Towards a decarbonised heating and cooling sector in Europe

Unlocking the potential of energy efficiency and district energy

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AALBORG UNIVERSITY
DENMARK

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Storage of twin pipes (DN 50 Series 3 - Logstor)
and building under renovation in Horsens, Denmark.
Image by Luis Sánchez-García

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Executive summary

Context

Achieving the European Union (EU) climate objectives - a reduction of the overall greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels - requires a complete transformation of the energy system.

One of the main challenges in meeting this ambition is the decarbonisation of the heating and cooling sector, which accounts for approximately 50% of the final energy demand in the EU and is mainly reliant on fossil fuels [1]. To move to a sustainable heating and cooling sector it is essential to both invest in energy efficiency to lower overall demand and replace fossil fuels with more sustainable energy sources.

Energy efficiency across the energy value chain (from primary energy through produced and final energy to delivered and useful energy) acts as an enabler for the integration of higher shares of renewable (and waste heat) sources. As such, the European Commission sees energy efficiency as a key element to reduce GHG emissions, foster European competitiveness, and ensure a secure energy supply. This has been translated into the 2030 objectives of the Energy Union, notably reducing Europe's energy use by 32.5% compared to the business as usual projections, which will significantly contribute to cutting GHG emissions by at least 40% below 1990 levels.

Optimising the heating and cooling sector is essential for the EU to be climate neutral by 2050 and to be in line with the Paris Agreement. The potential is significant, but to unlock it the electricity, gas and (district) heating and cooling sectors should work together to tackle any barriers imposed at EU and national level.

The European heating and cooling sector shows significant potential for improving energy efficiency and integrating renewable energy. With 2,845 TWh, the residential sector has the highest final energy demand for heating and cooling (dominated by space heating demands), followed by industry at 2,388 TWh and the tertiary sector at 1,119 TWh [1]. The European heating and cooling sector is characterised by different qualities of buildings and is mainly supplied by distributed production units in buildings. Gas is the most used fuel, supplying 42% of heat demand. Biomass accounts for 12% of the heat consumption but is largely used in inefficient stoves and boilers. District heating supplies 12% of space heating and domestic hot water demand for buildings [2]. Cooling is mainly powered by electricity, while heating is largely supplied by fossil-fuelled individual heating solutions at building level.

This report analyses, and where possible quantifies, the potential of energy efficiency and district energy as enablers of the decarbonisation of the European heating and cooling sector and the wider energy system, as well as the role of different technologies to improve the efficiency along the energy value chain. Based on this analysis, a roadmap for the decarbonisation of the heating and cooling sector is developed, including projections of investments and necessary development of district energy networks. Lastly, the report describes key milestones on the way to a full heat transition and recommends policy actions to drive the implementation of the roadmap.

Potential for district heating and energy efficiency in Europe towards 2050

District energy can play a key role in decarbonising heating and cooling, by enabling high levels of energy efficiency and renewable energy and sector coupling. The Heat Roadmap Europe studies [2]–[5] have shown that a smart energy system with 50% district heating and sector integration is more efficient than a decentralised/conventional system and allows for higher shares of renewable energy at a lower cost.

Heat Roadmap Europe 4 (HRE4) [2] represents the most recent iteration in the Heat Roadmap Europe project series and the most recent quantification of the potential for energy efficiency and district energy at a European level. The mapping and modelling in HRE4 cover 90% of the European heat market and look at 14 countries and their energy systems individually, which underpins the insight and analysis of the overall European perspective.

The HRE4 study demonstrated that an affordable decarbonisation of the European energy system is possible by implementing 30% end-use savings in heating by 2050 compared to 2015, expanding district heating (DH) in urban areas to supply around 50% of EU heat demands in 2050, and supplying the remaining heat demands in rural areas with heat pumps. By utilising energy system synergies and exploiting energy efficiency, the HRE approach thereby results in a reduction in CO_2 emissions of 85% compared to 1990 levels; a reduction in primary energy supply of 13% compared to a "conventionally decarbonised" scenario in 2050, with a renewable penetration of 87%; and an overall reduction in total energy system costs of approximately 68 B EUR/year. Decreasing fuel imports will increase the energy security of European Member States and free resources that can then be invested in further energy efficiency and new renewable energy capacity.

District heating systems should become integrated with other parts of the energy system. This happens through flexible production at Combined Heat and Power (CHP) plants complementing fluctuating renewable electricity production; use of waste heat from industry and services; and use of electricity in large-scale heat pumps and electric boilers during hours of high production of fluctuating renewable energy.

To ensure efficient district heating networks, it is important to maintain a sufficient linear heat density, effective controls and to use high quality insulated pipes. Moving from supply to demand-side driven systems with automatic controls brings about considerable efficiency improvements in heat transmission and distribution to and in the buildings. Metering and consumption-based billing, paired with adequate control equipment, enable consumers to control their heating expenses and incentivise investments in energy efficiency improvements.

Significant energy efficiency improvements can be achieved using technologies that are already well-known and used in (parts of) Europe today. In the future, energy efficiency improvements in buildings and networks will allow for decreasing the temperature in district energy networks and thus lead to further energy savings, as has been estimated for Denmark [6]. Extrapolating the figures for Denmark to EU level, moving to low-temperature district heating could lead in 2050 to primary energy supply savings around 120 TWh and cost savings up to 6 B EUR in Europe in the HRE 2050 scenario.

The expansion of district heating systems proposed by Heat Roadmap Europe forms part of meeting the Paris Agreement and is in line with the Smart Energy System approach enabling a conversion towards a 100% renewable energy system. In that perspective, it is to be noted that in the most recently envisioned European scenarios for reaching net-zero CO_2 emissions in 2050, A Clean Planet For All, distributed heat supply keeps the share of 4% final energy consumption that it holds in 2015 over the period up to 2050 in all scenarios [7]. This report showcases alternative scenarios demonstrating the role distributed energy can play to cost-effectively reach energy efficiency and decarbonisation targets.

Holistic energy system perspective

This report analyses the enabling role of energy efficiency in the transition towards a decarbonised heating and cooling sector in Europe and specifically in the district energy sector, including technologies to leverage the potential. To identify the most cost-efficient pathway, the report uses a holistic energy system perspective to account for system-wide effects across energy domains from different energy efficiency measures.

To assess the energy system transition it is important to consider how different energy sectors interact and can provide synergies to each other to identify an optimal solution for the overall system. The concept of *Smart Energy Systems* has shown the benefits of coupling smart electricity grids with smart thermal grids and smart gas grids [8]. In this approach, thermal grids have a central role to play, as they can integrate renewable energy and increase efficiency, which results in a lower overall energy system cost.

This report suggests assessing energy efficiency measures from an energy system perspective and considering the full effects of measures along the *energy efficiency value chain*. This perspective calls for assessing energy efficiency measures from primary energy to production, transmission and distribution, building conversion and finally building distribution to useful energy delivery at the energy consumer. This enables the discovery of supply chain effects from new technologies.

Of primary concern to this report is the establishment of district heating grids to exploit locally available excess and renewable heat sources. CHP plants can utilise otherwise wasted heat from power plants, thereby increasing their fuel efficiency by around 50%. Regardless of the fuel input, the HRE series of studies have shown that it is feasible to exploit the waste heat. And as district heating networks are agnostic to the fuel source, the infrastructure can later be used with renewable supply. This is an example of finding efficiency measures in the production step of the value chain. By optimising energy demands through a mutualisation of means of production, control system improvements, or renovation, not only will the primary energy consumption decrease, but it is also possible to decrease the production capacity to be installed and avoid costly upgrades of the existing infrastructure.

Roadmap for realising the Heat Roadmap 2050 scenario

This report outlines a roadmap for the decarbonisation of the European heating and cooling sector by 2050 with the help of district energy, including important milestones and recommendations for policy action. It is important that the heating transition towards renewables and energy efficiency is well established and underway in 2030.

To reach a fully decarbonised energy system in 2050 it is essential to implement the viable and available options today. District heating infrastructure allows access to renewable and low-carbon sources. Investments in district heating infrastructures enable increased energy efficiency and access to heat sources which are impossible to utilise on an individual building level [5]. Additionally, district heating systems provide significant energy system and sector coupling benefits to the remaining energy sectors that can be exploited when implementing further amounts of renewables.

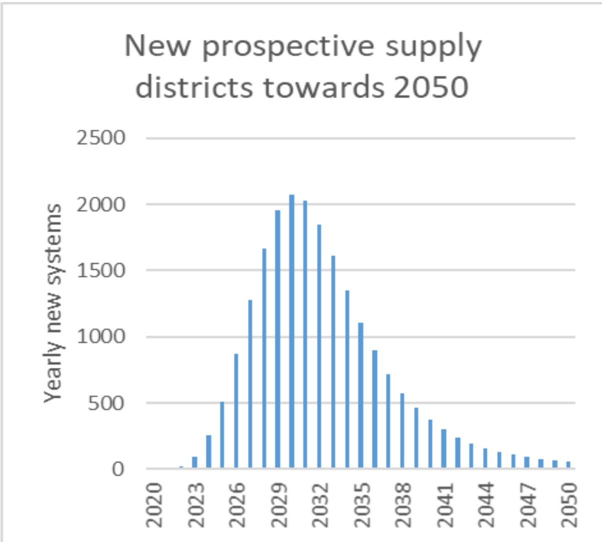


Figure 0-1. Approximate newly established and total amount of district heating systems in the 14 countries of HRE4 and Denmark needed for fulfilling the potential of distribution grid investments below 4 EUR/GJ.

Analyses using the Pan-European Thermal Atlas (PETA) geographical information system analysis tool [9] have identified Prospective Supply Districts (PSD) areas with a potential for supplying heat demand with district heating. These are estimated using a maximum annualised distribution grid investment cost of 4 EUR/GJ and a minimum heat demand density of 20 TJ/km². This results in a potential of around 25,000 PSDs in the EU, which would be in line with the HRE target of a 50% district heating share by 2050. This is a 7-fold increase in the number of district heating systems across Europe compared to the current situation.

To realise this potential of transitioning towards district heating systems, this report presents a roadmap outlining when necessary investments should be made in order to reach the HRE 2050 scenario. To start establishing district heating systems now and ensure that the potential 25,000 systems are operating in 2050, this report has assumed a significant build-out between 2025 and 2035. The number of newly established systems should increase from around 500 new systems in 2025 to a peak of 2,000 new systems established in 2030 in order to meet the HRE 2050 scenario potential. After 2030 a significant amount of systems should still be established, around 1,100 in 2035.

Accordingly, investments should start in 2020 and significantly increase during the years 2025-2035, where the main amount of new systems should be established. The analysis suggests that new investments in new district heating production units and that new investments in new district heating distribution infrastructure should peak at 13.2 B EUR and 47.6 B EUR in 2030 respectively. Investments in an energy efficient building stock are vital and should peak at 427.3 B EUR in 2030.

As shown in the HRE 2050 scenario, these high investments will result in an overall cheaper energy system compared to a conventionally decarbonised scenario as lower fuel, CO_2 and operation and maintenance costs offset the increased investment costs. Considering annualised heat sector costs, individual heating should go from accounting for 82% of the total heating sector investment costs today to 44% of annualised heat sector investment costs in 2050. Instead, annualised district heating investment costs should increase from its current 18% to 42% in 2050. Reinforcements of the electricity grid for heat pumps account for the remaining 14% in 2050.

The roadmap for realising the HRE 2050 scenario entails several implications that must be addressed to allow for the scenario to take place. First, it shows the need for increasing investments. Second, it is important to understand energy efficiency not as an isolated measure but from an energy system perspective. Third, this points to the importance of establishing a balance between increased heat savings and investments in renewable capacity. Fourth, in order to realise the HRE 2050 scenario, the period 2025-2035 will require significant action.

The tables below show an overview of milestones and policy recommendations in the periods 2020-2030, 2031-2040 and 2041-2050.

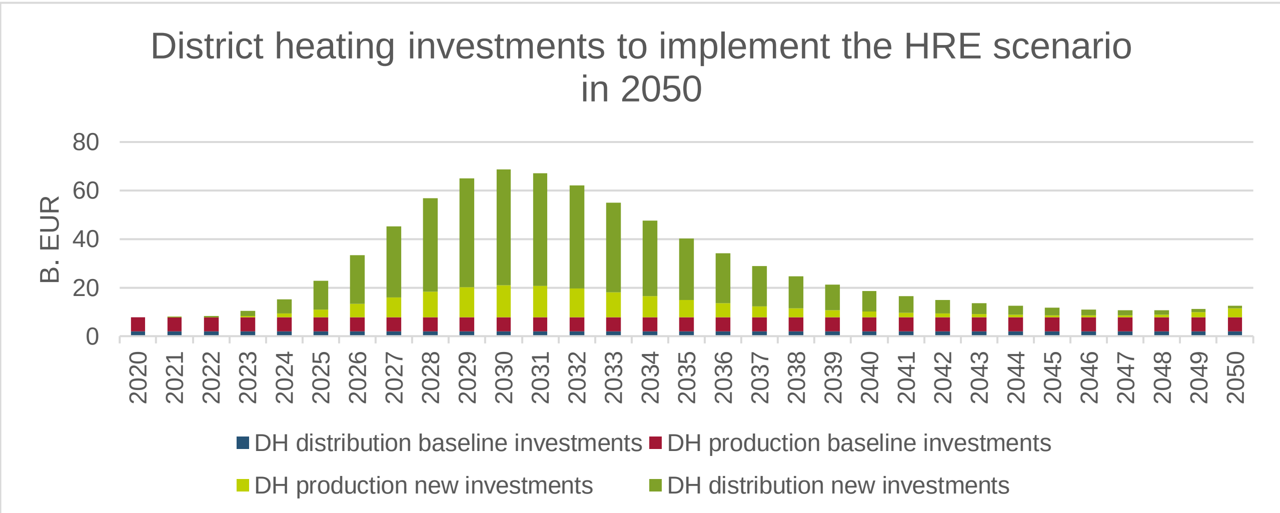


Figure 0-2 Estimation of distribution of district heating investments to reach the HRE 2050 scenario.

Important milestones and policy recommendations from 2020 to 2030

- **Establish national and local potentials and plans for district heating and cooling**: Establishing the tools and having firm processes in place to properly assess the potential for district heating and make a detailed plan for how to reach this potential is essential.
- **Increase investments in energy efficiency improvements in buildings** by creating an enabling policy framework (e.g. with building codes and renovation strategies). Overall, 30% savings in space heat demand compared to today are feasible, depending on the country.
- **End investments in new individual fossil fuel heating capacity** such as gas and oil boilers and instead transition to heat pumps that can utilise renewable electricity and district energy.
- **Set commitments to deploy actions in liaise with the local level**: In their assessments and plans, countries should include how to activate local governments and municipalities in the transition. Heating is a local energy demand, and it is important to enable coordination between the national and local levels.
- **Improve availability of data:** In order to enable a heat transition, it is essential that knowledge is expanded and data collection about the heating sector increased. To invest in district heating systems, it is important to have detailed knowledge about the heat demands, the status of the building stock and the availability of heat sources, as well as the performance of existing district heating systems.
- **Start investigating the potential and role of district cooling:** As cooling is one of the fastest growing of the thermal sectors, the potential to explore the role of using free cooling and higher levels of cold water thermal storage requires investigations to be able to fully understand the potential and role that district solutions for cooling could play on the wider energy system.
- **Ensure a level playing field for a decarbonised energy system:** Markets, investments, regulation, taxes and tariffs need to be adjusted to promote the technologies that fit into a low-carbon and energy efficient future. As a large amount of the transition will probably be market-driven, it is vital that the right incentives and signals are provided.
- **Take a system approach:** There is a need to assess the energy transition from an energy system perspective to utilise synergies between sectors and enable the energy value chain effects. This includes exploiting waste heat sources and for the district heating and cooling sectors to provide flexibility for the electricity sector.
- **Ramp up the establishment of new district heating systems:** As investments in district heating grids, infrastructure and supply are a future-proof measure, governments should start the establishment of district heating systems. Around 8,700 new systems should be established in this period.
- **Annualised investment costs in district heating supply and in distribution infrastructure** should reach around 16 B EUR/year and 20 B EUR/ year, respectively, during this period, from 8 B EUR/year and 4 B EUR/year. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 118 B EUR and 223 B EUR for the period from 2020 to 2030.

Important milestones and policy recommendations from 2031 to 2040

- **Saturate heating markets:** The prospective supply districts that have been established should start to cover the majority of their feasible supply areas. Energy renovations and efficiency measures should still be a major focus, and if any remaining low hanging fruits are left, such as connecting consumers with high energy demands or areas with high heat densities, they should be exploited in this period.
- **Establish remaining potential district heating systems** – about 11,000 new systems should be created in this period.
- **Annualised investment costs in district heating supply and in distribution infrastructure** should reach around 18 B EUR/year and 23 B EUR/year respectively during this period. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 127 B EUR and 273 B EUR for the period from 2031 to 2040.
- **Monitor the progress of district heating and cooling:** As district heating and cooling systems are being developed, communities start to capture some of their benefits, including gains on energy efficiency. These benefits should become visible in national energy statistics and reporting to the EU. It will be important to monitor the progress of district heating and cooling on decarbonisation and energy efficiency.
- **Remaining fossil fuel capacity must be phased out during this period**: This will likely require policies such as replacement schemes and banning of fossil gas and oil boilers. It is vital to ensure a just transition and have fair replacement schemes for those remaining on individual fossil boilers.

Important milestones and policy recommendations from 2041 to 2050

- **Achieve remaining benefits of sector coupling:** Sectors and demands should have already become interconnected with the overall energy system to realise the remaining energy efficiency potential and to decarbonise energy supply. As the last fossil fuel capacity is to be phased out in this period, it becomes important to exploit all flexibility measures and sector coupling benefits available.
- **The district heating market share** should be expanded to reach 50% and the remaining potential district heating systems be built.
- **Remaining fossil fuels in the energy system must be replaced in this period.** This includes gas in CHP plants, backup capacity and other flexibility mechanisms, as well as in the transport sector.
- **Annualised investment costs in district heating supply and in distribution infrastructure** remain at 18 B EUR/year and 24 B EUR/year, respectively, during this period. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 53 B EUR and 71 B EUR for the period from 2020 to 2030, which are mostly re-investments into maintaining existing infrastructure.
- **Ambitious decarbonisation policies**: During this period, ambitious regulation and policy will still be central in driving the low-carbon transition to take the last step towards a full decarbonisation of the energy supply.
- **Connecting remaining demands to district energy supply:** Virtually all potential district heating and cooling areas should have been established, so this period needs to focus on connecting the last remaining demands to these collective systems.

Country contexts

To reach the HRE 2050 scenarios, all countries in the EU should have established high amounts of district heating in their energy supply by 2050. However, the pathway to this scenario also depends on their current situation and context, from which the countries must adapt. Here, three types of countries with different heating infrastructures are considered: countries with high shares of district heating, countries with inefficient district heating systems and building stock as well as countries with no or very little district heating.

Countries with high amounts of district heating

This report outlines the approaches towards 4th generation district heating (4GDH) systems and the utilisation of low-temperature heat sources. This entails the modernisation of the building stock and distribution infrastructures to be able to exploit these resources at the same time as promoting a more interconnected energy system. Good examples of such systems can be found in the Scandinavian countries with high amounts of renewables and efficient systems.

Regulation, tax structures, tariffs and prices must also follow this transition. 4GDH entails new synergies that often are limited today due to ownership, taxation or market rules. High electricity taxes on the use of heat pumps is one example. A central challenge for energy systems moving towards 4GDH is to identify and value the total energy system benefits across the value chain of different technologies. The value of heat pumps for the integration of renewable electricity production should, for example, be considered. This challenge in identifying the total energy benefits applies to the heating sector today, but will only become a more central issue with the emergence of Power-to-X technologies [10] and increased penetration of electric vehicles. As technologies start to have considerable benefits across the whole energy value chain, it is important to assess these traits from a holistic energy system perspective and not merely based on, for example, their energy content or emissions.

4GDH allows the use of significant amounts of waste heat. New business models and regulations need to be developed to encourage the use of unavoidable waste heat. 4GDH as a technical concept focuses on lowering district heating temperatures to increase efficiency and the use of low-temperature sources. However, in doing this, the concept challenges conventional energy system regulation and will, in some regards, constitute a paradigmatic change towards an energy system which is more integrated in both technical and regulatory terms.

Countries with inefficient heat infrastructures and building stock

Some Baltic, Eastern and South-Eastern European countries have inefficient district heating systems, designed for high temperatures and an inefficient building stock. These countries face the issue of both establishing new systems as well as consolidating and expanding existing ones while improving efficiency in these systems and building sectors. Many of these countries will be moving from 1st and 2nd generation district heating to 3rd or 4th generation systems. This can happen with new production units, access to new renewable resources, efficient distribution infrastructure, highly efficient buildings that can utilise low-temperature supply and with improved heating controls, heat metering and consumption-based billing. A starting point should be to move towards demand-driven systems where customers can actively control their consumption. New systems should be established using state-of-the-art technologies along the value chain. For this type of countries, it is important to revise and expand district heating regulation and governance to allow for expansive investment in district heating grids and production units. This is connected to business models where the customer prices reflect the actual cost of heat production, operating and maintaining the system and other related costs, while at the same time avoiding monopoly pricing issues or that publicly-owned utilities transfer profits for other uses and thereby weakens the competiveness of district heating.

Countries with no district heating

Countries with no or very low shares of district heating today, such as the United Kingdom, the Netherlands, and some Southern European countries have to start establishing systems as soon as possible. An approach is to start with low-cost heat sources in areas with high demand, where the business case for district heating is best. These business cases should, however, include strategies for further expansion.

These countries will need to develop heat regulation, planning and frameworks for developing district heating supply. It is important to consider ownership models, competition among heating sources, pricing, and investments. Where district heating is set to compete against other supply options, it is important to make sure they do so on equal terms. It also includes considering the full energy value chain effects of different technologies and their alternatives.

At the same time as establishing district heating networks, building stock renovations must be carried out, including the optimisation of control systems. If they are carried out at the same time as new district heating networks are built, the full energy value chain benefits can be exploited. Optimal capacities to supply an energy efficiency heat demand, pipe and grid size, supply and return temperatures from the building stock can be calibrated to avoid over or under-investments. A risk is the different timeframes for establishing district heating grids and building renovations. Renovations can be much slower to implement and happen at a fragmented timescale, and thus a misalignment between investments in supply and end-use efficiency can happen.

Recommendations for the European heat policy

The Energy Efficiency Directive (EED) [11] and the Renewable Energy Directive (RED) [12] address several of the areas focused on by this report as it seeks to promote energy efficiency to decrease the climate impact from energy consumption [13].
The first round of comprehensive assessments (CA) of the potential for increasing energy efficiency through high-efficiency cogeneration and efficient district heating and cooling have been submitted by Member States, as specified by the Article 14 of the Energy Efficiency Directive (EED). Although some countries identified potentials for district heating, significant methodological and empirical challenges still remain in making district heating a tangible alternative [10].

Definition of Efficient District Heating and Cooling
The current definition of efficient heating and cooling in the EED and of energy performance in the RED do not consider the energy efficiency value chain or the energy losses in the system A distinction between supply and efficiency should be maintained. In implementing the RED, Member States should ensure that both the information about the renewable share of district heating supply and the efficiency of the systems are communicated to customers.

Expand the scope of the Comprehensive Assessments
CAs should entail a holistic energy system approach that includes all energy domains, although a primary focus on district heating should remain. It is important to analyse changes in the heating system in relation to wider energy system transitions to identify potential synergies or barriers.

Improve data collection and availability
Lacking data about the heating and cooling sectors is a barrier to implementing district heating and cooling and providing an energy efficient heating and cooling supply. The EED should promote and encourage a comprehensive data collection infrastructure and methodology.

Contents

Introduction

Achieving the objectives of the Paris Agreement to limit the increase in temperature below 1.5-2°C requires major improvements in energy efficiency (EE) and the integration of renewable energy sources (RES). Energy efficiency is a key element to a cost-efficient, secure and reliable energy transition. This has been translated into the 2030 objectives of the Energy Union, notably reducing Europe's energy use by 32.5% compared to the business as usual projections. Since heating and cooling represent about 50% of the final energy consumed in the European Union (EU) and around 80% of total final energy use in EU buildings, it is central to identify and promote potential savings in this area [1]. In addition, more than 80% of heating and cooling in the EU is still generated from fossil fuels, and most of the residential heating in Europe is provided by individual heating systems supplied by fossil fuel-based individual boilers, which advocates for a potential to decarbonise the sector and to reduce dependency from energy imports.

The decarbonisation of the heating sector can happen in different ways and should be a combination of applied measures in buildings, distribution networks and energy sources, enabling synergies across the value chain. Focusing on a holistic approach will enable the EU to increase the efficiency and the use of RES in the heating and cooling sector, and therefore the security of energy supply.

One efficient way to increase EE and the use of RES at a large scale and decrease significantly the use of fossil fuels in the heating and cooling sector is by transitioning from individual systems to District Heating and Cooling (DHC) systems in urban areas. DHC systems are one of the key solutions to decarbonising urban areas cost-effectively by integrating renewable energy and excess heat sources that cannot be accessed on a building level. These systems enable the use of Combined Heat and Power plants (CHP) and Waste-to-Energy (WTE) solutions, as well as the reuse of any available source of excess heat that would be wasted otherwise. Those latter sources generally tend to be located around urban areas, resulting in a perfect fit for the heat supply. DHC systems also allow further integration of RES such as geothermal and solar thermal heat and can play a key role in enabling high shares of volatile renewable electricity by providing thermal storage [14]. Moreover, the level of urbanisation in the EU is expected to grow from 75% in 2020 to almost 84% in 2050, predictions in line with the integral role to be played by district energy.

District heating systems also enable synergistic effects with EE measures that reduce the heating demands in the buildings. The capacity of the district heating grid and production units allows more buildings to be connected to the same grid; whereas more efficient buildings mean comfort is achieved by lower supply temperatures. This will reduce grid losses and will increase the recycling of heat and the efficiencies of the production units, enabling the use of low-temperature heat sources.

Efficient district energy systems can thus play a key role in the energy transition towards a low-carbon economy, acting as a backbone towards efficient energy systems.

Holistic approach to Energy Efficiency needed

In light of the objective to reduce Europe's energy use by 32.5% in 2030, EE potential must be promoted and clearly communicated on the national scale, as well as on a sector basis. A clear path forward will enable the prioritisation of means and efforts necessary to reach that objective. The EU Energy Efficiency Directive (EED) [11] aims at promoting savings across the energy value chain from energy generation and distribution to consumption. According to the European Climate Foundation (ECF), the Energy Union's Energy Efficiency First Principle (EEFP) can be explained as:

"[Efficiency First] means considering the potential value of investing in efficiency (including energy savings and demand response) in all decisions about energy system development – be that in homes, offices, industry

or mobility. Where efficiency improvements are shown to be most cost-effective or valuable, taking full account of their co-benefits, they should be prioritized over any investment in new power generation, grids or pipelines, and fuel supplies."[1]

These two approaches that consider the value chain and the cost-effectiveness of energy savings will be combined in this report. Energy efficiency assessments are vulnerable to the system delimitations and optimisation criteria. If saving energy is the sole purpose, then there could be tendencies to try to reach as low levels of energy consumption as possible. Estimating feasible levels of energy savings based on a marginal cost of energy or a Levelized Cost of Energy (LCOE) approach is problematic as well, as this does not consider important value chain effects, such as changes in supply temperature for district heating systems or lower capacities needed in production units and distribution infrastructure.

This report will combine these two approaches and discuss estimations of energy efficiency improvement from an *energy system perspective.* This gives the opportunity to assess feasible levels of energy efficiency based on criteria such as total energy system costs, CO_2 emissions or the exploitation of otherwise wasted resources. This both includes the value chain benefits of energy efficiency measures as well as avoids sub-optimising investments in specific sectors.

This study aims to enhance the understanding of EE measures regarding the heating and cooling sector, on EU, member state, and system levels considering bottom-up knowledge, hour-by-hour energy system analyses and future smart energy systems. It seeks to mediate the debate about EE levels, expansion of renewable generation capacity and DH market shares by examining these aspects from an energy system perspective.

Data and scope of the study

The purpose of this study is to provide a research-based analysis addressing what role efficient district energy systems can play in a future decarbonised and energy efficient European energy system. To do so, a description is given of what the European heating and cooling sector looks like, what it will look like in the future in a business as usual scenario, what the potential for energy efficiency is when focusing on district heating and cooling, and a roadmap is provided as well as recommendations for how to move forward.

The aim of the report is to quantify the energy efficiency potential in the European heating and cooling sector as enablers of the decarbonisation of the energy system. The report is particularly focused on providing answers to the following questions:

- How and how much can district energy systems contribute to the efficient decarbonisation of the European energy system?
- Where is the optimum balance between end-user energy savings and investments in a decarbonised heating supply?
- What are the key milestones for implementing the transition towards a decarbonised heating and cooling sector in 2050?

As an outcome, a roadmap for the decarbonisation of the European heating and cooling sector is developed, and policy recommendations in order to implement the suggested roadmap are made.

This report is the result of a literature review covering academic reports and peer-reviewed papers, including many developed by the Sustainable Energy Planning Research Group at Aalborg University. Much of the data

[1] European Climate Foundation during 2016 Efficiency First: A New Paradigm for the European Energy System

for the analysis and recommendations in this report are based on the Heat Roadmap Europe scenario 2050 from 2018, herein referred to as HRE 2050 scenario [2].

Heat Roadmap Europe is a series of four studies [2]–[5] that have been carried out since 2012. These studies analysed the synergy between the demand side energy savings and new supply options. The first study, which covered the EU27 countries, focused on increasing DH levels to cover approximately 50% of the total heat demand. The second study investigated the potential for a combined retrofitting and district heating strategy. The third study developed low-carbon heating and cooling strategies for five significantly different EU Member States. The fourth study quantified how to decarbonise the heating and cooling sector for the 14 largest EU countries.

The literature review included reports and papers on energy systems and 100% renewable energy strategies towards 2050, heating and cooling energy savings and strategies towards 2050; flexibility, storage and integrated energy production; and heating and cooling supply technologies. In total, more than 50 papers, reports, and books were reviewed, which can be found in the reference list.

The report is structured as a roadmap for the decarbonisation of the European heating and cooling sector.

The **first chapter** details the concepts, approaches and methods used to conduct the analysis.

The **second chapter** describes the current European heating and cooling sector and its efficiency, with a focus on district heating systems.

The **third and fourth chapters** describe the best available technologies needed across the energy efficiency value chain for transitioning towards a low-carbon heating supply, and future energy system scenarios. A quantification of the energy efficiency potential on the supply, distribution, and demand sides is provided, and the role of district heating as the enabler of the decarbonisation of the energy system is highlighted. This includes an analysis on the EU, national and local levels.

The **fifth chapter** provides an investment roadmap for the decarbonisation of the European heating and cooling sector, implementing the most energy-efficient scenario previously analysed.

The **last chapter** provides the key milestones and recommendations based on the current role of district energy and how it will need to change in relation to a holistic view of the energy system in the future.

1 Approach and Methods

1.1 Approach to energy efficiency from a system perspective

To grasp energy efficiency from a system perspective, the whole energy value chain should be considered. This is important when assessing the energy efficiency of district energy supply. CHP plants coupled with district heating systems will increase the plants' conversion efficiency significantly but introduce distribution losses compared to a system with extraction plants and household heat boilers. Despite these losses in the distribution of district heating, the entire energy system would still be more efficient.

In the Energy Efficiency Directive Art 2. (4) energy efficiency is defined as "the ratio of output or performance, service, good or energy, to the input of energy" [11]. While this understanding is also used in this report, it is sensitive to the definition of system boundaries. If only a certain process is considered and not the whole value chain, it might result in biased results. The approach to energy efficiency in this report is, therefore, to evaluate the processes from primary energy to useful energy in order to obtain the efficiency of the whole *energy efficiency value chain.*

The objective of energy efficiency is to reduce the amount of energy needed to fulfil the (useful) demands of an energy system. This means that efficiency is both considered in the reduction of useful energy demands (for example, through a higher thermal energy performance of buildings or optimisation of control systems), the minimisation of energy lost in transport and distribution, the reduction and recovery of energy lost in the transformation phase, and the better fit between production and distribution (role of smart control in a decentralised system using multiple sources of production).

While being a rather simple metric when analysing well-defined systems, energy efficiency becomes more difficult to quantify in larger interconnected technological systems. For example, should losses be attributed to the electricity or heating production or both when dealing with combined heat and power plants? Or how can we quantify the production efficiency for excess heat resources? Often when deploying a sector-specific approach, the synergies and system effects are not captured. By measuring the primary energy consumption of the whole energy system, these synergies or impacts will be included.

The process of energy conversion from primary energy to useful energy is shown in Figure 1-1. The energy efficiency value chain can be defined as the conversion process from primary energy through final and delivered energy to useful energy. *Energy process* is a type of conversion, transmission or distribution where the fuel or energy content is processed in one form or another. *Energy amount* is thus the amount delivered or received from the process. The efficiency of a process can be found by the ratio of the input and output amounts.

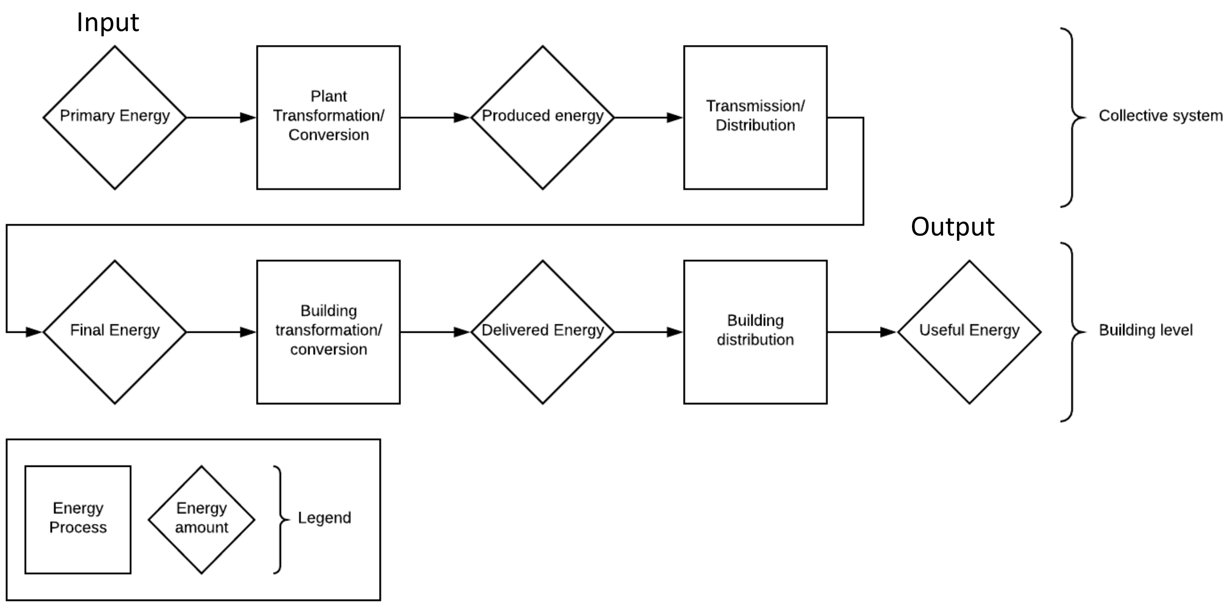


Figure 1-1. Energy efficiency value chain from primary energy to useful energy

Not all steps of the energy efficiency value chain are applicable to all types of heating. For some types of heating, such as individual oil, coal or gas-based heating, the primary energy is converted at the building level and can (in a simplified way) be regarded as final energy, thus skipping the collective system part of the value chain. Leakages and losses in fuel transport are not considered in this model. For some types of renewable energy and excess heat, the conversion from primary to produced energy can also be disregarded. This can be the case when it does not make sense to quantify the amount of energy not exploited from a resource, for example in wind power production or energy from geothermal resources. Excess heat sources can both be regarded as a primary or produced amount of energy. If the excess heat source is directly usable as a heat source, it can be regarded as produced energy, while a low-temperature heat source might need a conversion step through a heat pump to be considered produced energy.

1.1.1 Measuring energy efficiency

Energy efficiency can be measured in multiple ways. The approach above focuses on either using total energy amounts or relative shares to relate to losses through a system. The energy efficiency can thus be measured in primary energy, the total amount of energy utilised by the system to fulfil demands, or by the ratio between PE and later steps in the energy efficiency value chain.

Primary energy measurement uses total amounts of energy and is expressed in energy units such as MWh or GJ. Total primary energy measurement does not in itself express energy efficiency; by comparing measurements to various alternatives, the primary energy figuring in each scenario can be assessed.

By using a ratio between energy amounts in the energy efficiency value chain, the energy efficiency can be expressed in a percentage of energy output related to the input. The ratio of produced energy to primary energy will assess the efficiency of, for example, a thermal power plant. The ratio of useful energy to final energy can assess the efficiency of a household gas boiler. By finding the ratio between useful energy and primary energy, the energy efficiency ratio of the energy efficiency value chain can be found.

1.1.2 Assessing energy efficiency

This study is based on state-of-the-art science-based knowledge and methods, combining sectorial bottom-up knowledge with hour-by-hour modelling of the energy systems and spatial analytics [1]. Using bottom-up knowledge in the heating and cooling sector and a combination of temporal energy system analyses (Smart Energy Systems) and spatial analytics (geographical information systems - GIS), synergies between DHC EE potential and system's EE potential can be made operational.

The analyses consider all sectors of the energy system, which are electricity, heating/cooling, and transport. This is essential since the fundamental objective of the Smart Energy System is to utilise the synergies by combining the individual sectors of the energy system (see 1.2).

Short-term (hourly) fluctuations in renewable energy and demand are considered. Intermittent resources like wind and solar power will be the primary forms of energy production in a low-carbon and sustainable energy system. Accommodating their intermittency will be essential for the reliable operation of the future Smart Energy System. In order to compare investments and costs over different lifetimes, all costs are annualised in the analyses, except if otherwise noted. This is to provide a comparable cost between investments made at different points in time and to be able to compare data across types of investments and costs.

The analyses also consider the important spatial aspect of heat planning and assessments. To transport heat over long distances high capacities are needed, thus there is a risk of incurring high grid losses compared to electricity and gas transmission. Hence it is in many cases most feasible to use rather local sources of heating. The feasible distance for heat transmission depends upon the amount of energy that is being transported, and examples of district heating systems covering large urban areas, or of transmission of heating over, for example, 20 km, exist. In Copenhagen the transmission system operator operates +50 km of transmission grid. At the same time, significant amounts of excess heat are available throughout Europe. By using GIS tools for the spatial assessment of the location of heating demands and sources, this will provide an assessment of the potential for expanding district heating and exploiting local waste heat sources.

Furthermore, to assess the potential of energy efficiency, a socio-economic perspective is used to quantify costs and benefits. This allows for the development and design of future scenarios without sub-optimal decision-making based on current market design, an assessment and evaluation of what the system would look like for society at large, and a direction for where public funding and policy should be steering towards. Indeed, the objective of the study is to provide investment strategies but also policy recommendations. In practice, this approach translates into using a lower discount rate (3%) than typical business economic approaches utilise for impact assessment.

The energy system modelling has been carried out in the software EnergyPLAN[2]. EnergyPLAN is an energy system analysis tool specifically designed to assist in the design of national or regional energy planning strategies. It simulates the electricity, heating, cooling, and transport sectors of the energy system on an hourly basis over one year, thus accounting for the intermittency of some renewable energy resources.

[2] www.energyplan.eu

1.2 District Heating and Smart Energy Systems

A smart energy system is an energy system that integrates primary energy sources through smart electric grids, smart thermal grids, and smart gas grids to meet energy demands, with the purpose of increasing energy efficiency and integrating larger amounts of fluctuating renewable resources through sector coupling. This reduces the need for fuels and increases the cost-effectiveness of a renewable energy supply. Figure 1-2 shows that the different lines – the smart electric, thermal and gas grids – are connected through a number of different conversion technologies and recovery systems, which can be activated in different situations, e.g. high demands, low production of wind power, high production of solar energy etc. In smart energy systems, the focus is on the integration of the electricity, heating, cooling, and transport sectors, and on using the flexibility in demands and various short-term and longer-term storage across the different sectors.

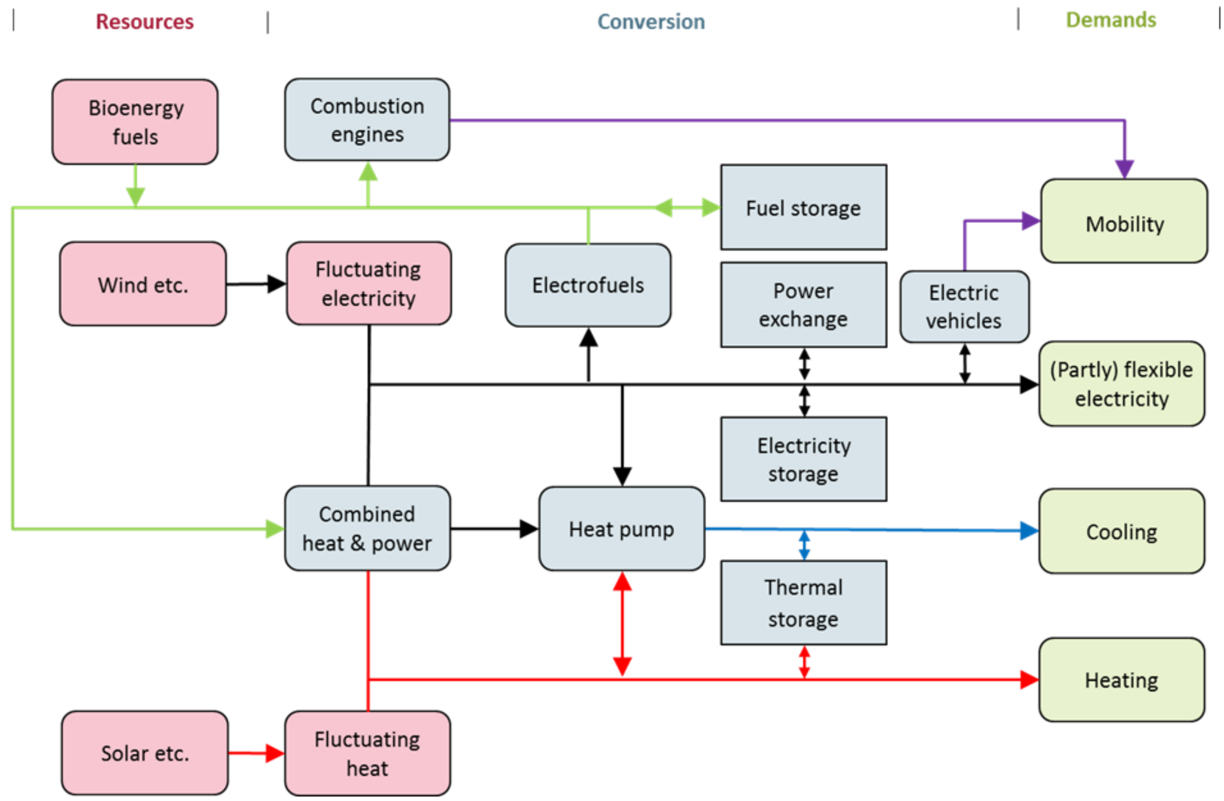


Figure 1-2. Principal interaction between sectors and technologies in a future smart energy system. Source: [2].

One of the most important traits of thermal grid infrastructure is the ability to access heat sources that would not be possible on a building level. District heating networks can be fed by various sources and are capable of distributing energy from district heating boilers, heat from CHP plants or from renewable sources such as geothermal energy. This can allow more efficient generation of heating or the usage of otherwise wasted heat.

District heating networks are also agnostic to the fuel source. A fossil-fuelled district heating supply thus only has to change the centralised heat source to decarbonise heat supply, in contrary to individual distributed heat supply on a building level where all fossil fuel boilers will have to be replaced.

It is important that all significant parts or sectors of the general energy-related supply, mainly electricity, heating, transport and industry, are included in the system perspective, and integrated to utilise the synergies between them. For example, an industrial facility can be integrated with a DH system by supplying an excess of process heat to the DH network to reduce energy consumption for the alternative source of heating.

The following diagrams illustrate how the strategic use of the synergies that can be created within interactions between the thermal and electricity sectors improves the energy efficiency of the system - and the role of CHP and district energy in such a system redesign.

Starting out with a theoretical energy system without any renewable sources and with a theoretical energy demand of 100 units distributed between 40 for electricity and 60 for heating and cooling, the traditional system needs an energy supply of 140 units using a power plant with a 50% electric efficiency and a 100% efficiency fuel boiler. By implementing 27 units (45%) of heat savings, the energy supply can be lowered to 113 units in total (Figure 1-3).

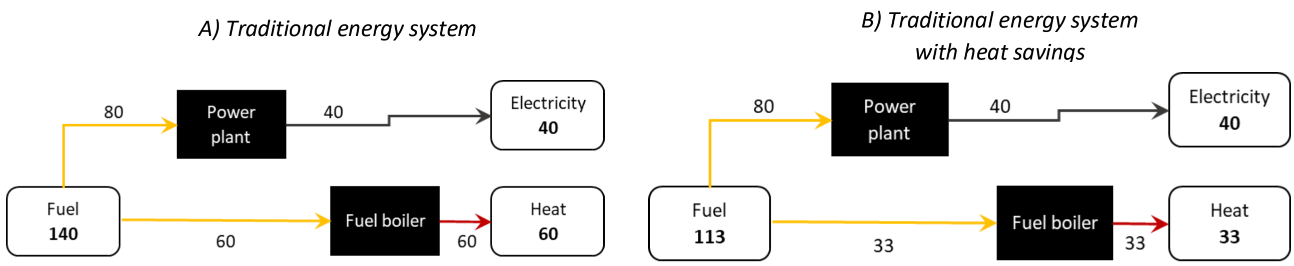


Figure 1-3. Traditional energy system with and without heat savings.

By implementing DH, it can be seen that a CHP system is more efficient than a traditional system supply with power plants and fuel boilers without sector coupling, even with 45% heat savings on the demand side (Figure 1-4. System redesign. The integrated CHP system allows for 45 units of savings compared to the traditional system, and 18 units compared to the traditional system with the implementation of 45% heat savings.). In system D) a CHP plant with a heat pump supplies both electricity and heating demand.

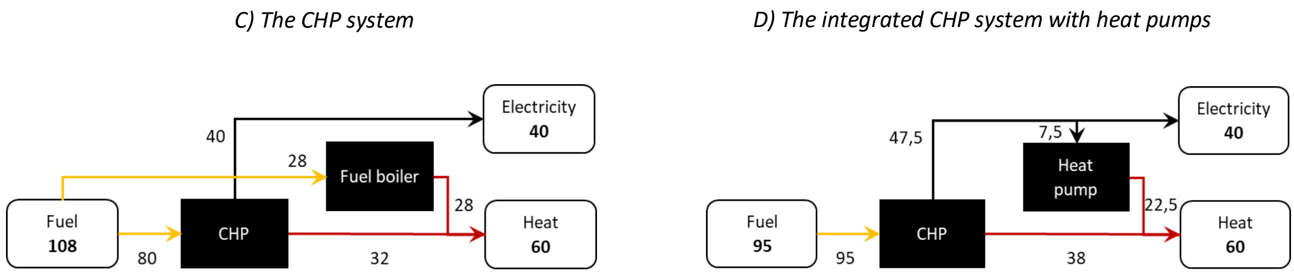


Figure 1-4. System redesign. The integrated CHP system allows for 45 units of savings compared to the traditional system, and 18 units compared to the traditional system with the implementation of 45% heat savings.

Figure 1-5 demonstrates the effects of including wind power generation in the traditional and integrated systems. The introduction of wind power in the traditional system allows for decreased production at the power plant thereby saving fuel. The E) system thereby uses 120 units of fuel and 10 units of wind totalling to 130 units. An integrated CHP system with district heating and heat pumps also allows for increased integration of electricity from renewable sources such as wind, as shown in Figure 1-5 with the example of

25% wind power. The F) system uses 75 units of fuel and 12 units of wind totalling to 87 units. It allows for 20% more integration, and wind represents in this system 13% of the energy mix, compared to 8% in the traditional system.

E) The traditional system with wind power production

F) The integrated CHP system with heat pumps and wind power production

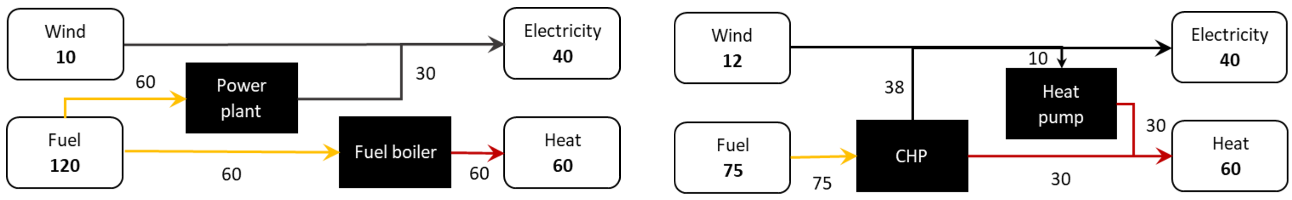


Figure 1-5. Integration of 25% wind power with a system redesign.

Introducing the direct use of excess heat with the redesign of the system allows for extra fuel savings, as shown in Figure 1-6 below with 12-15% of excess heat.

G) The integrated CHP system with heat pumps, wind power production and excess heat

H) The integrated CHP system with heat pumps, wind power production and excess heat, and heat savings

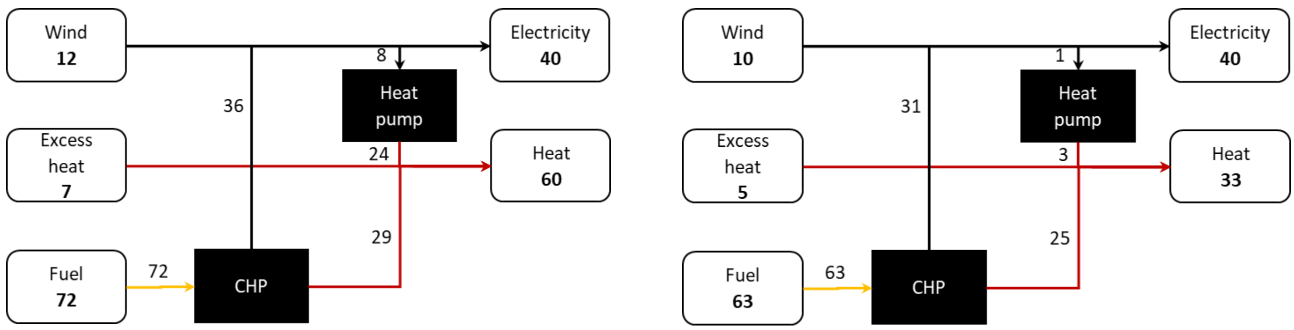


Figure 1-6. Integration of 12% excess heat with a system redesign and 15% with heat savings.

A first step to the decarbonisation of the heating and cooling sector (and the whole energy system) seems, therefore, to be a combination of heat savings and the redesign of the system with an increase of CHP and district energy. High amounts of fuel savings are available from exploiting excess heat from power generation and by establishing connections between the electricity and the heating sectors with heat pumps. Such a system can integrate more renewable energy, and therefore allows for a deep decarbonisation of the energy system.

Currently, the debate on sector coupling is nevertheless often reduced to the interconnection between electricity and gas grids, missing out on utilising an obvious energy carrier, namely district heating, which could easily cover 50% of heat consumption, as will be demonstrated in the following chapters.

1.3 4th generation district heating

Future district heating infrastructures should be designed for the future smart energy system described in the previous section. The concept of 4th generation district heating (4GDH) describes such future district heating technologies and systems, with reference to the previous three generations [14]. Figure 1-7 illustrates the major changes over time and the potential changes for the future of DH. The temperatures of the supply have been generally decreasing over time, in close connection to an increasing energy efficiency of the system. The increasing energy efficiency is a result of a reduction in the heat losses from the distribution grid, on the one hand, and the ability to integrate various new heat sources, such as renewable energy and excess heat, on the other hand. These new heat sources also imply decreased CO_2 emissions and increased integration with other energy sectors to improve the system's flexibility.

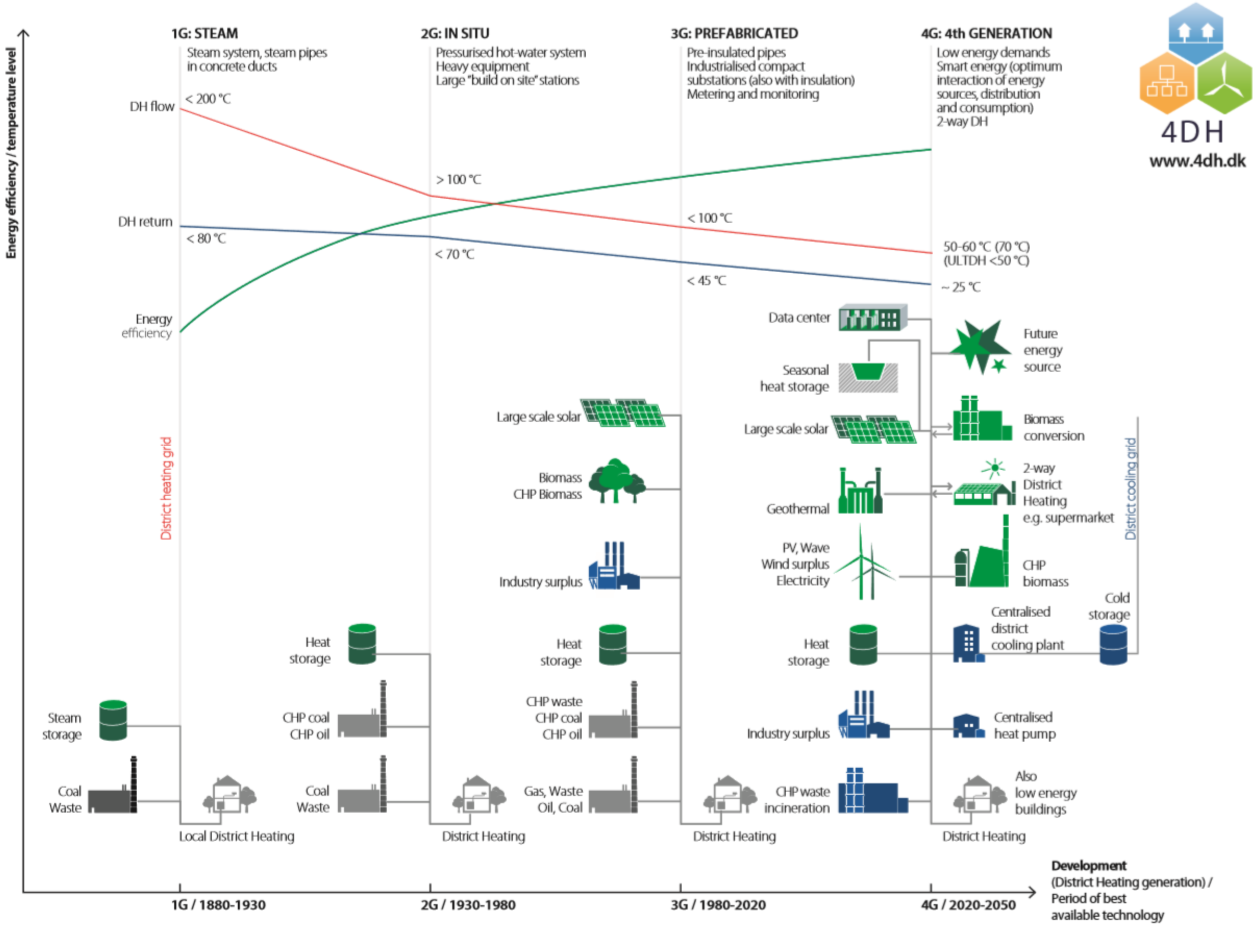


Figure 1-7. Illustration of the development of district heating technology and systems, categorising it in 4 generations. Source: [14]

Lower supply and return temperatures in the distribution networks will bring additional benefits for the supply part in the whole supply chain. Examples of these benefits are higher power-to-heat ratios in steam CHP plants, higher heat recovery from flue gas condensation, higher coefficients of performance in heat pumps, higher utilisation of geothermal and industrial heat sources with low temperatures, higher conversion efficiencies in central solar collector fields, and higher capacities in thermal energy storages if they can be charged to a temperature above the ordinary supply temperature [14].

The development of 4GDH systems and technologies involves energy savings and conservation measures in buildings as an important part of the technology.

Energy storages contribute to the integration of (intermittent) renewable energy sources and the flexibility of the system. Thermal storages, specifically connected to 4GDH, enable the decoupling of supply and demand of heat and play a key role in the operation of the smart thermal grids by allowing the integration of both intermittent renewables and stable, baseload-renewable thermal sources [15].

4GDH is accordingly an integrated part of the operation of smart energy systems, i.e. integrated smart electricity, gas and thermal grids.

Key finding

This report has the primary focus of promoting the **understanding of energy efficiency from a system perspective** and not as a single technology measure. When accounting for energy efficiency, it is vital to take full energy system effects into consideration. This understanding is a novel finding that remains to be adopted by policymakers, with decisions being made across the EU. An operationalisation of these terms should be the next step in realising an energy-efficient heating/cooling and energy supply. It is important to account for the supply chain effects from end-use efficiencies as well as re-designs of the supply system.

2 State of play of EU heating and cooling sector

2.1 Profile of the EU heating and cooling sector

With a final energy demand of 6,352 TWh in 2015, the heating and cooling sector accounts for approximately 50% of EU-28 final energy demand. Space heating represents 53% of the final energy demand for heating and cooling and it is significant in almost every European country, including southern countries: for example, the share of space heating is 61% in Italy, 50% in Greece, and 37% in Spain (Figure 2-1). It is the single highest end-use energy demand [1].

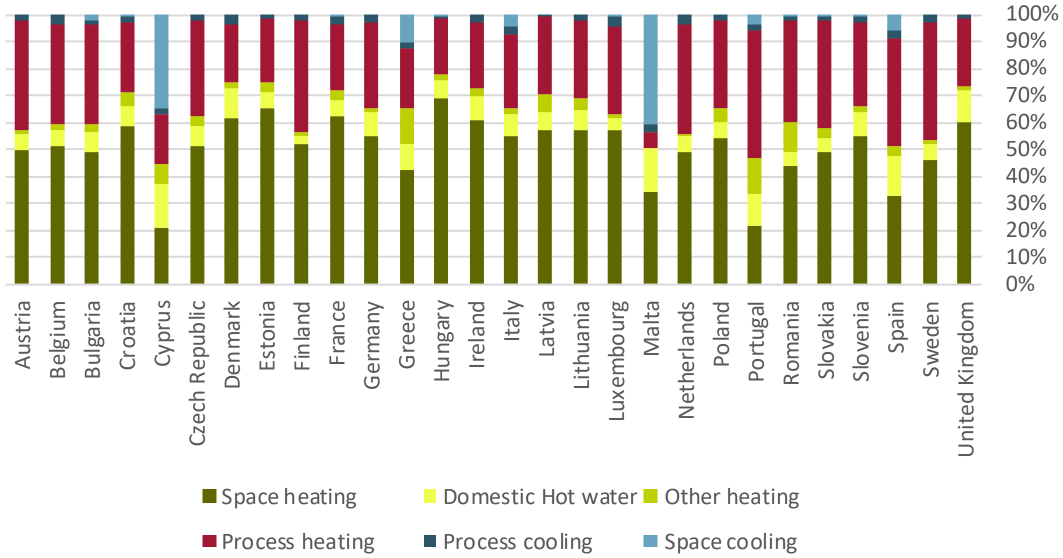


Figure 2-1. Share of type of end-use in total final heating and cooling demand by country in 2015 (EU-28). Source: [1]

With 2,845 TWh, the residential sector has the highest final energy demand for heating and cooling, followed by industry (2,388 TWh) and the tertiary sector (1,119 TWh) (see Figure 2-2).

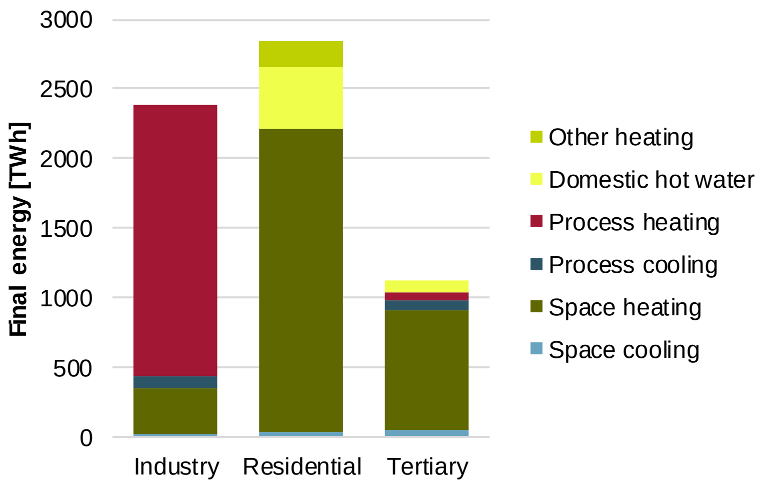


Figure 2-2. Types of end-use in final heating and cooling demand by sector in 2015 (EU-28). Source: [1]

Cooling accounts for less than 2% of total final energy demands and has low shares in most countries. Cooling demands differ from heating in that they are more balanced between space cooling and process cooling, and dominated by the service and industry sectors rather than the residential sector [1]. Space cooling is mainly relevant in southern countries (see Figure 2-3) but is expected to more than double towards 2050 (from 186 TWh in 2015 to 438 TWh in 2050) [16], as it has already done between 1990 and 2016 according to the International Energy Agency [17]. The heating and cooling sector is expected to continue to be dominated by space heating and process heating.

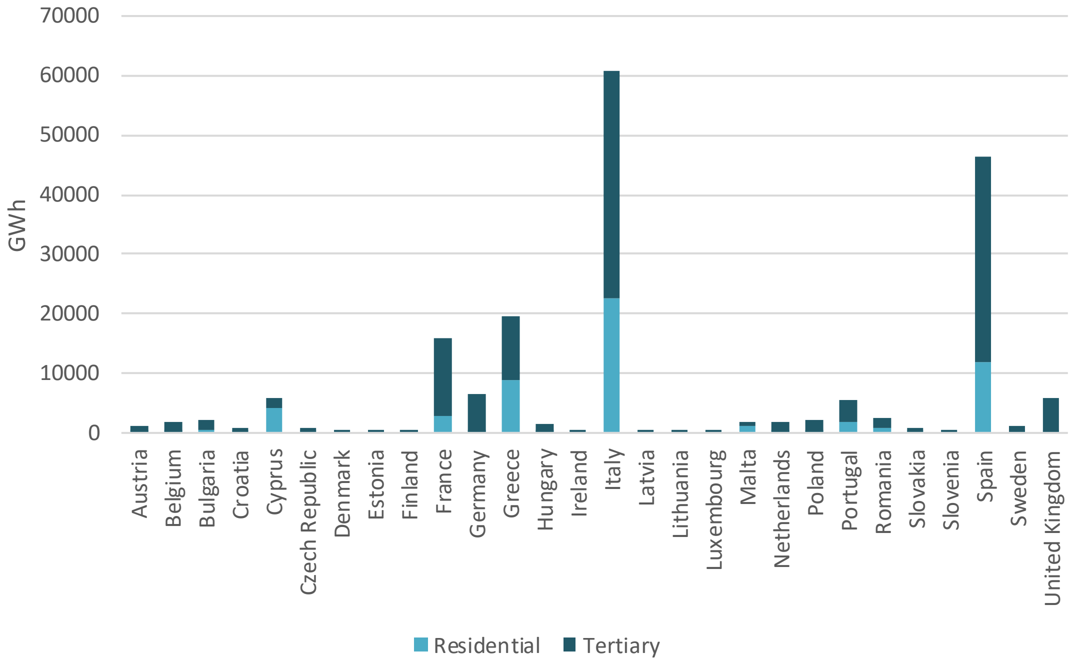


Figure 2-3. Total cooling supply for space cooling in residential and tertiary sectors by country in 2015 (EU-28).

This study will, therefore, focus on space heating in the built environment, which represents the decisive part of the heating and cooling sector in Europe and the market segment where district energy is more likely to develop.

The energy carrier mix in 2015 for supplying final heating and cooling demands shows that gas was the most dominant fuel in the EU (42%). Of the available RES, only biomass was used substantially (12%); solar thermal, geothermal and heat pumps are still marginal in almost every country. District heating accounted for 9% of the total final heating and cooling demands [1], and 12% of the heat market in the HRE14 countries [2].

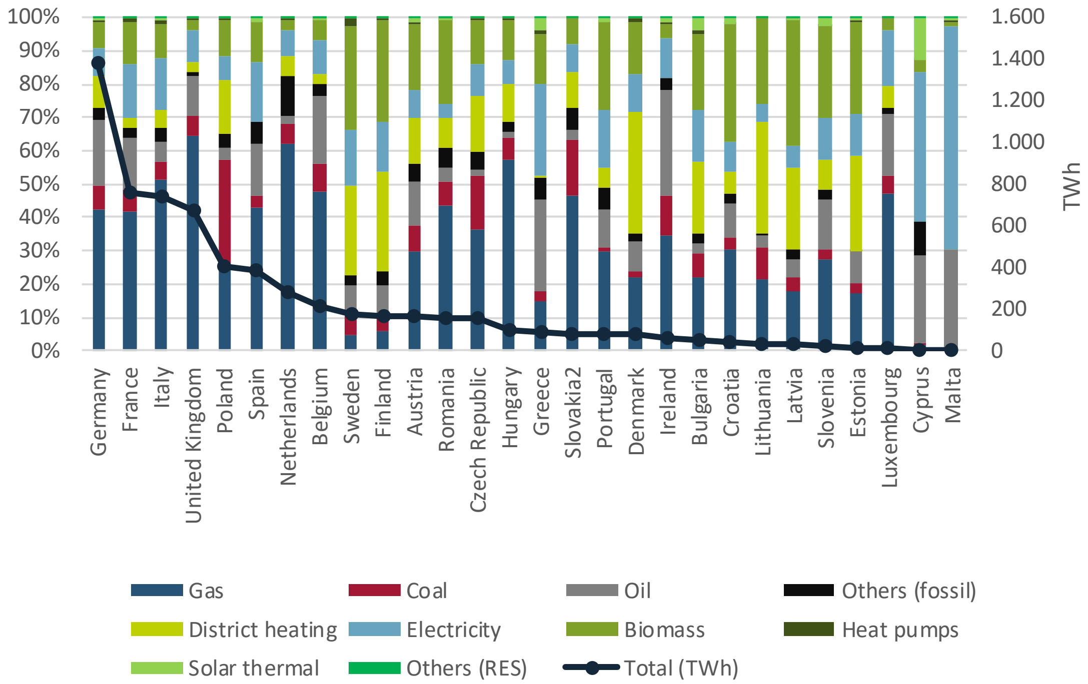


Figure 2-4. Share of energy carrier by country for the final heating and cooling demand for all sectors in 2015 (EU-28) [2].

However, as shown in Figure 2-4, the proportion of energy carriers for the heating and cooling supply is very diverse across countries [1]. While in some countries the heating and cooling sector is mainly supplied by gas boilers (e.g. the United Kingdom, the Netherlands), in others it is dominated by electric heating (Cyprus, Malta). Some countries still have significant shares of coal boilers (Poland, Czech Republic, Slovakia) while others have significant shares of district heating and biomass boilers or stoves (Scandinavian and Baltic countries). The majority of countries have a diverse heating fuel supply, which entails a mix of primarily heating supply options such as gas, oil, biomass etc., although most heating is supplied through individual boilers at the household level.

Gas boilers are the single most used technology for heating production of the EU building stock. Other main individual heating technologies are oil and coal boilers, direct electric heating systems, biomass boilers and heat pumps. Their respective average efficiencies have been estimated in a study of fuel consumption and technologies used in the heating and cooling sector in Europe, commissioned by the EU [18]. This study also indicated that most heating technologies in buildings were installed before 2002. Upgrading heating and cooling equipment such as boilers to the latest, most efficient technologies could save energy. However, it is not the most efficient option since it does not allow an escape from the *traditional* energy system lock-in, preventing the transition towards a smart energy system.

2.2 Status of district heating systems in the EU

Regarding the district heating market shares in the built environment (excluding industry), there is a large difference between the countries. District heating is generally more developed in Central, Eastern and North Europe (Figure 2-5), where in some countries it has reached a share around 50%.

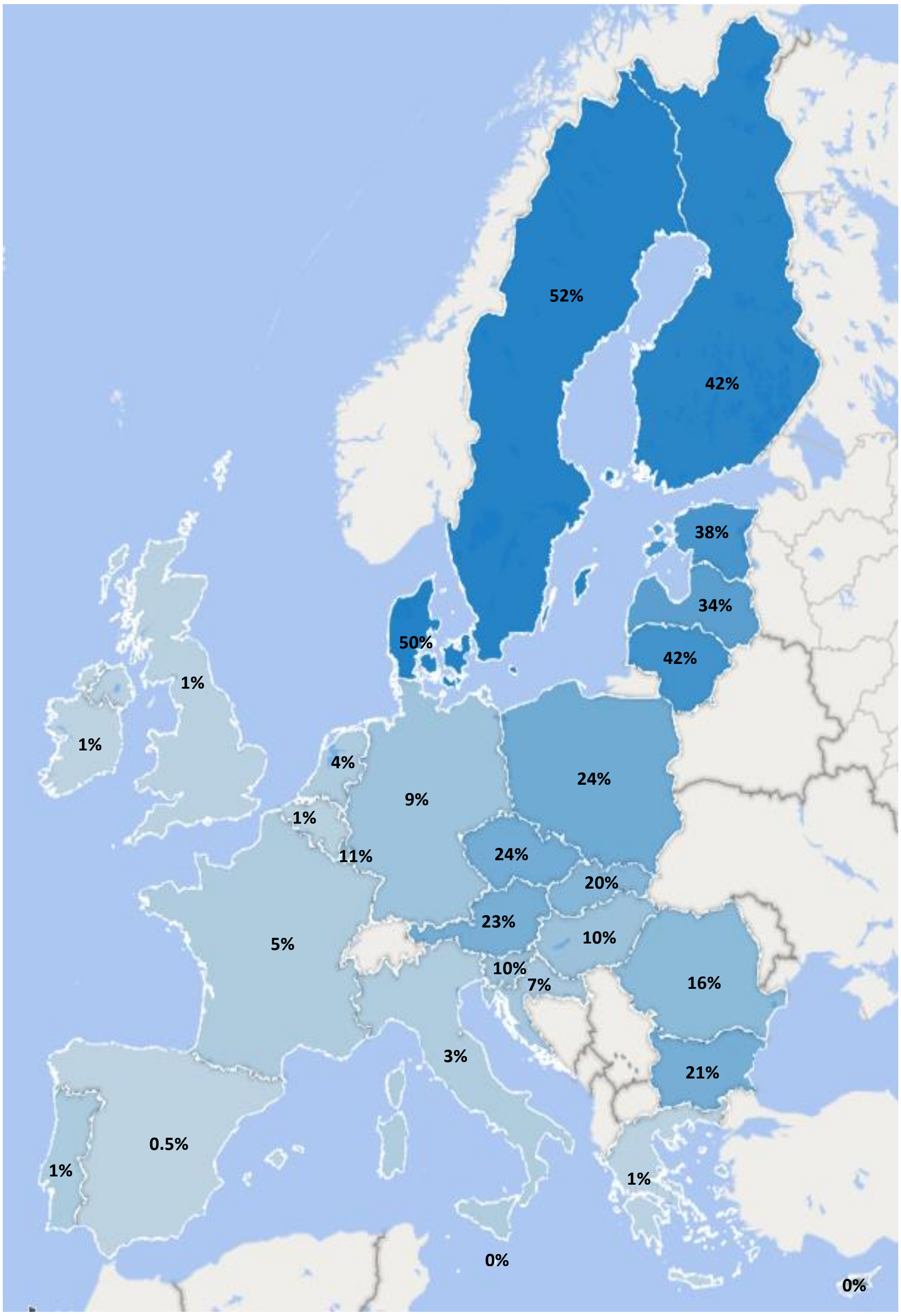


Figure 2-5. District heating share in final energy demand for space heating and domestic hot water in EU-28 in 2015. Data from [1]

Figure 2-6 illustrates the share of fuels used for district heating production in the EU-28 from 1990 to 2017. It shows how district heating is not tied to one supply type but is able to utilise different fuels. The European district heating production came in 1990 from more than 50% coal production. Since 1990, gas has expanded its share to around 1/3 of the total district heating production. 70% of the district heating supply came from oil, coal and natural gas in 2017. During the period 1990-2017, biofuels expanded its share to 20% and renewables account for 6% of the district heating production.

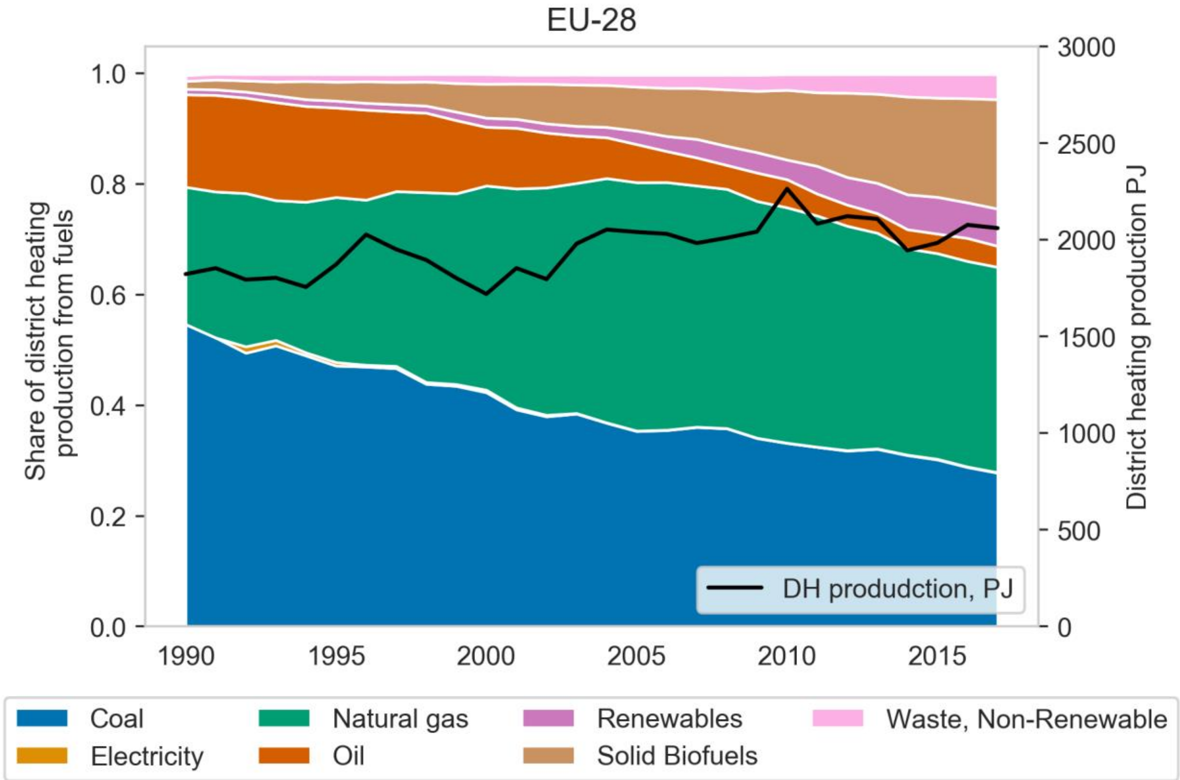


Figure 2-6. Share of fuels in EU-28 district heating production. [19], [78]

In Europe, CHP (combined heat & power) plants play a crucial role for generating district heat with the share of cogeneration exceeding 70% for the 14 Member States studied in HRE4. The energy mix, however, varies from one country to another, with some local specificities, such as a significant share of large-scale heat pumps in Sweden, or geothermal and waste incineration in France.

The current status of district heating in Europe is thus that it largely comes from CHP plants using fossil fuels. A transition is ongoing towards increased use of biofuels and renewables. There is thus high potential in changing the fuel supply towards renewable energy, as well as expand from the current heating market share.

2.3 Development of heat consumption in residential buildings

Residential heat consumption for space heating and hot water consumption has generally decreased since 1990 in the EU-28, even when facing an increased occupied living area as presented in Figure 2-7. While the occupied living area has increased by 40% over the last 25 years, the residential heat consumption decreased by 32% during the same period. This points towards increased end-use efficiency with more efficient new buildings and renovation of old buildings in the residential sector (including insulation as well as optimisation of technical building systems) [19].

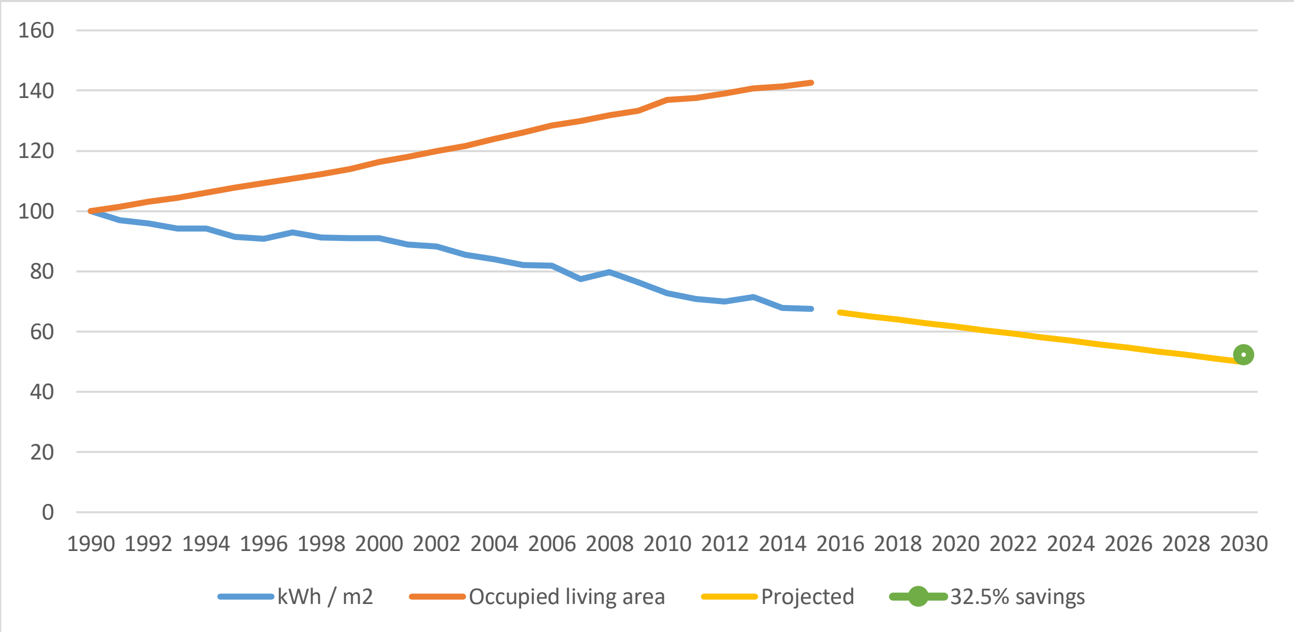


Figure 2-7. Development of residential space heat and hot water consumption per occupied living area. Index 100 = 1990 levels. Data from [19]

By simply making a linear extrapolation of the heat consumption in kWh/m^2 until 2030, the building stock should arrive at a heat consumption that, on average, is half of what it was in 1990. This is assuming that the past development can be maintained at the same rate.

This would mean that the building stock could achieve savings in line with the overall energy efficiency target of 32.5% in 2030 as set out in the EED [11]. However, it is not specified how much exactly the building stock is responsible for or should achieve. This question of the optimal renovation levels for the European building stock is addressed in chapter 4.1.

The most common heating distribution systems for centralised heating systems are: two-pipe riser system; two-pipe horizontal system; and single-pipe riser distribution system in old buildings [20]. Almost half of the installed radiator valves in Europe are manual valves [21]. This indicates potential for optimisation of control and metering systems, as described in the next chapter.

2.4 Estimation of distribution losses in district heating networks

DH systems are one of the most energy-efficient heating systems in urban environments, with proven reliability dating back many decades. Nevertheless, distribution systems do introduce an element of loss that is important to include in assessments of the energy efficiency of district heating systems. Relating to Figure 1-1, this section describes the distribution part of the energy efficiency value chain in district heating systems.

2.4.1 Current knowledge of district heating distribution losses

There is no comprehensive collection of data regarding distribution losses in district heating systems across Europe. These losses are known to potentially constitute a significant share of energy losses in the energy value chain, but can also be as low as 5-10%. Losses are generally related to the demand density of the given area: areas with very low demand densities, or old inefficient pipelines, can have high losses, while higher density areas have seen losses below 5%. It can, therefore, be difficult to assess the energy efficiency of existing and prospective district heating system without this knowledge. In this report, an attempt has been made to estimate distribution losses by means of a statistical analysis, based on available data from Denmark.

In a review of the national Comprehensive Assessments made in relation to Article 14 of the EED, the JRC collected the reported data on district heating distribution losses [22]. 11 countries did not report an estimation of national average losses at all (among those, Greece, Malta and Cyprus do not have district heating systems). The countries that did report losses, reported wide varieties, which highlights the difficulty of providing a single average for a country with several district heating systems. It also shows that there is no common methodology for how to assess and report national district heating distribution loss averages. Figures are based on a single case (Croatia), simple averages or weighted averages. For example, the reported value (24%) for Denmark corresponds to the simple average but calculating a weighted average, the value is 17.05% for 2018.

The figures used here in this report and found in statistics refer to yearly averages. This also constitutes a simplification as seasonal efficiency variations can impact the operation and efficiency of district energy systems. While the absolute losses of a district heating system are often slightly decreased during summer due to higher soil temperatures, the relative losses during summer can increase as less energy is supplied. However, for the purpose of this report, only yearly averages are considered.

The district heating distribution losses results of the analysis from the JRC about the Comprehensive Assessments are provided in Annex 7.1.

This points to two main issues for getting an overview of the distribution system losses on a European scale. First, there is simply a lack of data gathering and distribution. This is likely both an issue on national and European scale. Therefore, countries should start monitoring the distribution efficiencies of district heating systems. The second issue is related to methodology and the measuring of efficiency. There is a lack of consistent reporting and estimation of these losses, as they can be calculated in a number of different ways, as for example simple or weighted averaged, based upon single cases or taking into account seasonal varieties.

2.4.2 Using linear heat density to estimate national average district heating losses

The Danish District Heating Association collects yearly statistics about its district heating systems [23]. Among these are data regarding distribution losses, total heat sales, linear heat density, age, temperature, etc. Combined with data from Euroheat & Power on total heat sales and district heating network length [24], the estimate on country average district heating distribution losses will herein be provided. This includes high uncertainties and high differences among systems within countries and this should be considered before using the data.

The Danish dataset contains data from 2018 for 105 Danish district heating systems. The dataset has been stripped of missing values and outliers and as such represents about 25% of the approximately 400 Danish systems. Linear heat density and distribution losses from this dataset will be used to derive a general relationship between these two variables.

Linear heat density is a measure of the amount of energy supplied to a network divided by the length of the network [25]. It describes the average amount of energy supplied considering the length of the network. As such, it is a measure that allows for the comparison between systems of different sizes. As Figure 2-8 shows, the four largest Danish systems account for around 35% of heat supplied in the dataset used for the analysis. These four systems each had a heat production above 1 TJ in 2018. Using linear heat density, these high production systems can be compared to systems with lower production.

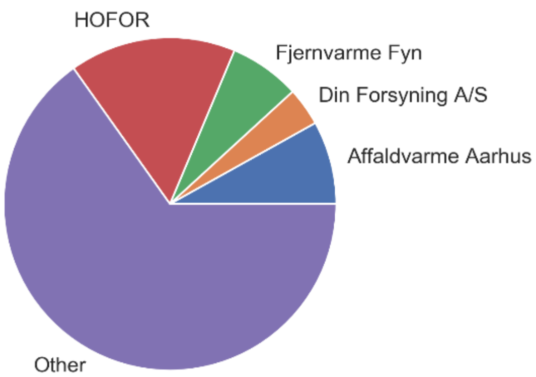


Figure 2-8. Share of the four largest district heating companies in Denmark and the share of the remaining companies in the used dataset

The model uses the total trench length, including both main and service pipes to estimate the linear heat density. Linear heat density can be a good predictor for district heat distribution losses. Although age, quality of piping, soil conditions and temperature levels also play a role, linear heat density is the single best predictor found for estimating distribution losses. Fitting a power function of the form $y = ax^b + k$ through the Danish dataset yields the model presented in Figure 2-9. The model can be described with the following equation:

$$y = -2.18 * x^{0.047} + 2.40$$

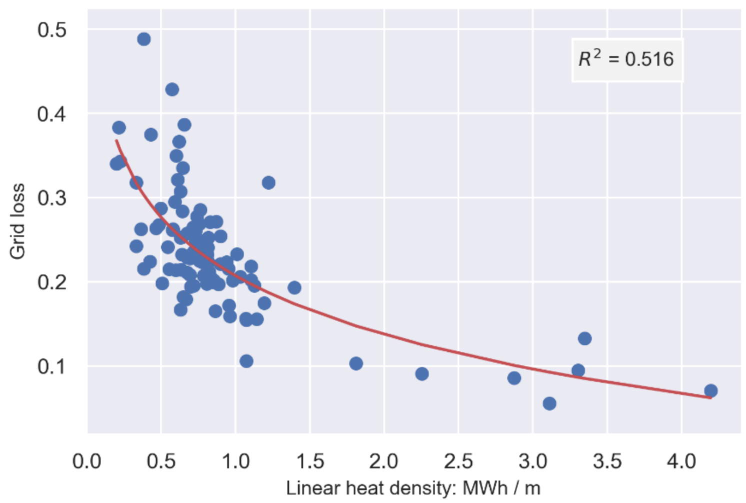


Figure 2-9. Power function describing the relation between linear heat density and distribution grid losses for Danish district heating systems

Using Danish data for approximating distribution losses across Europe has certain limitations. Danish district heating systems typically operate year-round, which might not be the case in other countries with shorter heating seasons or systems supplying specific heat loads. In addition, for a full year operating system, a longer heating season typically gives lower relative losses, while a shorter season results in higher relative losses. This approach might underestimate relative losses in countries with shorter heating seasons than the Danish climate and might overestimate relative losses in countries with longer heating seasons than the Danish.

The model can be used as a first approximation of national average district heating distribution losses using linear heat densities calculated from the Euroheat & Power Country by Country database [24]. The results are presented in Table 1 below.

Table 1 Estimated district heating distribution losses.
**Please note the value is estimated assuming the minimum loss value in the dataset, as the linear heat density is too high for the model to estimate.*

Country	MWh/m	Estimated losses	Country	MWh/m	Estimated losses
Austria	4.28	5%	**Latvia**	3.4	8%
Estonia	4.41	5%	**Lithuania**	2.71	10%
Bulgaria	3.19	9%	**Netherlands**	1.81	14%
Croatia	5.93	5%*	**Norway**	2.70	10%
Czech Republic	2.87	10%	**Poland**	2.98	9%
Denmark	0.95	21%	**Serbia**	3.06	9%
Finland	2.06	13%	**Slovakia**	9.86	5%*
France	4.81	5%*	**Slovenia**	2.31	12%
Germany	3.40	8%	**Switzerland**	3.46	8%
Italy	2.09	13%	**United Kingdom**	46.02	5%*

Due to data incompatibility and differences in data collection, comparing the weighted average value of 17% for Denmark with the estimated value of 21% illustrates a slight deviation. For the Danish case, this is likely due to a discrepancy in data collection. This points to the importance of the uncertainty that lies in using the model for estimating distribution losses, as there is both high uncertainty in the model and in the data used for estimation. Still, it is the most useful approach to estimating distribution losses of systems where these are unknown. To estimate these it is important to estimate comparable numbers and data. This is sensitive to which types of networks that are included in the reported trench length and how the supply amounts are measured. For the model presented in Figure 2-9, the total length of main and service pipes was used for the trench length and the energy delivered to the DH system for calculating the linear heat density.

While linear heat density is a useful measure for estimating distribution losses it is important to keep in mind that it does not describe overall district heating system efficiency, price levels, environmental impact or other factors. Higher heat losses could be justified with some types of heat supply, while for systems with high heat production costs, increased investments in savings to decrease losses might be justified.

This estimation highlights several implications. First, although Denmark has relatively higher distribution losses than the rest of the countries in the estimation, the Danish energy system and heat supply remain overall efficient [26]. Although district heating supply might introduce losses in the distribution, these can be offset by the increase in efficient generation, the avoidance of other fuel use by using waste heat or the introduction of renewables. Furthermore, it is clear that credible and precise estimations of trench length, district heating production and, if possible, the distribution losses are important data points to monitor when assessing the efficiency of district heating systems. Further data collection efforts should at least include these measurements in their data collection about district heating systems.

2.5 Energy efficiency and cooling

While heating needs largely exceed cooling needs in Europe (see 2.1), some factors make cooling, especially space cooling, interesting for efficiency gains. The warming of the climate, and in particular heat island effects, as well as the desire for increased thermal comfort, will increase the demand in the coming years (it is expected to more than double between 2015 and 2050), and even if cooling is currently produced quite efficiently, a significant margin for improvement in seasonal performance remains.

These improvements are important as a rising demand for cooling is already having a major impact on power systems since most cooling needs are met by electricity-powered fans or air conditioners. In Europe, space cooling accounted for around 15% of the overall growth in electricity demand between 1990 and 2016 [17].

Air conditioning (AC) systems available today vary enormously in scale, from small (movable) units designed to cool a single room to large-scale systems for entire buildings and district cooling networks for cooling groups of buildings. All those types of AC systems are usually powered by electricity, though large systems can also be fuelled by natural gas, excess heat or renewable energy.

2.5.1 Individual cooling

Split system is the dominant technology used for space cooling in the EU residential and tertiary cooling sector (See Table 2). It consists of two distinct units, with the evaporator placed in the indoor environment and the condenser placed in the outdoor environment.

The efficiency of the main space cooling technologies has been estimated in HRE4 [16] according to their seasonal energy efficiency ratio (SEER) which reflects the average annual energy efficiency of cooling equipment. The results are shown in Table 2 below.

Table 2. Space cooling technology in Europe. Data from [16].

2015	SEER of stock	SEER of sales	Cold generation capacity (kW)	Total installed capacity in residential and tertiary sectors (GW)
Air-cooled chillers	3.3	3.9	80 - 616	104.4
Water-cooled chillers	5.1	5.7	114 - 755	45.5
Movable units	2.3*	2.6	2.5	11.6
Split systems	3.6	5.9	3.5 – 7.5	248.8
Rooftop and package units	2.3	2.8	65	45.7
Variable Refrigerant Flow units	3.8	4.3	25	28.2

*Energy Efficiency Ratio, corresponding to a full load of operation under standard design temperatures

Improved standards and more efficient supply chains could reduce cooling energy consumption to one third of its current level, with the SEER of available air conditioning systems significantly more efficient than the market average energy efficiency [17].However, individual cooling solutions present a series of problems. On the one hand, the cooling towers employed in large buildings such as hospitals or shopping centres are susceptible to legionella outbreaks, which can propagate to considerable distances (6 km) [27]. On the other hand, the electric individual solutions could strain the grid and production due to the simultaneous effect of a higher cold load and lower coefficients of performance (COPs) of the cooling equipment (the instantaneous COPs can be fairly lower than the seasonal SEER). Furthermore, the heat released by the myriad of individual chillers contributes to an exacerbation of the heat island effect, already present in the large metropolises.

2.5.2 District cooling

The efficiency of existing district cooling networks has been estimated in HRE4 [16]. They are presented in Table 3, according to three zones: cold Europe (Scandinavian and Baltic countries, the United Kingdom, and Ireland); temperate Europe (Central Europe, Benelux and North of France); and warm Europe (South of France and southern countries).

Table 3. Efficiency of district cooling networks in Europe. Data from [16].

2015	Global Seasonal Energy Efficiency Ratio	Part Free cooling (% energy supply)	Network losses (% energy supplied)
Cold Europe	9.4	80	7
Temperate Europe	5.1	40	9
Warm Europe	4	20	11

The centralisation of cooling production is a prerequisite to reach a high efficiency insofar as it makes it possible to use “free cooling” or excess heat (or cold) sources [25]. The expected growth of the cooling demand, potential threat to the environment and to electricity supply infrastructure, can thus be converted into great opportunities if the cooling sector is approached in a smart energy systems perspective by exploiting synergies from connecting to other sectors.

The major advantage of district cooling from the customer perspective is that the buildings supplied in this way do not require their own air conditioning systems, but they only require compact heat exchanger units. This will free valuable space previously occupied by the chillers and cooling tower and it will also eliminate the risk associated with legionella.

From a production standpoint, important economies of scale remain in cold generation, which can be reaped by district cooling providers [25]. In addition, centralised production benefits from diversification (the maximum peak load of a series of buildings is lower than the sum of each individual peak load). Furthermore, district cooling can take advantage of low-cost cold sources such as industrial excess heat, industrial excess cold, solar or geothermal energy. Above all lies free cooling, where cold can be taken directly from seawater, rivers or lakes and electricity is only required for pumping. In this case, the efficiency of district cooling rises dramatically [16]. These sources are seldom accessible on a building level.

A crucial aspect for district cooling is storage in the form of cold water, slurry or ice, which enables load shifting. Load shifting can be employed for various purposes such as avoiding investments in peak generation (peak saving). Another common purpose is taking advantage of variable electricity prices, both in the spot market and distribution tariffs; some countries (e.g. Spain) have different network rates[3] depending on the time of the day and therefore economic savings can be attained producing only during the valley hours. Other reasons for its utilisation could be attaining higher efficiencies by operating the chillers continuously at optimum load or allowing for operation at night, which reduces peaks on the power system and increases the efficiency of the chiller if the excess heat is rejected to the atmosphere [25].

Storage also permits the utilisation of surplus electricity production stemming from non-dispatchable renewable energy sources, facilitating their integration in the energy system.

District cooling distribution costs can be substantial since the temperature difference between the supply and return flows is rather small (around 10°C), which leads to the need for big pipes. Thus, the distribution cost and losses need to be offset by low production costs, through higher energy efficiency, low operating and maintenance costs, and the economic profit of the freed space in the connected buildings.

District cooling can be deployed in different manners. An entire network could be built similarly to a district heating grid, provided that the demand is high enough. This is the case in Paris, where two networks cover a significant portion of the city centre [28]. Another option could be the construction of a small network to supply a service cluster.

With regard to production, the district heating network could be employed as the energy source thanks to absorption chillers; cooling, heating and electricity could be produced simultaneously (trigeneration) at the same plant or the cooling production could be completely detached from the heating production using any of the sources enumerated before.

2.6 Summary of the state of play and perspectives

Today, the heating and cooling sectors account for half of EU total final energy demand and show significant potential for improving energy efficiency and integrating renewable energy: it is a critical sector to invest in to fulfil the EU's climate and energy goals.

With about 2,850 TWh, the residential sector has the highest final energy demand for heating and cooling. The sector is very diverse, with many different technologies providing heating and cooling to a heterogeneous building stock. In some countries, the use of natural gas in local boilers prevails. In other countries, DH systems dominate the building heat market. Overall, gas is the most widespread fuel, supplying 42% of heating and cooling demands. Although DHC systems have already proven their effectiveness in some EU countries like Denmark and Sweden, where they have allowed aggregating heat loads to progressively optimise the energy supply and switch to renewable energy, these systems currently account for only 12% of HRE14 countries heat demand.

Energy efficiency improvements on both the demand and supply sides are necessary to achieve decarbonisation goals for the heating and cooling sector in a cost-effective fashion. The establishment of thermal grids is crucial for the redesign of the energy system and to enable better integration of renewable energy and excess heat sources. At the same time, future district energy systems need to be more energy-efficient and sustainable. The assessment of DH grid losses showcases a considerable lack of knowledge about the current state of DH in EU Member States.

[3] These rates refer to all the charges other than the electricity prices in the spot market. Spain has, for instance, six periods in high and medium voltage connection, with different prices for both capacity (kW) and energy (kWh) [77]. On top of this, the consumer will need to pay the spot price.

In that perspective, it is to be noted that in the most recently envisioned European scenarios for reaching net-zero CO_2 emissions in 2050, A Clean Planet For All, distributed heat supply keeps the share of 4% final energy consumption that it holds in 2015 over the period up to 2050 in all scenarios [7]. This study showcases alternative scenarios demonstrating the role distributed energy can play to cost-effectively reach energy efficiency and decarbonisation targets.

This redesign of the system will nevertheless be different from one country to another, as there is a diversity of profiles. Based on the classification from [29] and inputs from HRE4 profiles [1], three clusters of countries can be defined:

- **Countries with high amounts of district heating** with a tradition of heat planning and a mature district heating market, such as Sweden, Finland and Denmark, where the current district heating market share is high (almost saturated), and buildings generally are efficient, but still with room for increasing efficiency.
- **Countries with inefficient district heating systems and buildings** where a decent level of district heating exists, but with low-efficiency buildings and a decline in DH market share in the last few decades (e.g. Poland, Latvia, Slovenia). The common denominator for the DH systems in these countries is that they were introduced and developed within planned economies and supply-side driven, as well as mainly supplied by fossil fuels. These countries face issues with transitioning towards more demand-driven systems and activating customers control and operation of their heating systems.
- **Countries with low or no amounts of district heating** or areas with an underestimated heat demand (southern countries), and/or no consistent heat planning. DH systems can appear in some cities, but the total market share is low. This is typically the case of some parts of Germany, Belgium and France. It also includes the gas dominated countries (the United Kingdom and the Netherlands) that have gas heating in +90% of their building stock and are now envisaging a transition towards district heating.

Where possible, the analyses developed in this study will consider this classification.

Key finding

The lack of data in the heating and cooling sector is a considerable barrier to implementing district heating and cooling and energy efficiency improvements. Improving data collection on heat and cold demands, heat production, building characteristics such as age and insulation, and (the performance of) district heating and cooling grids will provide the **knowledge necessary to plan and carry out a heat transition**. District heating and cooling investments are capital intensive and it is important to base investment decisions on solid knowledge.

3 Technologies needed across the energy efficiency value chain

This section will present important technologies for a low-carbon heating supply. These technologies enable increasing energy efficiency as well as the introduction of new low-temperature renewable or excess heat resources, following the trends throughout the first three generations of district heating, and leading towards the 4th generation district heating presented in section 1.3.

This report presented the energy efficiency value chain above in section 1.1. to conceptualise the energy efficiency potential from production over distribution to delivery. Across the value chain, different technologies come into play to leverage the energy efficiency potential. Improvements close to the point of usage will have effects earlier in the value chain such as less need for production capacity or more efficient energy generation. This is why it is important to consider the impact across the value chain from useful energy to primary energy.

The parts of the energy efficiency value chain are identified in Figure 3-1 below. Figure 3-1 presents some related technologies to each part of the energy efficiency value chain. The impact of specific technologies depend on local conditions and are therefore not described in this report. However, different technology principles enable smart energy usage and systems optimisation.

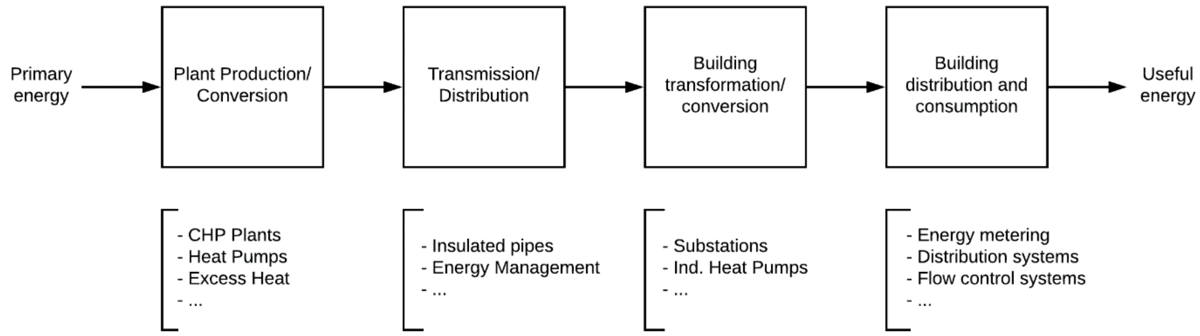


Figure 3-1 Examples of technologies related to different parts of the energy value chain

3.1 Plant production and conversion

The deployment of district heating can often render by itself efficiency gains in the energy system, provided that the systems fulfil the fundamental idea of district heating as defined by Sven Werner: "*utilize local fuels or heat that would otherwise be wasted*"[25].

Examples for local fuels are renewable energy sources such as deep geothermal, whose decentralised exploitation is generally not economically feasible in large scale, or biomass and solar thermal, which are cleaner, more efficient and more cost-efficient when implemented at a large scale in district heating systems compared to decentralised applications [25], [30].

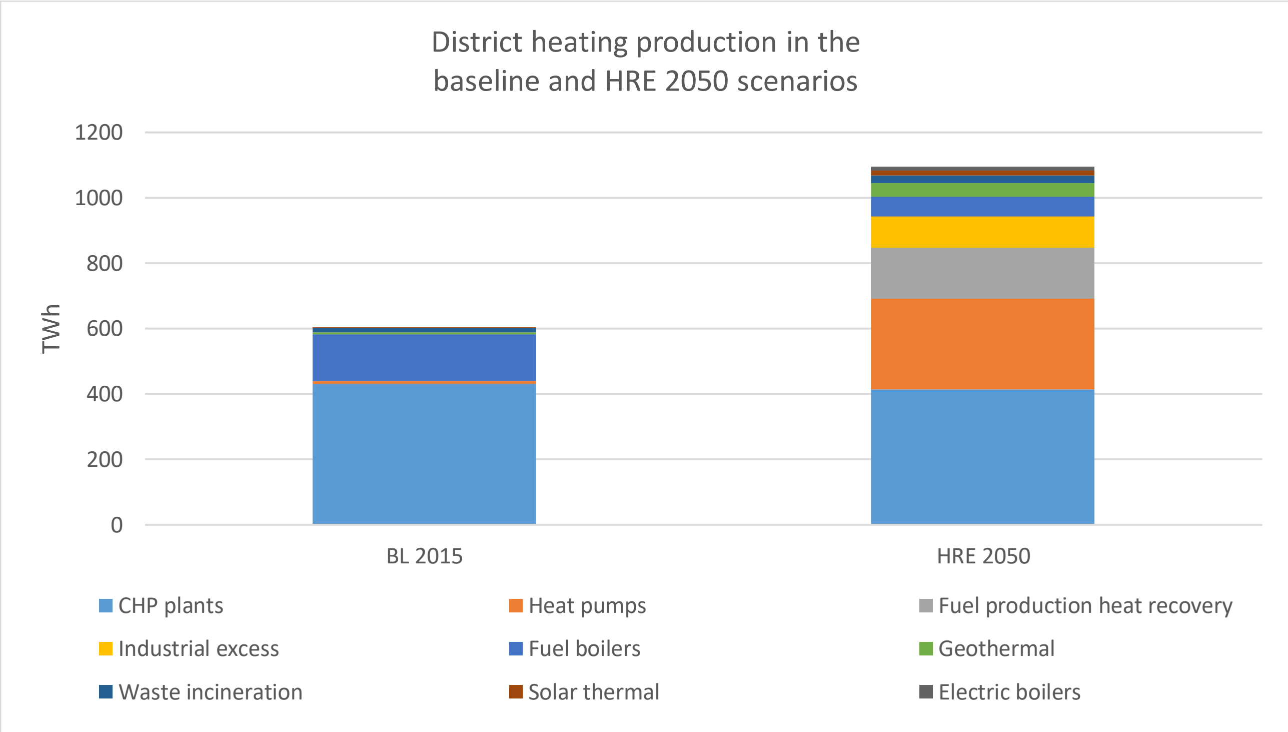


Figure 3-2 Annual district heating production in the baseline and HRE 2050 scenarios

Heat that would otherwise be wasted is exemplified by heat recovery from industrial processes. In this case, no extra fuel needs to be used for generating heat, leading to a net reduction of the primary energy supply and hence an augmentation of the energy system´s efficiency. In a broader sense, district heating systems can also leverage the excess electricity production due to non-dispatchable renewables or recover the waste heat from CHP plants, when renewables cannot meet the electricity demand [31]. The heat production from excess renewable power generation can be used at the moment or stored for later use at a cost two orders of magnitude cheaper than electric storage [32].

Figure 3-2 presents the current and potential heat production in 2050 [2]. It is clear from the figure that sweeping changes need to take place. Firstly, heat production must nearly double from 602 TWh/year to 1096 TWh/year to meet half of heat demand in 2050. Secondly, the production mix needs to undergo significant changes as the importance of cogeneration and fossil fuels ought to decrease and the proportion of heat pumps, industrial waste heat and renewables should increase.

A cornerstone parameter in district heating efficiency is the system temperatures, i.e. the supply and return temperatures. These have an impact on both distribution and production efficiencies. Regarding the latter, which is the focus of this section, lower temperatures nearly always translate into a better utilisation of the heat source. This is particularly true in the most common sources of the future district heating supply. For example, the COP of a heat pump increases with lower supply temperature. That means the lower the supply temperature, the less electricity is needed [25]. Similarly, the efficiency of a solar thermal plant increases the lower the supply and return temperatures are [33] and the electricity generation from a cogeneration plant increases as the supply temperatures falls and heat recovery increases with lower return temperatures [25].

3.2 Energy distribution

The HRE 2050 scenario relies on smart electricity grids, smart thermal networks and smart gas grids [34]. Notwithstanding, this report focusses on thermal networks, which will be addressed in detail hereafter.

In district heating systems, the main explanatory variable for distribution losses, and hence the efficiency of the distribution system, is the linear heat density as shown in section 2.4. DH systems should maintain adequate linear heat densities across systems, i.e. restraining from expanding into low-density areas, wherein decentralised solutions such as heat pumps are more efficient. The actual linear heat density that allows feasible operation will depend on local conditions. If local, abundant, and inexpensive renewable sources are available, then higher heat losses could be accepted. Iceland is a case where abundant geothermal resources allow for lower linear heat densities alongside cost-efficient heat supply. New networks can focus on starting to develop in high consumption areas first while existing networks can concentrate on increasing connection rates in their areas and expanding to nearby areas with feasible heat demands.

In addition to maintaining a sufficient linear heat density, high quality insulated pipes and optimised distribution and demand-driven system contribute to ensuring efficient networks. An example of this is provided by the utilisation of twin pipes, which have a similar cost to their traditional single pipe counterparts but are capable of nearly halving the heat losses [25]. Diffusion barriers [35] are another technology which is key to the long-term durability of the insulation, especially in smaller pipes [36]. A demand-driven system, as will be explained in the following section can also bring about considerable efficiency improvements. For instance, a reduction of the system temperatures renders an automatic reduction of the heat losses without any further intervention in the system.

Aside from the pipe network, the control of the pressure, temperature and flow are three factors where important energy savings can be reaped. Traditionally, the supply temperature of a district heating network is determined by the network's operator using a simple compensation curve based on the outdoor temperature. This results in supply temperatures higher than necessary as the operator will apply a safety margin so as to avoid consumer complaints. A state-of-the-art temperature optimisation system can estimate the minimum necessary supply temperature in order to fulfil the customer needs, thus reducing the heat losses of the system [37]. Furthermore, a pump control system, which continually adjusts the pump operation based on the differential pressure requirements at the critical consumers can attain significant electricity savings compared to fixed speed operation. In this sense, it is not far-fetched that in countries with a poorly developed district heating sector, system operators maintain a constant supply pressure regardless of consumption, or even a constant flow through the network.

In some countries, especially in Eastern Europe, group substations are still in use [38], [39]. These units serve as the interface between the main distribution network and a local grid which serves several buildings. Their utilisation was intended to economise on control equipment but their utilisation leads to poor control as the central control system cannot cope with the varying loads between, as well as within, the various buildings supplied [40]. Furthermore, the secondary system often presents a poor water quality, which leads to strong corrosion and water losses, and high return temperatures. In Central Europe, the conversion to building substation has led to overall heat supply savings reaching 15% on average by addressing the misbalance between the buildings [40]. The building level substations further open up for the possibilities of changing the system from being supply-driven to demand-driven, which is fundamental to realise smart energy systems. Thus, the elimination of group substations and substitution by building, or ideally flat, level substations should be prioritised.

3.3 Heat demands in buildings

This part of the energy efficiency value chain focuses on the building level. It covers the two main demands buildings have: heating and domestic hot water (DHW).

A common issue pertaining to both space heating and domestic hot water demands is the supply strategy adopted by the district heating operator. Systems can be either supply-side driven or demand-side driven. In the former strategy, which is still predominant in some countries, the systems are controlled only at the production facility, where the operator attempts to match the estimated aggregate heat demands from the consumers. The demand-driven systems have, on the contrary, consumer-based controls too, and in this case, it is the individual consumer who can adapt his consumption to his preferences.

In supply-driven systems, billing has often been based on lump sums and hence the system is frequently seen as unfair and outdated [20], [41]. In demand-driven system, consumers can adjust their energy consumption to their needs and if these controls are paired to metering and consumption-based billing, consumers will also have an incentive to energy conservation, which in turn, would pave the way for investments in energy efficiency [38]. The importance of metering in a demand-driven system reaches far beyond a proper billing of the energy consumed, since the deeper knowledge of the consumer patterns and conditions may enable the detection of faults in the consumer installations [42] or demand-side management [43].

Transitioning from a supply-driven operation to demand-driven operation with individual consumer-based controls, heat metering and billing according to consumption would increase trust in district heating due to higher transparency, which is highly needed in some legacy systems, such as in Eastern Europe.

3.3.1 Space heating

Heating is the main driver of heat consumption in the majority of buildings [25] (being passive houses a noteworthy exception) and, it is usually determining the lowest possible supply temperature during the coldest parts of the year; the extent of which will depend upon the design conditions of the heating equipment and their utilisation. Various measures can be taken in order to reduce the supply and return temperatures and therefore, increase the efficiency of production and distribution.

A renovation of the buildings' envelopes is a measure which would both trigger a reduction in the energy demand and also facilitate a reduction in the supply temperatures since the heat emitters will be oversized for the new conditions [44]. Furthermore, short term space heating peak demands will be reduced as the thermal inertia of the building is increased. This latter factor may also enable demand-side management [43], which could reduce the need for peak units at production level, which usually rely on fossil fuels [25].

An increase in the size of the heat emitters could also provide the same benefits in terms of system temperature reduction, but at a lower cost, especially if only a few radiators are undersized as research has unveiled is often the case [45].

Regarding the distribution network of the heating system, some old systems consist of single-string circuits. These had the advantage of a lower investment cost but nowadays they ought to be substituted by double-string circuits as the latter perform much better in terms of return temperature and control ability [46].

A building's refurbishment will fail to deliver the expected energy savings if the technical building heating installation is not adequate. Efficient technical building installation has the benefit that it ensures the right operating conditions and automatic operation of the end user controls, which the consumer uses for adapting the supply to his comfort requirements [20]. Thus, a key measure is the installation of adequate balancing equipment and individual controls in the heating installations.

The control of the heating systems can be established at different levels: at an area substation as it has been mentioned before, at a building substation, flat substation or the individual heat emitters; it is possible to combine several of the previous control levels, for example a building substation with thermostatic valves in the radiators (TRVs). Generally, the closer the control equipment is to the heat emitter, the better it will be in terms of comfort and energy conservation, leading to lower heating costs, although the capital expenditures will be higher.

At the building level (or flat level in the case of flat substations), state-of-the-art substations may adjust the temperature to meet the aggregate demands of the building. For example, weather compensation will regulate the supply temperature following the outdoor temperature and/or other weather parameters and the supply temperature will be reduced in days with partial loads [47]. Moreover, the flow rate through the heating system could also be adjusted; in older supply-side driven systems it is rather common to circulate a constant flow.

A correct hydraulic balancing of the heating system will be critical for meeting the heating demands of a building's dwellers with the minimum heat consumption. Balancing of the hydronic circuit guarantees that each heat emitter receives the required flow [48]. Otherwise some areas of the building may experience underheating whilst other zones are simultaneously overheated [49]–[51]. Balancing may be manual, semi-automatic or automatic [48]. In the first case, balancing is only guaranteed in constant-flow operation. On the contrary, semi-automatic balancing with differential pressure controllers or automatic balancing with flow limiters will ensure a correct balancing in variable flow systems at different loads [48]. Neither the building's substation nor the individual thermostats will be able to compensate a poor balancing of the hydronic system.

The pressure difference between the supply and return flows may be regulated by differential pressure controllers. These will maintain a constant pressure difference regardless of the heat load in the system, reducing the interaction between different parts of the hydronic system and ensuring the correct functioning of the TRVs [48]. They may be installed at various levels: building, riser, flat. In this sense, the closer to the radiator valve the differential pressure control is applied, the more stable the pressure difference will be at the TRV and thus, the more effective the TRV pre-setting and operation becomes [52].

As already mentioned, Thermostatic Radiator Valves (TRV) are devices installed at each radiator, which control the heat output of the radiator in order to maintain the indoor temperature at the desired set-point. They may well render heat savings [53], provided that they are operated correctly. This operation is either achieved by manual control or by automation which could reduce user misuse. This diminution in the heat consumption is achieved by reducing the heat output when solar or internal gains rise and adapting the flow rate to changes in the system's supply temperature. By tailoring the radiators' flow to the actual requirement, the TRVs maximise the cooling of the flow, which will have a positive effect on the district heating system and hence, the overall energy system. A new development of these apparatuses are electronic TRVs that monitor the radiator return temperature in addition to the room temperature [54]. On the other hand, digital TRVs could also help to remedy another persistent ill, which is consumers' misuse, as dwellers often ignore the proper functioning of manual TRVs and frequently utilise them as if they were manual radiator valves [55], [56].

The control technology described in the paragraphs above will ensure a simultaneous fulfilment of two requirements: the consumers' indoor temperature desires and the maximum cooling of the district heating water.

The last issue, which may affect the efficiency of the district heating value chain is consumer behaviour. In some countries, set-back periods are the norm as these can bring about considerable energy savings in poorly insulated buildings [25]. In well insulated building, set-back functions result in minimal savings due to large thermal inertia of the buildings. For example, Danish buildings, which are rather well insulated [57], experience savings lower than 10% when utilising night set-backs [58]. Depending on the building, supply system set-back functions can have negative impacts on the system efficiency. The more temperature dependent the supply system is, the more negative impact the set-back operation can bring. This can be a special challenge for heat pumps. For district heating systems set-back functions lead to larger peak demands due to reheating of the buildings, higher heat losses due to either higher supply or return temperatures, higher pumping costs due to increase flow rates and less efficient heat source operation, due to higher system temperature [59].

The implementation of the measures presented here will pave the way for the conversion of second generation networks into third or fourth generation systems. Better performance of the building's envelope accompanied by adequate controls will avoid overheating, lower operating temperatures in the network, and leverage low-temperature energy sources.

3.3.2 Domestic Hot Water

DHW may be prepared by means of instantaneous heat exchangers and storage tanks in district heating systems. Storage tanks require high supply temperatures (min 60°C) in order to avoid the proliferation of legionella [60]. In addition, the return temperature is typically rather high and seldom falls below 30°C [61]. Both facts hinder the transition towards lower temperatures, which are key for higher system efficiencies. Instantaneous heat exchangers can operate, on the contrary, with lower temperatures (50°C-15°C) [6] and since the DHW preparation is instantaneous, the risk of legionella growth is negligible [62]. Their deployment will be instrumental in attaining the goals of the 4th generation district heating (4GDH) [6]. A supplementary benefit of instantaneous heat exchangers with respect to storage tanks is a fall in the flows circulating through the network [61], which translates into savings in electricity for pumping.

Furthermore, DHW can be prepared centrally, at building level, or decentrally, with the so-called flat substations [63]. Whilst in the first case, a circulation system is needed, this system is redundant when flat substations are employed. Circulation systems have three main disadvantages: first of all, high supply temperatures must be provided due to the legionella hazard; secondly, the return temperatures are also higher than necessary, even using external heat exchangers for charging the tank; and finally, heat losses may be substantial (higher than 30%) compared to instantaneous DHW applications [64].

From health concerns and temperature requirements outlined in the two paragraphs above, flat stations with instantaneous DHW heat exchangers is the preferred solution for hot water preparation in 4GDH systems, not only in new buildings, but also in the legacy building stock. The higher capital expenditure in the flat stations is compensated by zero investments in a recirculation system and other ancillary equipment, and lower running costs such as avoided heat loss from the tank and the circulation system [65]. From the overall perspective, thus savings are simultaneously present in production and distribution due to both lower supply and return temperatures and flow rates in the distribution system.

Within the buildings, the minimum supply temperature of the building installation is determined by the temperature requirement of the space heating system or hygienic and comfort standards of the DHW supply. For low energy buildings and buildings with floor heating, the supply temperature constraint stems from the DHW. If a supply temperature below the aforementioned 50°C is required, local boosting for DHW is needed, using either heat pumps or small electric boilers [66]. However, research has shown that this is generally more costly and less energy efficient than providing the required 50°C by the district heating system to the consumer [67].

3.4 Towards a holistic energy system transition

This section has presented some key technologies across the energy efficiency value chain that contribute to achieving the HRE 2050 scenario. While all the technologies and energy efficiency measures have merits on their own, they also provide significant synergies and energy efficiency value chain effects. For example, it is important to assess the ramifications of the implementation of CHP plants and district heating systems together with building renovation and control systems.

Therefore, it is vital to examine their impact from an energy systems perspective instead of merely focusing on the impact of their specific use. The next section will address this topic and present an energy system approach for assessing feasible levels of district heating supply and heat savings on an EU scale, with a focus on how to exploit cross-energy system synergies to lower primary energy consumption, CO_2 emissions and total energy system costs.

Key findings

From isolated heat production systems, the district heating systems should become **integrated with other parts of the energy system**. This happens through flexible production at CHP plants complementing fluctuating renewable electricity production, use of excess heat from fuel production and industry, and use of electricity in heat pumps and electric boilers during hours of high production of fluctuating renewable energy.

To ensure **efficient district heating networks**, the main concern is maintaining a sufficient linear heat density and utilising high quality insulated pipes.

Demand-side driven system through state-of-the-art **control systems, paired with metering and consumption-based billing**, also bring about considerable efficiency improvement in heat transmission and distribution to the buildings.

4 Quantification of energy efficiency and district heating potential in the European heating and cooling sector

This chapter highlights the energy efficiency and district energy potential in the European heating and cooling sector. To do so, this chapter builds on reviews of state-of-the-art research studies which developed scenarios of future energy systems allowing for a comparison between their efficiency and reference scenarios. Starting with a broad European perspective, this chapter presents the scenarios and results of the Heat Roadmap Europe studies ([2]–[5]), illustrating the potential for district energy in general, and building-level energy efficiency, on a European and a national level. Following this, the Smart Energy Europe study [68] is presented, evaluating the role of DH networks in a 100% renewable energy scenario. Lastly, the chapter zooms in on the move to 4th generation district energy and presents the analysis and results of two case studies, *i.e.* Denmark and the city of Aalborg.

4.1 District heating and energy efficiency potential in Europe

Quantifying the potential for heating, and particularly district heating and energy efficiency has traditionally received less attention than other sectors. This is partially true because heating has largely been considered a local issue, and early European energy roadmaps and energy modelling exercises did not place any emphasis on it. In addition, the technical potential and costs for district heating are very locally determined and require explicitly spatial knowledge in order to be able to meaningfully assess. Simultaneously, in order to be able to make explicit the advantages of district heating and sector coupling, energy models are needed that can specifically simulate and correctly quantify the operation of district heating in a highly renewable context. This means energy system models are required which can combine end-use savings; more efficient energy conversion technologies; renewable and excess heat for district energy; and the interaction of the heating sector with the electricity sector in a comprehensive manner. Energy models are needed that can take into account the interactions between all these mechanisms and allow for the quantification of their respective impacts.

4.1.1 Developing a Heat Roadmap Europe approach

To overcome these challenges, and be able to better understand and quantify the potential of energy efficiency and district energy, the Heat Roadmap Europe approach has been developed between 2012 and 2019. This has included the development of tools, methodologies, data, and scenarios that allow for the analysis and quantification of the potential of energy efficiency and district energy in the future. The approach combines the development of local thermal atlases with specific knowledge on the built environment and heat demands into national- and European wide energy system models, in order to be able to take into account both the local nature of heating and its impact on the wider energy system.

The energy system boundaries in HRE considers the energy efficiency value chain as presented in section 1.1. It takes primary energy consumption, energy generation, transmission and distribution as well as consumption into account. Fuel extraction and losses in this part are not considered.

The thermal atlases that have been developed in the Heat Roadmap Europe projects bring together both local energy demands and different renewable and sustainable resources for heating. This includes a top-down heat demand model, which geographically represents the distributions of the thermal demands in the European countries considered at the hectare level. In addition, the geographic locations of excess heat and different types of renewable (thermal) energy are identified and allocated to potential district heating areas, to understand what proportion of district energy could be based directly on low-carbon sources.

With the spatial explicit information on both heat and cold demand and potential resources for heat production, a prioritisation of heat synergy regions has been made on a NUTS3 level for all of the 14 Member States in the project. A very high priority is given to regions with high levels of both excess heat and renewable thermal energy and heat demand, and high priority is given to regions with moderate levels of excess heat and renewable thermal energy and high heat demand. These types of regions are found in all 14 Member States, as shown in Figure 4-1.

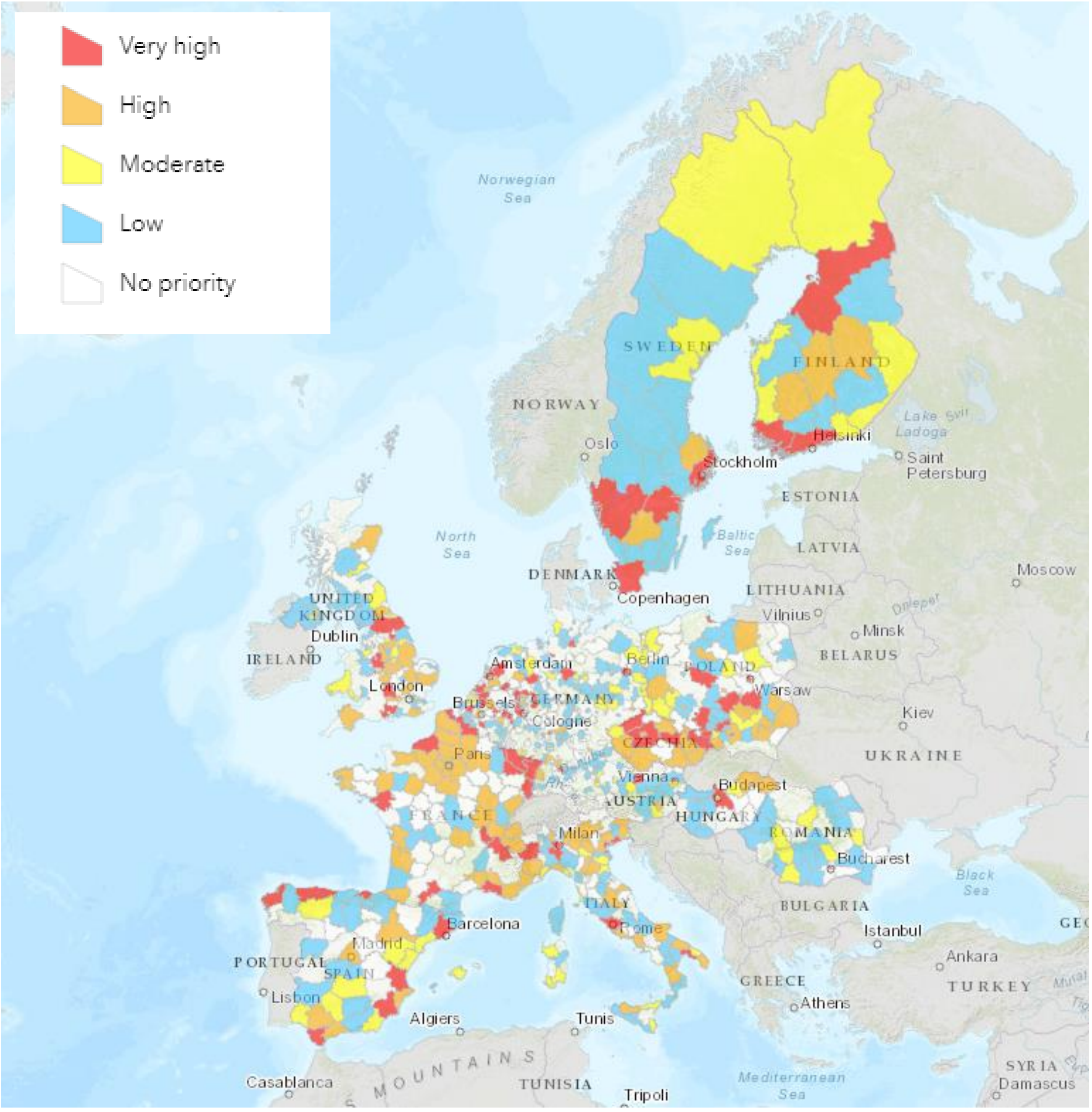


Figure 4-1. Heat synergy regions prioritised on a NUTS3 level. Source [9]

The energy system modelling combines specific knowledge about the cost of different types of end-use savings (focussing on renovations) and their associated heat demand reductions with the different supply options. Conceptually, energy savings with marginally lower costs than the marginal cost of supplying renewable energy supply should be implemented. However, energy supply costs are more complex than the simple levelized cost of energy (LCOE) values, as energy system synergies should be taken into account. As energy efficiency investments generally lead to higher LCOE, it is important to look at the total energy system cost per year, which includes investments in energy efficiency as well as the energy generation costs. This means that the level of energy savings that can be recommended cannot be seen outside the context of the different heat supply options. Based on this, the Heat Roadmap Europe approach takes into account that there is a synergistic effect with regards to achieving affordable heating; without sustainable heat supply options, more savings in buildings are necessary at a higher cost; similarly, without energy savings in buildings, it becomes more expensive to implement renewable and sustainable heat supply options – including district heating.

The options considered include different types of individual and collective systems, with the explicit inclusion of district heating. Since the energy system modelling covers not only the heating and cooling sectors but also electricity and transport, the impacts of the design of the heating are considered from the perspective of the wider energy system. This means that the modelling also clearly takes into account and quantifies the benefits of e.g. flexible heat pumps or cogeneration and increased levels of (intermittent) renewable electricity due to increased flexibility in the heating sector. This results in holistic scenarios for the future energy and heating systems, which take into account both the needs of the heating sector and the need to also affordably address the other energy system sectors. Based on these approaches, the potential for district heating and energy efficiency to contribute to the full and affordable decarbonisation of the energy system can be much better analysed and quantified than using conventional approaches.

4.1.2 Heat Roadmap Europe project series

The Heat Roadmap Europe approach was developed in a series of 4 studies conducted between 2012 and 2019, as represented in Figure 4-2 below.

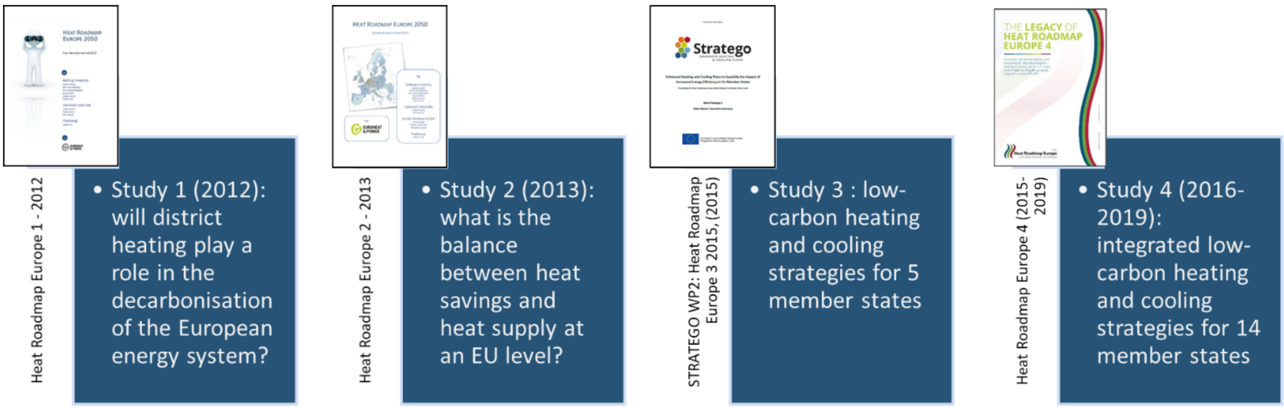


Figure 4-2. Evolution of the research questions from Heat Roadmap Europe first pre-study to HRE4.

Heat Roadmap Europe 1 (HRE1) [5] addressed the main question: could district heating be beneficial for the European energy system in the current policy implementation (CPI) scenario? The HRE1 study indicated that the market shares for district heating for buildings could be increased to 30% in 2030 and 50% in 2050, and provide a better alternative than a CPI approach as proposed in the 2012 EU's Energy Roadmap.

Compared to the CPI reference, 50% DH together with renewable energy decreased primary energy consumption by 5%, fossil fuel consumption by 10%, CO_2 emissions by 13% and could save 14 B EUR/year. The HRE1 study thus established that expanding district heating can play an important role in future European energy systems.

Heat Roadmap Europe 2 (HRE2) [4] investigated the balance between heat savings on the one hand and supplying sustainable heat through district heating systems on the other hand. The study found that while deep renovations are very necessary, there is also a large potential for supplying sustainable forms of heat [4]. Specifically, HRE2 concluded that total heat demand in Europe should be reduced by approximately 30-50%. However, after this point, the price of sustainable heat supply is likely to be lower than the price of further heat savings. In doing so, HRE2 emphasised that not only can district heating play an important role in future European energy systems, but an approach based on heat savings alone will not lead to a cost-optimal solution.

Heat Roadmap Europe 3 (HRE3), which was part of the Stratego project, moved towards national-level heating and cooling strategies for 5 European countries. This was the first time that cooling was fully considered, that supply options in the rural areas were investigated, and that cooling demands and supplies were fully integrated [3]. HRE3 found that by investing in energy savings, district heating and heat pumps as a solution for the heating and cooling sector in these 5 countries, a cost reduction of 15% of the energy system (35 B EUR/year) can be achieved. In addition, the combined reductions in CO_2 emissions (275 Mt/year) achieved by the proposed 5 country Roadmaps represent more than all of the CO_2 emissions emitted from the Czech Republic, Croatia, and Romania today.

4.1.3 Overall results from Heat Roadmap Europe 4 (HRE4)

Heat Roadmap Europe 4 (HRE4) represents the most recent iteration in the Heat Roadmap Europe project series and the most recent quantification of the potential for energy efficiency and district energy at a European level. The mapping and modelling in HRE4 cover 90% of the European heat market and looks at 14 countries and their energy systems individually, which underpins the insight and analysis of the overall European perspective. HRE4 also represents the most advanced application of the Heat Roadmap Europe approach in terms of the level of detail in the tools, methodologies and data used to develop the overall quantification.

HRE4 assessed the savings potential both in the built environment (residential and tertiary sectors) as well as industry for the 14 Member States studied. Regarding potential savings in the residential sector, in the Baseline scenario, the total delivered heat demand for space heating is estimated to be 25% lower than today, even though the building stock is expected to expand. This indicates that the current policy which exists under the framework of the Energy Performance of Buildings Directive and its local adoptions have the potential to be relatively effective, especially at the European scale, in terms of enabling delivered energy savings. However, the level of Baseline savings expected varies quite widely between different EU Member States, from only a 5% expected reduction in Spain, to more than a 35% reduction in delivered energy demands in Germany.

An additional 400 TWh savings on top of the Baseline scenario has been found feasible, considering eleven additional refurbishment packages defined to enlarge the possibilities of cost-effective combinations of energy-efficiency renovations that could be applied by 2030 or 2050 (from low insulation of walls to passive houses).

For industry and the service sector, basically, all technologically available options currently on the market are cost-effective. This is especially the case for the industry, where the per-unit energy savings are the cheapest of all the sectors overall. However, the quantity of energy that can be saved is fairly limited, because the technical ability for energy savings in many industrial processes is in many ways quite limited. So most of the savings – and the most interesting part in terms of achieving a transition, are in the space heating, particularly of the residential sector.

Based on these results, HRE4 demonstrated that an affordable decarbonisation of the European energy system is possible, by:

- Implementing 30% end-use savings in space heating by 2050 compared to 2015: 5% savings in addition to the 25% already in the baseline;
- Expanding DH in urban areas to supply around 50% of EU heat demands in 2050;
- Supply the remaining heat demands in rural areas with heat pumps.

CO_2 emissions

Current ambitions, translated in the Conventionally Decarbonised (CD) scenario, are to reduce the CO_2 emissions by 80% compared to the 1990 levels. By redesigning the heating and cooling sector, the HRE scenario shows above 85% reduction in CO_2 emissions at a cost level similar to the CD scenario (Figure 4-3).

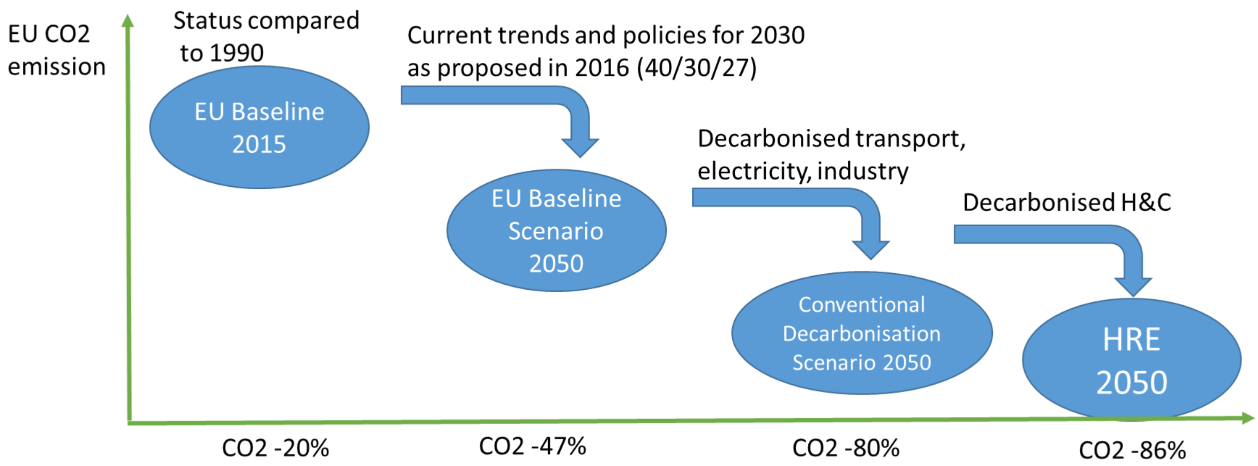


Figure 4-3. Scenario structure and reduction in EU CO2 emissions from Baseline 2015 to HRE 2050 scenario

Primary energy supply

The 2015 baseline scenario has a Primary Energy Supply (PES) of 16.2 PWh/year consisting of 73% fossil fuels, 17% nuclear and 10% renewables. Two decarbonisation strategies are presented in Figure 4-4 the HRE strategy and a CD approach.

The CD approach has an increased PES to 17.5 PWh in 2050 compared to the 2015 baseline situation, an 8% increase. Fossil fuel supply is significantly decreased but still has a share at 17% of PES, with nuclear supplying 4%. Renewables increase their share to 79% of the PES in the CD scenario.

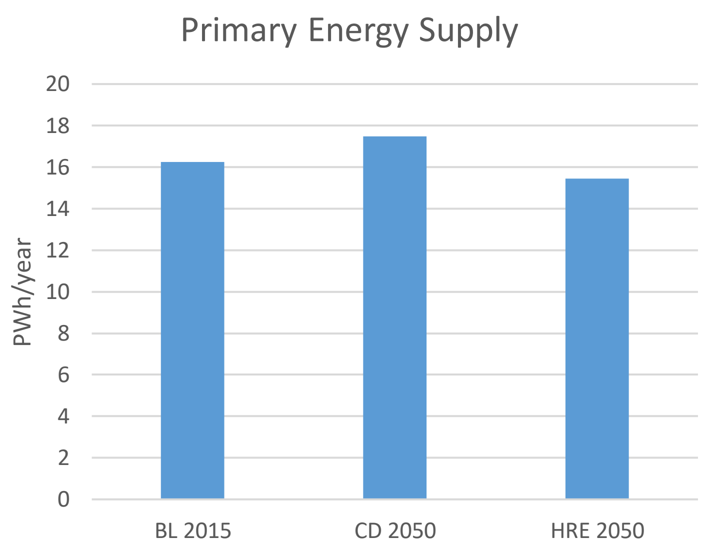


Figure 4-4. Primary Energy Supply of the Heat Roadmap Europe 4 and a Conventionally Decarbonised European energy system [70]

Compared to the CD scenario, the HRE approach results in lower PES than the 2015 baseline and a higher penetration of renewables. The HRE scenario has a PES of 15.5 PWh in 2050, enabling a 5% reduction from the 2015 baseline. The renewable penetration reaches 87% in 2050, with a remaining share of 9% fossil fuels and 4% nuclear.

Energy system costs

The HRE 2050 scenario results in a total energy systems costs of 1.120 B EUR/year in 2050 compared to 1.188 B EUR/year for the CD scenario. The HRE scenario is comprised of 53% investment costs, 29% fuel costs and 18% operation and maintenance costs. The CD scenario is divided between 47% investment costs, 36% fuel costs and 18% operation and maintenance costs (Figure 4-5). By utilising energy system synergies and exploiting energy efficiency the HRE approach thereby both results in lower PES, lower CO_2 emissions and lower total energy systems costs than a CD approach.

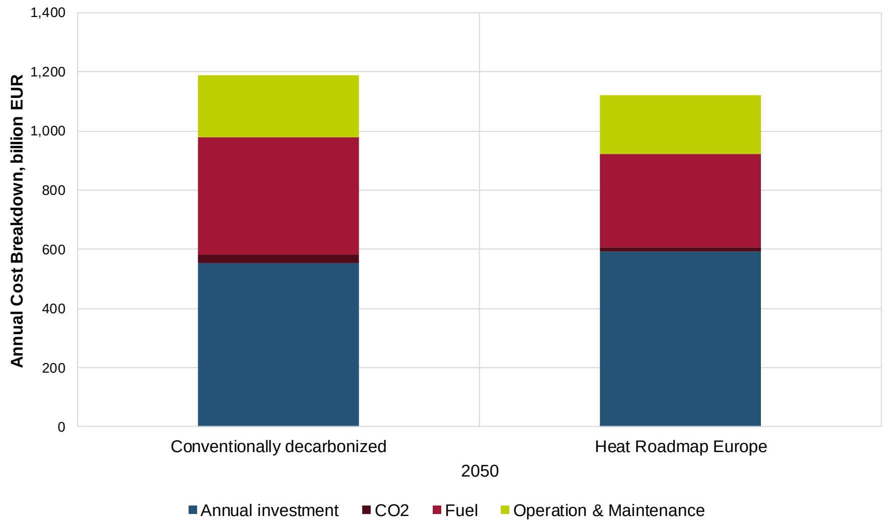


Figure 4-5. Annual cost breakdown of the Heat Roadmap Europe 4 and a Conventionally Decarbonised European enery system [70]

Balance between heat supply and savings

Figure 4-6 demonstrates feasible levels of district heating market shares and heat savings considering the total costs of energy systems for the HRE14 countries. Figure 4-6 displays aggregated results for the HRE14 countries. However, as will be discussed in section 4.2 there are distinct national differences across the countries. For example, the Czech Republic, Poland, Hungary and Romania all have potential for 25% additional heat savings compared to the baseline.

Based on Figure 4-6, it becomes clear that the approach considering both residential energy savings and the different types of heat supply is necessary, in order to understand what the (cost) optimal levels are. Two trends become clear. As a higher level of energy savings is implemented, a cost reduction initially follows. However, after a certain level, the investment needed in order to achieve the same reductions in delivered heat demand becomes more expensive. A similar trend occurs regarding the implementation of district heat at different levels: while lower market shares reduce the overall cost of the energy system, at very high market shares the investment costs needed do not justify the further expansion of the district heating market segment.

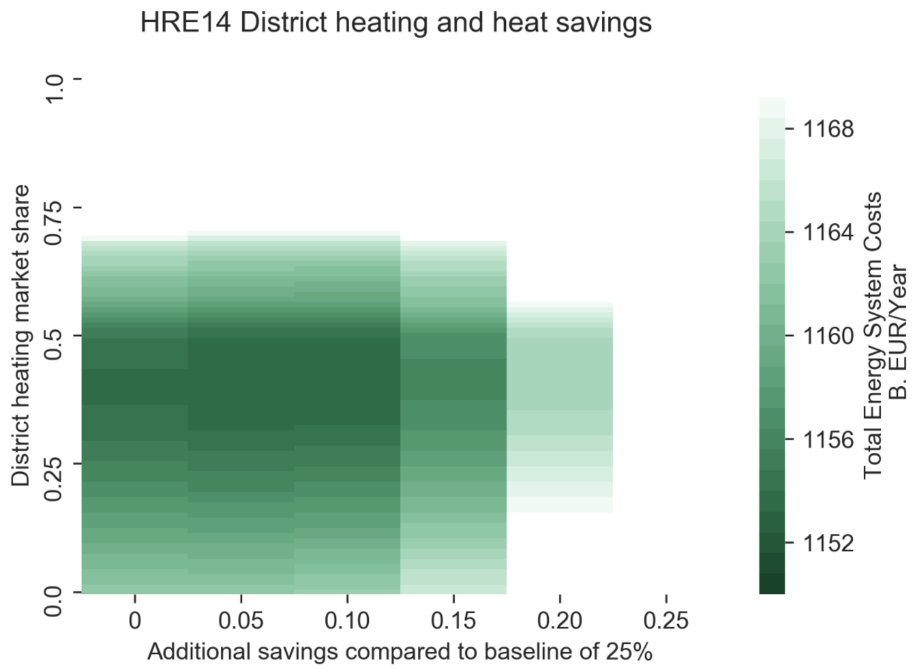


Figure 4-6. Residential district heating supply and heat savings synergies for total energy system costs for HRE14 countries. The dark green area in the middle is where optimal levels of district heating and end use savings are achieved [2].

The figure also illustrates the area where different configurations of district heating and heat savings are feasible. Rather than illustrating one optimal level of investment, multiple levels in the area around 50% district heating and 5% additional savings are feasible.

The combination of these two trends results in an overall image of the optimisation plan that supports a view that there is not necessarily a trade-off between delivered energy savings and district energy in the residential sector, but rather there is likely to be a synergistic effect between the two. Unless both heat savings and district energy are delivered, the decarbonisation of the heating system will be more expensive. Similarly, an approach that focusses only on achieving the highest level of heat savings technically possible, or that only focusses on expanding the district heating system to its full technical potential, is unlikely to result in a cost-effective system.

4.2 Improving the energy efficiency of the heating and cooling sector on a country level

Generally speaking, the previous section has outlined the potential for expanding district heating and energy efficiency on the EU level. There are, however, large differences from one country to another.

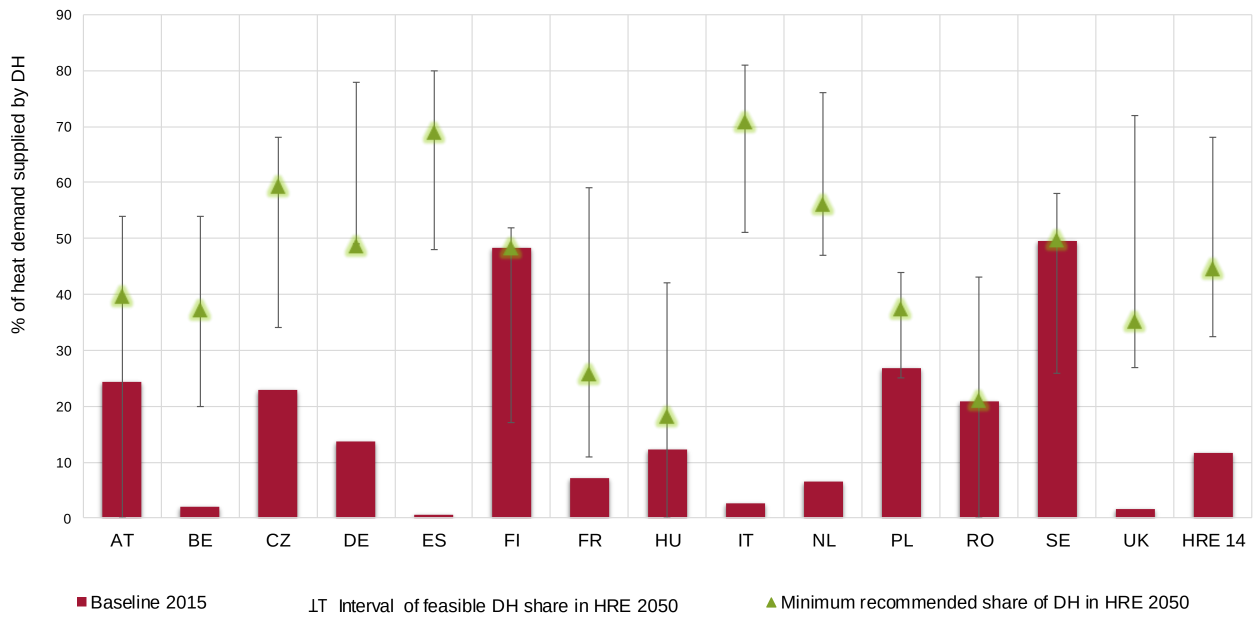


Figure 4-7. Baseline district heating share of residential heat demand in 2015 and the minimum recommended level of district heating share in the residential sector [2]

Figure 4-7 shows the feasible district heating market shares for the countries included in HRE4. The interval bar points to the district heating market share obtained by a 0.5% sensitivity of the total energy systems costs.

Figure 4-7 shows that the potential for district heating development is very dependent on a country's category. The main drivers to these differences are the typology of the urban fabrics and the availability of excess heat. Contrary to what is commonly thought, potential for expanding DH is correlated neither to the climate (in fact, some of the warmest countries have the highest potential, see for example Spain), nor to the current level of DH, that is more a function of the planning practices than an indication of what the techno-economic potential is.

Using the categories proposed in 2.6, the following section will use the Netherlands as an example of a country with a low amount of district heating, Poland as a country with potential for refurbishment of district heating and the building sector country and Sweden as an example of a country with already high amounts of district heating [29]. The expansion to 4th generation district heating is further elaborated on in 4.4.1, considering the transition from 3GDH to 4GDH.

4.2.1 Countries with low amounts of district heating: The Netherlands

Total energy system costs (M€/year)		Residential sector space heating savings additional to a 20%reduction already in the baseline					
		0%	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	55312	55296	55305	55280	55345	55843
	5%	55275	55254	55259	55230	55291	55783
	11%	55210	55186	55187	55154	55209	55698
	19%	55098	55069	55066	55029	55079	55563
	28%	54973	54940	54933	54891	54937	55417
	38%	54856	54819	54809	54763	54803	55280
	47%	54776	54735	54719	54670	54705	55178
	56%	54763	54718	54697	54643	54674	55142
	66%	54792	54742	54716	54658	54683	55147
	76%	54927	54872	54842	54778	54799	55259
	86%	56568	56509	56475	56407	56422	56878

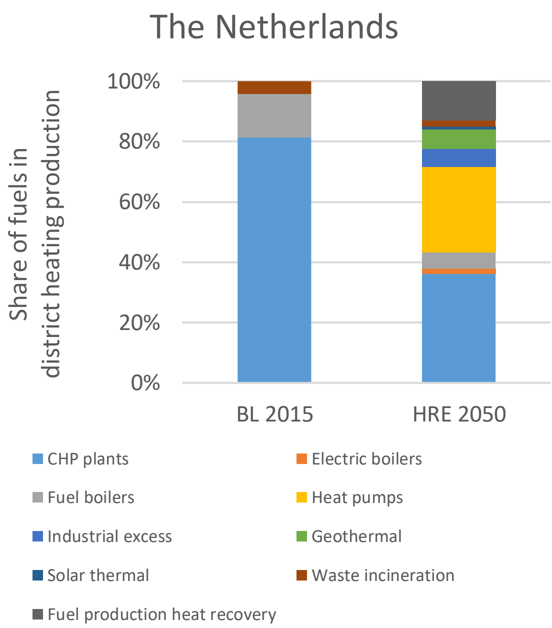


Figure 4-8. Matrix of district heating and heat savings synergies for total energy system cost, and annual district heating production in the baseline and HRE 2050 scenario for The Netherlands.

The Netherlands possesses significant potential for expanding district heating as well as increasing space heating savings. The Netherlands can expand the district heating share in the residential sector from around 7-8% to 56%. This district heating expansion combined with 15% additional space heating savings to the baseline would result in the lowest energy system costs for the Netherlands. The main desirable transformation for the Netherlands in order to achieve a transition towards a decarbonised energy system in a cost-effective fashion is the building of new infrastructure.

Today, the district heating production in The Netherlands is mainly constituted by CHP production. In 2050 the supply should change to a mix of mainly heat pumps and CHP plants while also using excess heat from industry and electrofuel production, geothermal resources and a small part from fuel peak boilers.

For the Netherlands, this transition mainly consists of establishing new grids and decreasing energy consumption in buildings. The Netherlands faces many new connections to district heating systems to realise the HRE 2050 scenario.

4.2.2 Countries with inefficient heat infrastructures and building stock: Poland

Total energy system costs (M€/year)		Residential sector savings additional to a 30% reduction already in the baseline					
		0	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	65098	65003	64928	65098	65050	64960
	3%	65051	64953	64873	65042	64987	64893
	7%	64969	64870	64785	64949	64892	64795
	12%	64855	64752	64664	64825	64764	64662
	19%	64729	64621	64530	64685	64622	64516
	25%	64626	64515	64421	64575	64507	64398
	31%	64577	64464	64365	64516	64444	64330
	37%	64573	64456	64354	64501	64425	64308
	44%	64717	64595	64489	64633	64553	64433
	50%	65101	64976	64866	65005	64921	64797
	57%	68120	67992	67878	68012	67925	67797

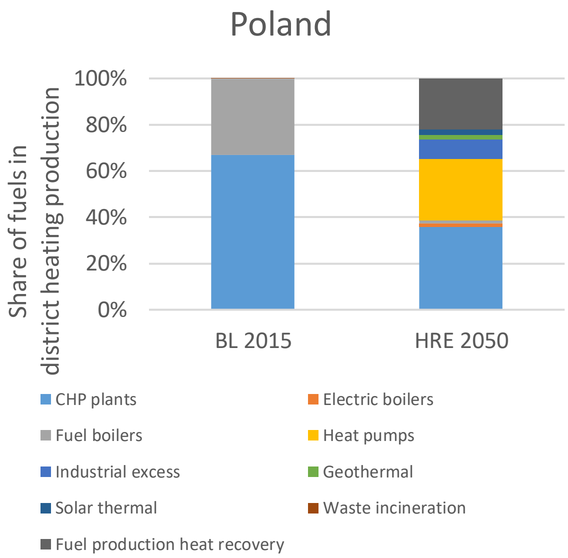


Figure 4-9. Matrix of district heating and heat savings synergies for total energy system cost, and annual district heating production in the baseline and HRE 2050 scenario for Poland.

Poland already has a significant share of district heating. In 2015, around 27% of the Polish residential heat demand was supplied by district heating, largely consisting of CHP plants and fuel boilers. Although the total district heating supply could decrease due to savings, the residential district heating market share could increase to 37%. The challenge for Poland is the modernisation of the district heating sector, moving from networks running on high temperatures, buildings with low efficiency and dependence on fossil fuels to more sustainable systems.

Poland can transition towards the same fuel mix in district heating as Germany and the Netherlands, with significant shares of district heating from CHP plants and heat pumps. Poland has a high potential for utilising excess heat from the fuel production which can supply around 20% of the district heating supply in 2050

4.2.3 Countries with high amounts of District Heating: Sweden

Total energy system costs (M€/year)		Residential sector savings additional to a 20% reduction already in the baseline					
		0	0.05	0.1	0.15	0.2	0.25
Percentage of market share covered by DH	0%	42297	42456	42659	43223	44635	44835
	5%	42242	42397	42598	43157	44566	44762
	12%	42129	42281	42477	43034	44439	44632
	19%	42046	42195	42387	42940	44341	44531
	26%	41976	42122	42310	42860	44257	44444
	34%	41907	42049	42232	42779	44172	44355
	42%	41887	42026	42205	42748	44137	44317
	50%	41930	42065	42240	42780	44165	44342
	58%	42069	42201	42371	42908	44288	44462
	66%	42446	42575	42741	43275	44651	44822
	76%	44584	44710	44872	45402	46775	46942

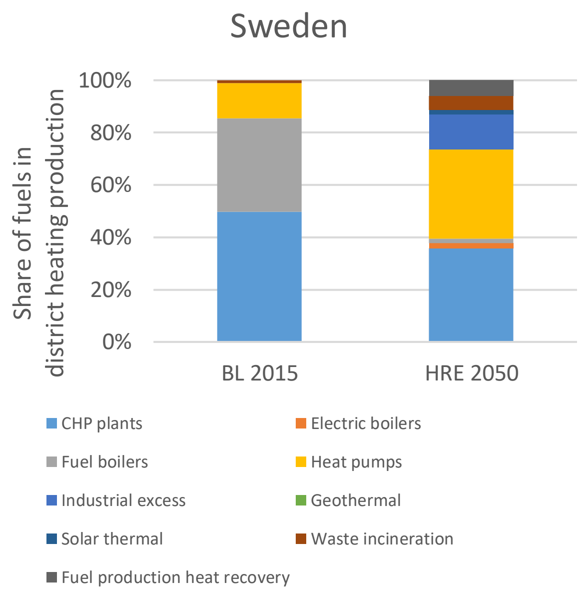


Figure 4-10. Matrix of district heating and heat savings synergies for total energy system cost, and annual district heating production in the baseline and HRE 2050 scenario for Sweden.

According to the HRE 2050 scenario, Sweden is already around the suggested amount of district heating of 42% of the market share. Sweden also has a rather efficient building stock as well as ambitious policies for renovation, so no additional savings are necessary. Still, there are necessary changes that must be carried out in order to realise a low carbon heat supply in 2050.

Swedish district heating systems should expand the share of heat pumps and decrease the number of fuel boilers used. Other sources of supply should also be used such as excess heat. CHP plants should also decrease in share but still remain as the largest supply source covering around 1/3 of the Swedish district heating demand.

4.2.4 Country summary

This section has highlighted some of the main differences in the HRE 14 countries. Large differences lie in the amount of feasible additional heat savings. All countries can expand the market share of district heating, even if Sweden, Finland and Romania should maintain current market shares or expand slightly within the feasible intervals shown in Figure 4-7. At the same time, all countries face a reconfiguration of their technology mix, from being based largely on CHP and fuel boilers to a mix with the introduction of heat pumps, excess heat and renewable sources.

This section has presented the results of the consideration between district heating supply and final energy savings in the residential sector. These results entail very different implications for the different countries considering their current situation. The Netherlands and other countries with very small amounts of district heating will have to establish new infrastructure which also requires new organisations, business models and regulation. For Poland, the main challenge is the refurbishment of the systems and building stock. Some Eastern European countries with 1st or 2nd generation systems can also benefit from implementing control systems to enable heat demand controls, billing and metering. These systems are often also in need of refurbishment of the distribution infrastructure. Germany is in a position in between these two types of countries and must both focus on the expansion of existing systems as well as the refurbishment of old systems.

4.3 The role of district heating in fully decarbonising the EU energy system

While the previous sections explored the role of DHC in improving the energy efficiency of the energy system, this section looks at the role of district heating in transitioning towards a fully decarbonised energy system.

Smart Energy Europe [69] presented one possible pathway to 100% renewable energy for the European energy system by the year 2050. The transition from a business as usual situation in 2050 to a 100% renewable energy Europe is analysed in a series of steps.

The first steps consist of implementing "general consensus": decommissioning nuclear power, implementing 35% heat savings compared to the business-as-usual scenario and converting 80% of the private car fleet to electricity. These three steps already allow for a significant reduction of around 15% in both the PES and the CO_2 emissions compared to the business-as-usual scenario.

Regarding the heating sector, first, four versions of individual heating have been analysed: heat pumps, electric heating, oil boilers, and biomass boilers. In each case, all of the heating in the EU, both rural and urban areas, are supplied using only the individual heating technology being analysed. Then, based on this analysis, the optimal individual heating technology (heat pumps) has been combined with both network heating options (thermal and gas grids) for 50% of the heat demand, corresponding to urban areas. The results in terms of primary energy supply and CO2 emission are shown in Figure 4-11.

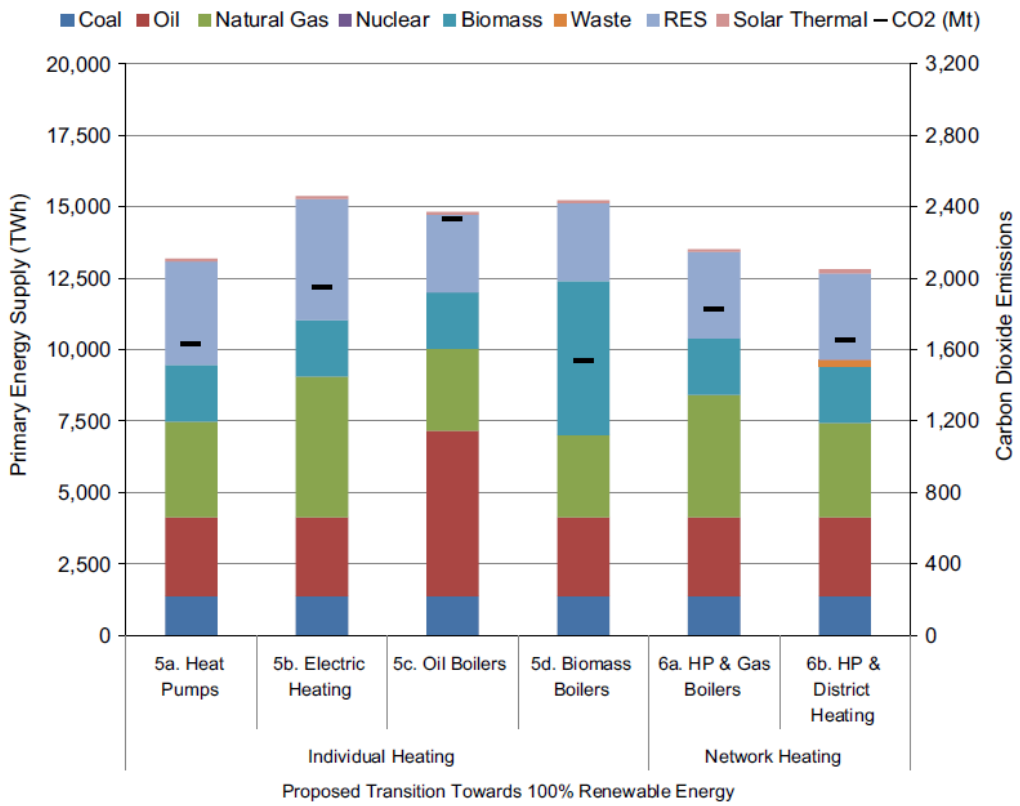


Figure 4-11. Primary energy supply by fuel and CO2 emissions for the individual and network heating steps in the transition to a Smart Energy System for Europe. Source: [69]

The study concluded that district heating is more efficient than the natural gas alternative since it utilises excess heat in the energy system, such as heat from power plants, industry, and waste incineration. This means that there is less additional fuel required for heating buildings when district heating is utilised compared to natural gas. In addition, the CO_2 emissions are lower in the district heating scenario due to this lower demand for fuel and also because the district heating network enables the utilisation of more renewable energy, both direct use of geothermal and solar thermal for supplying heat to the buildings, and wind and solar since large-scale heat pumps can be used to supply heat to the district heating system. These new technologies for converting electricity to heat, combined with relatively cheap thermal storage, mean that the district heating system can be used to accommodate more intermittent renewable energy than the natural gas alternative. This combination of less fuel and more renewable energy means that the total European CO_2 emissions are reduced by around 10% compared to the natural gas scenario (or 85% less carbon if the heating sector is considered in isolation). This represents an additional 15% reduction in CO_2 emissions in the district heating scenario compared to the previous "general consensus" steps. This is similar to the scenario with individual heating only (no network heating implemented), but it is achieved at a lower cost, as shown in Figure 4-12.

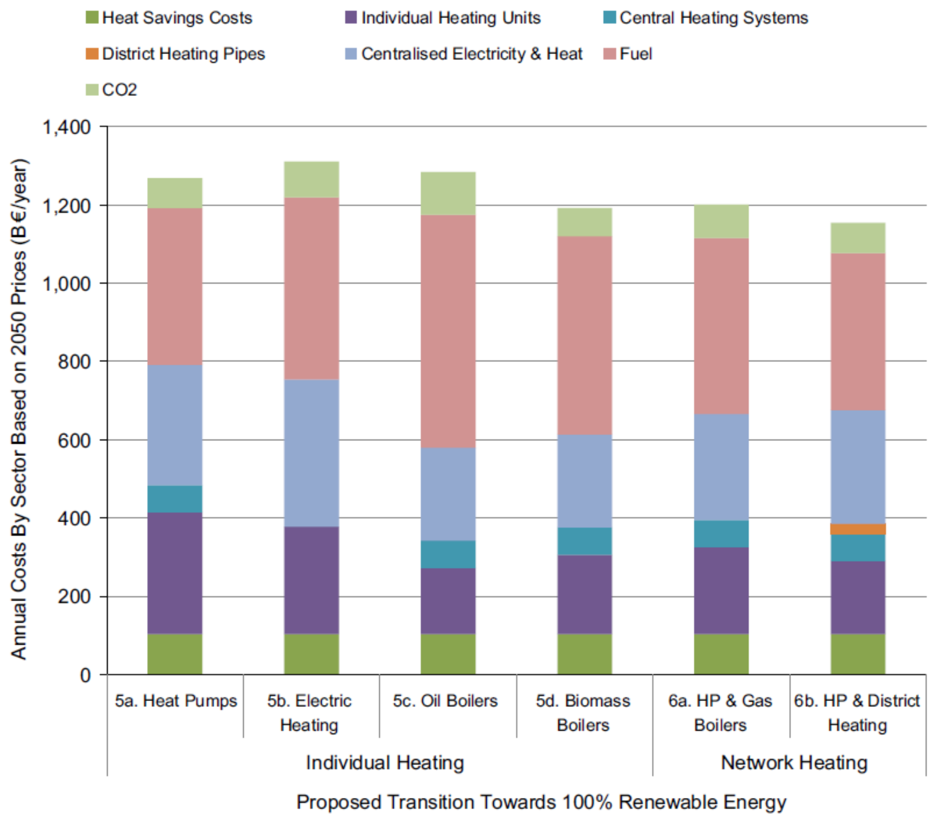


Figure 4-12. Annualised cost by sector for the individual and network heating steps in the transition to a Smart Energy System for Europe. Source: [69]

Finally, the Smart Energy Europe scenario implement further steps regarding the transport and industry sectors, with the introduction of electrofuels to replace oil in trucks, ships, and aeroplanes; and lastly the replacement of the remaining coal, oil and natural gas with biomass and methane, to reach a fully decarbonised energy system in 2050.

The Smart Energy Europe scenario demonstrated the enabling role of DH networks in cost-effectively fully decarbonising the EU energy system.

4.4 Energy Efficiency in 4th generation district heating systems

The scenarios developed in HRE4 rely on design choices mainly based on the use of proven technologies, rather than relying on the radical improvement or innovations of future technologies. Some learning and improvements are considered, but the measures and technologies that are contemplated in the Heat Roadmap scenarios are all relatively well developed and market mature in different parts of the European energy system. The approach was to design a system that shows how we can reach decarbonisation using existing technologies that do not stand in the way of a possible transition to a 100% renewable energy system for a no-regret pathway. Regarding district heating, this means that the technologies considered are mainly the ones of the 3rd generation district heating (3GDH). This section explores studies that assessed the impacts of implementing 4th generation district heating (4GDH).

As explained in section 1.3, the main characteristics of 4GDH are:

- operating existing, renovated and new buildings with low-temperature for space heating and DHW;
- distributing heat in networks with low grid losses;
- recycling heat from low-temperature sources and integrating low-temperature renewable heat sources such as solar and geothermal heat;
- being an integrated part of a smart energy system.

For this assessment, a national study of Denmark and a local study of Aalborg will highlight the potentials. An extrapolation of the results to the European scale is proposed, as an “upgrade” of the HRE 2050 scenario.

4.4.1 From 3GDH to 4GDH in a 100% renewable energy scenario in Denmark

In order to assess the technical and economic advantages and disadvantages of 4GDH systems compared to 3GDH systems, the two approaches were compared for the case of the Danish energy system [6]. The comparison is based on a 100% renewable energy scenario in 2050 developed for the Danish Society of Engineers, based on the principles of Smart Energy Systems, using the same modelling tool as HRE4 (EnergyPlan). In this scenario, the heating demands are largely covered by DH from a variety of sources including excess heat from industry, geothermal, heat pumps, CHP, solar thermal and conversion losses from the production of electrofuels. For the analysis, the demands and the general supply structure are maintained; however, technical and economic factors are modified to reflect 3GDH and 4GDH systems, respectively. These modifications are detailed in Table 4

The main changes are the lower supply and return temperatures, which entail a reduction in the grid losses. As explained in section 1.3, this also allows for better coefficients of performance in heat pumps, more integration of excess heat sources with low temperatures, higher power-to-heat ratios in CHP plants, higher heat recovery from flue gas condensation in biomass boilers, higher capacities in thermal energy storage which thus becomes cheaper, and increasing efficiency of solar collector.

Table 4. System configuration with 3GDH and 4GDH in a 100% renewable energy scenario in 2050 for Denmark.

	3GDH system	4GDH system
Yearly average supply/return temperatures at DH plant	80°C/45°C	55°C/25°C
DH grid losses	28%	19%
DH heat pump COP (yearly average resource temp. 5°C)	2.9	3.9
DH heat pump COP (yearly average resource temp. 35°C)	4.2	7.1

Excess heat sources for direct use	0.83 TWh +2.28 TWh from district cooling	2.4 TWh +2.28 TWh from district cooling
Excess heat sources for indirect use through heat pumps	1.67 TWh	2 TWh
CHP efficiency (Combined cycle)	η_e=52% and η_t=39%	η_e=52% and η_t=44%
DH biomass boilers efficiency (with condensation)	95%	105%
Thermal storage (investment cost)	3.17 M€/GWh	3.70 M€/GWh
Solar thermal (investment cost)[4]	544 €/MWh	382€/MW h

The implementation of 4GDH compared to 3GDH results in reduced investment and operation costs equal to an annual cost of 300-350 M EUR/year. This energy system saving corresponds to the reduced DH supply from 3GDH to 4GDH, thanks to reduced DH grid losses; and the reduced need for investments in wind and electrolysers, due to a more efficient use of heat pumps and CHP plants.

Research [6] demonstrates how existing, as well as new buildings, can be transformed into the 4GDH concept without significant costs: the overall additional costs of a full implementation of 4GDH compared to 3GDH results in a cost range of 50-100 M EUR/year. This covers investments needed to reduce the return and the supply temperatures with improved control systems for space heating and DHW and installation of systems removing legionella in larger buildings, assuming that energy renovations will take place in the scenario over the next 30 years as part of general renovation and energy savings also expected in the 3GDH scenario.

Research also demonstrates how existing and new district heating grids can be converted to operate with 4GDH temperatures at minor and affordable costs: with a ΔT of 35 K in 3GDH and 30 K in 4GDH, either the investment or the operation costs (additional pumping costs) will be a little higher in the 4GDH alternative, but it is estimated not to exceed 10 M EUR/year.

In conclusion, the switch from 3GDH to 4GDH in a 100% renewable energy scenario in Denmark allows for global savings of 200-300 M EUR/year, and a reduction of 11% in PES.

4.4.2 Aalborg case study

As part of the Aalborg Energy Vision 2050[5], the entire building stock of Aalborg municipality was mapped in detail. Heat demands and savings opportunities and their costs were evaluated geographically and then compared to supply costs, to find the optimal level of savings. The main conclusion stemming from the initiative identified the saving level for the central area of Aalborg to be in the order of 30% (520 GWh/year).

The study also estimated the opportunities to utilise industrial excess heat in the district heating supply in Aalborg. The system currently receives approximately 300-330 GWh/year from the cement producer Aalborg Portland and smaller supplies from other excess heat sources in the municipality. This corresponds to over 20% of the total district heating demand. The lower the supply temperature that the district heating can operate with, the more excess heat can be utilised. Aalborg Energy Vision 2050 conducted an inventory of possible new excess heat sources. It was calculated respectively in relation to the current temperature levels in the district heating network (3GDH), as well as a low-temperature level of 55-60°C supply flow and 25-30°C return flow (4GDH) and it is shown in Table 5. The study estimated that the 4GDH could increase the excess heat exploitation to 683 GWh/year directly and an additional 180 GWh/year in combination with a heat pump. Approximately half the district heating demand in Aalborg could thus be supplied with excess heat.

[4] This figure constitutes the necessary investment per MWh in Denmark. The actual cost of energy will also depend on the amortisation period and the interest rate. Furthermore, southern countries, with a higher insolation will have lower investment costs per MWh.

[5] Work in progress, not yet published.

Table 5. Identified new excess heat sources in Aalborg Municipality, which are included in the scenario development.

	Excess heat sources in current 3GDH	Additional excess heat potential in 3GDH		Additional excess heat potential in 4GDH	
	Direct	**With HP**	**Direct**	**With HP**	**Direct**
Aalborg Portland	300-330 GWh/y	-	-	46 GWh/y	671 GWh/y
Retail		-	8 GWh/y	-	12,8 GWh/y
Other		113 GWh/y	-	134 GWh/y	-
Total (new)		**113 GWh/y**	**8 GWh/y**	**180 GWh/y**	**683 GWh/y**

Several alternatives to Aalborg Energy Vision 2050 have since been considered. The purpose of these calculations is two-fold: show the importance of heat savings and 4th generation district heating, and analyse the robustness of the district heating system if access to the main excess heat source was no longer possible. In addition, an alternative has been studied with the district heating system being replaced by individual heat pumps.

The socio-economic effects are illustrated in Figure 4-13.

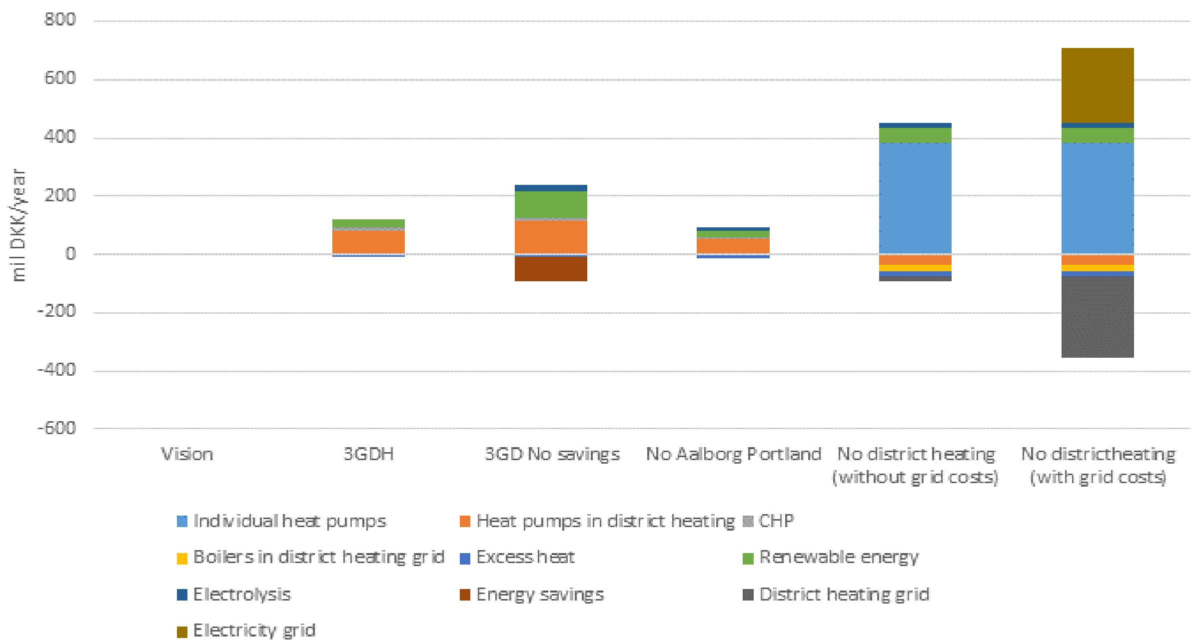


Figure 4-13. Change in costs in alternative scenarios compared to Aalborg Energy Vision 2050 scenario.

The first alternative (3GDH) shows what will happen if Aalborg does not switch to 4th generation district heating and instead continues at the current temperature level. Compared to 4GDH, such a solution will have higher network losses and partly reduce the efficiency and possibilities of utilising excess heat, geothermal, heat pumps and cogeneration. This increases the need for wind power and heat pumps and becomes a significantly more expensive solution.

The next alternative (3GDH and no savings) shows what will happen if Aalborg does not carry out heat savings as part of the renovation of the existing buildings while choosing not to move to 4th generation district heating. These two changes are linked since energy renovation is often a prerequisite for being able to lower the temperature level. As can be seen, the consequence is increased costs and the need for additional wind power and heat.

The third option (Without Portland) shows what will happen if Portland cement factory no longer supplies excess heat to Aalborg. In this case, it is assumed that Aalborg would instead increase the investments in heat pumps and geothermal. As can be seen, it will increase costs, but it is still the option with the second-lowest costs compared to the Aalborg Energy Vision and thus cheaper than other supply options.

In the fourth alternative (Individual heat pumps), district heating would be replaced by heat pumps in all houses and apartments. This alternative is significantly more expensive than continuing with district heating: it does not utilise excess heat, and the required investments in individual heat pumps and electricity are higher than the investments in the district heating network. The fourth alternative has both been estimated with and without grid costs. This provides no major change to the result, as savings from lower investments in district heating grids are offset by higher investments in the electricity grids. Therefore, the main reason why individual heating is not cost-competitive is simply the costs of the individual heating technologies.

4.4.3 European perspectives for 4GDH

Unlike the first three generations of district heating, the development of 4GDH involves meeting the challenge of more energy-efficient buildings as well as the integration of district heating into a future smart energy system based on renewable energy sources.

This section quantified the costs and benefits of 4GDH in future sustainable energy systems, compared to 3GDH. Costs involve an upgrade of heating systems and of the operation of the distribution grids, while benefits are lower grid losses, a better utilisation of low-temperature heat sources and improved efficiency in the production compared to previous district heating systems. It is quantified how benefits exceed costs by a safe margin with the benefits of systems integration being the most important. Therefore, along with the implementation of future smart energy systems based on RES, there is a large incentive for society, utilities and heat consumers to reduce their temperature demands.

An extrapolation of the 4GDH potential modelled for Denmark to a European level can give an indication of the energy efficiency and energy system potentials on a European scale. For the Danish system, the transition from a 3GDH system to a 4GDH system entails costs of 75 M EUR/year and 5 M EUR/year for investments in buildings and district heating operation costs respectively. The savings amount to 325 M EUR/year due to lower investments and better operation as a result of the lower grid temperature. This applies to a district heat market of 39 TWh.

Potential for expanding the HRE 2050 scenario to 4GDH is here estimated based on the same potential. The simple assumption is that if the HRE 2050 is realised, it will result in a 3GDH system. Therefore the Danish potential is considered reasonably applicable on a European scale. The HRE 2050 scenario estimates the heat supply for the HRE14 countries to be 1096 TWh. A low temperature heating system, as defined by 4GDH, could, based on the Danish case, achieve a 11% reduction in primary energy supply for heating the HRE14 countries, resulting in 120 TWh savings in PES.

The cost potential would then be increased investments in buildings of 2,100 M EUR/year and district heating operation costs of 140 M EUR/year. The total savings from investments and operation due to lower temperatures would be 9,101 M EUR/year resulting in a net saving of 6,860 M EUR/year for the HRE14 countries, if they expand from the 3GDH modelled in the HRE 2050 scenario.

This does not take into account local differences in energy system configurations and is a rough estimation. However, it indicates a potential for expanding further from 3GDH to 4GDH on a European scale.

Key findings

District heating is a viable heat supply option in a decarbonised energy system
HRE demonstrated that district energy is the most efficient and cost-effective solution for urban areas, where there are sufficiently high densities to achieve cost-effective transport of energy from e.g. excess heat or centralised HP facilities. DH should supply around half of the heat demand at EU level – ranging from 20% to 70% depending on the country.

Increase investments and achieve total energy system savings
The HRE 2050 scenario showcases that it is possible to increase investments while lowering overall energy system costs. Thereby, it is not enough to simply assess the costs of investing in energy efficiency or low-carbon technologies, but assessments should be made from an energy system point of view. Investments in efficiency measures across the energy value chain will decrease fuel consumption and operation and maintenance costs, more than offsetting the increases in investments. In addition to the positive socio-economic effect, it produces several additional positive benefits such as reduced dependence on energy imports, increased energy security, reduced pollution, improved air quality and public health as well as employment effects.

Balance heat savings and installed capacity
By deploying the energy system perspective to the question of heat savings and installed capacity, it is possible to identify a compromise that decreases the total energy systems costs. Using this approach ensures that planners and decision-makers avoid sub-optimising specific sectors by over- or underinvesting without considering other parts of the energy efficiency value chain.

In most European countries, higher end-use energy savings than planned in current policies should be implemented. Both increasing heat savings and expanding district heating supply leads to overall lower energy system costs. Overall, 30% savings in space heat demand compared to today are feasible, depending on the country.

Country specific approach
There are indeed big variations between the countries. In countries with low amounts of district heating, such as the Netherlands, the focus should be on building new infrastructure; countries with inefficient heat infrastructures and building stock present high potential for end-use savings and should also modernise their DH systems; whereas countries with high amounts of district heating infrastructures should focus on switching to 4GDH.

5 Roadmap for the decarbonisation of European heating and cooling sector

This section outlines a detailed roadmap for the transition of the European heating and cooling sector by 2050 towards a decarbonised and energy-efficient energy supply, based on the Heat Roadmap Europe 4 (HRE4) results [70] covering 90% of the European heating consumption. The roadmap presents the potential for reducing the Primary Energy Supply and the Energy Systems Costs if energy efficiency is increased. This includes primarily the expansion of district heating and the decrease in end-use demands. In order to enable this transition, specific technologies are presented according to their position along the energy efficiency value chain and their role in the overall energy system.

The analysis takes a system approach to energy efficiency to show the potential of identifying and exploiting synergies across energy sectors. By deploying this approach, heating and cooling cannot be separated from other energy domains and are therefore presented in the context of a full energy system transition.

In order to model the timing of investments until 2050, it is assumed that the heating transition should be well underway in 2030. To reach a decarbonised energy system and society in general in 2050, it is important to implement the necessary infrastructures for reaching this goal. As outlined above in section 4, district heating infrastructure is an enabler for increasing the amount of renewables, increasing energy efficiency, providing access to heat sources and utilising synergies across different energy sectors [5]. District heating is using known technology and implementing district energy grids provides benefits to the wider energy system in terms of flexibility and the integration of renewables. Therefore, it is important to start establishing district heating systems now in order to enable further decarbonisation measures.

Here it is assumed that the yearly establishment of new systems and necessary district heating investment should peak in 2030 in order to optimally leverage their decarbonisation potential. This means that the majority of district heating investments should be made in the years around 2030. This will ensure that a feasible amount of district heating systems and infrastructure have been established to enable the rest of the energy system to transition into a low-carbon energy-efficient and integrated system.

The following section presents a roadmap for reaching the HRE 2050 scenario. Transitions can be described in four main phases: pre-development, take-off, breakthrough and stabilisation [71]. These phases can be described with a logistic growth curve [72]. Here, logistic diffusion curves are adopted to present the rates of investments of the HRE 2050 scenario. The formula used for estimating the yearly investments is presented in equation [1].

$$y = min + \frac{max - min}{1+\left(\frac{x50}{x}\right)^{m}} \quad [1]$$

Min and max represent the upper and lower asymptote, the starting and final values of the curve. X50 is the X coordinate for the midpoint, and m represents the slope at the midpoint. For the roadmap, X50 is set to be in 2030, representing the year with the highest rate of change. Min is the volume of investments in the starting year 2020 and max is the endpoint in 2050. The m value is set to 4, which is found based on the necessary slope or rate of change needed in order to reach the goal in 2050.

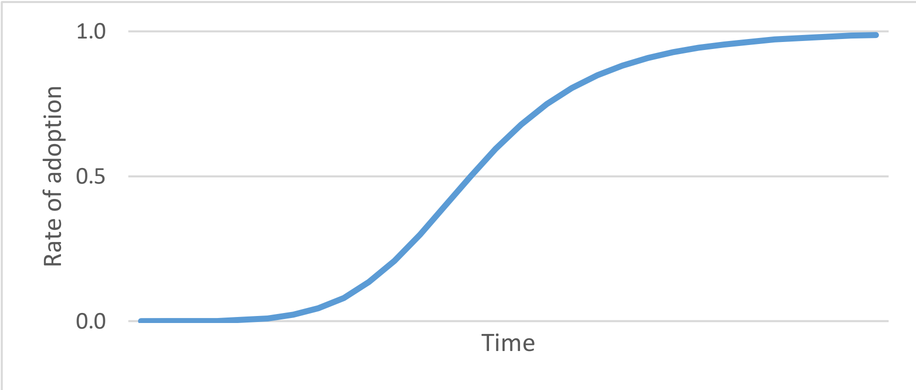


Figure 5-1. Representation of logistic growth model.

5.1 Establishment of new district heating systems in the HRE 14

Currently, about 3,500 district heating systems are known to be operated in the HRE14 countries plus Denmark [73] . Analyses using the PETA GIS analysis tool [9] have identified Prospective Supply Districts (PSD), areas with potential for supplying heat demand with district heating. These are estimated using maximum annualised distribution grid investment costs of 4 EUR/GJ and a minimum heat demand density of 20 TJ/km^2. This results in potentially around 25,000 PSDs in the EU-28, which would be in line with the HRE target of a 50% district heating share by 2050 or a total heat production of 1097 TWh. This is a 7-fold increase in the number of district heating systems across Europe.

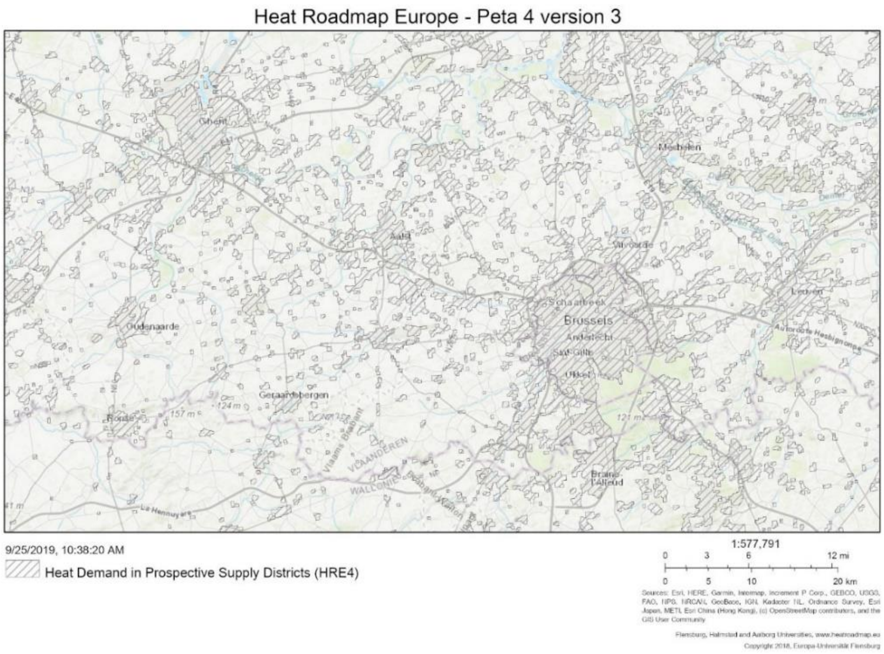


Figure 5-2. Example of PSD areas in the area around Brussels, Belgium [9]

PSDs might consist of several district heating systems, or one district heating system might cover more PSDs. Likewise, the ownership and operation might be divided within a PSD or include several PSDs. Figure 5-2 illustrates the PSD areas around Brussels in Belgium. Some of these areas will likely be merged into one supply district, while some of the larger areas perhaps will be split between different supply systems. Nevertheless, PSDs provide an indication of the number of areas that can be supplied with district heating and the amount of necessary new areas in order to reach around 50% district heating.

5.2 Estimating yearly new prospective supply districts towards 2050

Figure 5-3 uses the logistic growth model from equation [1] to model when new PSDs should be established. It models yearly new PSDs in order to reach 25,000 in 2050, with the assumption that the establishment rate of new systems should peak in 2030, as explained previously.

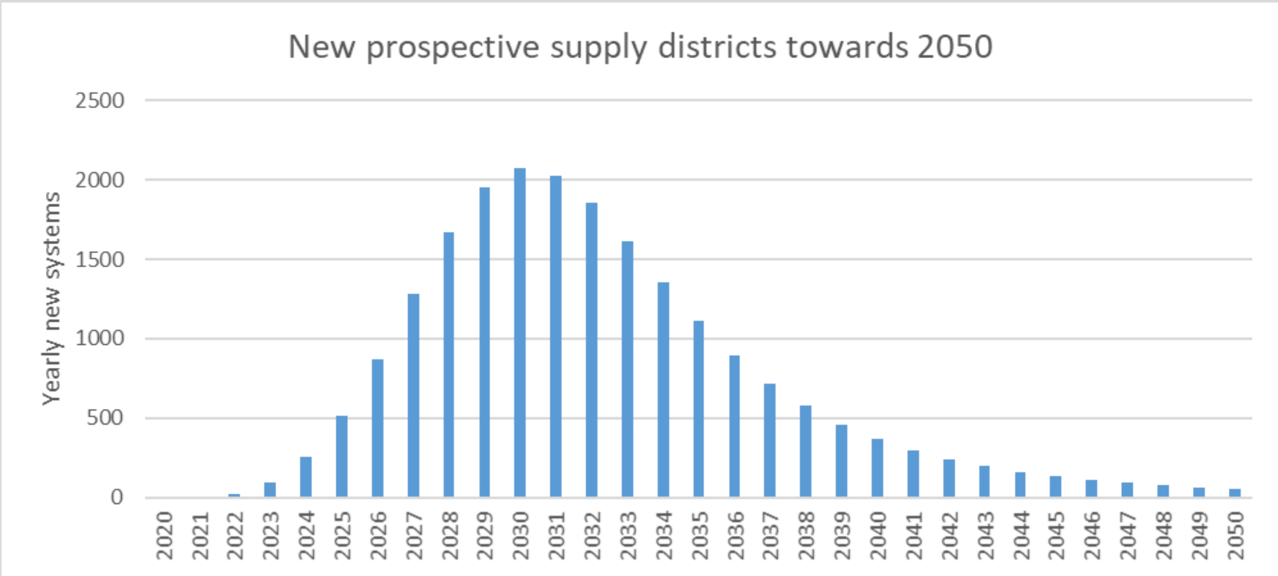


Figure 5-3. Approximate newly established and total amount of district heating systems in HRE14 and Denmark needed for fulfilling the potential of distribution grid investments below 4 EUR/GJ. X50 = 2030, m = 4.

Figure 5-3 illustrates an assessment of when new district heating systems should be established and does not illustrate when the systems should be fully operational or cover their feasible area. As argued above, it shows that the number of newly established systems should peak in 2030 at around 2000 new PSDs that year. The high rate of new systems entails the initial establishment of systems and not necessarily a saturation of the markets. These systems should be based on most feasible business cases, supplying high heat demands or exploiting available heat sources. After being established, a further focus can then be on reaching their feasible market shares. The growth model concentrates the establishment of new systems to the period 2025-2035, with an estimated need of establishing 16,000 district heating systems during this 10-year period.

5.3 Yearly investments in district heating infrastructure towards 2050

The HRE4 study provides energy system costs as annualised equal costs of investments. This allows the comparison of the costs of technologies with different lifetimes but does not specify the exact year of investment. Rather, annualised costs provide a measure of the yearly costs of the investment spread over its lifetime, with a discount rate to account for the time value of money. In order to illustrate the amount of investments needed and when they should be carried out to fulfil the HRE 2050 scenarios, the initial investments must be calculated based on annualised costs. Equation [2] calculates the initial investment based on the annualised costs (P), lifetime (n) and the discount rate (r).

$$Initial\ investment = \frac{P \cdot (1-(1+r)^{-n})}{r} \quad [2]$$

Here is used a discount rate of 3%, a lifetime of the district heating infrastructure of 40 years, and a lifetime of district heating production units of 25 years [2]. This corresponds to the average values used in HRE4. The low discount rate is an expression of assigning importance to the future and therefore keeping the time value of money low. The annualised investment costs from HRE4 and estimated initial investments are provided in Table 6 below.

Table 6 Estimating initial investments in district heating infrastructure. Data from [70]

	Type	Annualised Investment Costs	Estimated Investments
Baseline 2015	District heating production units	8,168 B EUR	142,231 B EUR
	District heating distribution infrastructure	3,557 B EUR	82,219 B EUR
HRE 2050	District heating production units	18,023 B EUR	313,837 B EUR
	District heating distribution infrastructure	24,130 B EUR	557,759 B EUR

By estimating the total investments needed in the HRE 2050 scenario, it is possible with the logistic growth model to map out the years these investments should be carried out. The investment for the baseline 2015 district heating system is a highly theoretical value as this is the cost of establishing today's systems. Here, it is assumed that an amount is re-invested every year based on the lifetime of the technologies to maintain the current system. For district heating production units with a lifetime of 25 years, a value of 1/25 of the initial investment would have to be invested every year to maintain the 2015 baseline system. Correspondingly, for district heating distribution infrastructure there is a need to invest 1/40 of the total investments every year due to their lifetime of 40 years. These investments are needed to maintain the current system and are assumed to happen whether or not the HRE scenarios are implemented.

To transition towards the HRE scenario, new increased investments are necessary. As these are investments into new capacity, units and infrastructure, they are not spread evenly over the period but are assumed to follow the establishment of new district heating systems as presented above. These investments are needed to establish the new infrastructure needed for the 2050 HRE scenario. For estimating the spread of these investments, the logistic growth model from equation [1] is used. Again, the parameters are *m = 4* describing the slope and rate of change and the midpoint set to *X50 = 2030*, which assumes the highest rate of change 10 years into the period. This concentrates the majority of district heating investments needed for the HRE 2050 scenario in the period 2025-2035. The spread of investments is presented in Figure 5-4. As the lifetime for district heating production units is estimated at 25 years, the new investments made until 2025 require re-investments in the years approaching 2050. This results in slightly increasing investments from 2048 for production units.

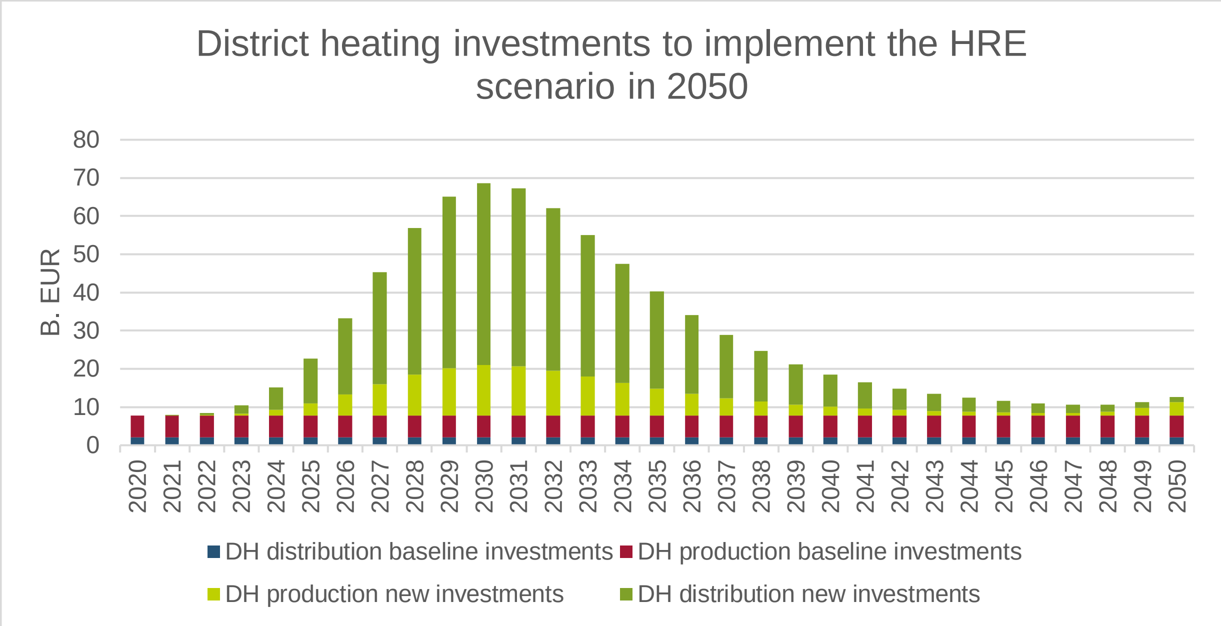


Figure 5-4. Estimation of distribution of district heating investments to reach the HRE 2050 scenario. X50 = 2030, m = 4

It is assumed that the baseline investments can be shifted into new technologies supporting the HRE 2050 scenario. Therefore these investments will be maintained throughout the period 2020-2050 in a stable pattern. The majority of the new investments necessary to reach the HRE 2050 scenario is carried out during 2025-2035. Figure 5-4 shows that the majority of new investments should be made in new distribution infrastructure. In 2030, 47.6 B EUR should be invested in new district heating distribution infrastructure. 13.2 B EUR should be spent the same year for new district heating production units. In total, investments in district heating production and distribution infrastructure are estimated at 68.6 B EUR in 2029 in order to meet the HRE 2050 scenario.

5.4 Investments in heat savings in building stock

A similar approach is used here for estimating when investments in building stock renovations for decreasing heat consumption should be placed. The annualised costs necessary to reach the savings in the HRE 2050 scenario is 192 B EUR/year [70]. The savings in HRE 2050 are overall 5% more ambitious than current planned policy, resulting in about 630 TWh of space heating savings [2]. Using equation [2] again for estimating the total investments with a lifetime of 40 years and a discount rate of 3% results in a total of 430 B EUR needed to be invested before 2050 to reach the desired savings. Using equation [1] with a midpoint in 2030 and a slope of 4 results in the distribution is presented in Figure 5-5.

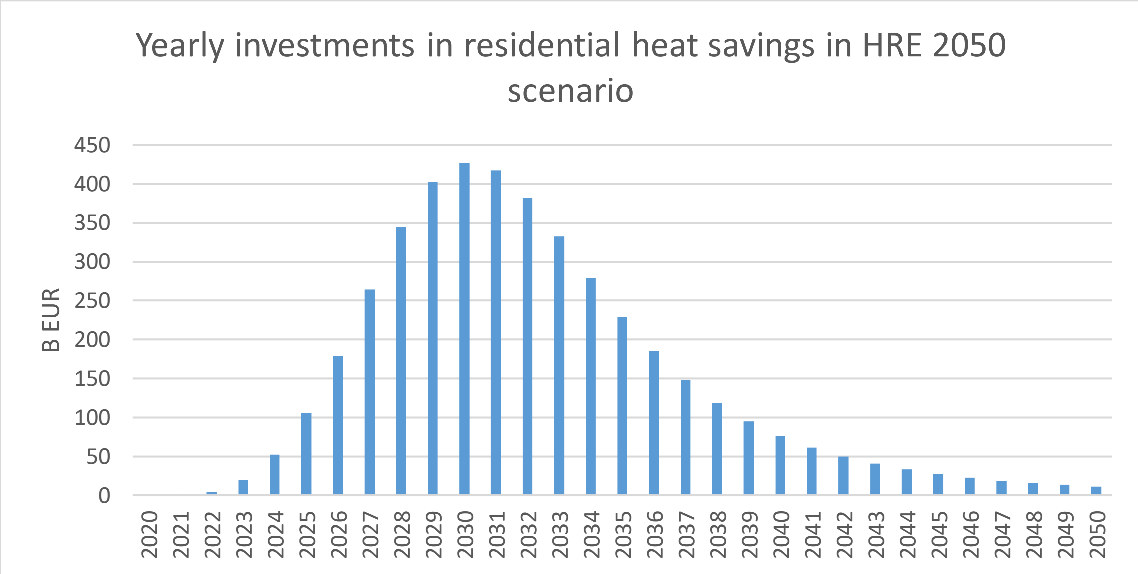


Figure 5-5. Estimation of yearly investments in residential heat savings. X50 = 2030, m = 4

This illustrates the need to invest heavily in heat savings in the period until 2035 with continuing investments afterwards. The investments should peak in 2030 in order to achieve an energy-efficient housing stock to deliver supply chain effects along the energy efficiency value chain and enable low-temperature renewable sources into the energy mix.

5.5 Annualised investment roadmap for heat supply

Instead of illustrating the year of investment, annualised investment costs represents the annual costs for an investment over its lifetime. Amortisation of the payments over the lifetime of the investments with a discount rate gives the costs of the investments spread over every year of its lifetime. It calculates the equal annual costs of an asset and can be used to compare units and assets with different lifetimes.

It involves the discount rate which in HRE4 was set to 3%. All investments are annualised to allow the comparison of different investments such as in individual heat pumps, district heating distribution infrastructure and CHP plants.

The logistic growth model for representing annualised investment costs into heating infrastructure shows the rate of changes needed in order to reach the HRE 2050 scenario. It shows an important breakthrough period during 2025-2035 when changes in the annualised investment costs should take place. Shifting from individual to collective heating systems as well as increased investments are the primary changes. Annualised heat sector investment costs increase from 70 B EUR/year in 2015 to 100 B EUR/year in 2050. Individual heating should change from accounting for 82% of the annual heat sector investment costs to 44%, corresponding to supplying about half of the European heat consumption by collective measures and half by individual solutions in 2050. District heating supply units and distribution infrastructure make up 12% and 5%, respectively, of the yearly heat sector costs in the 2015 scenario. They are set to increase to a share of

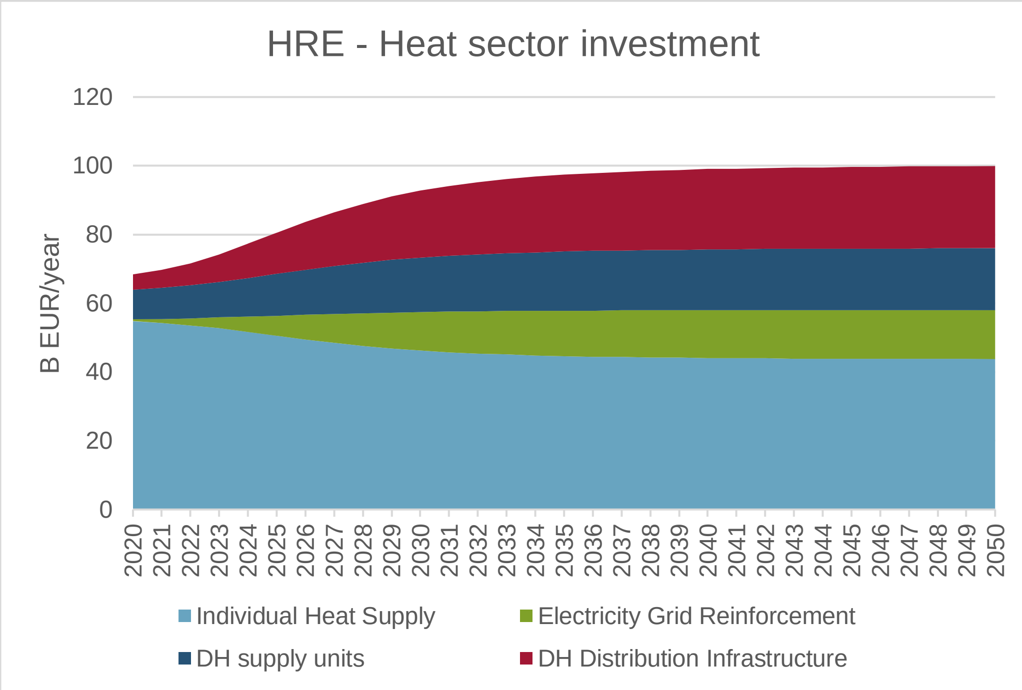


Figure 5-6 Annualised heat sector investment costs roadmap. Based on HRE [2]. X50 = 2030, m = 4

18% and 24% in 2050, or 18 and 24 B EUR/year respectively. In order to accommodate the increased use of electricity in heating, mainly through the use of individual and district heating heat pumps new investments in electricity grids are also needed. These new investments reach 14 B EUR/year in 2050 in the HRE scenario. Refer to Table 8 for a detailed outline of annualised investment costs throughout the period.

5.6 Summary

In order to enable the transition towards the HRE 2050 scenario, it is important to ensure a significant establishment rate of district heating systems until 2035. An early start of the transition will enable a wider decarbonisation of the energy system through supply chain effects as outlined in the above sections.

This section has presented how the implementation of investments in district heating production, distribution and heat savings should be divided during the period 2020-2050. Again, the assessment is that a rapid transition is necessary during 2025-2035 to ensure that a large enough proportion of the heating sector is transitioned towards an energy-efficient and decarbonised energy supply at the latest in 2050. To do this, the establishment of new district heating systems is necessary. Analyses from PETA4 show that 25,000 prospective supply districts should be reached before 2050, with the majority of new systems being established between 2025 and 2035.

Key findings

2025-2035: A significant period for the decarbonisation of heating

The investment roadmap analysis, using a logistic growth model, points toward 2025-2035 as a crucial period in the transformation of European heating systems. In this decade, major shifts in investments from individual supply options to collective solutions are expected. This period is crucial in moving the decarbonisation forward and in increasing the energy efficiency of European energy systems.

While this report stresses the urgency of immediate action towards the establishment of new district heating systems, systemic and re-designs of energy systems requires long-term strategic energy planning. It is necessary to maintain long-term goals and translate these into actionable steps such as investment levels, new capacity targets, energy efficiency targets and others.

6 Milestones and policy recommendations towards 2050

6.1 Important milestones for implementing the HRE 2050 scenario

The analysis above has outlined a potential roadmap for heat sector investments for implementing the HRE 2050 scenario. Here, a qualitative discussion of important milestones for reaching and enabling this transition is presented based on the above analysis and data. The discussion below outlines important milestones towards the HRE 2050 scenario by dividing the period into 3 sections: 2020-2030, 2030-2040, and 2040-2050. The milestones are indicative and an estimate based on current technological knowledge with an inherent uncertainty. District energy infrastructures will still be needed to distribute heating and cooling to dwellings regardless of heat production source and can thus adapt if, for example, geothermal potentials are found to be higher than estimated in this report.

6.1.1 2020-2030

Between 2020 and 2030 the transition should focus on the establishment of new district heating systems and investments in energy efficiency measures across the energy value chain. In order for the regulatory framework to drive this development, policymakers should take into account the following points:

- **Ramp up the establishment of district heating systems:** As district heating grids, infrastructure and supply are a future-proof measure, governments should start and ramp up the establishment of district heating systems. First, the development can take place in high-demand, low-cost areas where low-hanging fruits can be exploited, as long as this is done with a focus towards further expansion of the systems, exploiting local heat sources as well as modernising existing 1st or 2nd generation systems to demand-driven 3rd or 4th generation systems.

- **Establish national potential and plans for district heating and cooling**: As a first step, it is important to establish the tools and processes to properly assess the potential for district heating, to identify potential energy sources and savings potentials. It is important that cities and national governments seriously assess the potentials in their areas for district energy solutions. Some of this work has already begun, for example with the comprehensive assessments in the EED's article 14 [11]. However, a lack of data and a fragmented approach limited the usefulness of the results [13]. Countries should expand this work to identify the potentials for district heating, to establish planning procedures and to support the establishment of new district heating systems.

- **Invest in building level measures:** It is important to start decreasing the energy demand in buildings. This can be achieved with implementing heating controls to move towards demand-driven systems and energy efficiency improvements during building renovations. Buildings should also be prepared for the use of low-temperature district heating supply. Significant investments should be made in energy efficiency improvements of buildings towards 2030 and 2050.

- **End investments in new individual fossil heating capacity:** It is important to end investments in new fossil capacity in individual heating such as gas and oil boilers. When faced with the necessary investment in new heating capacity, the option should ideally be between a district heating connection and a heat pump in areas with low heat density.

- **Ensure a level playing field for a decarbonised energy system:** Markets, investments, regulation, taxes and tariffs need to be adjusted to promote the technologies that fit into a low-carbon and energy-efficient future. As district energy solutions are cost-effective in the long run, but capital intensive upfront, it is important to provide the right market conditions that allow these kinds of long-term investments to be made. This can include certainty from governments, access to low-cost capital, but also by promoting socio-economic calculations and assessments of district energy.
- **Take a system approach:** There is a need to assess the energy transition from an energy system perspective to enable the energy supply chain effects. This approach can start identifying synergies across energy domains, exploiting sector coupling and the energy efficiency value chain presented in this report. In order to facilitate an effective system approach, it is important to involve relevant stakeholders in the process and to identify and remove obstacles for sector integration. Grid operators and system operators should be obliged to assess synergies with other sectors when making decisions. Planning for sector coupling is important to initialise during this period, as it will only grow more important towards 2050.
- **Involve the local level**: Countries should include in their assessment plans how to activate local governments and municipalities in the transition. Heating is a distributed and local energy demand [74], and it is important to enable coordination between the national and local levels. Local governments often possess detailed knowledge about the building stock, heat sources and population which is important to include in the heat planning processes. At the same time, national coordination is important to make sure all actors steer towards the same goals. Otherwise, over-investments in some areas and under-investments in others might occur, such as too high biomass consumption or lack of CHP capacity acting as a backup for the electricity sector.
- **Improve availability of data:** To enable a heat transition, it is important that knowledge is expanded and data collection about the heating sector increased. In order to invest in district heating systems, it is important to have detailed knowledge about heat demands, the status of the building stock and availability of heat sources. Therefore, an important area for improvement is for local and national governments to increase data collection about the heating sectors, as well as the performance of existing district heating systems.
- **Start investigating the potential and role of district cooling:** As cooling is one of the fastest growing of the thermal sectors, the potential to explore the role of using free cooling and higher levels of cold water thermal storage requires investigations to be able to fully understand the potential and role that district solutions for cooling could play on the wider energy system.
- **Improve cooperation and knowledge sharing:** While some countries and cities have many years of experience with developing and operating district energy systems, for many these are new technological systems. There will be a large need to share experiences in relation to how to implement new systems, how to organise ownership, operation and involvement of citizens and many other areas. There already exists platforms and organisations for knowledge sharing of district energy system and with the expansion of district energy in European Member States these will become more important.

Period	Milestones
2020 – 2030	- Identify and start establishing potential district heating systems – around 8,700 new systems in this period. - Annualised investment costs in district heating supply and in district heating distribution infrastructure should reach around 16 B EUR/year and 20 B EUR/year, respectively, during this period. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 118 B EUR and 223 B EUR for the period from 2020 to 2030. - Expand current district heating systems where feasible - Make national and local plans for how to reach 50% district heating supply (or the respective national potential) - End new investments in individual fossil fuel heat supply - Increase investments in building renovation and make sure to fully use no-regret measures with high energy efficiency impact. Annualised investment costs should reach 190 B EUR/year in heat savings in this period. - Increase investments in energy efficiency improvement of existing district heating systems in order to prepare them for a transition to more sustainable and low-temperature sources - Plan for and invest in increasing electricity grids for increased individual heat pump use. Annualised investment costs should reach 11 B EUR/year in grid reinforcements in this period. - Make plans for how to phase out any remaining gas and oil boilers in individual heat supply

6.1.2 2030-2040

From 2030 to 2040 the newly established district heating areas should be consolidated and their market share expanded. At the same time, any remaining prospective supply districts should convert to district heating systems. The estimations on new prospective supply districts in section **Error! Reference source not found.** show that around 11,000 new districts should be established in this period.

- **Saturate heating markets:** The prospective supply district that has been established should start to cover the majority of its feasible supply areas. Energy renovations and efficiency measures should still be a major focus, and if any remaining low-hanging fruits are left, they should be exploited in this period. Further connections to district heating networks must be ensured, potentially via heat zoning or mandatory connections. These political levers are obviously up to local and national governments, but they will be important with effective policy tools for promoting district energy. Regarding individual heat supply, the electricity grid must be reinforced and made ready for increased heat pump use (as well as for electric vehicles and other new electricity demands).

- **Remaining fossil fuel capacity must be phased out during this period**: This will possibly require policies such as replacement schemes o the banning of gas and oil boilers. Gas operators should provide an end date for finishing gas supply or governments should provide incentives for switching away from gas or oil. Potentially local plans prescribing the heat supply within a specific area should be used to facilitate the transition.
- **Act on data and knowledge about the heating and cooling sectors**: Together with new governance and policies for local energy planners, knowledge about the heating and cooling sectors should promote action on utilising excess heating and geothermal resources. Based on new knowledge about the heat sectors, it is likely that new needs for governance, planning and policy will emerge. It is important that the governance systems are able to adjust to new and emerging needs of the energy system, such as increased sector coupling or new energy demands. This becomes increasingly important as energy system domains start to converge during this period. Here electricity, heating and transport with new sectors such as e-fuels must exploit synergies across these domains. Therefore, the heat sector will start to serve multiple purposes from solely serving heat demands to also providing flexibility to the electricity sector and cheap storage for excess heat from e.g. fuel production.

Period	Milestones
2031 – 2040	- Consolidate and expand district heating areas in order to reach their full potential market share - Annualised investment costs in district heating supply and in district heating distribution infrastructure should reach around 18 B EUR/year and 23 B EUR/year, respectively, during this period. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 127 B EUR and 273 B EUR for the period from 2031 to 2040. - Establish the majority of remaining potential district heating systems – about 11,000 new systems in this period - Existing district heating systems should reach full supply potential - Replace existing fossil fuel capacity in individual heating with heat pumps - Annualised investment costs in energy savings should increase to around 192 B EUR/year - Follow up on phase-out of gas and oil boilers. Possibly with replacement schemes, zoning and mandatory replacements

6.1.3 2040-2050

During the 10 years from 2040 to 2050, the transition towards connected smart energy systems must be completed. Here the last steps of realising an integrated, low-carbon and energy-efficient energy system should be made.

- **Achieve a fully integrated energy system:** All sectors and demands should become interconnected with the overall energy system to realise the remaining energy efficiency potential and to decarbonise energy supply. To realise this potential it is important to already have a functioning infrastructure that can be used to exploit the potential of different energy sectors. Here, all energy demands such as electricity, heating, cooling and mobility should be an interconnected system.

- **Remaining fossil fuels in the energy system must be replaced in this period.** This includes gas in CHP plants, backup capacity and other flexibility mechanisms, as well as in the transport sector. It is important to already have established a district heating sector that can utilise excess heating and provide flexibility for other sectors.
- **Ambitious decarbonisation policies**: During this period, ambitious regulation and policy will still be central in driving the low-carbon transition to take the last step towards a full decarbonisation of the energy supply.
- **Connect remaining demands to district energy supply:** Virtually all potential district heating areas should have been established, so this period needs to focus on connecting the last remaining demands to these collective systems. This can be coordinated with the increasing amounts of new excess heat sources, new utilisation of geothermal and solar thermal resources.

Period	Milestones
2041 – 2050	- The remaining 1,400 district heating systems should be established - District heating systems should be expanded to reach 50% district heating market share - Annualised investment costs in district heating supply and in district heating distribution infrastructure remain at 18 B EUR/year and 24 B EUR/year, respectively, during this period. This corresponds to accumulated investments in district heating supply and distribution infrastructure of respectively 53 B EUR and 71 B EUR for the period from 2020 to 2030, which are mostly re-investments into maintaining existing infrastructure. - Energy renovation annualised investment costs should be maintained at 192 B EUR/year. - Replace remaining fossil fuel capacity in individual fuel supply

6.2 Approaches for countries with different types of heating sectors

While the milestone recommendations provided above address all European countries, it is possible to elaborate on strategies for specific countries with different heat sector categorisations as defined in section 2.6

To reach the HRE 2050 scenarios, all countries in the EU should have established high amounts of district heating in their energy supply by 2050. Therefore, the three types of countries mentioned in section 4.2 can also be seen as a process which countries should go through to reach the HRE 2050 scenario. As countries without district heating start to establish systems they can begin to consider the challenges mentioned for countries with low amounts of district heating and so on.

6.2.1 Countries with high amounts of district heating

Countries that already have high amounts of district heating supplying heat demands must focus on energy savings, the switch to renewable supply and ensuring feasible business models facing potentially decreasing heat demands. This could be a significant challenge but, as this report has shown, there is still significant potential for district heating supply in an energy-efficient future energy system. It is important to make viable business models for district heating supply that reflect the costs of the heating supply, are competitive with individual heating supply and operate in a transparent and efficient manner. This ensures that funds remain for further investments, maintenance and the expansion of systems.

This report has outlined approaches towards 4G district heating systems and the utilisation of low-temperature heat sources. This entails a reconfiguration of the building stock and distribution infrastructures to be able to exploit these resources at the same time as promoting a more interconnected energy system.

Regulation, tax structures, tariffs and prices must also follow this transition. 4GDH entail new synergies that often are limited today due to ownership, taxation or market rules. High electricity taxes on the use of heat pumps is one example. A central challenge for energy systems moving towards 4GDH is to identify and value the total energy system benefits across the value chain of different technologies. The value of heat pumps for the integration of renewable electricity production should, for example, be considered. This applies to the heating sector today, but will only become a more central issue with the emergence of Power-to-X technologies [10] and increased penetration of electric vehicles. As technologies start to have considerable benefits across the whole energy value chain it is important to value these traits from a holistic energy system perspective and not merely based on, for example, their energy content or emissions.

4GDH allows the use of significant amounts of excess heating. New business models and regulation of this needs to be developed to encourage the use of unavoidable waste heat while at the same time not encouraging business and industries to increase their excess heat production because it is profitable.

4GDH as a technical concept focuses on lowering district heating temperatures in order to increase efficiency and the use of low-temperature sources. However, in doing this, the concept challenges conventional energy system regulation and will, in some regards, constitute a paradigmatic change towards an energy system which is more integrated in both technical and regulatory terms.

6.2.2 Countries with inefficient heat infrastructures and building stock

Especially Central and Eastern European countries have district heating systems with high losses, designed for high temperatures and with an inefficient building stock. These countries face the issue of both establishing new systems as well as consolidating and expanding existing ones while improving efficiency in these systems and building sectors. Many of these countries will be moving from 1st or 2nd generation district heating to 3rd or 4th generation systems. This can happen with new production units, access to new renewable resources, efficient distribution infrastructure, insulated buildings that can utilise low-temperature supply and with heat control systems, heat metering and consumption-based billing. New systems should be established using state-of-the-art technologies along the value chain. For these types of countries, it is important to revise and expand district heating regulation and governance to allow for expansive investment in district heating grids and production units. This is connected with business models where the customer prices reflect the actual cost of heat production, operating and maintaining the system and other related costs, while at the same time avoiding monopoly issues with pricing or that public-owned utilities use profits for investments in other public sectors such as transport or waste management. It is important to maintain a cost-efficient heat supply where customers pay for the service they receive.

6.2.3 Countries with no district heating

Countries that currently have no or very little district heating have to start establishing systems as soon as possible. The first steps should be to exploit available low-cost heat sources in areas with high demand (customers), where the business case for district heating is best. Later efforts can focus on connecting smaller heat demands and expanding district heating supply to cover larger areas. It is vital to include the possibility to expand systems from "the low-hanging fruits" in local urban areas with extremely good conditions to city-wide networks. Here, funds and knowledge generated from connecting profitable heat demands should be recirculated into expanding district heating systems further.

Countries such as the UK and the Netherlands have significant potential for district heating but are currently mainly supplied by gas networks. Southern European countries also show significant potential for district energy systems, potentially coupling both heating and cooling supply. Although having a shorter heating season than northern European countries, there is a significant heat demand in the south with a spatial concentration which is high enough to make district energy systems feasible.

These countries will need to develop heat regulation, planning and frameworks for developing these infrastructures. It is important to consider ownership models, competition among heating sources, pricing, investments and more. It is important to allow local, municipal or collective ownership of the district heating grids and distribution infrastructure. This should be treated as the countries also treat electricity, gas or water distribution infrastructure. Part of establishing a level playing field between different heating sources entails differentiating between supply options of today's energy system and supply in future systems. It does not align with a low-carbon energy system to compare, for example, district heating supply to the price of gas if the gas supply is not part of the future system configuration. Instead, district heating and cooling grids should be seen as an enabler for renewable energy and energy efficiency.

At the same time as establishing district heating networks, building stock renovations must be carried out, including the optimisation of control systems. If they are carried out at the same time as new district heating networks are built, the full energy value chain benefits can be exploited. Optimal capacities to supply an energy efficient heat demand, such as sizes of pipes and grids, as well as supply and return temperatures from the building stock, can be calibrated to avoid over or under-investments. The risk is the different timeframes for establishing district heating grids and building renovations. Renovations can be much slower to implement and happen at a fragmented timescale, and thus create a potential misalignment between investments in supply and end-use efficiency. This dilemma needs to be taken into account, as this report has shown how important aspects of energy efficiency measures along the value chain are. This can potentially be addressed by local authorities and heat planners who work with citizens and the local area by involving main stakeholders in the planning process. An integrated energy planning approach is important for considering these aspects at the same time during the process.

6.3 Impact on EU level heat policy

As the HRE 2050 scenario was developed before the EU energy efficiency target of 32.5% and as it mainly considers improvements in the heating sector, the HRE 2050 scenario and the EED targets are not directly comparable. Nevertheless, the HRE methodology has shown to be able to improve energy scenarios by deploying a special focus on the potential of district heating to improve energy efficiency and decarbonisation.

The Energy Efficiency Directive (EED) [11] and the Renewable Energy Directive (RED) [12] address several of the areas focused on by this report as it seeks to promote energy efficiency to decrease the climate impact from energy consumption [13]. Article 14 of the EED specifies that Member States must carry out comprehensive assessments (CA) of the potential for increasing energy efficiency through high-efficiency cogeneration and efficient district heating and cooling. This is an important step in realising the district energy potentials and reaching the HRE 2050 scenario. The first round of CAs have been submitted by Member States, and although some countries identified potentials for district heating, significant methodological and empirical challenges still remain in making district heating a tangible alternative [22]. The method for the second round of assessments was updated to ensure a clearer methodology while allowing the Member States to include relevant local aspects [75]. The Renewable Energy Directive contains articles on both renewables in heating and cooling (Art. 23) and on district heating and cooling (Art. 24) [12], and includes important parts on data collection about the heating and cooling sectors in the EU-28. These aspects will be covered below.

Definition of Efficient District Heating and Cooling

The EED Art. 2 (41) defines 'efficient heating and cooling' according to the source of supply with the following thresholds: at least 50 % renewable energy, 50 % waste heat, 75 % cogenerated heat or 50 % of a combination of such energy and heat [11]. This does not consider the energy efficiency value chain or the energy losses in the system. Such definitions should relate efficiency to energy performance and not to the type of supply. Energy supply sources should be labelled as renewable or waste shares.

This also relates to the inadequate definition of *energy performance* in the RED. In the RED Art. 24 (1) it is stated that Member States must make information about the energy performance about district heating and cooling systems public and on bills. Again, a distinction between supply and efficiency should be maintained. In implementing the RED, Member States should ensure that both the information about the renewable share of district heating supply and the efficiency of the systems are communicated to customers.

Expand the scope of the Comprehensive Assessments

The CAs specify that an "integrated approach to demand and supply options" should be taken, but it is not specified in the technical mapping section exactly how to do this. This should entail a holistic energy system approach that includes all energy domains, although a primary focus on district heating should remain. As this report shows, it is important to analyse changes in the heating system in relation to wider energy system transitions to identify potential synergies or barriers.

Improve data collection and availability

Lacking data about the heating sector is a barrier to implementing district heating and providing an energy efficient heating supply. Improving data collection about heat demands, heat production, building characteristics like age and insulation, and about district heating grids will provide necessary knowledge in order to plan and carry out a heating transition. Especially district heating investments are capital intensive and it is important to base investment decisions on solid knowledge.

As discussed in section 2.4, about district heating distribution losses, there is a twofold problem: first, lacking knowledge about district heating grids makes it difficult to assess the losses. Second, lacking data collection and reporting methodologies makes it difficult to compare data from different sources, as they might count and assess systems differently. Therefore, the EED should promote and encourage a comprehensive data collection infrastructure and methodology.

The RED Art. 23 (3 and 6) [12] promote data collection and sharing of renewables in heating and cooling supply. These are important steps towards increasing the knowledge about the status and progress. The RES Art. 23 (3) specifies that Member States may establish lists about responsible parties, such as fuel suppliers, public or professional bodies which according to RED Art. 23 (6) should ensure the reporting of the amount of total energy, renewable energy and waste energy supplied for heating and cooling. As the designation of responsible bodies is voluntary, however, the effectiveness is still uncertain. Instead, the appointment of responsible parties for collecting, monitoring and reporting data and knowledge about heating and cooling should be made mandatory and publicly available through, for example, Eurostat or a similar data provider.

7 Annex

7.1 Results from JRC analysis of Comprehensive Assessment reporting on district heating distribution infrastructures

Table 7. Reported data on district heating distribution losses in national Comprehensive Assessments made in relation to Article 14 of the EED. (Data from [22]*)*

	Base year	**Base year distribution losses**
Austria	2012	10% on average
Belgium	2012	Fl. NA Wa. Correction factors used in simulation but not reported Br. 5-20%
Bulgaria	2014	23,7% (2,77 TJ/km)
Croatia	2013 (services, industry) 2015 (residential)	13% (in the city of Karlovac)
Cyprus	2013	NA
Czech Republic	2013	10.8%
Denmark	2012	24.0%
Estonia	not clear	16-26%
Finland	2010 (heating) 2015 (cooling)	8-9%
France	2013	7,5-14%
Germany	2012	12-13%
Greece	2010	NA
Hungary	2015	NA
Ireland	2015	10.0%
Italy	2013	16.0%
Latvia	2014	15.4%
Lithuania	2012	15.6%
Luxembourg	2012	NA
Malta	2013	NA
Netherlands	2008	NA
Poland	2012	12.9%
Portugal	2014	NA
Romania	2013	25.0%
Slovakia	2014	NA
Slovenia	2014	NA
Spain	2013	NA
Sweden	2011	15.0%
UK	2012	NA

7.2 Roadmap targets

Table 8 Annualised heating sector investment costs

Year	Annualised heating sector investment costs	Changes in annual investment rates since last period
2015	- DH Supply units: 8.2 B EUR/year - DH distribution infrastructure: 3.6 B EUR/year - Electricity Grid Reinforcements: 0 B EUR/year - Heat Savings: 186.4 B EUR/year - Individual Heat Supply: 55.2 B EUR/year	-
2020	- DH Supply units: 8.7 B EUR/year - DH distribution infrastructure: 4.7 B EUR/year - Electricity Grid Reinforcements: 0.9 BEUR/year - Heat Savings: 186.7 B EUR/year - Individual Heat Supply: 54.6 B EUR/year	Since 2015: - DH Supply units: +1.4% - DH distribution infrastructure: +6% - Individual Heat Supply: - 0.2%
2030	- DH Supply units: 16.4 B EUR/year - DH distribution infrastructure: 20.7 B EUR/year - Electricity Grid Reinforcements: 12.1 B EUR/year - Heat Savings: 190.9 B EUR/year - Individual Heat Supply: 45.6 BEUR/year	Since 2020: - DH Supply units: +6.5% - DH distribution infrastructure: +15.8% - Individual Heat Supply: - 1.8%
2040	- DH Supply units: 17.8 B EUR/year - DH distribution infrastructure: 23.6 B EUR/year - Electricity Grid Reinforcements: 14.1 B EUR/year - Heat Savings: 191.7 B EUR/year - Individual Heat Supply: 43.9 B EUR/year	Since 2030: - DH Supply units: +0.8% - DH distribution infrastructure: +1.3% - Individual Heat Supply: - 0.4%
2050	- DH Supply units: 18 B EUR/year - DH distribution infrastructure: 24 BEUR/year - Electricity Grid Reinforcements: 14.3 B EUR/year - Additional Heat Savings: 191.8 B EUR/year - Individual Heat Supply: 43.7 B EUR/year	Since 2040: - DH Supply units: +0.1% - DH distribution infrastructure: +0.2% - Individual Heat Supply: - 0.05%

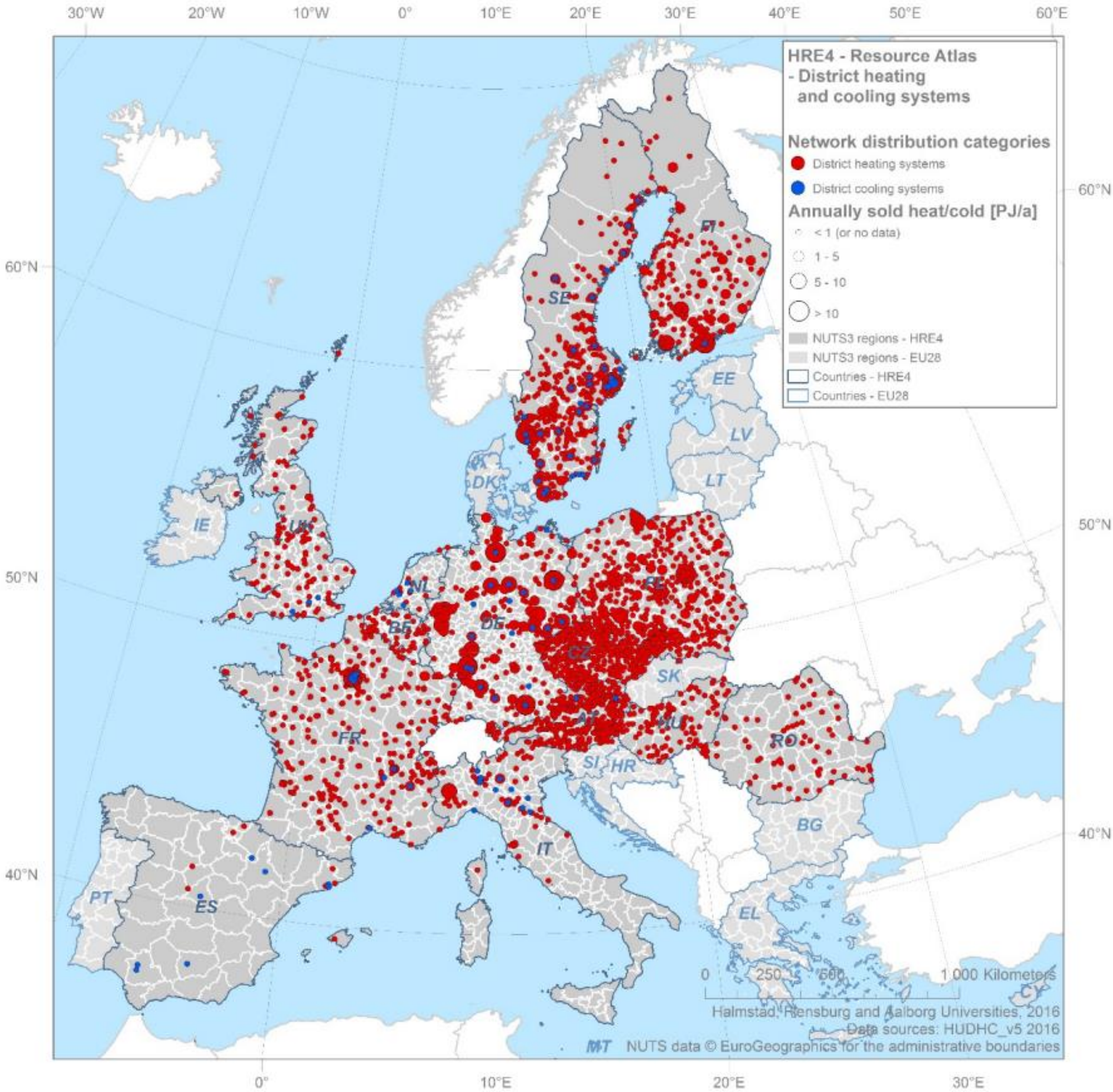
7.3 Data on district heating in EU-28

	Total heating and cooling final energy demand 2015	Total final heating demand 2015	Gas share in final heating demand 2015	Final energy demand for space heating and DHW (excl. Industry) 2015	DH share in FED for space heating and DHW (excl. industry) 2015	Variation of DH trench length 2009-2015	Variation of total DH heat sales 2009-2015	Variation of total installed DH capacity 2009-2015	Estimated DH losses
Source	HRE4	HRE4	HRE4	HRE4	HRE 4	EUHP	EUHP	EUHP	AAU
Unit	TWh	TWh	%	TWh	%	%	%	%	%
Austria	164.97	161.10	30.68%	77.5	23.11%	22.65%	17.59%	9.47%	5%
Belgium	214.40	206.82	49.19%	111.0	1.23%				
Bulgaria	49.92	48.05	22.74%	23.1	20.66%	3.03%	-11.59%	-1.64%	9%
Cyprus	7.67	4.81	2.80%	2.8	0.00%				
Czech Republic	157.04	153.67	37.23%	79.0	23.92%	-0.78%	-20.35%	-4.65%	10%
Germany	1383.90	1345.97	43.46%	817.4	8.97%	8.86%	-9.10%	2.90%	8%
Denmark	77.29	74.24	23.02%	53.7	50.23%	9.93%	5.39%	5.77%	21%
Estonia	16.84	16.58	17.28%	11.1	38.29%	0.21%	-7.38%	-5.97%	5%
Greece	85.97	75.27	16.99%	40.3	1.23%				
Spain	383.22	348.66	46.90%	156.5	0.38%				
Finland	169.94	166.41	5.70%	71.0	42.08%	19.75%	-7.90%	2.89%	13%
France	758.08	728.95	43.58%	482.5	4.53%	42.67%	-9.46%	12.11%	5%
Croatia	40.17	39.03	31.23%	26.6	7.18%		-7.71%		5%
Hungary	99.43	97.80	58.43%	71.3	10.48%	-5.56%	-48.25%	-12.90%	
Ireland	56.86	55.08	35.57%	36.3	0.55%				
Italy	735.47	683.67	55.35%	427.7	3.30%	70.47%	23.44%	23.75%	13%
Lithuania	27.17	26.65	21.91%	16.0	41.70%	0.20%	-12.40%	16.38%	10%
Luxembourg	15.24	14.60	49.46%	8.4	10.71%				
Latvia	27.01	26.79	18.09%	15.9	33.96%	-5.56%	-5.98%	-21.37%	15%
Malta	1.90	1.08	0.69%	0.9	0.00%				
Netherlands	283.67	272.43	64.45%	138.8	4.29%	5.26%	3.07%	5.41%	14%
Poland	402.81	395.03	26.94%	234.1	24.45%	6.07%	-24.41%	-3.86%	9%
Portugal	77.63	73.04	31.41%	20.2	1.49%				
Romania	159.93	156.95	44.63%	71.7	16.04%			-4.94%	
Sweden	178.30	173.48	4.88%	84.3	51.71%	21.20%	-10.82%		
Slovenia	24.50	23.81	28.18%	14.1	10.12%	22.13%	-6.21%	-18.95%	12%
Slovakia	79.77	78.28	47.20%	31.0	20.44%		-11.59%		5%
United Kingdom	673.12	662.04	65.77%	446.9	1.30%	0.00%	0.00%	0.00%	5%

7.4 Data on district cooling in EU-28

	Total heating and cooling final energy demand 2015	Total cooling final energy demand 2015	Total FED for process cooling 2015	Total FED for space cooling 2015	Total FED for space cooling in residential sector 2015	Total FED for space cooling in tertiary sector 2015	DC share in total cooling FED 2015	Variation of DC trench length 2011-2015	Variation of total DC sales 2011-2015	Variation of total installed DC capacity 2011-2015
Source	HRE4	HRE4	HRE4	HRE4	HRE4	HRE4	HRE4	EUHP	EUHP	EUHP
Unit	TWh	TWh	TWh	TWh	TWh	TWh	%	%		%
Austria	164.97	3.87	3.33	0.53	0.03	0.28	1.91%	46.15%	53.05%	260.00%
Belgium	214.40	7.58	7.04	0.54	0.01	0.42				
Bulgaria	49.92	1.86	0.92	0.95	0.13	0.64				
Cyprus	7.67	2.86	0.21	2.66	1.90	0.74				
Czech Republic	157.04	3.37	2.90	0.47	0.02	0.19				
Germany	1383.90	37.93	35.40	2.53	0.12	1.58	0.43%	7.85%	37.72%	55.71%
Denmark	77.29	3.05	2.95	0.10	0.01	0.07				
Estonia	16.84	0.26	0.24	0.02	0.00	0.01				
Greece	85.97	10.70	1.70	9.00	4.27	4.04				
Spain	383.22	34.56	11.20	23.36	5.43	13.26				
Finland	169.94	3.53	3.24	0.29	0.00	0.08	4.79%	30.63%	30.67%	55.77%
France	758.08	29.14	22.89	6.25	1.20	3.37	3.19%	21.20%	5.71%	7.63%
Croatia	40.17	1.14	0.77	0.38	0.09	0.28				
Hungary	99.43	1.63	1.15	0.48	0.10	0.30			68.60%	180.00%
Ireland	56.86	1.78	1.75	0.04	0.01	0.01				
Italy	735.47	51.80	21.31	30.49	10.93	14.72	0.20%	15.97%	24.76%	25.41%
Lithuania	27.17	0.52	0.46	0.06	0.00	0.04				
Luxembourg	15.24	0.64	0.58	0.06	0.00	0.02				
Latvia	27.01	0.22	0.19	0.03	0.00	0.01				
Malta	1.90	0.83	0.05	0.77	0.52	0.25				
Netherlands	283.67	11.24	10.66	0.58	0.01	0.44				
Poland	402.81	7.78	7.13	0.65	0.03	0.54	0.90%	20.00%	30.68%	65.38%
Portugal	77.63	4.59	1.80	2.79	0.85	1.43				
Romania	159.93	2.98	1.96	1.02	0.26	0.67				
Sweden	178.30	4.82	4.53	0.29	0.00	0.22	19.70%	31.80%	1.22%	
Slovenia	24.50	0.68	0.44	0.24	0.02	0.18		0.00%	16.80%	0.00%
Slovakia	79.77	1.49	1.02	0.47	0.01	0.04				
United Kingdom	673.12	11.08	9.57	1.51	0.06	1.07				

7.5 Map of DHC systems in the major cities of the 14 member states of HRE4, by network distribution category, and annual volumes of heat and cold sold. (Source: [76])



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List of abbreviations

4GDH	4^{th} Generation District Heating
CA	Comprehensive Assessment
CHP	Combined Heat and Power
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EE	Energy Efficiency
EED	Energy Efficiency Directive
EU	European Union
GHG	Greenhouse Gas
GIS	Geographical Information System
HRE	Heat Roadmap Europe
HRE 2050	Heat Roadmap Europe scenario for 2050 from the HRE4 study
PETA	Pan-European Thermal Atlas
PSD	Prospective Supply District
RES	Renewable Energy Sources
TRV	Thermostatic Radiator Valve

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