermal supply system, district/central thermal energy storage, combined with large-scale heat pumps and electric boilers, functions as a large electricity battery capable of utilising excess power generation, particularly from RES, and avoid power consumption for heating purposes during periods of low share of RES.
Multi-source and multi-fuel DHC systems: These systems offer the possibility of effective shifting between input energy supplies, reducing energy dependencies and providing stable thermal energy costs for societies.
Growing DH systems: While not a prerequisite for a smart thermal network, integrating smaller DH systems into larger ones can offer operators increased flexibility, resilience and more optimisation opportunities.
Smart meters and improved data: The use of smart meters and better data at the building level enables DH operators not only to optimise heat plants and networks but also to consider conditions at the demand side.

Source: Based on input from (Euroheat & Power, 2023) (Gudmundsson, Interview with expert, 2024)

The improved competitiveness of RES and waste heat is a 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 DHC operators to find new solutions to bring heat and cold to their customers.

Low-temperature DH and the use of low-grade and renewable heat sources also necessitate a larger role for digitalisation. Thermal networks are becoming increasingly complex, with added considerations including multiple heat production sources and end-user engagement. Smart thermal networks also tend to be integrated

(7) The future ambition of the low-temperature thermal networks is perhaps around 65-70 ºC but most current systems have more like 70-80 ºC (often dependent on system size) for majority of the year, and raise the temperature during high load periods.
(8) However, should the return temperature from the district heating network fall below that of the waste heat, there is potential for partial direct use by pre-heating the return flow using a heat exchanger.

with other energy sectors, like the gas and electricity networks. Specifically, in combination with the addition of thermal storage capacity, which provides means for decoupling the heat generation from the heat demand, and demand side management, which takes advantage of the thermal mass of connected buildings and influences end-users behaviours - are enabling technologies to increase the share of 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).

Smart Thermal Network market in 2023

The sector is steadily moving towards more sustainable and efficient DHC systems. This shift is particularly evident in Denmark, one of the more progressive countries from a DHC perspective, where 2023 saw a growing interest in large-scale heat pumps, electric boilers, and the utilisation of waste heat from various sources, including geothermal energy[9]. While this trend continued, the falling gas prices and financial uncertainties led to a stagnation of investments in DHC in 2023.

Globally, the DHC market experienced an increase in investment in 2023. The value of the global DHC market is estimated at approximately EUR 275 billion in 2023 and it is forecast to expand at a annual growth rate of 5.7%, with projections indicating a rise to EUR 447 billion by 2032[10]. Investments in smart thermal networks have also seen a considerable growth, yet driven by increased funding, supportive policies, and technological advancements, particularly on the digitalisation front. The focus has been on integrating RES, enhancing efficiency through lower temperature networks, and leveraging smart technologies[11].

At the same time, European investments in 2023 fell short of expectations according to industry experts[12]. They ascribe this to political uncertainty and higher costs of financing. There was a notable change from 2022, when investments in the sector were strong. This was driven by the gas crisis and a push toward energy savings and a move away from fossil fuels among utility companies and consumers. However, with the fall in gas prices, the urgency to switch to sustainable options like DH has declined. Particularly for consumers who now see fewer financial advantages in moving away from natural gas. At the same time, the costs of switching to alternative heating solutions have also increased, driven by higher prices for both components and labour[13]. A similar trend can be seen in other sectors, like residential heat pumps, where the market also experienced a stagnation in 2023[14].

Policy framework

The EU recognises DHC as an important component for improving energy efficiency and reducing greenhouse gas emissions in its member states. To support the development and optimisation of DH systems, the EU has several provisions and policy frameworks in place including:

- The Energy Efficiency Directive (EED), which defines efficient district heating and cooling (Art. 2) and mandates Member States to conduct economic and geographic analyses to identify DHC potentials (Art. 25).
- The Renewable Energy Directive (RED), which sets a target for an annual increase in the percentage of renewable heating and cooling (Art. 23) and establishes an annual goal for increasing the share of RES in DHC (Art. 24). RED also requires Member States to facilitate access for energy producers using RES and waste heat and cold to DHC networks (Art. 24).
- The European Performance of Buildings Directive (EPBD), which contains several provisions aimed at improving the efficiency of both new and existing buildings, a prerequisite for the development of lower-temperature DHC networks.
- The Cohesion Policy Funds: These funds support regional development projects, including investments in energy infrastructure like DH systems, particularly in less developed regions of the EU.

(9) Input from industry experts
(10) Estimates from EuroHeat & Power
(11) Input from industry experts
(12) Ibid
(13) Ibid
(14) European Heat Pump Association, "Market Data" https://www.ehpa.org/market-data/#:~:text=Heat%20pump%20sales%20in%2021,13.7%25%20rise%20on%202022's%20total

- InvestEU is a EU funding program that provides financial support to various sectors, including DHC, through a combination of loans, guarantees, and equity, aimed at stimulating investment and fostering sustainable infrastructure, innovation, and social inclusion.

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[15] 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. The related European Partnership for Clean Energy Transition[16], 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[17].

The Smart Cities Marketplace[18] supports this mission by offering knowledge, capacity-building support and facilitation of finance solutions for cities. Finally, DHC falls under the umbrella of EU's New European Bauhaus initiative[19], in which digitalisation of DHC is described to play a key role in advancing sustainability of urban environments. For example, digitalisation in DHC can empower end-users through awareness raising tools and by giving them more control of their energy consumption. Smart DHC systems can also contribute to resilience of the whole energy system through sector coupling (Motoasca, et al., 2023).

(15) European Commission "Strategic Energy Technology Plan" [Website] Available: https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en
(16) CETPartnership [Website] Available: https://cetpartnership.eu/
(17) European Commission "EU Mission: Climate-Neutral and Smart Cities" [Website] Available: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en
(18) European Commission "Smart Cities Marketplace" [Website] Available: https://smart-cities-marketplace.ec.europa.eu/
(19) European Commission "New European Bauhaus" [Website] Available: https://new-european-bauhaus.europa.eu/index_en

Smart thermal network trends in focus

This chapter discusses a few trends that are currently influencing the development of smart thermal networks in the EU. The widening scope of DHC encompasses both innovative technologies but also new types of business models. Digitalisation is at the core the transition, enhancing system optimisation and efficiency. The harnessing of waste heat is gaining traction as an effective solution, converting an otherwise overlooked energy source into a valuable contribution to the network. The implementation of large-scale heat pump technologies is crucial in elevating system efficiency and minimising environmental footprint. Moreover, the 5th Generation DHC represents a totally different type of smart thermal network. This chapter offers a concise overview of these pivotal trends, highlighting their role in the transition to smart thermal networks.

More than just a thermal network

DH systems are evolving from mere conduits of heat to complex networks that incorporate a diverse range of energy sources and diverse consumers. In this transition, buildings are being transformed from passive recipients of heat into active components of the system that can produce, store, and manage energy themselves. They are increasingly equipped with systems such as solar panels, heat pumps, and thermal storage, allowing them to contribute excess energy back to the grid or adjust their demand in response to supply fluctuations.

One trend is that utilities are increasingly recognising the importance of ensuring that building level heat interfaces, substations, are continuously maintained and optimised. This is leading to extended utility business models, where the utilities take ownership of the heat interface units and rent it out to the building owners. This enables the utilities to get better understanding of the system operation and condition. End-users benefit from this trend as it shifts large investments, maintenance requirements and operational optimisation, from the building owners to the utilities[20].

The DH utility in Viborg, Denmark, has successfully engaged end-users through a motivational tariff in an effort to lower temperatures, resulting in financial gains for both individual building owners and for the DH operator (Diget, 2019). Their approach demonstrates a long-term strategy that aligns with the utility's broader objectives to lower the operating temperature of DH and facilitate its transition to RES. In order to achieve this, they address both the conventional thermal system and the connected buildings.

Sector coupling between DHC and electricity systems allows the whole system to become more effective. The smart thermal network operator can respond to price fluctuations in the electricity market and help balance the grid by producing, avoid consuming or consuming more electricity. This also enables significantly lower power generation capacity than would be needed if building heating and cooling demands were electrified at building level. It represents a great opportunity for the EU's power and heating and cooling sectors. Networks with multiple thermal generation plants can offer great flexibility, especially if coupled with thermal energy storages. Advanced control and management of generators in multi-source systems can serve the same purpose as thermal energy storage by capturing excess power generation and avoiding fuel consumption, instead of storing heat in a thermal energy storage the energy is stored in the unburnt fuel. It can also contribute to resilience of the whole system, which was shown during the 2022 gas crisis, where cities with DH networks and a higher share of RES, also experienced relative lower energy prices.

Digitalisation

Digitalisation in thermal networks enables a higher level of control, which is a prerequisite for the modern low-temperature DHC networks. Smarter thermal networks can take part of 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). Digitalisation in DHC networks marks a significant shift from traditional control methodologies that rely on manual settings and static feedback loops. Unlike these conventional systems, digital and intelligent control methods harness the power of machine learning and adaptive algorithms to dynamically fine-tune operations. These advanced systems are capable of self-optimisation, continuously analysing performance data to refine control strategies in real-time. Such intelligent control is not just beneficial but essential for the efficient management of smart thermal networks, which typically involve a complex interplay of multiple generation sources and variable consumption patterns.

The development of digitalisation in DHC networks can be divided into data, analytics and connectivity (Schmidt, 2023). The integration of advanced sensor technology into district heating systems allows for real-time monitoring and data collection. The data collected through sensors can be used to optimise heat production,

(20) Input from industry experts

distribution, and consumption, leading to more efficient and sustainable energy system. AI and machine learning enables faster ways of analysing large data sets and making informed decisions based on them. Digitalisation also enhances connectivity, which facilitates the exchange of data between different components of the DHC network. This interconnectedness allows for better system control, predictive maintenance, and the ability to respond dynamically to changes in demand or supply conditions (Schmidt, 2023).

The use of digital twins in DHC systems is quickly growing, with this concept representing a comprehensive digital model that mirrors the physical network in real-time, enabling operators to simulate, monitor, analyse, and optimise its performance efficiently. By leveraging digital twins, operators are equipped to test various scenarios, predict system behaviour, conduct predictive maintenance, and make informed decisions that enhance the efficiency, reliability, and overall operational effectiveness of DHC infrastructures. This trend underscores the significant benefits of employing digital replicas to augment the planning, operation, and maintenance of district heating systems, leading to improved decision-making, increased reliability and reduced operational costs (Schmidt, 2023).

One example highlighted in the report IEA Annex TS4: Digitalisation of District Heating and Cooling, is the DistrictLab.H™, an advanced software tool that facilitates the design and operation of DH networks by allowing users to build detailed models from GIS data and simulate network performance to optimise efficiencies. It has been deployed in complex, large-scale pilot networks, where the software integrates with metering infrastructure to provide real-time decision support, enabling optimal temperature control, cost-effective operation, and the potential for reduced carbon emissions (Schmidt, 2023).

The digitalisation of DH networks is hampered by a range of challenges, including the need to coordinate with numerous stakeholders and the heterogeneity of systems across the EU. Obstacles also stem from outdated, enduring non-smart infrastructure and a fragmented landscape of digital solutions with many bespoke local systems. A shortage of experts in digital transition, issues with system interoperability, and reluctance of utilities to be dependent on a single supplier further complicate matters. Additionally, accurately assessing the value and constructing a compelling business case for the emerging DHC model has shown to be difficult[21].

Waste Heat

Waste heat recovery is gaining significant traction throughout Europe, with a growing focus on integrating large-scale heat pumps. This interest is particularly concentrated on harnessing waste heat from data centres, industrial processes, and urban infrastructures, including building cooling systems, wastewater treatment plants, hospitals and metro systems. Many of these pioneering projects benefit from EU funding, aimed at demonstrating the potential efficiency gains and creating flagship, or 'lighthouse', cases. However, a major hurdle hindering a widespread adoption is the development of a viable commercial model that aligns with the economic expectations of both utilities and waste heat producers.

Waste heat is the process of recouping and using surplus heat from various sources. For example, the melting procedure in steel production releases an exhaust gas with a temperature of up to 500°C, which can be reused in other industrial processes or as heat in DH networks. There is a wide range for the temperatures at which waste heat is available, varying from 50°C to 1 000°C (Papapetrou, et al., 2018), which limits the potential and possible usage.

Several research papers have explored the total potential of waste heat in the EU. One study conclude the current waste heat potential could cover 17% of today's heating demand in buildings (Manz, et al., 2021) Another study concludes the potential is around 300 TWh/year (Papapetrou, et al., 2018), which also covers around 17% of household's final heat consumption. Another report suggest 30-60% of the surplus heat from industrial processes could be useful as waste heat (Persson, 2015). Yet another study examining the thermal energy discarded by industrial activities estimates that the theoretical potential of waste heat in the EU amounts to 920 terawatt-hours (TWh), with a practical recovery potential—based on Carnot's principle—of approximately 279 TWh (Bianchi, et al., 2019).

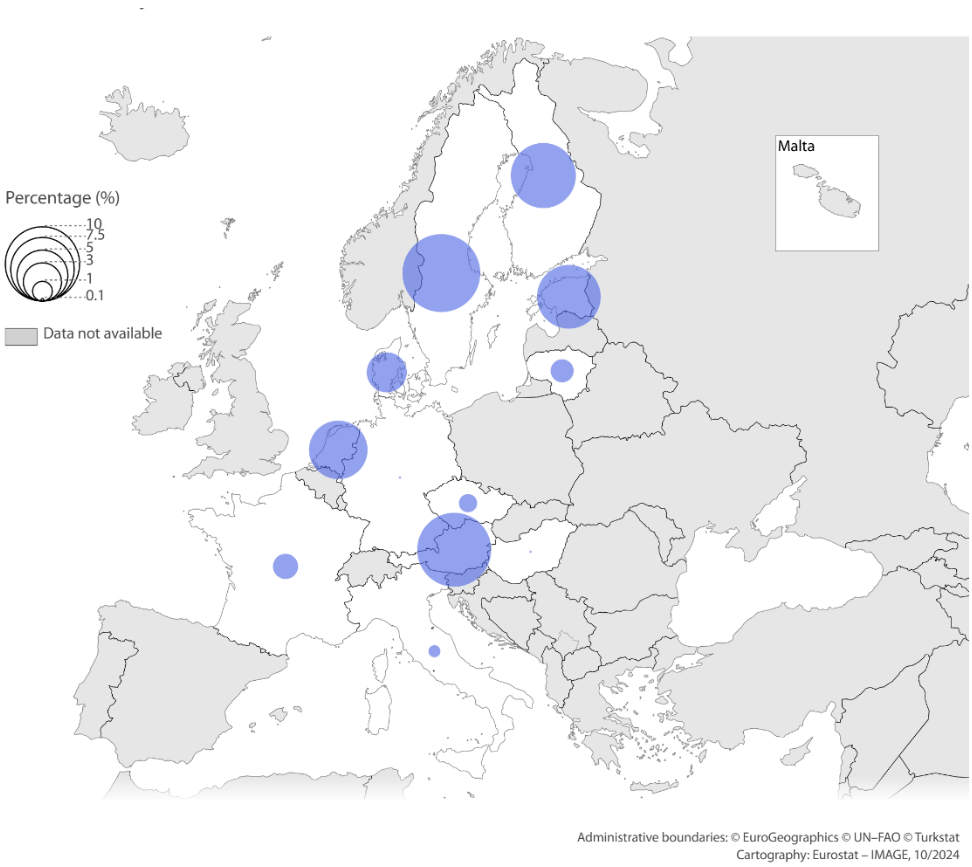
Integrating industrial waste heat into existing energy infrastructure can significantly improve sustainability. If the facility of the waste heat source is already connected to a DH network, it would often be possible to use the existing connection, or expand that pipe capacity, for delivering the waste heat into the DH system. In other situations, it may be necessary to establish a transmission pipeline from the waste heat source to a suitable connection point of a DH system. The viable length of the transmission pipeline generally depends on the capacity of the waste heat source, with larger capacities allowing for longer pipelines.

(21) Input from industry experts

Waste heat can be especially valuable to low-temperature DH networks, with supply return about 50/20°C, as they can utilise waste heat at lower temperatures (Lund, et al., 2014). The effectiveness depends on the level of temperature of the waste heat source and the temperature of the network, as well as if the source will need an increase of temperature or not. For example, if the DH network works at 90°C and the waste heat is at 50°C, the source is not directly useful, it can however be exceptional heat source for heat pumps. For industry zones with multiple waste heat sources, a water loop can be used to recover the waste heat from various processes and deliver it to a central heat pump, which both cools the water loop via the evaporator and delivers the waste heat at useful temperature to the DH system via the condenser of the heat pump. The waste heat collection water loop would avoid the need for a dedicated heat pump for each waste heat source.

Figure 2 shows the share of waste heat of total DH deliveries in 10 different Member States.

Figure 2: Share of waste heat of total DH deliveries, in percentage (%) for the year 2021.



Source: Data from 2021. Based on EuroHeat & Power compilation (Euroheat & Power, 2024)

Large heat pumps

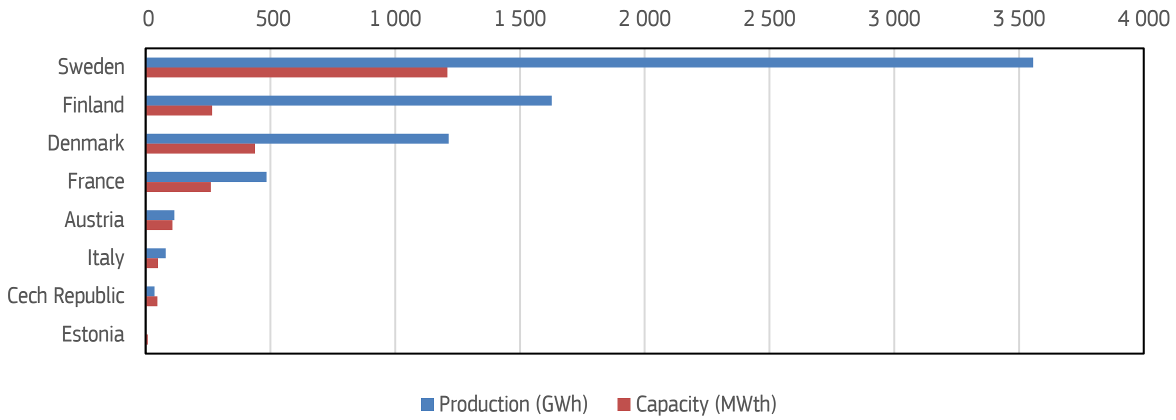
Large heat pumps are central to smart thermal networks, leveraging and recouping various low-temperature heat sources. They strengthen the thermal networks by efficiently elevating the temperature of renewable and waste heat sources—such as ambient air, groundwater, seawater, or industrial waste heat—to levels suitable for space heating and domestic hot water. Despite operating on the same principles as smaller units, these large-scale heat pumps differentiate themselves with a substantially higher capacity, meeting the heating requirements of numerous buildings or entire communities, thus boosting the overall efficiency of DHC networks.

Today large heat pumps represent around 2.5 GW_{th} installed capacity in the DHC fuel mix at European level - or approximately 1% of the total capacity - highlighting a large potential for further uptake. Based on the investment plans of some of the largest DHC systems in Europe, this capacity is expected to increase by over 80% by 2030 representing changes in generation portfolio and growth of networks (Euroheat & Power, 2024) (Toleikyte et al, 2024).

Large heat pumps already play a crucial role in DHC networks in some markets where they upgrade sources such as waste and renewable heat to a temperature suitable for heating and cooling of buildings. There have been many examples of implementation across Europe. Two notable examples are in Denmark and Germany. In Denmark, one of the world's largest heat pump (60 MW_{th}) has been installed in Esbjerg, providing heating for around 100 000 people.[22] In Germany, the largest heat pump in the country (24 MW_{th}) delivers heat to 10 000 households, reducing CO_2 emissions by 15 kt per year.[23] Combined with thermal storage, electric boilers and CHP they enable the integration of sustainable sources into the energy system and open up ways for sector integration.

The Katri Vala heat pump plant in Helsinki is the largest heat pump plant in the world to produce heat and cooling, with an impressive 165 MW_{th} of heat capacity and 100 MW_{th} of cooling capacity[24]. The plant exemplifies the effective use of synergies between DHC systems by utilising the city's wastewater as a source of energy. The plant is used to satisfy the city's heating and cooling needs but also to support the power sector by helping to balance the power grid.

Figure 3: Large scale heat pumps in district heating in 8 Member States.



Source: (Euroheat & Power, 2024)

Pit Thermal Energy Storage

The last years there has been an increased interest and focus within the DH utilities towards establishing large scale pit thermal energy storages. Unlike traditional use of large scale thermal energy storage, which is towards seasonal storages, the boost of interest in pit thermal energy storage systems aims to provide large-scale and high-capacity energy storage, offering enhanced flexibility to the power sector to manage fluctuations in demand and supply over short intervals such as minutes and hours, as well as extended periods spanning days to weeks. This entails a new active operating principle for these systems, which traditionally are operated as seasonal energy storages.

Larger tanks and pits can also facilitate long-term storage of thermal energy, preserving the heated or cooled water (or another medium). The main strength of large tanks and pits is their vast capacity. Several barriers do exist such as limited space in urban dense area and the necessity geological conditions (Guelpa & Verda, 2019). The solutions are technologically feasible but not always cost-effective due to thermal losses and high construction costs (Bauer, et al., 2010). One innovation potential is improved liner material, with the potential to operate with, and for longer periods, 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 of construction methods (Dahash, et al., 2021).

The trend is moving towards larger and larger pits, as the marginal cost becomes lower and lower. The development of pit thermal energy storage has mainly taken place in Germany, Sweden and Denmark, due to

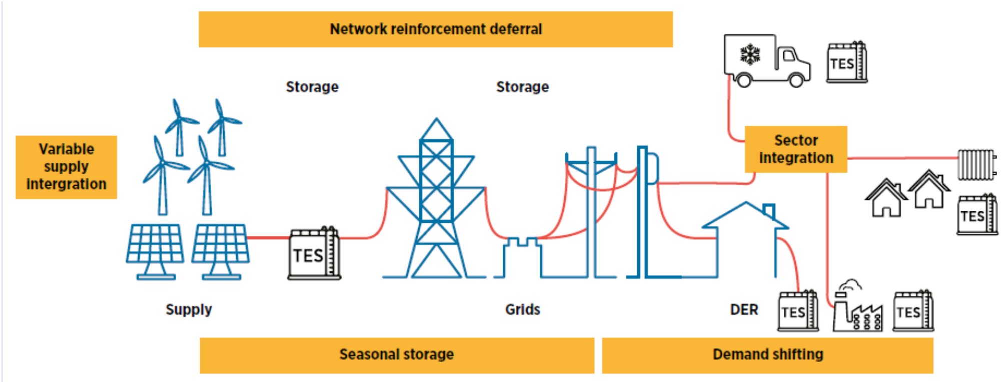
(22) The 60 MW seawater heat pump system will run together with a new 60 MW wood chip boiler based on 100 % sustainable wood chips and a 40 MW electric boiler plant (for peak and back up load). www.man-es.com/docs/default-source/document-sync/esbjerg-heat-pump-reference-case-eng.pdf?sfvrsn=45a29f76_5

(23) www.enbw.com/unternehmen/presse/grosswaermepumpe-liefert-fernwaerme-fuer-10-000-haushalte.html

(24) Katri Vala heating and cooling plant https://www.helen.fi/en/about-us/energy/energy-production/power-plants/katri-vala-heating-and-cooling-plant

many research projects and progressive DH owners. One example is the newly built 70.000 m^3 pit thermal energy storage in Høje-Taastrup in Copenhagen[25], unlike existing pit thermal energy storages, which are generally seasonal storages, the Høje-Taastrup storage is planned to operate as a giant virtual power battery, enabling 3.300 MWh flexibility, with approximately 30 MW flexible thermal capacity[26].

Figure 4: Role of thermal energy storage – providing flexibility to DHC and power sectors.



Source: IRENA, 2020.

Note: DER = distributed energy resources.

5th Generation District Heating and Cooling

The 5th Generation District Heating (5GDH) represents a significant departure from the 4GDH[27], the latter being an advanced iteration of traditional DH systems. Historically, DH networks have operated with centralised heat plants that convert energy sources into thermal energy, which is then directly distributed to consumers. In contrast, the 5GDH approach decentralises this process by delivering the energy source directly to consumers, who then utilise local heat pumps to convert it into usable heat or cooling.

Since the thermal loop operates at a temperature that is insufficient for direct building heating, individual heat pumps are installed at the building level, complemented by a storage tank to ensure a consistent supply of hot water. This configuration, encompassing both the thermal loop and the storage elements, effectively functions as a sizable thermal battery. It possesses considerable capacity to stabilise the power grid by storing excess electricity generated from photovoltaic panels and wind turbines, thereby enabling its use when demand increases.

Although 5GDH offers the potential to markedly reduce distribution losses, it does so at the expense of energy input flexibility. For instance, it relies heavily on electricity to power the heat supply (Gudmundsson & Thorsen, 2021). Despite the sequential numbering of 4GDH and 5GDH suggesting a generational continuity, their underlying philosophies and capabilities are distinctly different. Moreover, while 5GDH could be characterized as a smart thermal grid, its logic and potential diverge from the topics discussed in this report.

Cities must carefully consider which system aligns best with their specific circumstances, factoring in their existing DHC infrastructure, prevalent heating technologies, building insulation standards, grid capacity, RES availability, and any construction limitations. To this end, local heat planning can be an instrumental tool in guiding cities to make informed decisions that cater to their unique needs.

(25 Ingenioren [Website] https://ing.dk/artikel/largest-pit-thermal-storage-its-kind-about-be-put-service#:~:text=The%20pit%20thermal%20storage%20is,52%20and%2072%20meters%20wide

(26) Input from leading industry experts

(27) Some experts argue the 5GDH and the 4GDH should be seen as a parallel rather than a sequential. See e.g. https://www.sciencedirect.com/science/article/pii/S0360544221007696

2. Technology State of the art and future developments and trends

The EU is a global leader of clean heating technologies, including DHC, high-efficiency cogeneration, large heat pumps and certain thermal energy storage systems. Smart thermal networks have proven effective and the key sub-technologies are mature. While only incremental improvement can be expected in the investment cost and efficiency of distribution networks and boilers, there are considerable innovation potentials in other parts of the system. For example, large heat pumps (as discussed in the separate CETO report on Heat Pumps[28]) are expected to deliver significant efficiency improvements when optimised for specific services. Furthermore, digitalisation can offer considerable energy savings for the end-users by detecting inefficient and faulty operations, as well as unlock the flexibility potential of the building thermal mass for either reducing peak demands or increase the potential usage of fluctuating RES. Finally, the potential of integrating and utilising waste heat for heating of buildings is huge.

Most DHC systems in place within the EU cannot be considered smart thermal networks and must be upgraded before they effectively can offer the services discussed in this report. There is a lack of data to monitor the evolvement of *smart thermal networks* in the EU. First, there is a lack of data regarding the status of DHC systems, including the temperatures at which they operate and the technologies they utilise[29,30]. Secondly, thermal networks are local in nature and local public and private actors can be hesitant to reveal sensitive information about technologies used. Third, in most cases a smart thermal network is an evolvement of a conventional thermal system, and is difficult to decide when it should be accounted for as a smart thermal network (e.g. the level of digitalisation and control strategies, the number of thermal sources applied, or the level of integration with other sectors). Fourth, there is no mechanism in place to monitor the adoption of smart thermal networks in the EU. The lack of data is an obstacle for future development as more evidence and examples are needed in some regions to convince more cities to opt for this infrastructure investment.

(28) https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto/ceto-reports-2024_en

(29) However, Member States, in line with Article 14 of the Energy Efficiency Directive (2012/27/EU), are requested to carry out a comprehensive assessment on efficient heating and cooling, including status quo and potential of district heating systems, cogeneration and waste heat. The comprehensive assessments do not include information making it possible to track the development of smart thermal networks across the EU. The assessments can be found: https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en

(30) The industry association Euroheat & Power are collecting data and information from their partners but also this data lacks the required granularity that would enable us to monitor its development over time. The data is available: https://www.euroheat.org/

2.1 Technology readiness level

The technology readiness level (TRL) system used by the EU is a scale from 1 to 9 that measures the maturity of technologies. TRL 1 indicates basic concepts, and TRL 9 signifies a fully matured technology ready for widespread use. As technologies progress through the levels, they undergo increasingly rigorous testing and development, from concept to prototype to final product.

Most individual components of smart thermal networks have reached a high level of technological readiness (i.e. TRL of 8 or 9), including sensors and intelligent control systems, high-efficient cogeneration, large heat pumps and thermal energy storage technologies. However, the integrated concept of smart thermal networks has considerable innovation potential left. With the integration of machine learning/AI technologies, smart thermal networks have become much more intelligent and able to manage more complex systems. Control systems are likely to evolve quickly, following the rapid development of AI language models during the last couple of year. A considerable innovation potential lies with the digital/control part of the thermal networks rather than with the actual networks themselves.

Table 2: Technological readiness of a selection of (sub-) technologies relevant for smart thermal networks

	TRL (Technology Readiness Level)								
(Sub-) technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Smart thermal network[31]					■	■	■	■	
Management and control									
Advanced management and control	No data								
Machine learning/artificial intelligence			■	■	■	■	■	■	■
Digital twins			■	■	■	■	■	■	■
Sensors									■
Smart meters									■
Renewable and energy efficient generation technologies									
Bioenergy									■
Industrial waste heat									■
Waste incineration									■
Combined Heat and Power									■
Electrolysers and fuel cells						■	■	■	■
Pyrolysis and gasification						■	■		
Solar thermal									■
Geothermal									■
Heat pump <90°C									■
Heat pump <110°C								■	
Heat pump <150°C						■			
Heat pump <160°C			■						
Electric resistance boiler									■
Electrode boiler									■
Electric resistance heater									■
Seawater source heat pump						■	■	■	
Air source absorption heat pump			■	■	■				
Distributed absorption heat pumps		■	■	■					
Thermal Energy Storage									
Tank-Pit thermal energy storage									■
Tank thermal energy storage									■
Aquifer thermal energy storage									■
Borehole thermal energy storage									■

Source: An assessment by the European Commission's JRC based on interviews with experts and existing literature (Rehman Mazhar, Liu, & Shukla, 2018) (Maruf, Morales-España, Sijm, Helistö, & Kiviluoma, 2022) (IRENA, 2020)

(31) Indication based on literature review and discussion with industry experts. The TRL depends on the definition of smart thermal networks.

More information on TRL can be found in the related CETO reports, including the reports on Heat Pumps, Novel Thermal Energy Storage systems, and Smart Grids[32].

2.2 Installed energy Capacity, Generation/Production

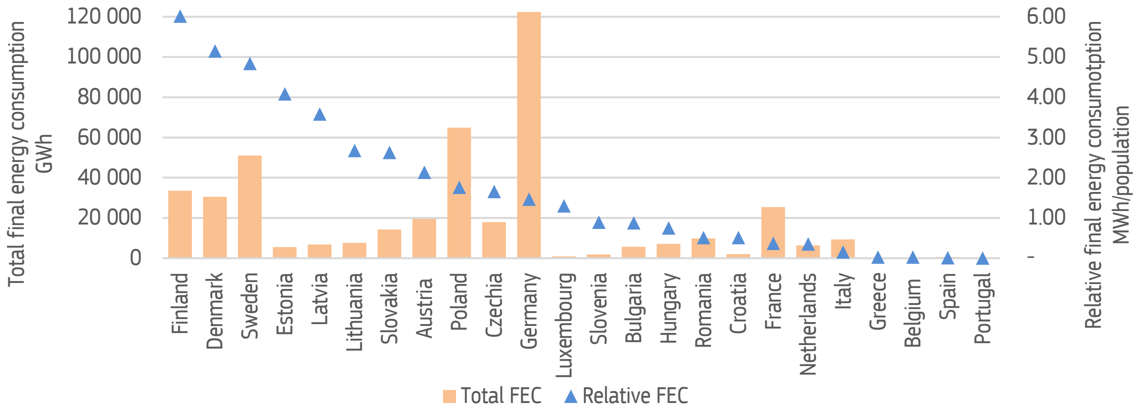
This section focus on the current state of DHC networks across the EU. The available data on the uptake of smart thermal networks is, however, currently too incomplete to include in this section.

According to EuroHeat & Power, there are around 19 000 district heating networks in Europe[33]. Heating and cooling constitute half of the EU's energy consumption. As of 2022, the collective installed capacity of the district heating systems across Europe amounts to approximately 333.4 gigawatts thermal (GWth) (Euroheat & Power, 2024). District cooling (DC) is much less common in EU, with a total installed capacity of 7.74 (GW) and around 200 installations (Pezzutto, et al., 2022). District cooling is experiencing gradual adoption and expansion across various regions in Europe beyond the leading countries of Sweden and France, which currently are accounting for around two-thirds of the total district cooling supplies in the EU (Euroheat & Power, 2024).

DH, despite supplying just 13% of this demand, plays a pivotal role in the energy strategies of countries that excel in reducing carbon emissions, notably the Nordics. In certain EU Member States, DH is integral to the vision of achieving a flexible, efficient, and decarbonized energy system, whereas it is scarcely present in others. For instance, DH satisfies a substantial portion of the heating needs in Denmark (66%) and Finland (45%) (Euroheat & Power, 2024). Moreover, Germany, Poland, and the Nordic countries accounted for 68% of the EU's total DH consumption in 2018 (Eurostat, 2022). In contrast, the adoption of DH in the Benelux countries and most of Southern Europe remains limited.

Figure 5 illustrates that Germany and Poland have the highest levels of DH consumption among the EU countries. Conversely, the Nordic and Baltic states exhibit the highest per-capita density of DH consumption. The figure also illustrate that the prevalence of DH in several Member States in close to non-existing, which is a considerable barrier for the uptake of smart thermal networks. Figure 6 illustrates a similar story by showing the share of households per types of fuels used for residential space heating.

Figure 5: District heating, final energy consumption.

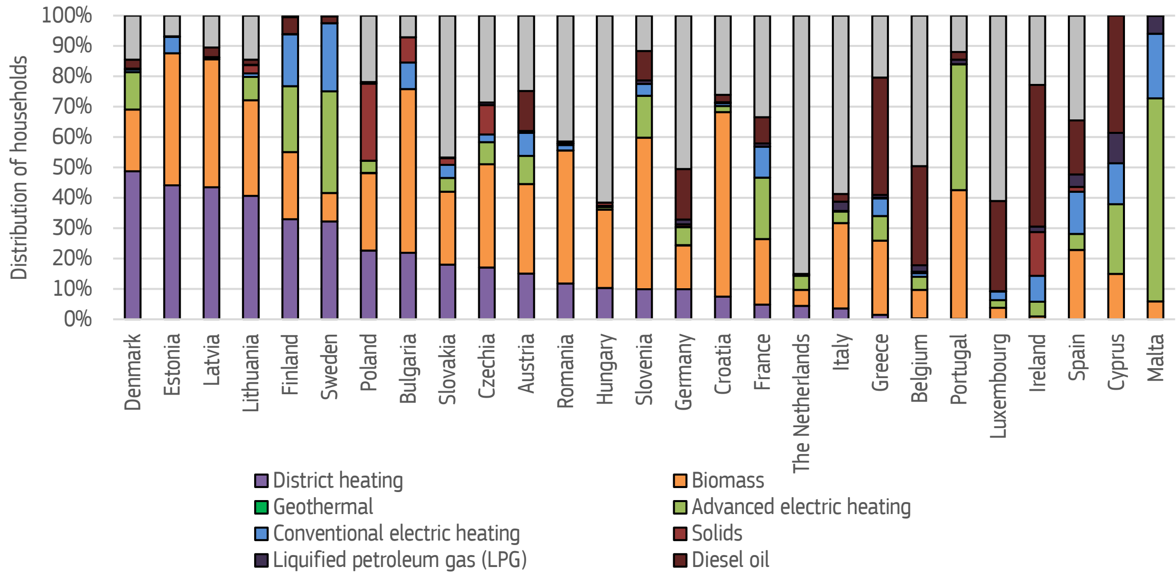


Source: (European Commission, 2022). Data for the year 2018.

(32) https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto/ceto-reports-2024_en

[33] Including also non-EU countries such as Norway, Switzerland and the UK.

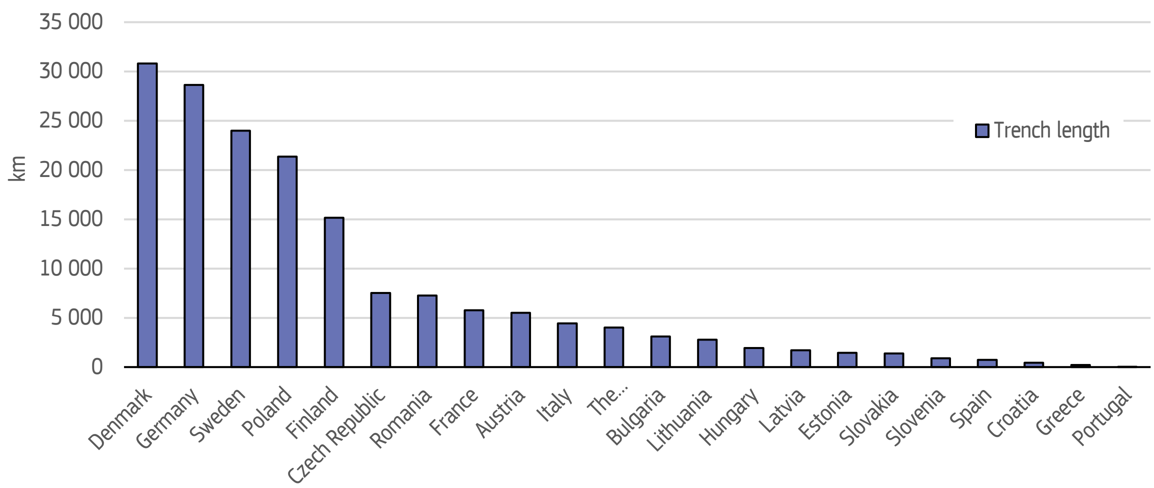
Figure 6: Share of households per types of fuels used for residential space heating, per MS in 2021



Source: European Commission JRC, IDEES, 2024.

Figure 7 illustrates the trench length (i.e. how much DH pipeline been installed) in the EU countries, where the bars indicate the actual length of installed pipelines. The results are heavily correlated with the consumption figures, where Germany, Poland, Denmark, Finland and Sweden are in the lead.

Figure 7: District heating networks, trench length.



Source: (European Commission, 2022). Data for the year 2018.

While reliable recent data is missing on the development of smart thermal networks, interviews with experts indicate that they are becoming increasingly popular, especially in countries with a history of DHC networks and a relatively high share of RES (especially Denmark and Sweden). However, France and Germany have implemented ambitious policies during the last years to support the implementation of smart thermal networks. For example, since 2009, France has almost doubled the length of their thermal networks, from 3 450 km to 6 529 km as of 2021 (Euroheat & Power, 2023). Table 3 shows a compilation of targets/projects of new DHC connections by 2030.

Table 3: Expected growth in installations until 2030.

Countries	Expected growth by 2030	Source
Austria	+ 350k new households	Forecast of Austrian Energy agency (2022)
Denmark	+250/300k new households by 2028 (Phase out of 400k gas boilers to be replaced by District Heating and individual heat pumps)	Estimate by stakeholders
France	+ 215k households/year	Estimate by the national association
Germany	Between 300-600k households/year	Estimate by the national association
The Netherlands	+ 500k households	Climate agreement between government and sectors - Klimaatakkoord (2019)

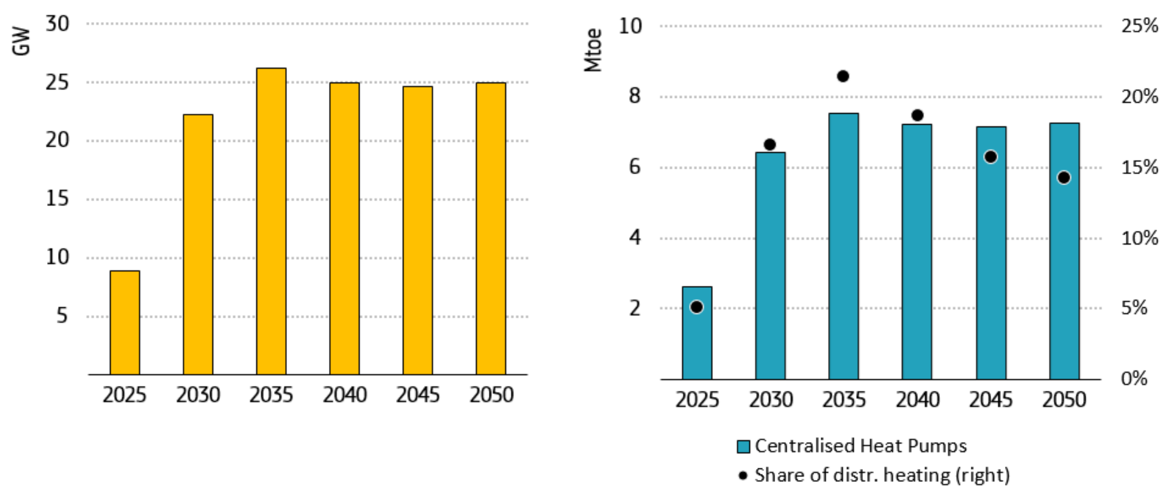
Source: Compilation by Euroheat & Power, 2023.

POTEnCIA CETO 2024 Scenario projections

POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) is a modelling tool developed by the JRC that allows a robust assessment of the impact of different policy futures on the EU energy system. Within in the wider context of the CETO project, POTEnCIA has been employed to model a technology-oriented deep decarbonisation scenario allowing for high detail projections of the various CETO technologies: the POTEnCIA CETO 2024 Scenario. The modelling approach focuses on projecting the uptake of centralised heat pumps, which are predominantly employed within DHC networks.

The capacity of centralised heat pumps is projected to increase by 147% from 2025 to 2035 in the EU, rising from 10 GW to over 26 GW (see Figure 8). The projected amount of ambient heat is expected to reach 3 Mtoe in 2025, covering 5% of the total heat generation for DHC. By 2036, the projected ambient heat is set to experience a significant increase to almost 8 Mtoe, covering over 20% of the total heat generation for DHC.

Figure 8: Capacity of centralised heat pumps for district heating (left figure) and ambient heat from centralised heat pumps (right figure, left side) as well as share of heat generation (right figure, right side)



Source: JRC POTEnCIA CETO 2024 Scenario

2.3 Technology Cost – Present and Potential Future Trends

DHC networks, smart or not, require a considerable upfront investment. The initial setup requires constructing an extensive network of pipelines, connecting buildings with heating sources. Moreover, implementing efficient and modern heat generation technologies, such as CHP plants, large heat pumps or waste heat recovery systems, adds to the overall investment required. However, it's essential to consider that these upfront costs are usually offset by long-term savings and especially for cities moving towards a carbon neutral energy supply[34]. Furthermore, the flexibility offered through sector coupling can reduce costly capacity upgrades of the power grid. Finally, a sector integration between DH and waste heat sources would generally lead to lower cost of both heat generation capacity for the thermal system as well as reduced cost of disposal of the waste heat by the waste heat owner.

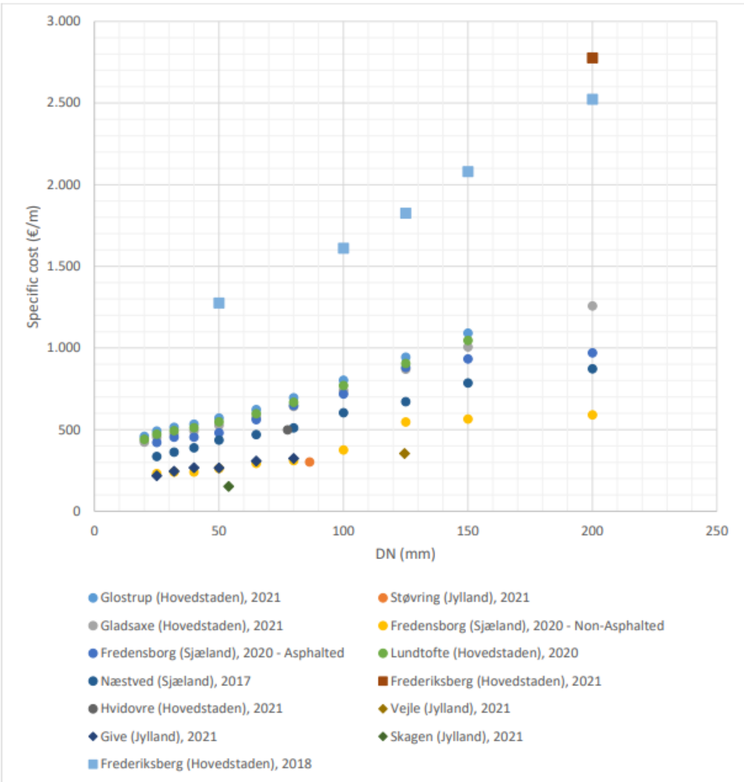
Table 4 shows the current and projected cost development for the piping networks, which are expected to remain somewhat constant.

Table 4: Projection of district heating piping costs.

Projection (EUR/rm)	2020	2030	2040	2050
Nominal investment (total)	498	496	494	490
Equipment cost	199	198	197	196
Installation cost	299	298	297	294

Source: (Grosse, Christopher, Stefan, Geyer, & Robbi, 2017)

Figure 9: Construction cost of distribution district heating pipes in various Danish projects.



Source: (Sánchez-García, Averfalk, & Persson, 2022)

Similarly, Figure 9 illustrates total investments costs per meter of varying pipe nominal diameters (i.e. width) for establishing DH distribution pipelines from 16 projects in Denmark (Sánchez-García, Averfalk, & Persson, 2022). In the same report, the authors conclude project cost is correlated with the labour cost. In other words, it is cheaper to install new DH systems in countries and regions where the salaries are lower (ibid, 2022).

The cost of implementing new thermal systems come with a considerable cost for the public authorities and possess one of the main barriers. In countries with a long DH tradition, such as Sweden and Denmark, the thermal networks are seen as critical infrastructure or public goods, needed to cost-effectively provide the citizens with heating. The technology cost of smart thermal networks ought to be seen in the light of all the benefits.

(34) What should be considered is that if fossil fuels are to be phased out other energy generation facilities will be needed, meaning that it is not so that the investments in heat generation plants would not be needed in case of electrified heating or transition to hydrogen. In other words, the decarbonisation of heating and cooling will require infrastructure investments.

One benefit of smart thermal networks is their ability to operate at lower temperatures compared to traditional systems. The reduced operating temperature make renewable technologies, like geothermal heat, industrial excess heat, and heat pumps, more cost-effective. Thus, the roll-out of DHC networks operating at lower temperatures enables a higher share of renewables and waste heat in the systems (Averfalk & Werner, 2020). Table 5 illustrates how the increased heat generation efficiencies from renewables in smart thermal networks (i.e. 4GDH) make them more cost-effective.

Table 5: Estimated annual heat supply costs for different operational modes for the 3GDH and 4GDH temperature levels.

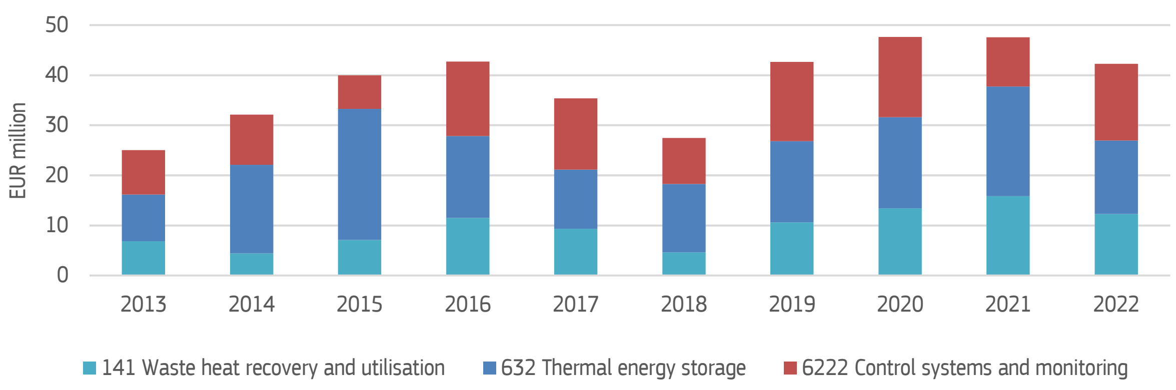
	Annual Heat Supply Costs [MV]	
Technology/Operational mode	***3GDH***	***4GDH***
Waste CHP	*-9.9*	*-10.7*
Biomass CHP	*5.1*	*3.4*
Biomass boiler	*12.7*	*11.2*
Geothermal	*10.8*	*3.3*
Geothermal investment	*11.0*	*6.0*
Industrial excess heat	*17.4*	*11.6*
Heat pump	*15.9*	*8.9*
Heat pump investment	*15.1*	*10.5*
Solar thermal investment	*14.5*	*10.2*

Source: Table and analysis comes from (Averfalk & Werner, 2020)

2.4 Public R&I funding

Public research and innovation (R&I) funding plays a key role in driving the development of smart thermal networks, enabling innovative features to be developed and tested. Figure 10 shows the public research and development investments in DHC related fields, namely thermal energy storage, waste heat and control systems and monitoring. Notably, aggregated R&D investments in the sector saw a 19% increase, comparing the 2018-2022 period to the 2013-2017 period.

Figure 10: Public R&D investment [EUR million] over 10 years in DHC related fields



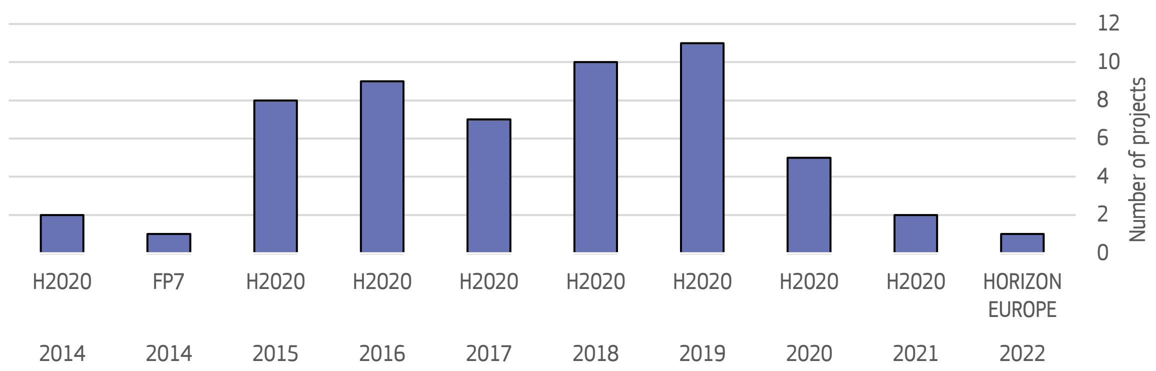
Source: JRC based on (IEA 2024)

The EU granted EUR 438 million to 63 research projects related to smart thermal networks between 2013 and 2022. Most projects were enacted between 2015 and 2019, as shown in Figure 11. The EU has persistently funded research projects aiming to improve the implementation of smart thermal networks, including technical innovations, digital solutions and new business models[35]. Examples include Heat Roadmap Europe, THERMOS, COOL DH and 4DH which are examples of projects looking at the potential of smart thermal networks, while STORM, TEMPO, OPTi and FLEXYNETS are examples of projects exploring intelligent control and optimisation

(35) Many of the projects have received funding through the Horizon Europe and the LIFE programme.

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 thermal energy storage systems. A recent report provides a comprehensive overview of support activities and projects of the European Commission on DHC[36]

Figure 11: New signed EU funded projects related to smart thermal networks, per year.



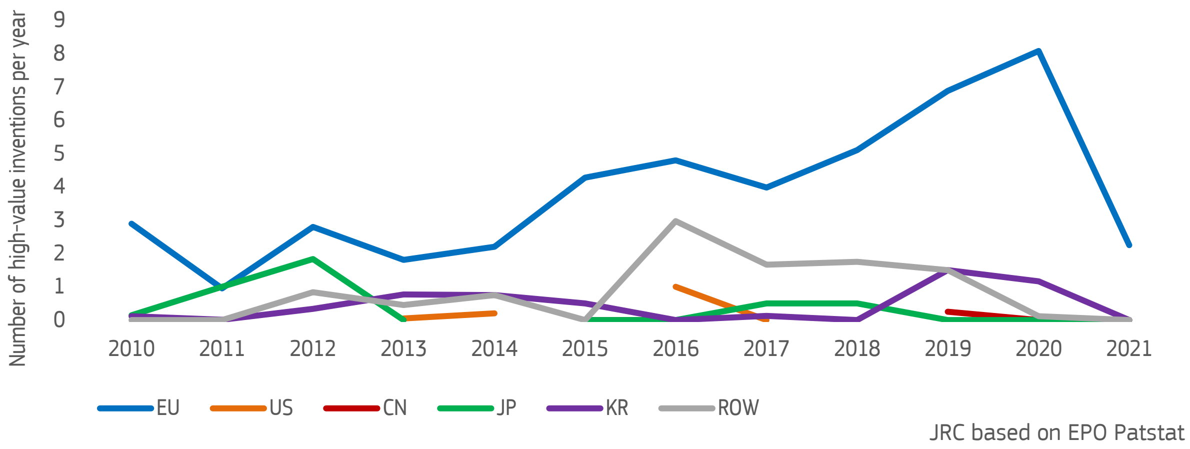
Source: European Commission's Joint Research Centre (JRC) analysis based on CORDIS, 2023 data.

2.5 Patenting trends

Patenting trends offer valuable insights into innovation and technological advancements in different sectors. Analysing these trends reveals emerging areas of focus, innovation pace, and the competitive landscape in the sector.

The EU holds 79% of all high-value inventions recorded in the period from 2019 to 2021. Sweden and Germany, countries with a relative high penetration of DHC networks, are the leading patenting countries globally (see Figure 12). Swedish E.ON Sverige AB is the leading patenting company, followed by the German companies Siemens aktiengesellschaft and Delta systemtechnik (see Figure 13).

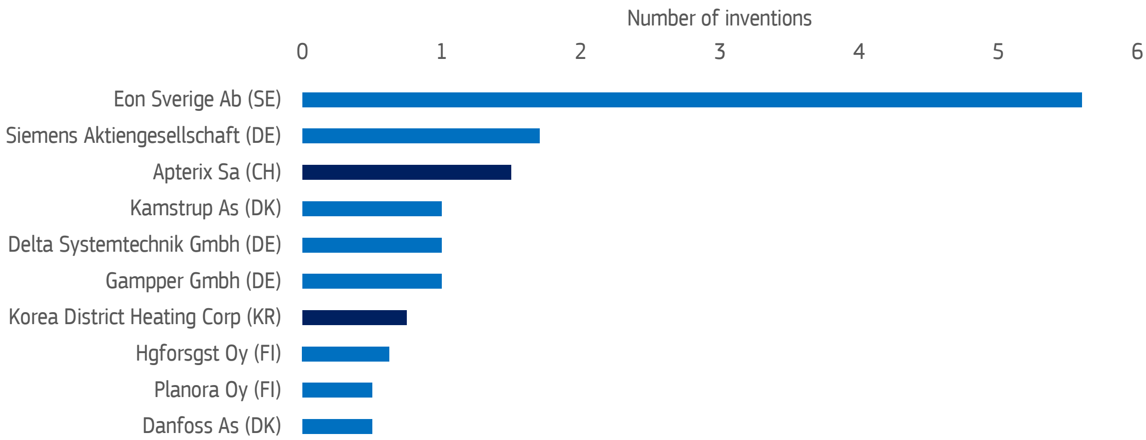
Figure 12: Trend in high-value inventions for major economies (left) and top 10 companies in 2016-2019 (right)



Source: European Commission's Joint Research Centre (JRC) analysis based on EPO Patstat.

(36) European Commission, Directorate-General for Energy, Lettenbichler, S., Corscadden, J., Krasatsenka, A., Advancing district heating & cooling solutions and uptake in European cities – Overview of support activities and projects of the European Commission on district heating & cooling, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2833/51155

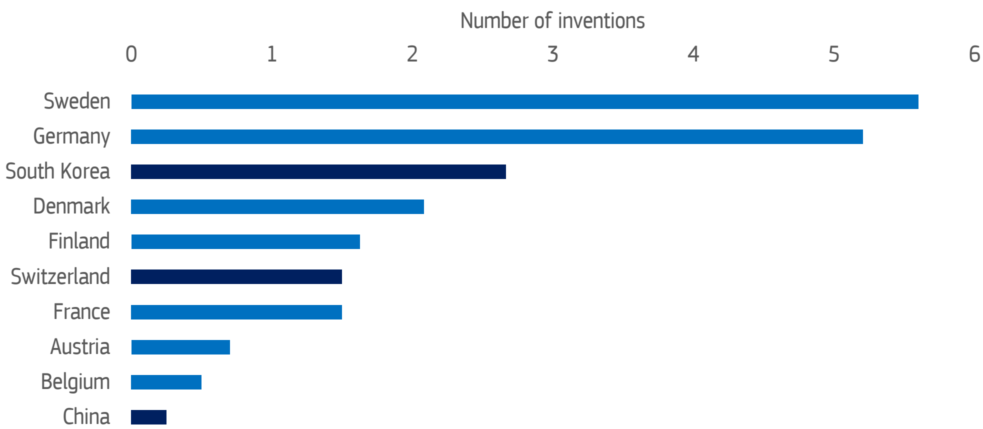
Figure 13: High-value Inventions - Top 10 companies (2019-2021)



Source: JRC based on EPO Patstat

The EU scores well in innovation-related indicators, showing leadership in the development of decarbonised DHC networks. The EU hosts nearly half of all identified innovating companies in the sector. In production of heat exchangers, the EU performance is medium as, while production is growing, it is growing slower than the EU gross domestic product overall.

Figure 14: High-value inventions - Top 10 countries (2019-2021)



Source: JRC based on EPO Patstat

2.6 Value chain analysis

The pandemic in 2020 and the gas price surges in 2022 revealed several supply chain challenges within the sector. This includes a shortage of qualified labour, which can hamper a fast rollout of thermal networks and components. The labour shortage that emerged following the gas crisis is likely to persist as an ongoing challenge, especially with the accelerated deployment of new thermal systems and the modernisation of existing systems into smart thermal networks. This is because both initiatives draw from substantially the same pool of labour resources[37].

The DH sector faces a significant challenge in terms of skilled workforce, with an ageing workforce and a decline in students pursuing technical fields. This shortage of qualified professionals is expected to worsen, with countries like Sweden needing to replace 1 700 retiring technicians and engineers with 8 000 new hires in the next three years. To address this gap, industry associations, private companies, and educational institutions are taking proactive steps. In Austria, for example, the national association FGW has created a new "district heating technology" apprenticeship program, which provides 3.5 years of in-depth training in district heating and installation technology, generation and distribution, and system servicing. Additionally, Austria estimates that 2 100 annual jobs will be created with investments in sustainable district heating by 2040, highlighting the need for skilled professionals. Similar initiatives are also underway in other countries, such as Estonia, where the Estonian Association of Thermal Engineers offers monthly professional seminars and trainings to upgrade skills and qualifications, and Italy, where the Italian Association of District Energy promotes and fosters similar activities (Euroheat & Power, 2024).

Industry experts[38] have identified the following labour and material challenges as most pressing for the EU smart thermal network actors.

Labour related supply challenges:

- Technical expertise: There is a shortage of workers with skills in renewable energy integration, ICT, and IoT technologies.
- Training and education: Insufficient training programs and educational initiatives hinder workforce development.
- Competition for skilled labour: high demand in other technology sectors intensifies competition for skilled workers.
- Geographical disparities: some regions lack the necessary skilled labour for smart thermal network projects.

Material related supply challenges:

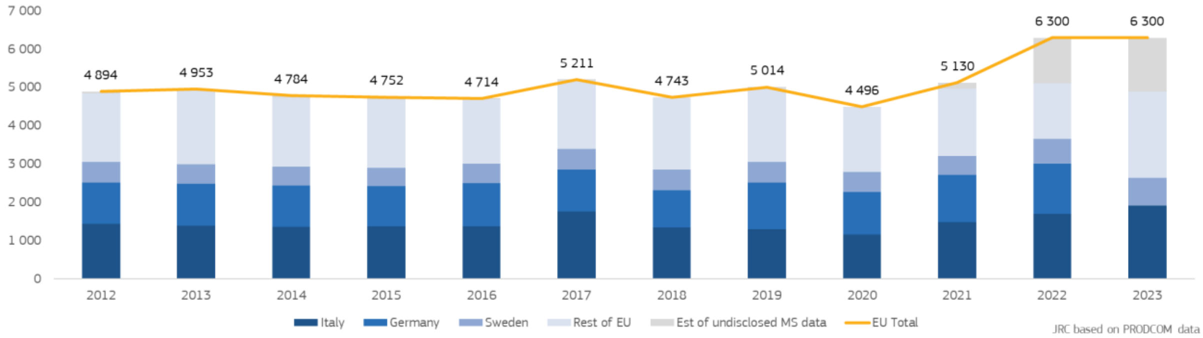
- Metals and minerals: Shortages in copper, aluminium, and rare earth elements can impact component production.
- RES components: supply chain constraints affect components like solar panels and geothermal pumps.
- Production capacity: limited production capacity for key materials and components can delay projects.
- Semiconductors and electronics: the global semiconductor shortage affects availability and costs.
- Sensors and control systems: shortages in these essential components could slow deployment.

(37) Input from leading industry experts
(38) Input from leading industry experts

Heat exchange units is used as a proxy, in the next section, to monitor the EU's trade trends for heating and cooling networks. While not a perfect proxy, heat exchange units are integral components of heating and cooling networks, changes in their trade volumes and values can reflect broader trends in the trade of heating and cooling systems. By monitoring the import and export figures of heat exchange units, it is possible to understand the overall performance and demand for heating and cooling technologies within the EU market and in trade with non-EU countries.

In 2023, the production value of heat exchange units within the EU remained constant at EUR 6.3 billion, as indicated in Figure 15. Italy and Germany were the largest producers in the EU, together contributing to almost half of the total production value, followed by Sweden.

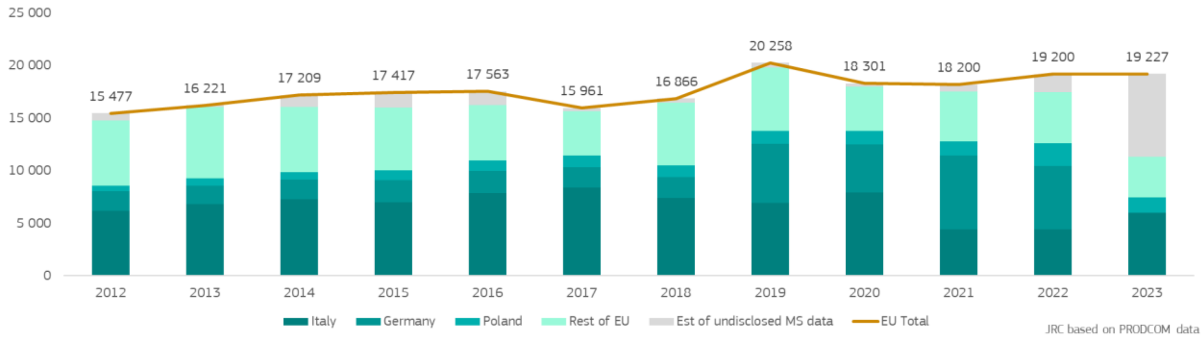
Figure 15: EU production value and top producers among the Member States disclosing data [EUR million]



Source: JRC based on PRODCOM data. The figures of Germany is not disclosed for 2023 but is included in the EU total.

In the EU, production levels have remained somewhat consistent at approximately 19 million units, as illustrated in Figure 16. Among the EU Member States, Germany and Italy are the largest producers, with both Poland and Sweden also making substantial contributions to EU's total production output.

Figure 16: EU production in quantities [Thousand pieces]



Source: JRC based on PRODCOM data. The figures of Germany is not disclosed for 2023 but is included in the EU total.

3. EU position and Global competitiveness

EU companies are global leaders in DHC systems and smart thermal network technologies. Europe stands at the forefront of integrating renewables into DH systems, with 25% of its DH supplies generated from renewable sources. Leading this movement are Sweden, Denmark, Austria, and the Baltic states where the adoption of RES is high, accounting for over 50% of their DH production (IEA, 2023). The demand and use of smart thermal networks are also higher in markets with a higher share of renewables.

3.1 Global & EU market leaders (Market share)

The EU has been the global leader in the domain of efficient DHC networks for a long time and possess a head start in smart thermal networks. EU, its Member States, cities and companies have invested in state-of-the-art technologies and in integrating more RES and waste heat into DHC systems. There are over 19 000 DH networks in Europe supplying heat to around 70 million citizens (Euroheat & Power, 2023). The average carbon intensity of European DHC networks is lower than the rest of the world, due to a higher efficiencies and larger share of renewables (IEA, 2023).

The EU has also developed a broad policy framework to facilitate the uptake of DHC networks and increase the share of renewables in the thermal networks. The Energy Efficiency Directive (EED)[39] defines *efficient district heating and coolin*g (Art. 2) and requires Member States to conduct economic and geographic analyses to identify DHC potentials (Art. 25)[40]. 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 renewables 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)[41]. In addition, the European Performance of Buildings Directive (EPBD)[42] sets out several provisions to improve the efficiency of new and existing buildings, which is a prerequisite for lower-temperature DHC networks[43].

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 ([44]) 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[45], 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[46] supports this mission by offering knowledge, capacity-building support and facilitation of finance solutions for cities. Covenant of Mayors for Climate and Energy[47] 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 (Volt, et al., 2022).

(39) 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

(40) 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

(41) 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

(42) 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

(43) 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).

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

(45) CETPartnership [Website] Available: https://cetpartnership.eu/

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

(47) Covenant of Mayors [Website] Available: https://www.eumayors.eu/en/

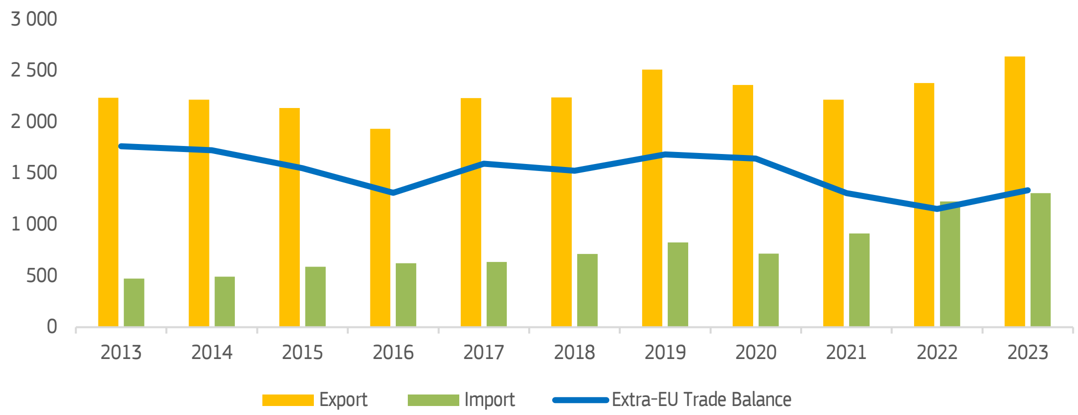
3.2 Trade (Import/export) and trade balance

Heat exchange units is used as a proxy, in the next section, to monitor the EU's trade trends for heating and cooling networks. While not a perfect proxy, heat exchange units are integral components of heating and cooling networks, changes in their trade volumes and values can reflect broader trends in the trade of heating and cooling systems. By monitoring the import and export figures of heat exchange units, it is possible to understand the overall performance and demand for heating and cooling technologies within the EU market and in trade with non-EU countries.

The EU has a strong presence as global exporter of heat-exchange units[48]. In 2023, the extra-EU imports of heat-exchange units increased by 11% compared to 2022, reaching almost EUR 2.4 billion, while extra-EU exports increased by 7%, reaching more than EUR 1.2 billion. The trade surplus increased by 16% reaching more than EUR 1.3 billion (7). Italy, Sweden and Hungary were the Member States with the biggest trade surpluses (EUR billion +0.8, +0.3, +0.2, respectively, in 2023), while Slovakia, Ireland and Austria had the biggest trade deficits (EUR million -5, -37, -23, respectively, in 2023)

In 2023, the import of heat-exchange units from non-EU countries into the EU grew by 11% from the previous year, amounting to nearly EUR 2.4 billion. Concurrently, the EU's export of these units to countries outside the EU rose by 7%, surpassing EUR 1.2 billion. This led to a 16% increase in the trade surplus for heat-exchange units, which exceeded EUR 1.3 billion. Among EU Member States, Italy recorded the largest trade surplus in this sector, at approximately EUR 0.8 billion. Sweden and Hungary followed with significant trade surpluses of their own, at around EUR 0.3 billion and EUR 0.2 billion, respectively. Slovakia, Ireland, and Austria faced the most considerable trade deficits in the trade of heat-exchange units, with deficits of EUR 5 million, EUR 37 million, and EUR 23 million, respectively, in 2023.

Figure 17: Extra-EU trade for heat-exchange units [EUR million]

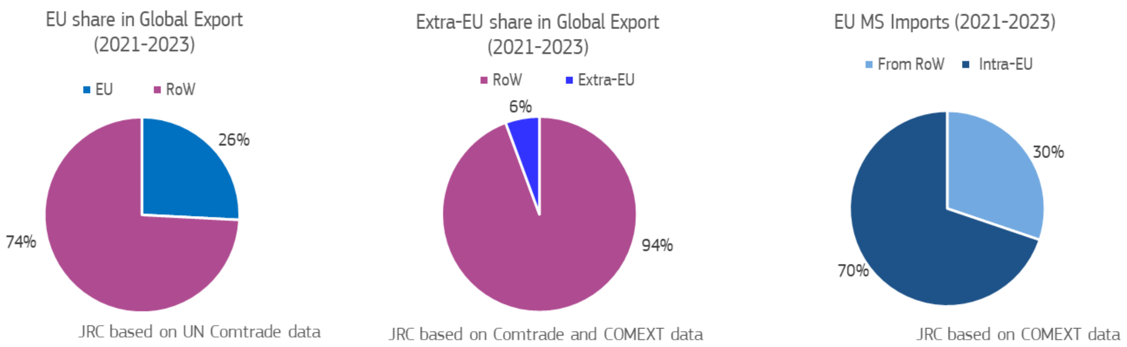


Source: JRC based on COMEXT data

Between 2021 and 2023, the EU maintained a dominant position in global trade, with its exports constituting over 25% of the world's total exports. Moreover, trade with countries outside the EU, known as extra-EU trade, accounted for approximately 6% of the EU's total exports during this period. When it comes to imports, intra-EU trade, which refers to trade between EU member states, was responsible for around 70% of the EU's total imports, indicating a strong internal market within the EU (see Figure 18).

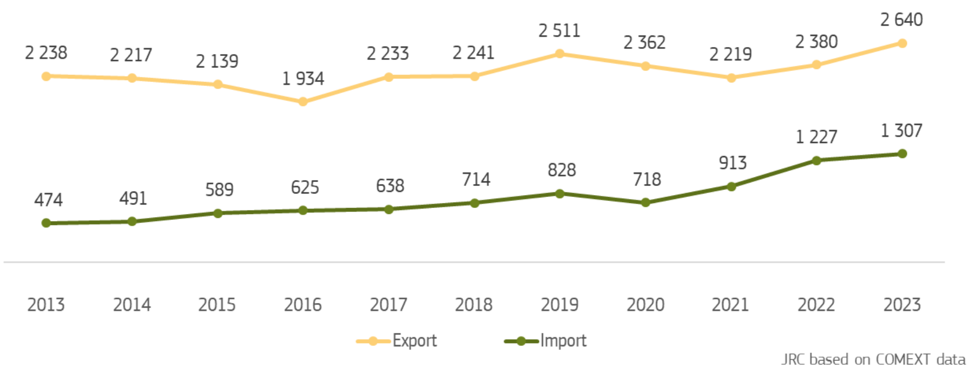
(48) The code 841950 (Heat-exchange units) of the Harmonised System (HS) classification is used as a proxy to monitor the EU's trade trends for heating and cooling networks. The code excludes heat exchange units used with boilers, domestic or electric units. Nevertheless, the traded goods reported under that code are not used exclusively in heating and cooling networks.

Figure 18: EU share in global export (left), extra-EU share in global export (middle) and EU imports (right) [2021-2023]



Source: JRC based on COMEXT and COMTRADE data

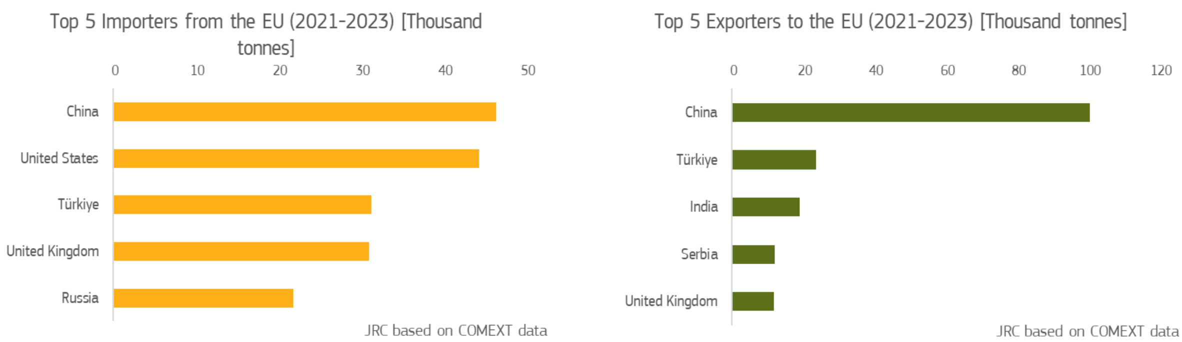
Figure 19: Extra-EU export and import [EUR million]



Source: JRC based on COMEXT and COMTRADE data

During the same time period, the China, the United States, Türkiye, and the United Kingdom were notable as both key importers from and exporters to the EU, as illustrated in Figure 20. This trade pattern implies that these countries may be re-exporting goods to the EU after adding value, or they might be acting as transhipment hubs, forwarding goods to third countries. It could also point to arbitrage prospects arising from factors that impact prices, such as variances in taxation, supply and demand imbalances, or other economic considerations.

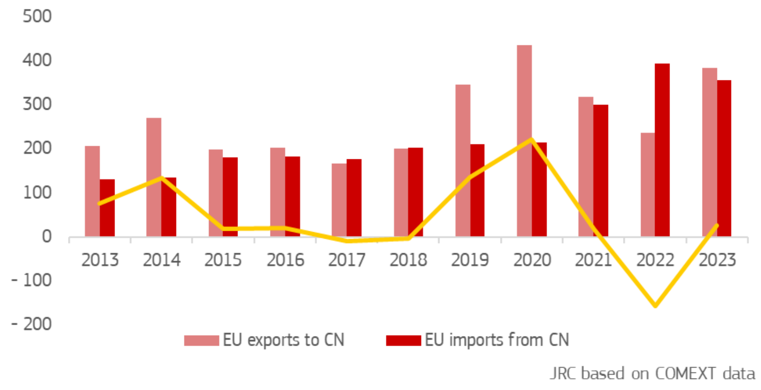
Figure 20: Top countries importing from (left) and exporting to (right) the EU (2021-2023) [EUR million]



Source: JRC based on COMEXT data

Regarding trade with China, the EU's exports of heat exchange units surpassed the value of its imports, as depicted in Figure 4. While the EU's trade balance with China shifted to a deficit in 2022, it rebounded to a surplus in 2023. Nevertheless, when examining the volume of trade, the EU consistently imported a greater quantity of heat exchange units from China than it exported to the country. This suggests that the EU exports these units at a higher unit price than the imports, resulting in a higher export value despite lower volumes.

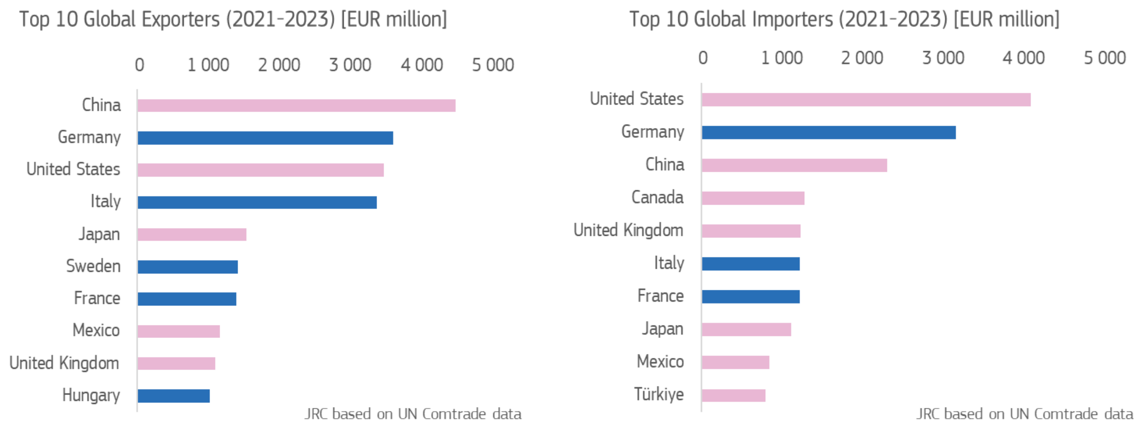
Figure 21: EU trade with China in value [EUR million]



Source: JRC based on COMEXT data

The EU featured prominently among the leading global exporters, with Germany, Italy, and France not only contributing to export but also featuring as major importers, according to Figure 22. China stood out as the leading global exporter and was also listed among the key global importers, a group that included other economic heavyweights such as the United States, the United Kingdom, and Japan.

Figure 22: Top global importers (left) and exporters (right) (2021-2023) [EUR million]



Source: JRC based on COMEXT and COMTRADE data

Conclusions

Smart thermal networks can be a central and dynamic element of a low-carbon energy system, with the ability to integrate local low-temperature RES and offer flexibility to the wider energy system. Smart thermal networks enable operators to run the networks with lower temperatures, making renewable options like geothermal heat, industrial excess heat and heat pumps, more energy-efficient and cost-effective. They utilise advanced control strategies, using sensors and intelligent monitoring solutions, which improves the performance of the network and enables the integration of more RES. In many urban areas, a smart thermal network is a necessity for a cost-effective decarbonisation transition.

The uptake of smart thermal networks goes hand in hand with EU climate and sustainability goals. Most cities that have developed a net-zero climate plan do expect a vital role for a smart thermal network. The EU also has increased its focus and funding for DHC as part of its Green Deal and the Fit for 55 package, aiming to reduce greenhouse gas emissions by at least 55% by 2030.

Most individual components of smart thermal networks have reached a high level of technological readiness, including sensors and intelligent control systems, high-efficient cogeneration, large heat pumps and thermal energy storage technologies. However, the integrated concept of smart thermal networks has considerable innovation potential left. There are local networks that have been incrementally built towards becoming smart thermal energy systems, although they still have quite some path to go before becoming truly smart.

The EU is a global leader when it comes to smart thermal networks, with more networks operating at lower temperatures and with a higher share of RES than non-EU countries. The opportunity is there for the EU to spearhead the transition to smart thermal networks and showcase their value in a low-carbon reality.

Technology trends:

- Digitalisation and the increased use of smart meters and sensors in the networks have dramatically increased the amount of data available, which can be used for advance planning and operational optimisation. Thermal networks are becoming more complex, making it possible and necessary to collect more data at various stages of the system's operation and to use advanced digital tools to process and acquire insights that can be transformed into actionable solutions. New emerging control strategies could further boost this development, and thus the performance of the system.
- There has been a general trend toward lower temperatures in DH networks over the last decade, which has gained momentum since the war in Ukraine. This interest is driven by the need for improved system efficiency and better compatibility with alternative low-temperature heat sources. From a European perspective, the expected benefits of reduced operating temperatures push the utilities to gain better understanding of their distribution networks, for being able to reduce the operating temperatures without impacting their customers.
- The path towards decreasing the operating temperature has traditionally been achieved by trial and error, e.g. the utility lowers the supply temperature until they start to receive complaints from their customers. With the development of advanced digital solutions and increased amount of data from sensors around the network this process of reducing the operating temperatures is simply done more smart.
- Pit thermal energy storages are becoming more popular, where the trend is moving towards larger and larger pits, as the marginal cost becomes lower and lower. The development of pit thermal energy storage has mainly taken place in Germany, Sweden and Denmark, due to many research projects and progressive DH owners. The pit thermal energy storage in Høje-Taastrup is planned to operate as a giant virtual power battery, enabling 3.300 MWh flexibility, with approximately 30 MW flexible thermal capacity.
- Large heat pumps already play a crucial role in DHC networks in some markets where they upgrade sources such as waste and renewable heat to a temperature suitable for heating and cooling buildings. There have been many examples of implementation across Europe. Two notable examples are in Denmark and Germany. In Denmark, the world's largest heat pump (60 MW_{th}) has been installed in

Esbjerg, providing heating for 100 000 people.[49] In Germany, the largest heat pump in the country (24 MW_{th}) delivers district heat to 10 000 households, reducing CO_2 emissions by 15 kt per year.

– The role of DHC networks has shifted from simply ensuring sufficient supply to optimising the whole system, from supply point to end-users. Smart meters can help by giving a better understanding of the current condition of the network and supporting advanced short-term forecasting of heating and cooling demands. Buildings are increasingly being viewed an as integrated element of the DHC system.

(49) The 60 MW seawater heat pump system will run together with a new 60 MW wood chip boiler based on 100 % sustainable wood chips and a 40 MW electric boiler plant (for peak and back up load). www.man-es.com/docs/default-source/document-sync/esbjerg-heat-pump-reference-case-eng.pdf?sfvrsn=45a29f76_5

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List of abbreviations and definitions

3GDH	Third generation district heating
4GDH	Fourth generation district heating
5GHD	Fifth generation district heating
CETO	Clean energy technology observatory
CO2	Carbon dioxide
DC	District cooling
DH	District heating
DHC	District heating and cooling
EED	Energy efficiency directive
EPBD	Energy performance of buildings directive
EU	European Union
GHG	Greenhouse gases
JRC	Joint Research Centre
RED	Renewable energy directive
RES	Renewable energy sources
TRL	Technology readiness level

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Annex 1 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 1.1 POTEnCIA Model

AN 1.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

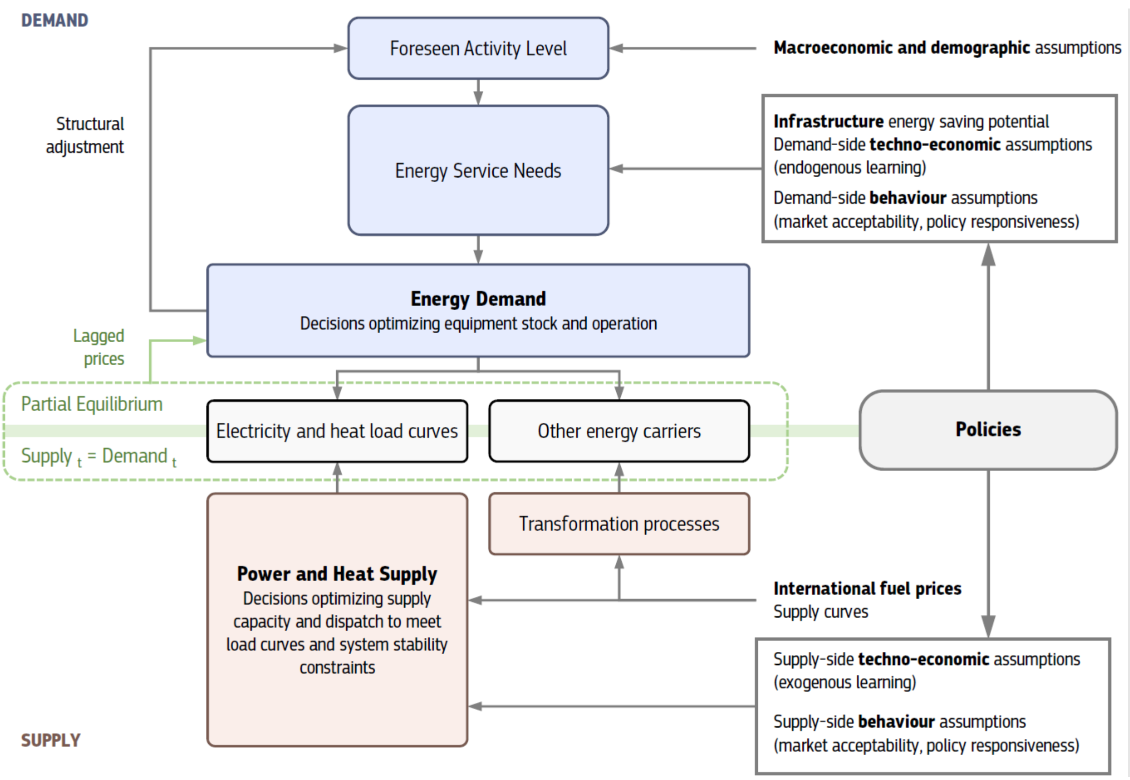
— By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;

— By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;

— By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (detailed in Mantzos et al., 2017, 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimise its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 23: The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; Rózsai et al., 2024).

AN 1.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl et al., 2024).

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