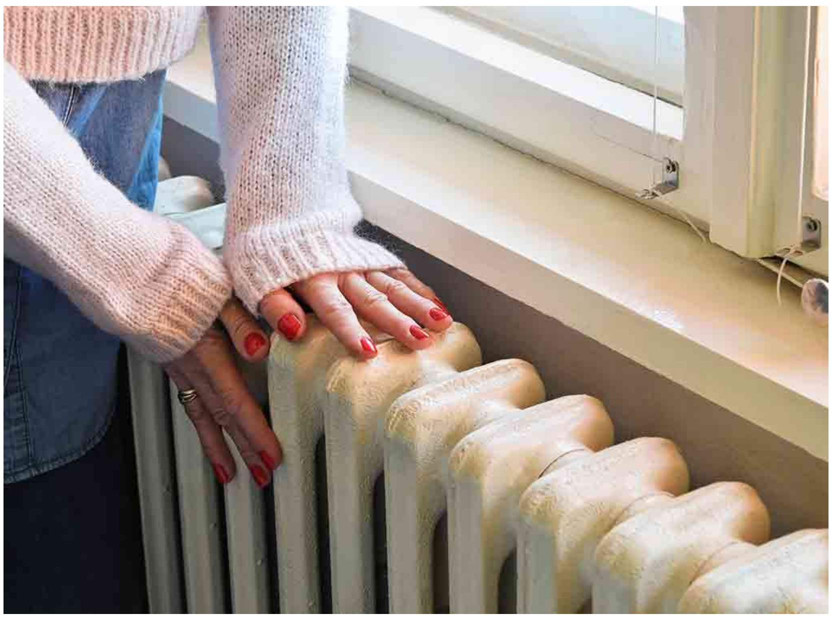

Heat Roadmap Europe

Towards a sustainable, resilient and competitive heating sector by 2050 – Executive Summery

This report shows how ambitious heat savings, a large-scale district heating deployment to a 55% market share and smart electrification can cut EU primary-energy use, eliminate fossil-fuel dependence, and enhance competitiveness. More than 3 PWh of waste and renewable heat has been located with at least 650 TWh of these usable. By integrating renewable and waste heat with adaptive, low-temperature networks, large-scale heat pumps and thermal storages Europe can achieve a sustainable and resilient heating sector by 2050. The report focuses on the EU level but has exploitable country level results.

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Executive summary

The share of natural gas for heating buildings in the EU has increased by 50% since 1990. This dependency has exposed both citizens and businesses to the erratic evolution of energy prices, mainly determined by geopolitical developments. The recent conflict between Russia and Ukraine has highlighted the dependency of Europe on imported fuels, reflecting the high dependency of Europe on imported fossil fuels to heat our homes. Fossil fuels remain the dominant source for heating in Europe, providing around two-thirds of total supply.

The transition from a European focus on the COVID-19 crisis to addressing sanctions and the energy crisis was abrupt, triggered by the outbreak of war in Ukraine. However, the signs of the energy crisis was visible earlier, as natural gas prices began to rise during the summer of 2021 due to reduced inflows of Russian natural gas from into European storage facilities. In fact, European citizens have been lured into a dependency on natural gas for heating with low natural gas prices due to Russian imports for decades.

REPowerEU and the effects of recent efforts to change the heat markets

Over the past years, the European Union's approach has evolved from addressing the immediate energy crisis – through sanctions and emergency measures under the REPowerEU initiative – to a focus on a broader strategy aimed at enhancing European competitiveness, strategic autonomy and accelerating decarbonisation. This strategic shift reflects key developments in the global energy landscape and the policy direction of the new European Commission. It is clear however, that the focus on system level energy efficiency is largely lacking and that the potential benefits of a Smart Energy Systems approach to this is not present in the public debate or in the current policies. With this report we hope to deepen the understanding of this much needed shift of focus to significant energy system re-designs emphasising the role of the heating sector.

Initially, the EU's response, centered on securing energy supplies and mitigating the impact of skyrocketing energy costs on citizens and businesses. The REPowerEU plan, launched in May 2022, aimed to reduce dependence on Russian fossil fuels by 1) a diversification of energy supplies in fuel shift, 2) by promoting renewable electricity and 3) by promoting energy efficiency. This included initiatives also focused on common gas procurement and significant investments in energy infrastructure (EC, 2022). As a result, the 2030 targets in Fitfor55 were tightened and the energy efficiency focused directives EPBD and EED were updated.

In May 2025 the REPowerEU Roadmap was launched to implement several bans and mandates to create member state level Russian energy exit plans if approved (EC, 2025) Despite the structural dependency on natural gas remaining a challenge, public attention has shifted, driven by relatively lower prices and a greater focus on global geopolitical issues. The EU now faces challenges not only from Russia but also from China and the United States, reshaping its priorities. In the May plan there is no enhanced focus on the actual phase-out or phase down of natural gas for heating buildings.

The EU has achieved a historic drop in natural gas consumption, cutting demand by 23% between 2021 and 2024 (Czyzak et al., 2025). This marks a major break with previous trends, when natural gas was promoted as a transitional energy source - particularly in displacing coal from power generation. While this is indeed a remarkable achievement, it also highlights the struggle and failure of including the heating sector in the transition. EU natural gas demand is traditionally spread quite evenly across three major sectors: power generation, industry, and buildings (both residential and commercial use) - each accounting for roughly 30–35% of total natural gas use. Yet the reasons behind the recent reductions are quite different in each case.

While investments in renewables have been the most impactful in replacing gas in power generation, sufficiency behaviors in households and businesses due to high prices - played an unexpectedly large role in that sector (Czyzak et al., 2025). In contrast, electrification, while strategically important, has so far had limited short-term impact on gas reduction. Nowhere is this clearer than in the heating sector, where the infrastructure, incentives, and systems needed for decarbonisation are still lacking. Without urgent action and a holistic redesign, the risk is that recent gains will be temporary, and the deeper transformation needed for climate neutrality will stall. Heat for buildings and hot water demands still accounts for roughly one-third of the final energy demand. -75% of which stems from burning fossil fuels (Kranzl et al., 2021). Europe's strategy for decarbonizing the heating sector has primarily hinged on two pillars: improving energy efficiency and reducing heat demand in both new and refurbished buildings, as well as expanding the deployment of renewable electricity sources. While EU energy efficiency policies have led to greater efficiency per square meter in buildings compared to the year 2000, the overall energy demand remains almost unchanged due to an increase in the number of dwellings, larger homes, and more appliances (Odyssee-Mure, 2021).

- The REPowerEU plan and Roadmap has not addressed sufficiently the need for structural changes in the heating systems. While the increased focus on the energy efficiency of buildings in various Directives is positive, there is too little focus on district heating infrastructure and the use of renewable and waste heat sources.
- There is a lack of a system-level focus including the heating system in the overall redesign and transition to a decarbonised energy system in which the heating sectors enhances the overall integration of renewable energy in the electricity sector.

Geopolitics and Energy Efficiency: The missing piece in the Draghi Report

As the energy crisis developments stabilized, attention shifted towards ensuring that Europe remains competitive in a rapidly changing global economy, particularly considering challenges posed by other global powers. The EU recognised that while addressing energy security is critical, there is an equally pressing need to enhance its economic resilience and global standing amid competition from countries with less stringent climate policies. The EU's Green Deal Industrial Plan, introduced in early 2023, is designed to facilitate the scaling up of net-zero technologies and ensure that the EU's manufacturing base can meet ambitious climate targets while also addressing the competitive challenge posed by China's manufacturing dominance in clean energy technologies. This also represents a possible set of responses to the United States' Inflation Reduction Act, which has spurred a competitive landscape for green technologies. (Dekeyrel, 2024)

The Draghi Report, published in September 2024, reflects this new focus by linking decarbonization efforts with industrial competitiveness in focus (EC, 2024). The report outlines the necessity of significant investments in clean energy technologies and infrastructure to bolster both energy independence and economic growth, ensuring Europe can compete effectively with nations like China that are rapidly advancing their green technologies. The report has clearly described the challenges ahead of us: 'The European Union must spend twice as much as after the second world war' to remain competitive and develop a more resilient and sustainable economy. The energy sector is designated as one of those strategic sectors where the pace of change must accelerate (EC, 2024).

The Draghi report focus the power and fuel prices for citizens and industries. While important, the use of heat in buildings is a source of significant costs and security of supply vulnerability. The report suggests important transformations of the electricity market that aims to lower electricity prices but does not recognize neither energy efficiency overall as a possible competitive advantage, nor the capacity of heat networks to enhance the robustness, resilience and security of supply short term and long term. Also, there is very little recognition of the benefits of electrification and the need to harness untapped and wasted heat resources, which can play a vital role in achieving energy efficiency and sustainability.

District heating systems can capture and distribute waste heat from various sources, including industrial processes and power generation. This infrastructure not only allows for the efficient use of waste heat but also provides an opportunity to integrate renewable heat sources, such as geothermal and solar thermal energy, into the energy mix. By prioritizing the establishment and enhancement of district heating networks, Europe can optimize the utilization of its available heat resources, which are otherwise wasted while also enabling a higher integration of renewable electricity using large-scale heat pumps and thermal storages. Addressing this gap in European energy policy is crucial not only for sustainability but also for the economic competitiveness of European industries.

In the Heat Matters report published in November 2023 we highlighted that district heating can contribute to energy security by up to 24 bcm natural gas savings in 2030, increasing the long-term energy efficiency and thus competitiveness of Europe (Mathiesen, Brian Vad, Wild et al., 2023). The build out of district heating infrastructure goes hand in hand with energy refurbishment of the building envelope and a decarbonised industry. In addition to this an electrification of the remaining district heat supply not covered by waste heat provides additional benefits for the electricity sector, giving a boost to local resources and flexible integration of renewable electricity with large-scale thermal storages. This can enhance competitiveness, strategic autonomy and accelerate decarbonization, but is not recognised as such in EU policies.

Additionally to an increased competitiveness, district heating and energy efficiency in buildings can also address the energy crisis which is still looming. While the recent initiatives have been designed to handle the situation with energy imports from Russia, the challenge for Europe is much greater. Despite the EU's climate ambitions and progress in deploying renewable energy sources and higher energy efficiency, the EU remains heavily dependent on energy imports. As of 2024, approximately 55–60% of the EU's energy consumption is covered by fossil fuel imports, with oil and natural gas dominating. This structural reliance on external suppliers exposes the EU to significant economic and political risks, especially during global market disruptions. Although natural gas markets have regional differences oil price shocks often spill over into gas markets, including liquefied natural gas (LNG) shipments to Europe. The escalating tensions and conflict risk in the Middle East, particularly in the Gulf region, further amplify these vulnerabilities. Any disruption in output or transport, such as through the Strait of Hormuz, could trigger global oil price spikes. These shocks not only affect crude oil but also indirectly raise European LNG import prices, as global LNG carriers are re-routed or repriced to reflect higher overall fuel market stress. The REPowerEU initiative and its 2025 roadmap rightly aim to eliminate Russian energy imports, but this must be complemented by a more decisive strategy to cut all fossil fuel dependency and as part of this a phase out plan for natural gas. Although the new directives following REPowerEU has posed a focus on heat planning for cities larger than 45.000 inhabitants (European Union, 2023), the policies so far and the Draghi report misses technical and economical viable options. Options that are obvious and based on EU technological knowledge.

To compensate, the EU replaced Russian gas supply with imports from other international suppliers. Norway and the U.S. have become the EU's largest gas suppliers, providing 31% and 25% of EU gas imports respectively in the first quarter of 2025 (Bruegel, 2025). The share of LNG is now 50% of the supply and 50% of that is from the USA. This creates a significant vulnerability to global supply chains and price fluctuations subject to geopolitical tensions and global unrest. on its hands the proven solutions to transform the heat market and bring to citizens heat that is both affordable and sustainable. While seeing significant steps forward the spending for Russian natural gas still reached 22 billion € in 2024 (Czyzak et al., 2025).

- There is a clear lack of understanding the need for further support and initiatives in the heating sector to increase competitiveness by decreasing the cost of the heating sector with improved energy efficiency.
- There is a lack of understanding in the Draghi report that the heating sector as part of enhancing EU's strategic autonomy in both the heating sector and also by enhancing the integration of local renewable electricity production that can improve the security of supply.
- The increased dependency of LNG, even with lower demands, highlights that the energy security of supply situation is still critical and will become more critical with the phase out of the remaining

natural gas import from Russia. The new global geopolitical situation creates a need for a more decisive natural gas phase out plan in heating and in general.

State-of-the-art methods, knowledge and decision support in this report

This report analyses solutions to address two main challenges: 1) the EU's climate targets and the broader climate crisis, and 2) the need to enhance European competitiveness, autonomy, and resilience. The report aims to provide a comprehensive understanding of the potential for a fundamental transformation of the EU heat markets. It focusses on the role of energy efficiency in a traditional understanding, namely end-savings and combines this focus with efficiency improvements in specific technologies and within the energy system design i.e. also sometimes called energy efficiency 2.0. Traditionally the focus on energy efficiency is aimed at reducing the end-demands in individual sectors e.g. industry or buildings which is important. In this report we aim to combined this with a focus on cross-sector synergies aiming at utilising waste heat resources, using electricity and renewable heat combined with thermal storage and lower temperature needs in district heating and buildings. Energy efficiency 2.0 is not just about using less. It enables a fundamental smarter, integrated energy system unlocking flexibility in smart energy systems to support an energy efficient system design. Covering a 25-year horizon to 2050 with intermediate steps, the research focuses on cost-efficient reductions of the primary energy supply (PES) as well as staying within the limits of local constraints with regards to renewable energy sources such as wind power, PV, biomass, geothermal etc.

In addition, the research reflects a smart energy systems coupling between the different sectors heating, industries and transport. The energy system and heat markets will be influenced by advances in industrial and transport efficiency and electrification due to those sectors decarbonisation. All of which results in a suggestion to gradually combine the increased electrification with a complete redesign of the heat markets using renewable heat sources and waste heat sources which are still present in a decarbonised energy system.

The knowledge and exploitable results in this report amongst others can support:

- an acceleration of and implementation of the tightened Fitfor55 package and the updated energy efficiency focused directives EPBD and EED.
- on the ground and country level heat planning.
- the efficient district heating in the light of the new EU definition of efficient district heating will provide a compass for heat decarbonisation.
- a modernisation of existing district heating schemes.
- the European Commission's renewed Heating and Cooling Strategy to be published in the first trimester of 2026.
- the development of new and improved targets for energy efficiency, infrastructure and renewable energy for 2040 and 2050.
- initiatives in member states on improving the heating sector.

In the following sections we present the most important findings in the research conducted through combining hundreds of hourly energy modelling of the energy system with a high-resolution mapping of energy demands and available resources to understand the challenges and paths towards a climate neutral Europe by 2050. The research also highlights the importance of 2040 milestones, as most of the investment to develop a more resilient, affordable and sustainable heating sector must begin now. The key novelties we present in this report are:

- **An Enhanced Heat Atlas** with improved accuracy, incorporating three different future heat demand scenarios based on data from the FORECAST tool used in the EU research project sEEnergies (Mathiesen, Brian Vad et al., 2022b).

- **An Advanced GIS (Geographical Information System) Modelling** to identify potential district heating areas, covering over 60% of the market, enabling a detailed analysis of district heating scenarios ranging from minimal to extensive coverage.
- **An Integrated Refurbishment Energy System Analysis of Heat Supply Options examining** three different refurbishment levels in combination with varying district heating levels to assess their impact.
- **A Comprehensive Waste Heat Assessment** evaluating current and future waste heat sources to explore their potential integration into district heating networks considering temporal and geographical boundaries.
- **A Multi-Level EU and National set of Analysis is** conducted for the EU27 level and national levels, considering multiple district heating market share scenarios as part of a fully decarbonised energy system by 2050.
- **A Strategic City Mapping where** cities with exceptionally optimal district heating potential, integrating renewable energy and waste heat from both conventional and unconventional sources while factoring in district heating investment costs.
- **An Estimation of Investment needs** to develop heating infrastructure in the perspective of a fully decarbonised energy sector by 2050, with milestones for 2030 and 2040.
- **A large set of Exploitable Results** for further research and feasibility analyses from energy system analysis on the EU level and for Germany, Spain, France, Hungary and Poland as well as for district heating grid costs and waste heat estimations for the EU27 countries.

The development towards a decarbonised energy system

To understand what a future decarbonised heat market entails we also need to understand the energy system context of such a future heat market. The results suggest to gradually combine the increased electrification with a **complete redesign of the heat markets** including a utilisation of the vast amounts of renewable and waste heat sources can create a robust and cost-effective energy system which has both a higher security of supply and can meet the decarbonisation targets. This also effects the rest of the energy system and requires a strong focus on renewable electricity.

In Figure 1 the primary energy supply of the scenarios for the decarbonised energy system in 2050 is illustrated together with potential 2040 and 2030 the steppingstones towards the integrated 2050 smart energy system for all sectors. Note that the system design is robust as to stay within the limits of renewable energy from wind power, PV and bioenergy due to energy efficiency measures and the energy system redesign. This 2050 energy system is just one of many possible designs of the heat supply analysed in this project for 2050.

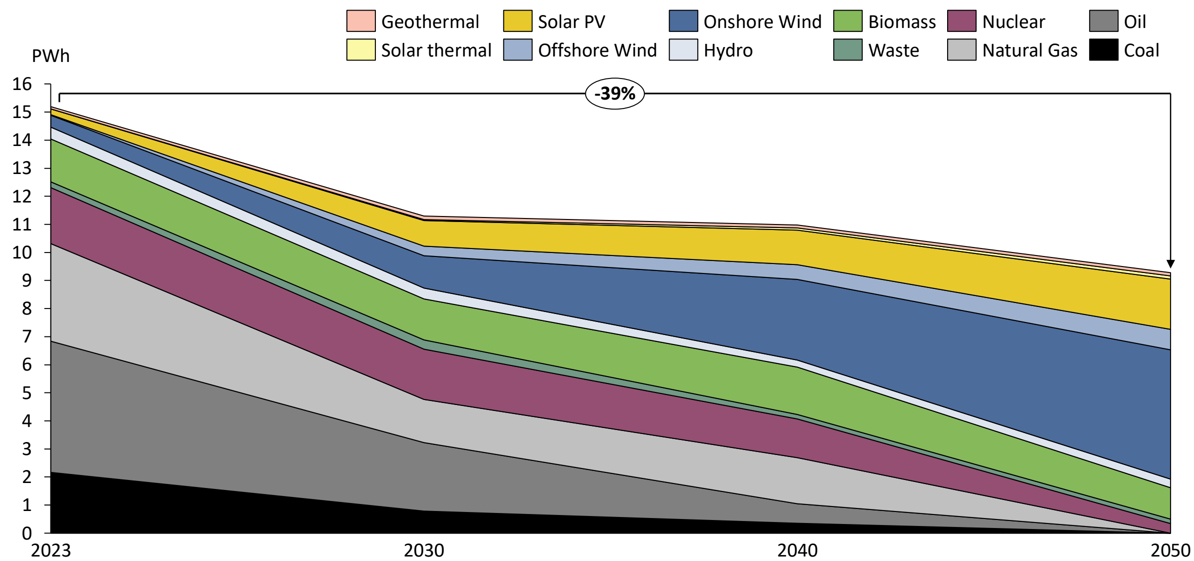

Figure 1. Primary energy supply in 2023, 2030, 2040 and 2050 for all sectors in EU27.

Onshore wind power, offshore wind power and PV in 2050 amount to 4,61, 0,73 and 1,79 PWh production based on an installed capacity of 1.985 GW, 221 GW and 1.634 GW respectively. Nuclear power also contributed in 2050 and is expected to provide 130 TWh based on 21 GW capacity. Apart from heating the **transport sector and the industrial sector** is completely decarbonised with the majority electrified in industry and transport and with power2X and hydrogen for mainly aviation, shipping and hard to electrify industries. There are vast waste heat sources in such future energy systems – from power2X but also from the decarbonised industry in Europe.

In Figure 1 a general decrease in the overall primary energy demand. There are five main drivers for this gradual reduction towards a smart energy system:

1) Increased insulation of buildings creating a lower heat demand, especially during the cold season – an end demand efficiency improvement.
2) Increased use of renewable energy systems eliminating the losses in producing electricity in power plants and combined heat and power plants – a system efficiency improvement.
3) Increased use of waste heat and renewable heat in district heating grids replacing fossil fuel boilers – a system efficiency improvement.
4) Increased electrification of all sectors, industry, buildings, mobility - system efficiency improvement.
5) Use of several energy carriers and storages between the production of electricity, heat and power2X fuels and the end demands

In Figure 2 the development of the demand pr. sector until 2050 is illustrated. This fundamental energy system redesign entails that industry is electrified where possible, electrolysis producing hydrogen for mainly synthetic fuels for aviation and shipping as well as for hard-to-abate industries. Buildings use mainly heating and electricity and the electricity for cooling increases while the demand for heat decreases as illustrated in Figure 5.

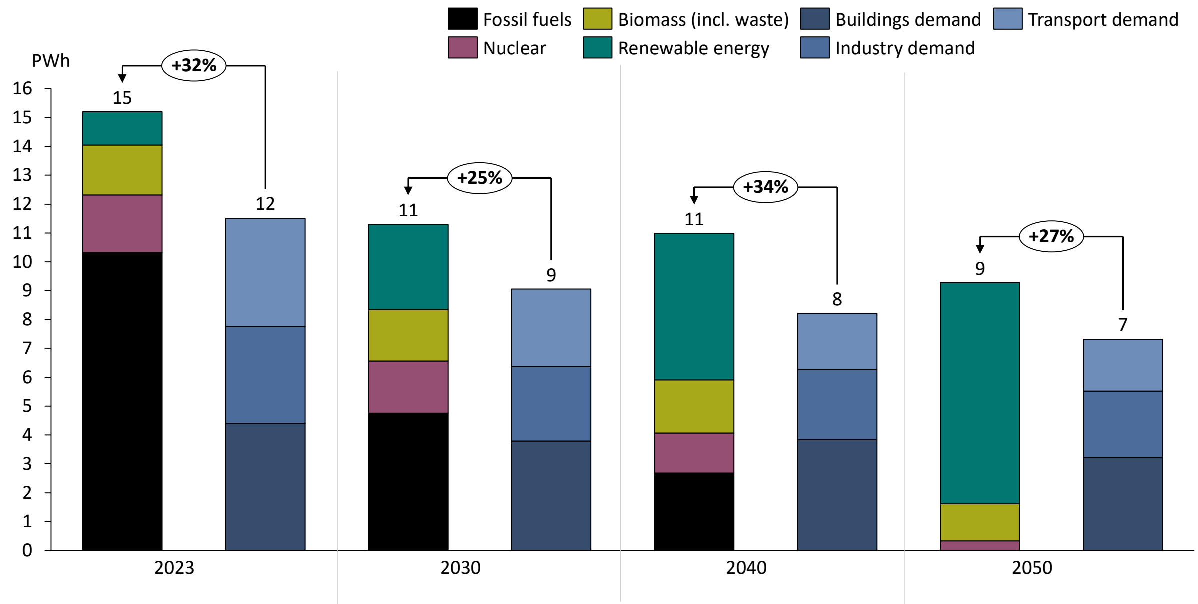

Figure 2. Primary energy supply and end demand development pr. sector towards 2050.

Large investments in the energy system enables an energy system which is self-sufficient and has a high security of supply replacing the costs of importing fuels. Until 2050 the fossil fuel and biomass consumption are decreased substantially. The results in the 2050 recommended scenario enable a low consumption of biomass of 1,1 PWh or approximately 10 GJ/capita a year which is well below the 15-40 GJ/capita range for the potential for sustainable biomass within the EU. Which in turn enables biomass also for materials for products, chemicals etc.. The energy system redesign that enables this will also reduce the use of fossil fuels in the transition period and is achieved with the five drivers mentioned above. The use of solid or gaseous fuels in the future heating system is very limited to peak load situations and for security of supply in both the electricity and heating sectors. The power plant and combined heat and power capacity supporting the electricity grid is in the same range as today, but the operation hours are 5-15% meaning that the waste heat is also very limited.

Accelerating the EU heat transition for a sustainable, resilient and competitive Europe

In order to achieve the overall redesigned smart energy system in 2050, the heat market's structure needs to change fundamentally. The redesigned more efficient heating sector is able to be a flexible market player absorbing waste heat and renewable heat using thermal storage and mega heat pumps to exploit cheap renewable energy electricity. The results show that the key features of an adaptive, decarbonised and resilient heat market and district heating systems are a combination of three key elements: heat savings in buildings, district heating in urban areas and individual heat pumps predominately in rural areas.

A wide range of heat supply options have been analysed varying the district heating markets share from 5% to >60% combined with an assessment of the feasible level of heat savings - moderate, ambitious, and very high savings of respectively 16%, 43% and 53% by 2050. In energy system analysis this is seen in the context of several future climate neutral and resilient energy system scenarios in 2050 as well as GIS analyses, see Figure 3.

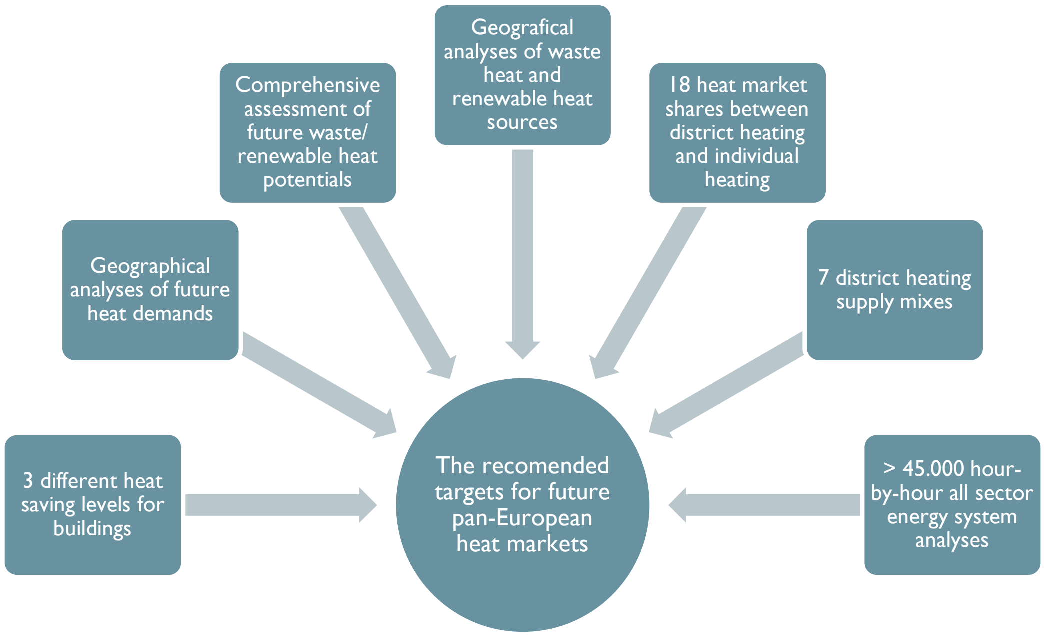

Figure 3. Simplified illustration of the inputs and analysis to reach a recommended 2050 energy system and a future heat market and layout.

The future of heating in urban areas depends on the transformation of the existing traditional district heating systems into **adaptive systems** as well as an expansion of the district heating networks with a supply system that enables flexibility and integration of diverse energy sources. In rural areas individual heat pumps provide the most efficient and robust option that can also be combined with solar thermal and a limited amount of biomass boilers using local resources. Together, they provide a foundation for a more efficient, low-carbon, and economically robust heating sector. In Figure 4 the main features of the recommended future decarbonised heat market in Europe is described, including the main recommendations resulting from the analysis. In the following sections we will elaborate on these results.

The transformation of the heating sector is a key element in achieving a smart, resilient, and decarbonised energy system. In urban areas, this transformation depends on the development of adaptive district heating systems and the introduction of heat markets that allow for flexibility, integration of renewable energy, and improved efficiency. Together, these elements support a low-carbon heating future by enabling a dynamic interplay between supply and demand while leveraging local resources.

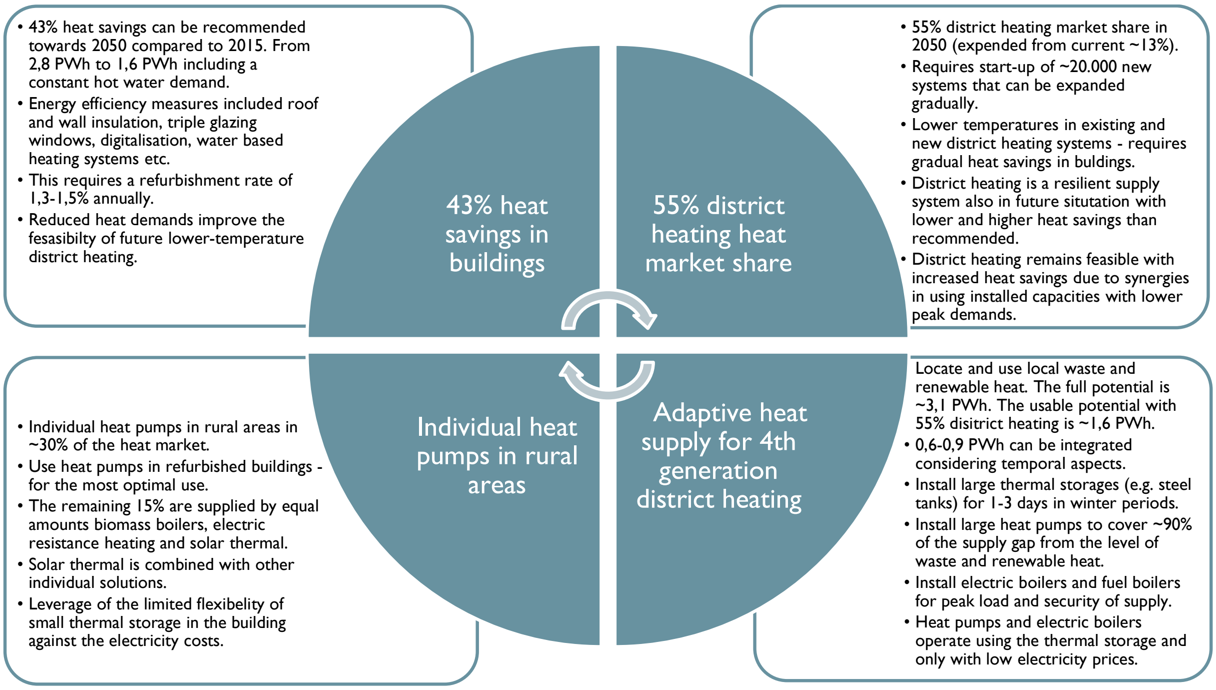

Figure 4. Main structures in future decarbonised heat market.

An adaptive district heating system is designed to respond flexibly to varying conditions in heat demand, ambient temperatures, and electricity prices. It relies on a wide range of heat sources, including waste heat from industry, data centres, heat from electrolysis, wastewater treatment and others, as well as the renewable sources geothermal and solar thermal. Power-to-heat technologies, including electric boilers and large-scale heat pumps together with large-scale thermal storage, play a critical role, particularly when electricity prices are low.

The full available potential of local waste and renewable heat sources in 2050 is estimated to be 3,11 PWh, out of which 1,2 PWh is renewable heat and 1,5 PWh are traditional and unconventional heat sources and 0,36 PWh stems from power production plants. Approximately 1,57 PWh is considered technically possible to use. The full potential is reduced due to the vicinity to heat demands and given the temporal aspects of the heat demand over the year.

Further, given the geographical and temporal constraints, energy system analyses, heat savings in buildings and energy supply technology costs 676 TWh of the full available potential is considered usable. This also takes into account that some resources are located in the same urban areas. This level is used in the recommended supply scenario for the district heating coverage of 55 % of the market share. This is assessed feasible considering the costs of the construction of district heating grids, the supply system and the decarbonised energy system context. This also means, that the expansion of district heating networks is robust, as the access to current and future waste heat and renewable heat is vast, and much larger than implemented here. Should the end savings in buildings be less ambitious towards 2050 or hard to implement i.e. not achieve the 43% savings, waste heat can still cover substantial parts of a larger heat demand. This also means that the 55% market share for district heating is robust.

A central feature of adaptive systems is their ability to operate at low or ultra-low temperatures, corresponding to **4th generation district heating**. These lower temperatures reduce distribution losses, increase the COP[1] of large-scale heat pumps and waste heat from waste to energy. Overall it increases the feasibility of using and integrating decentralised and intermittent sources with lower temperatures. This is particularly important in newly refurbished buildings that require less heat input. The may be areas where refurbishment to a level that is suitable for low temperature grids is not possible, e.g. in old city centres. In such cases 3rd generation district heating is suitable. In any case it can be feasible to prepare also investments in 3rd generation district heating for future lower temperature district heating solutions.

Achieving energy savings in buildings is crucial and this study shows that a **43% reduction in heat demand** by 2050 compared to 2015 is feasible from a resource point of view and with similar costs compared to today. The demand is reduced from approximately 2,8 PWh to 1,6 PWh annually, even with constant hot water usage. These savings require refurbishment measures such as roof and wall insulation, triple-glazed windows, water-based heating systems, and digitalisation. To achieve this, **an annual refurbishment rate of 1,3 – 1,5%** is needed considering energy improvement with other renovations cycles. Three levels of savings in buldings have been analyses: Moderate savings, 16%, ambitious savings, 43% and very high savings 53%. The 53% savings being equal to the level in the report a Clean Planet for All (European Commission, 2018).

- A 43% reduction in end-use heat demands compared to moderate savings in 2050 is equivalent to 0,5 PWh. This not only lowers overall energy consumption but also enhances the feasibility of low-temperature district heating and reduces peak loads. This leads to lower required capacities and consequently lower system CAPEX. Furthermore, these reductions generate significant savings on the system level equivalent to around 280 TWh savings. Still, moving to ambitious savings by 2050 entails slightly higher total heating system costs, particularly if not combined with an increase to a 55% district heating share. Yet, such ambitious savings substantially reduce dependency on both biomass (120 TWh) and renewable electricity (160 TWh) generation, leading to a more resilient energy system that is less vulnerable to fluctuations in fuel and electricity prices.
- Increasing heat savings from ambitious (43%) to very high (53%) provides direct end-use savings of ~280 TWh. This results in biomass savings of about 50 TWh and 70 TWh renewable electricity savings across the full energy supply chain. The savings in the end-demand results in lower savings in the primary energy supply input, i.e. compared to 120 TWh, due to a rather efficient energy system design. Also achieving these higher savings requires a combination of hot-water demand reduction and costly refurbishment measures that may also be hard to implement. The marginal system level cost of reducing biomass and renewable electricity consumption when going from 43% to 53% end building level savings is about 3 times higher per kWh compared to progressing from moderate to ambitious savings. Should there be an ambition to increase savings to this very high level, district heating still provides the most feasible option, as the unit costs of heating systems in the building level is higher in efficient buildings and as district heating systems provide an option to utilize waste heat and renewable electricity and heat.

Adaptive systems are supported by advanced control systems, using thermal grids, thermal storage and the components in the concrete plant to either use or produce electricity at the right times. The thermal storage enable the shifting of heat consumption to periods when energy is cheaper or more abundant. Buildings' thermal inertia is also used to balance demand. **Thermal energy storage** should be installed in most cases, e.g. in the form of large steel tanks that can store enough heat to cover one to three days of winter demand in the supplied areas. Seasonal pit storages are only relevant in smaller communities – typically >10.000 inhabitants – with low land costs.

[1] COP: Co-efficient of performance. The electricity input compared to the heat output. The COP varies with the heat source temperatures and the temperature needs.

These systems support sector coupling by integrating with the electricity grid**. Large heat pumps can cover more than 90% of the supply gap between waste heat and renewable heat**, while electric boilers can provide peak load capacity. In cases of extreme demand, emergency or planned maintenance, fuel boilers can still be used to ensure security of supply. Heat pumps and electric boilers are typically operated using low-temperature waste heat, but can also use seawater and geothermal sources. They are activated when electricity prices are low, enabling both cost efficiency and grid flexibility.

The design of adaptive systems is modular and decentralised. Local waste heat sources or large heat pumps can be integrated as the system expands. This design enhances resilience and enables the stepwise development of infrastructure suited to the needs of different areas. District heating grids play an essential role in enabling adaptive systems. By 2050, the aim in the recommended scenario is to **increase the district heating market share to 55%,** up from roughly 13% today. Achieving this will require the establishment of **~20.000 new district heating systems**, which can be gradually expanded. Importantly, district heating remains a viable and resilient solution even under scenarios with lower-than-expected or higher-than-expected heat savings, due to the synergies in storage, the optimised use of installed capacities and vast amounts of waste heat and renewable heat.

A well-functioning heat market allows open access to infrastructure and competition among producers, including industrial waste heat providers and independent renewable suppliers. Transparent pricing mechanisms that reflect production costs, supply-demand dynamics, and carbon pricing can incentivise low-carbon solutions and help balance the system. Standardised contracts for heat delivery and flexibility services will be essential for reducing transaction costs and ensuring reliable operation, as well as a local engagement with citizens, local ownership and cost-real pricing.

While adaptive district heating systems and heat supply markets will serve the majority of urban areas, **individual heat pumps will continue to play a key role in rural areas**. These are expected to serve about 30% of the total heat market. They require refurbished, energy-efficient buildings. The remaining ~15% are supplied by biomass boilers, electric resistance heaters, and solar thermal systems, where the solar thermal is typically integrated with either of the other individual supply options. These solutions use small-scale thermal storage and are best suited for buildings located outside dense urban areas, where district heating is not economically viable.

In summary, the future heating system will rely on a combination of energy efficiency, adaptive district heating, sector integration, thermal storage, and well-regulated heat markets. Together, these elements will ensure that heat is delivered in a secure, cost-effective, and climate-friendly way – tailored to the specific needs and resources of different regions.

Recommended key technologies for a new EU27 resilient and decarbonised energy system

The recommended 2050 heat market shares and heat supply design is listed below for in the form of key technologies needed for a new heat market in EU27 by 2050 in combination with intermediate 2030 and 2040 targets. In Figure 5 the development in the supply share and supply technology is illustrated with a gradual lower demand and a gradual development towards a higher market share of district heating. Large-scale heat pumps in district heating and small heat pumps meet more than half the heat demand.

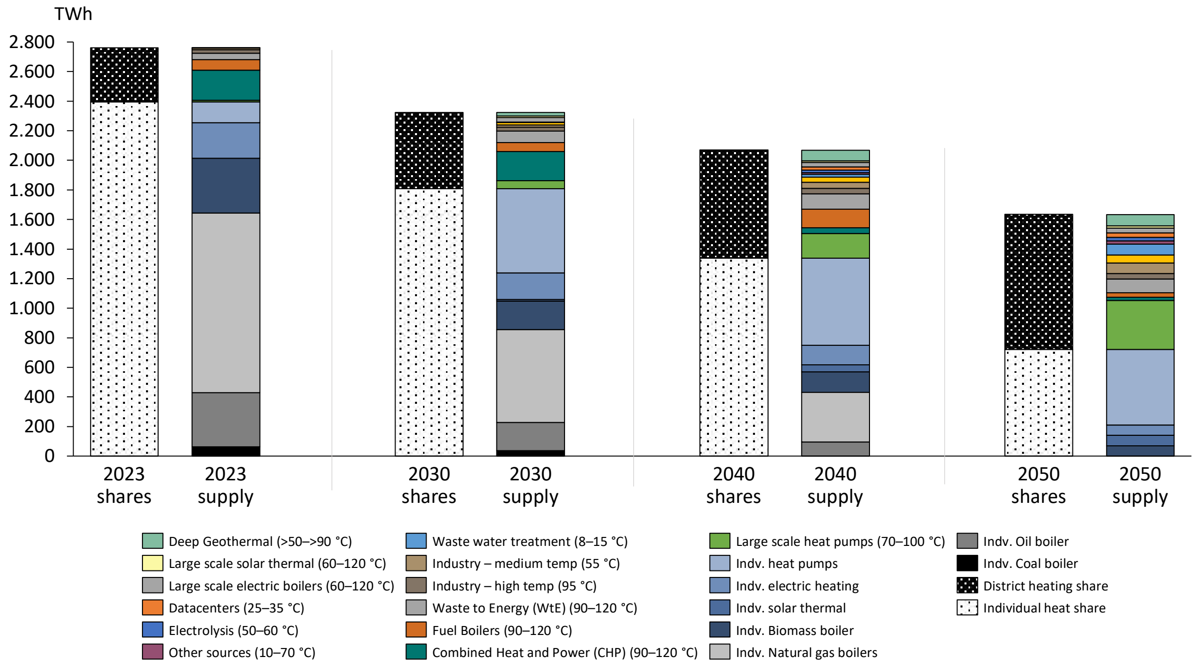

Figure 5. The development of the heat market, i.e. heating and hot water. Supply technologies and division between district heating and individual solutions. Industry sources, wastewater treatment, supermarkets and in some instances geothermal need large scale heat pumps. In this figure these sources are extracted heat amounts not including the electricity contribution from heat pumps. The heat pump contribution to those sources is included in the large-scale heat pump category. Grid losses are excluded.

The investments below more than out-way the reductions in costs due to lower fuel consumption, phase out of fossil fuels in the heating sector, and higher amounts of local renewable energy and waste heat sources. The investments listed are large but should be seen in the light of a total energy and transport system costs in 2050 of about 1,8 trillion € annually, see Figure 12.

- **Refurbishment of buildings** should have a high priority. Until 2050 about 2,0 trillion € investments is needed in the sector due to energy saving measures. Ambitious heat savings is recommended equal to the total heat demand in buildings reduced by 43% by 2050 compared to 2015 levels (2030: 8%; 2040: 25%). This requires a refurbishment rate of 1,3-1,5% pr. year. These investments are instrumental to reduce heat demands with energy efficiency measures - roof insulation, triple glazing windows, digitalisation etc. - and to enable the expansion of lower-temperature renewable and waste heat sources. The heat demands in buildings are reduced from 2,8 PWh to 1,6 PWh in 2050. These investments have a lifetime of 40 years on average.
- **An expansion of the district heating grids to cover at least 55% of the heat market** is recommended from the ~13% today. This is equivalent to 0,9 PWh in heat and hot water demand. The 55% district heating market share is robust also with lower building insulation levels. Until 2050 1,16 trillion € in investments is needed in the low temperature 4th generation district heating infrastructure alone, enabling savings in other investments and fuel consumption. Milestones of 20% and 33% are recommended for 2030 and 2040 to reach the 2050 level requiring investments of ~320 billion € by 2030 and 540-610 billion € by 2040. Current district heating grid replacement costs are estimated to be ~190 B€ and is included in the investment figures for 2030, 2040 and 2050. These investments have a lifetime of 40 years on average. These targets require an acceleration of investments to a growth rate of about 7% pr. year and investment growing towards 70 billion € annually by 2030. France and Germany achieved 6% this from 2019 to 2023 and Austria achieved 6% in a period from the 1980's until now. A high growth rate is achievable with a targeted policy. After 2030 a more moderate growth

rate of 5% can achieve the long-term targets. On the EU level the expansion rate was about 2,3% pr. year in recent years.

- Existing 2nd and 3rd generation as well as new district heating grids is recommended to **transition to low temperature 4th generation district heating**. This is well suitable to better insulated refurbished buildings and enhance the efficiency of all heat supply technologies. The up-front grid investment cost for 3rd and 4th generation is 1,12 and 1,16 trillion €, i.e. 30 billion € in difference. But overall from the systems perspective the lower temperature levels provide system level energy savings of about 3-6% depending how you compare the scenarios. Partly due to lower losses, higher efficiencies of technologies e.g. heat pumps and partly due lower biomass input in winter periods on the energy system level. If supply mix has little or no waste heat included the advantages of going towards 4th generation district heating are comparably higher due to higher fuel consumption when the waste heat utilisation is reduced. The 55% district heating market share is robust also with fully or partly 3rd generation district heating systems.
- The district heating supply is covered by a range of technologies, see Figure 6 and Figure 7. Below the inputs for the district heating grid in the recommended scenario is listed before grid losses (~20-23%):
    - **Large-scale thermal storage** in district heating creates the flexibility and local robustness in the use of electricity combined with waste heat sources and renewable heat. A total storage capacity of about 11 TWh[2] in 2050 is recommended with 2030 and 2040 levels of 4,4 and 6,9 TWh respectively. The investments are 13, 27 and 44 billion € for the three target years respectively. Today the thermal storage level is likely >0,5 TWh. This is typically large steel tanks able to uphold 1-3 days of supply in cold periods and will depend on local conditions. Such thermal storages can cover heat demands 4-7 days in the summer.
    - **Renewable heat and waste heat sources** cover 54% of the district heating production in the recommended diversified heat supply configuration. The sources in the recommended scenarios are listed as the direct input from each source before use of heat pumps to elevate the temperatures where needed. The supply mix only illustrates one of many possible heat exploitation scenarios for 2050:
        - Geothermal heat covers ~8% or 98 TWh
        - Large scale solar thermal covers ~2% or 22 TWh
        - Waste heat from waste to energy plants (WtE) covers ~10% or 121 TWh
        - Waste heat from the decarbonised 2050 industry covers ~18%:
            - Industry high temperature heat: 48 TWh
            - Industry medium temperature heat: 93 TWh
            - Industry low temperature heat: 68 TWh
        - 20% of the 200 TWh heat potential from data centres is utilised covering 3% (40 TWh) and 20% of the electrolysis waste heat is used coverting 3% (33TWh)
        - Waste heat from wastewater treatment plants (WWT) covers 99 TWh (8%) and waste heat from supermarkets and metro stations cover in total 25 TWh, a total of (~2%)
        - Additionally, 676 TWh waste heat is available as future untapped potential sources exchangeable or additional with the sources above provided the right geographical and temporal conditions are present. This represents additional waste heat from geothermal, solar thermal, industry, WWT, data centres, nuclear waste heat, electrolysis respectively in 2050: 153 TWh, 102 TWh, 119 TWh, 9 TWh, 161 TWh,

[2] The current battery capacity installed in EU27 is expected to reach about 75 GWh in 2025 and to growth to above 300 GWh in 2030 (Solar Power Europe, 2025). Electricity storage cost in Battery Energy Storage System is ~100 times more expensive than thermal storage systems considering lifetime and expected cost reductions (Danish Energy Agency, 2018)

12, 131 TWh. This heat is not used in the recommended diversified heat supply configuration but is in principle useable if the costs are low enough.

- Technically slightly higher amounts could be integrated than suggested here e.g. by placing data centres close to areas with no industrial or geothermal heat. If the heat sources are places in the vicinity of heat demand with district heating grids theoretically waste heat can cover about 73% of the heat demand. This considers energy system analysis i.e. the temporal aspects of waste and renewable heat sources compared to the heat demands.

- **Large-Scale heat pumps** or mega heat pumps cover 36% (430 TWh) of the district heating production in the recommended supply scenario to have a capacity of 24 GW_e[3] in 2050 (2030: 7,9 GW_e; 2040 14,1 GW_e). They have an operation time between 25% to 40% depending on the concrete circumstances, they partly utilize lower temperature waste heat sources and geothermal heat as well as thermal storages to enable large-scale use of low-cost electricity sources. The investments are 24, 36 and 61billion € for the three target years respectively.
- **Large scale electric boilers** are installed to create low-cost flexibility to exploit very low electricity prices and cover 3% (40 TWh). The operation time should be lower than 15%. A total capacity of 33 GW in 2050 is recommended with an investment level of 4 billion €.
- **Large-centralised boilers** are needed for security of supply, maintenance of other heat supply plants and for peak load situations. They should have a very low operation time as it is an in-efficient heat supply technology and cover 3% of the production. The total capacity in 2030, 2040 and 2050 is 150, 200 and 225 GW.
- **Non-baseload Combined Heat and Power plants (CHP)** contribute to only 3% of the heat supply in the recommended scenario of district heating supplying 55% of heat demands from buildings by 2050. Where feasible, replacing conventional power plants with combined heat and power (CHP) plants can enable use of the access heat. By 2050, both CHP and conventional power plants should reduce their operational time significantly, from current base-load operation levels of over 50% annually to just 5–15%. While the operation of the power plants requires 490 TWh of fuel and in principle could provide 235 TWh, only 30 TWh is usable. Many of the production hours will occur in the wintertime meaning that there is an option of using the waste heat from electricity production and also to lower the electricity production costs in those hours. This shift is driven by the need for flexible generation to accommodate large shares of wind and solar power, alongside the continued base-load contribution from existing nuclear power. Despite these changes, the required electrical capacity of CHP and power plant installations in 2050 remains similar to today to ensure a stable power supply, at times with no wind and solar, at approximately 480 GW.

- The remaining 45% (~720 TWh) of the heat market is covered by individual solutions, mainly with **individual heat pumps** for a total of 201 GW_e installed capacity covering 510 TWh demand. This is combined with 70 TWh small solar thermal in 2050. Also supplemented by 70 TWh of conventional electric heating and by a small share of biomass boilers providing about 70 TWh of the heat demand.
- **Bioenergy has a changing role** and will primarily be focused on security of supply as well as covering peak demands. The biomass in a future system will go more towards the electricity and industrial sectors compared to today, preferably in the form of biomass or gasified biomass. In the heating sector biomass boilers may create a solid security of supply, but the utilisation hours will be very limited.
- There is a large potential for **district cooling** for space and process cooling. Cooling demands are expected to grow from about 200 TWh currently to about 450 TWh in 2050 but is not expected to

[3] GW_e capacity on the electricity input side.

represent more than 20% of the total heating and cooling sector in total in Europe in 2050 (Paardekooper et al., 2018), i.e. the heating sector remains more important. Today the cooling compared to the total heating and cooling demand excluding hot water is 5-10%. The majority is in the service sector where there is a vast district cooling potential (e.g. offices, hospitals, schools, and commercial buildings). The spatial analysis and energy system modelling that lead to this result are not as methodologically robust as those for the heating market hence the 450 TWh demand is likely an underestimation of the potential.

The consequences of utilising waste heat and renewable heat are significant. While the share of district heating is expected to increase substantially, the use of more traditional heat sources from CHP plants and fuel boilers will decline - both in relative terms and in absolute TWh of delivered heat, see Figure 6.

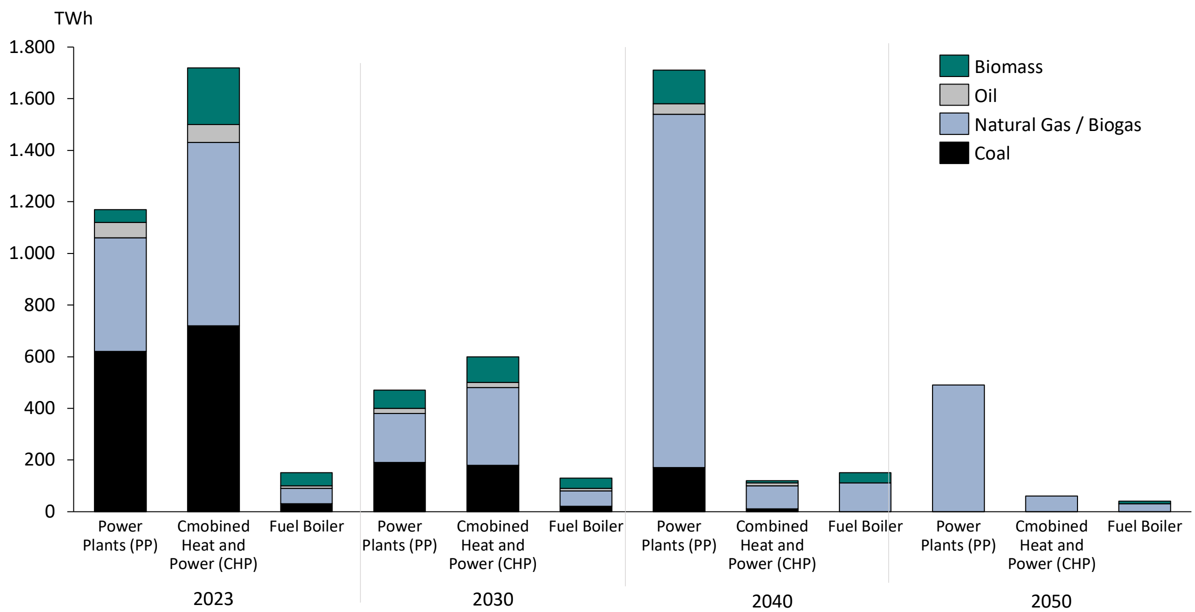

Figure 6. Fuel consumption in power plants, CHP plants and fuel boilers towards the recommended scenarios in 2050, including the fuel mix.

This transformation of the heat market structure by 2050 is essential to unlock the full potential of Energy Efficiency 2.0 and to enable the integration of the electricity and district heating systems. Achieving a higher share of renewable electricity requires that:

1. less electricity is generated in conventional power and CHP plants, and
2. electricity is used more flexibly within the heating sector in large-scale heat pumps combined with thermal storages and across other sectors.

In turn, this shift paves the way for a wider range of both conventional and unconventional heat sources—used directly or indirectly - alongside large-scale heat pumps. In Figure 7 the district heating production mix is illustrated before the losses in the district heating grids in order to illustrate the changes in the overall supply structure as we as to illustrate the demand level in comparison to the overall potentials of waste heat and renewable heat sources.

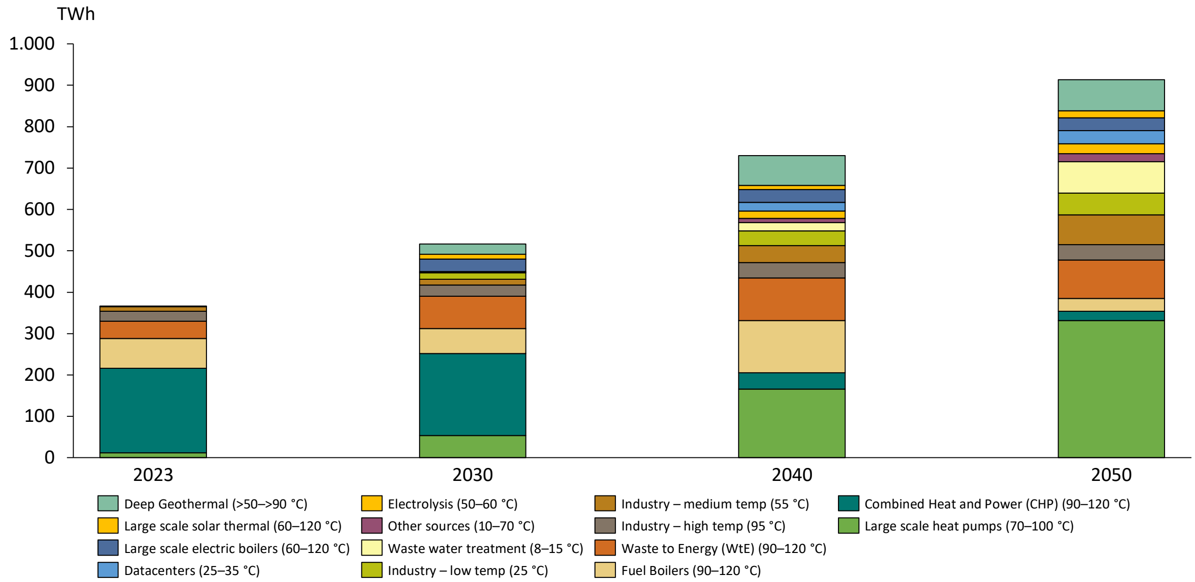

Figure 7. District heating supply mix from 2023 until 2050 excluding grid losses in the recommended mix and share.

Fact Box 1. The World's largest natural refrigerant seawater heat pump for district heating

Case: Aalborg's shift to a flexible district heating market player – 177 MW Seawater heat pump

Location: Aalborg, Denmark (approx. 200.000 people)
Project: Norbis Park Seawater Large-scale heat pump plant
Technology: Large-scale CO_2-based heat pump + thermal storage

Aalborg is pioneering the electrification with the largest seawater heat pump installation globally for district heating based on natural refrigerants. It will enable renewable electricity to be utilized when low price, replacing fossil fuels and biomass. In periods with high prices the thermal storage creates up to 9 days of flexibility if electricity prices are high. Together with the other supply options this completely replaces fossil fuels and biomass. The plant will deliver one third of the heat demand. The other two thirds are delivered by waste heat from industry (mainly Portland) and from waste heat from waste to energy (WtE). Key Features:

- 177 MW heat output from 4 CO_2-based heat pump lines at 3 °C seawater. 1 MWh electricity → 3 MWh heat (annual average COP ~3.0). 2/3 of the heat is from seawater and 1/3 from electricity (incl. own renewables). It maintains performance even at low seawater temperatures. 67 MW in maximum electricity demand.
- 180 MW electric boilers connected to the thermal storage as well.
- Produces heat up to 98 °C, suitable for existing DH networks – normally 90 °C out / 38 °C return
- Uses existing seawater infrastructure from the former coal power plant
- Environmentally friendly natural refrigerant (CO_2) and rapid load regulation that supports grid flexibility
- 250.000 m³ thermal storage integration enables system balancing and sector coupling (including the existing 50.000 m³) The thermal storage can cover heat demands in 1-3 days in cold periods and 4-7 days in the summer. With gradually improved insulation of buildings these periods can increase.
- Ability to rapid regulation on the electricity side helps to optimize the operating economy in combination with thermal storage.
- Construction of buildings started April 2024 and of technical systems in May 2025, first tests will be in June 2026, and the final testing and commissioning is expected in April 2027. The picture below shows the four new 50.000 m³ thermal storage tanks in Aalborg.

The vast waste heat and renewable heat sources in Europe

The Energy Efficiency 2.0 principle used in the modelling results in a radically different fuel mix in district heating systems. The district heating systems combine waste heat and renewable heat with smart electrification. The concrete local district heating mix depends on the local resources. In order to assess the utilisation of waste heat sources and renewable heat these have been quantified using several geographical and temporal methodologies. The current waste heat levels are compared to the current heat demands in buildings for EU 27 in Figure 8. Using energy system analyses the potential use of these sources has been estimated to be 30% with a hypothetical level of district heating at 55%. Currently the utilisation is about 7% where 5% is from combined heat and power (CPH) and 2% is from mainly high temperature industry heat sources. In the following the potentials are described together with an assessment of the future potential use of waste and renewable heat sources.

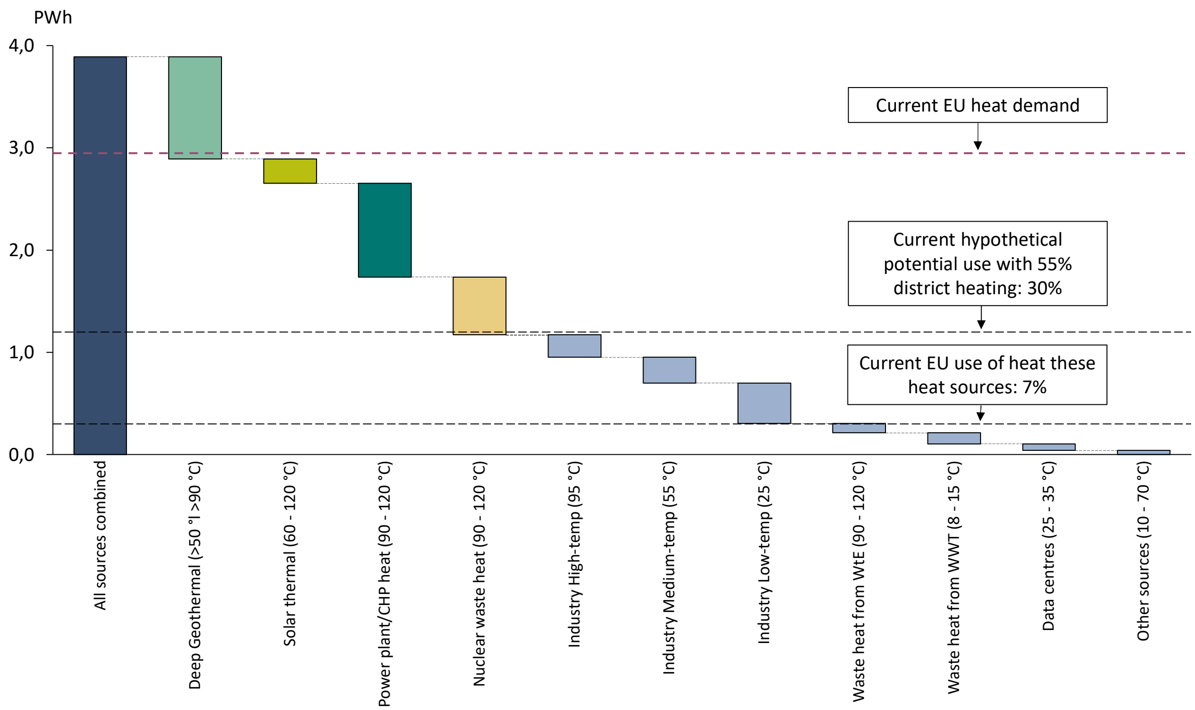

Figure 8. Diagram of the current EU27 heat sources combined and divided into sources. The sources are compared to the current heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands. WWT: wastewater treatment. WtE: waste-to-energy, other sources include supermarkets and metro stations.

The sources mapped give a full potential of 3,8 PWh. This is a combination of geothermal heat and solar thermal, power plants and CHP plants, nuclear waste heat, industrial waste heat with difference temperature levels, waste heat from waste to energy (WtE or waste incineration), data centres as well as waste heat from wastewater treatment plants, supermarkets and metro stations. Parts of this potential is out of reach from a temporal perspective and parts due to the geographical vicinity of heat demands. However the potential for synergies between the sources from other sectors and district heating for buildings is still vast:

Waste heat can theoretically about 90% the full current heat demands in buildings in EU27 counting in waste heat from electricity production. Not all these sources will be there in the future. Adding also the renewable heat sources from geothermal and from solar thermal, **the combined potentials can theoretically cover ~130% of the current heat demands**. In practice though, this will not be the exploitable level. Solar thermal is suitable for smaller cities and sometimes in combination with large thermal storages while geothermal is suitable in larger urban areas. While the geographical analyses of the location of the heat sources is important, heat demands are seasonal and most sources constant during the year making the temporal aspects equally important. This limits the utilisation of solar thermal and geothermal. The analyses show that with 55% district heating coverage, renewable heat and waste heat can cover up to 73% of the district heating production today, utilising about 30% of the current potential. The challenge is to understand the potential and possible use of these sources in a future with much more efficient buildings.

In Figure 9 the potential future waste heat and renewable heat sources are illustrated. Supermarkets and WWT as well as renewable heat potentials may be the same today and in 2050, but this may not be the same for all waste heat sources e.g. in industry that is being gradually decarbonised.

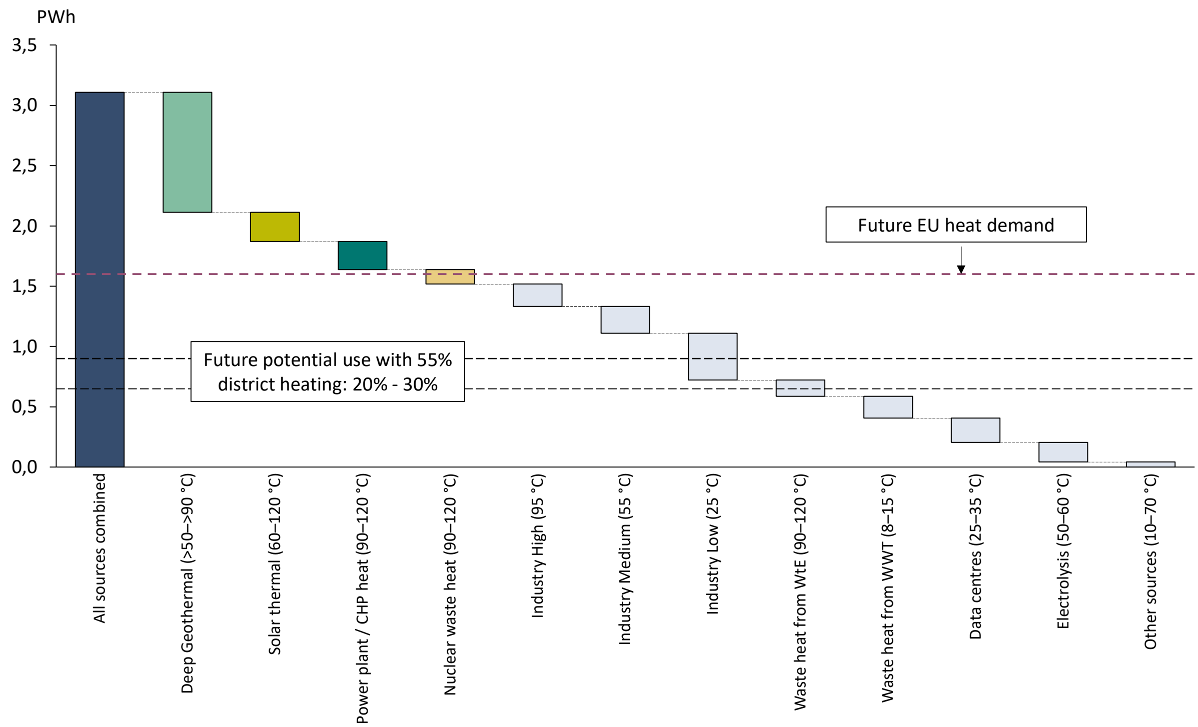

Figure 9. All future EU27 heat sources combined is illustrated as well as divided into sources. The sources are compared to the future heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands except data centres and electrolysis. WWT: wastewater treatment. WtE: waste-to-energy is aligned with current and expected future recycling and circular economy policies and a geographically located closer to those areas that generate the waste, i.e. the geographical distribution is different compared to today. Other sources include supermarkets and metro stations

The estimation of the technical potential of geothermal sources considered the future heat demands and potential district heating systems and is based on the spatial intersections of these with the identified areas with geothermal potential, considering a base load heat demand. An additional criterion for estimating geothermal energy is based on the size of the potential district heating system, as investments in geothermal potential are not recommended in small district heating systems due to their high cost. In the recommended scenario a minimum of 40 MW potential is considered for base load heat demand. In Figure 10 the considered areas are illustrated. The full potential is 997 TWh however the usable potential is much smaller (~10 of this level).

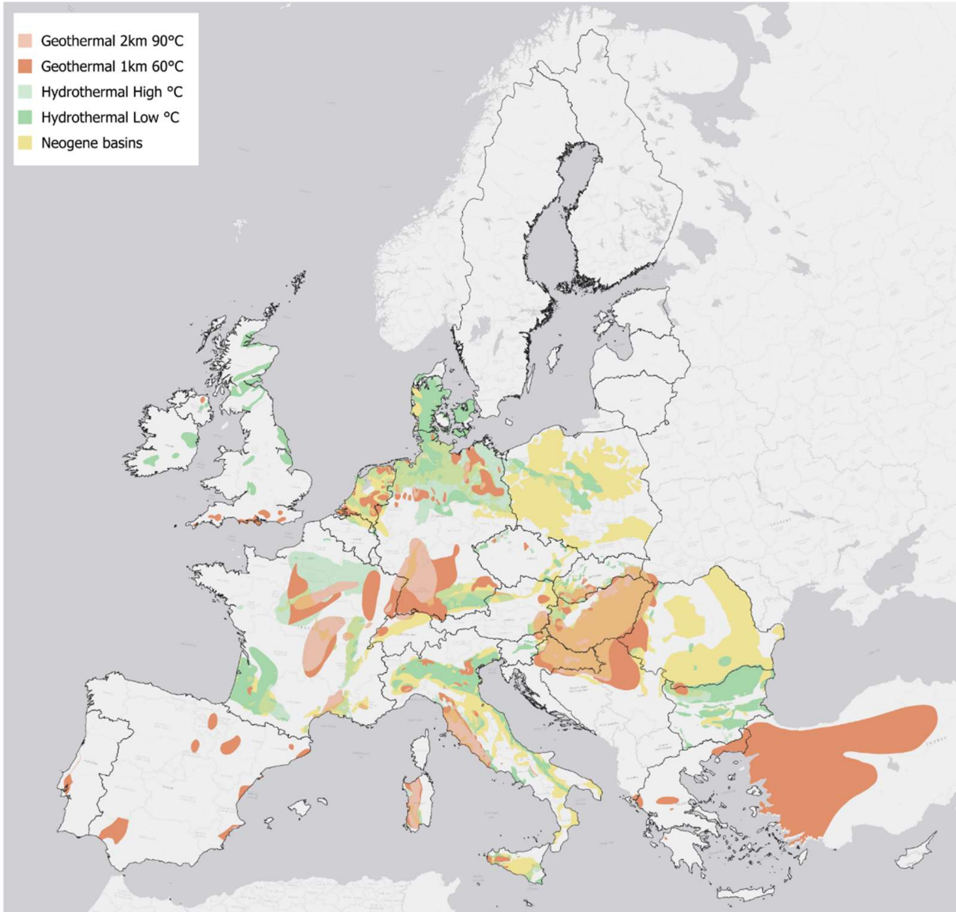

Figure 10. Areas with geothermal potentials in Europe.

Solar thermal plays a role in district heating; however it is limited by the seasonal nature of the sources. In the analyses here two sets of potentials have been considered with a focus on smaller communities, due to the possibility here to have also larger thermal storages together with solar thermal. The maximum potentil considering the temporal aspects of the source is assessed to be about 239 TWh, however the usable potential is much smaller (10-20 % of this level).

Waste heat from power production (CHP) is expected to decrease due to a redesigned energy system while the capacity for CHP and Power plants remains at the same level as today to ensure security of supply in the electricity grid when wind power and solar PV production is low. The operating hours should be completely aligned with the needs of the electricity sector and not the heating sector and will have an operation time of between 5-15%. While the future potential countries in the operation time of power plants may be 230 TWh heat, only about 30 TWh is usable. Nuclear waste heat is not used for district heating currently; however, it remains a source which is in principle useable had the geographical location been in closer vicinity to heat demands. Nuclear waste heat is expected also to be present in the future, but to a smaller extent. The largest potentials for nuclear wate heat in 2050 are found in France 83 TWh/y, Germany 12 TWh/y, Sweden 9 TWh/y, Spain 8 TWh/y), and Czech Republic 6 TWh/y. Together, these countries contribute about 118 TWh/y, accounting for more than 95% of the EU27 potential which in total is 123 TWh/y for nuclear waste heat in 2050. Due to geographical distances and lack of current utilisation the sources are not used in the recommended scenario. In any case due to temporal aspects the usable heat would be in the wintertime i.e. about 40-50% of the potential.

In a future fossil-free European energy system, total **industrial waste heat is expected to be about 10% lower than today**, but the volumes remain enormous, close to 800 TWh (2.900 PJ) annually across EU27 industries. The changes are uneven across sectors: iron and steel output drops by around half, while non-ferrous metals and non-metallic minerals also see clear declines. By contrast, chemicals and foundries remain almost stable, paper and pulp changes little, and heat from 'other' industries (including engineering, food, drinks and textiles etc.) even grows by up to 18%. (Johannsen et al., 2023; Mathiesen et al., 2023). Waste heat is not just a fossil fuel issue but a structural feature of many industrial processes, from chemical reactions to metal and mineral processing e.g. cement, which will continue to produce large amounts of recoverable energy even in an electrified, fossil-free economy even utilising best available technologies (BAT). Where possible industry is electrified and where not electrified, fuels such as biogas or hydrogen are used. With a higher degree of electrification or a higher internal industrial heat re-use than assumed here, the lower temperature heat sources may increase, but the total amounts of wasted heat can still give a significant contribution to district heating grids as available inputs for large-scale heat pumps.

Fact Box II. Recovery of waste heat

Case: Brescia's heat pump

Location: Brescia, Italy (approx. 200.000 people)
Project: Qarnot 2 project
Technology: Large-scale heat pump + heat recovery

Brescia has a district heating network that is one of the most advanced in Europe: over 684 km of pipelines connecting over 22,000 costumers, it reaffirms its role as a hub of ecological transition adding a waste heat recovery system from the steel mill to the citizens of Brescia. This upgrade is another step forward in the commitment to make district heating increasingly more sustainable.

Key features:

- 6 MWth systems that recovers waste heat and sends water up to 105°C.
- COP, coefficient of performance, of 8.46
- Saving 178 tons of CO_2-eq in 2025 heating season
- The system in the steel plant will provide the city with 50 thermal GWh

High temperature industrial waste heat (>95°C) is set to decrease by 15% and - as this is only a smaller part of the waste heat sources - the reduction is only 10% overall. Medium (55°C) and low (>25°C) temperature heat sources decrease 10% and 2% respectively. The high temperature industrial waste heat (>95°C) proportion remains around only 25 % of the overall available waste heat by 2050. On a country level; the largest contributions come from Germany (128 TWh/y), France (95 TWh/y), Italy (75 TWh/y), Spain (70 TWh/y), and Poland (32 TWh/y). Together, these five countries provide about 400 TWh/y, nearly three-quarters of the EU27 total industrial waste heat supply in 2050.

Waste heat from WtE is expected to remain at the same level but will be distributed differently across European countries. Even with tightened recycling and a focus on circular economy beyond the current EU targets in 2030, the amounts remain similar to today, due to the very high amounts landfilled currently. In the future landfill will be very limited and direct or indirect recycling will dominate. However, a fraction will remain for WtE. The largest potentials for WtE waste heat are in Germany (35 TWh/y), France (25 TWh/y), Italy (20 TWh/y), Spain (12 TWh/y), and Sweden (10 TWh/y). Together, these countries contribute around 102 TWh/y, making up more than 75% of the EU27 total of 133 TWh/y potential.

The **waste heat from datacentres** is projected here to increase to about potentially 200 TWh/y towards 2050. The largest potentials for datacentre waste heat are in Germany ~30 TWh/y, France ~25 TWh/y, the Netherlands ~19 TWh/y, Ireland 19 TWh/y, and Sweden 17 TWh/y. Together, these five countries account for about 110 TWh/y, which is more than half of the EU27 total potential by 2050. The potential has been estimated in this project using the latest forecast including expected gradual efficiency gains. The use of these heat sources will depending on the ability for member states to plan the location of these in the vicinity of district heating areas.

Wastewater treatment plants, supermarkets as well as metros are ubiquitous in urban areas, making them a promising source for heat recovery. According to the Reuseheat project (ReUseHeat, 2022), 84% of the EU population is connected to a sewage network, with higher concentrations in urban areas, of course. Wastewater carries thermal energy that can be captured and utilised to heat nearby buildings via district heating systems. The temperature of wastewater, which remains relatively stable throughout the year, can be used to extract heat through heat pumps. The full technical potential has been assessed combining these geographical data from Reuseheat with the data on heat demands in this project. WWT plants are assessed with locations and characterized by annual wastewater flow, average effluent temperature, and proximity to potential district heating networks. Supermarkets are identified from commercial databases and waste heat is estimated from refrigeration system capacity and operating hours. Metro systems are assessed via ventilation shaft locations, tunnel lengths, and waste heat temperature profiles. The potentials are 183 TWh, 31 TWh and 9 TWh for WWT, supermarkets and metro stations respectively.

In a future decarbonized energy system the need for **electrolysis** may be high due to the need for hydrogen mainly heavy-duty transport (shipping and aviation) as well as partly for industry and products. Energy system analyses reveal that the full potential of heat may be up to 164 TWh. Like for data centers the use of these resources will depend on the location of these new production facilities.

Only parts of the waste and renewable heat sources have been utilised in the recommended district heating scenario with 55% district heating. In fact there are many options to further develop scenarios or to exploit the data behind the recommended scenarios. In Table 2 the percentages of the use of the heat sources is listed as well as the mix. In between the technical potential with 55% district heating and recommended use scenario, geographical analyses is performed where lower cost sources such as e.g. industrial waste heat and heat from WtE is used before geothermal heat sources. Also e.g. solar thermal is not utilised if other sources available to cover the demands, as they are also able to cover heat and hot water demands for a larger part of the year.

Table 1. List of full potential renewable and waste heat sources in 2050, listed as the full future potentials, the technical potentials and mix with the recommended 55% district heating share as well as the percentage utilization rates.

	Future Full potentials (TWh)	Technical potentials 55 % DH (TWh)	Recommended use, 55% DH	% mix	Unused (TWh)	% of Full potential	% of technical 55% DH potential
Geothermal	997	250	98	8%	153	10%	39%
Solar thermal	239	124	22	2%	102	9%	18%
Reneable heat sources (Total)	**1237**	**374**	**120**	**10%**	**254**	**10%**	**32%**
Waste heat from WtE	133	121	121	10%	-	91%	100%
Industry High	186	52	48	4%	4	26%	92%
Industry Medium	224	100	93	8%	7	41%	93%
Industry Low	387	176	68	6%	108	18%	39%
Waste heat from WWT	183	107	99	8%	9	54%	92%
Datacenters' heat	201	201	40	3%	161	20%	20%
Electrolysis	164	164	33	3%	131	20%	20%
Others sources (supermarkets and metro)	41	28	25	2%	3	62%	91%
Excess heat sources	**1517**	**948**	**527**	**44%**	**422**	**35%**	**56%**
Renewable and excess heat	**2754**	**1322**	**646**	**54%**	**676**	**23%**	**49%**
Power plant/CHP heat	235	235	30	3%	205	13%	13%
Nuclear waste heat	123	12	0	0%	12	0%	0%
PP/CHP/nucler heat sources	**358**	**248**	**30**	**3%**	**218**	**8%**	**12%**
Excess heat , incl PP/CHP	**1876**	**1196**	**557**	**47%**	**639**	**30%**	**47%**
All incl. CHP/PP	**3112**	**1569**	**676**	**57%**	**893**	**22%**	**43%**

Heat market structure and heat supply configurations

In order to identify the feasible level of district heating, refurbishment rate and recommended 4th generation district heating, several different heat supply options have been analysed for each situation resulting in thousands for modelling results. The heat supply options draw on the results of the GIS analyses as well as the temporal energy system analyses. Different prioritizations have been modelled which allows to check and compare different configurations regarding system effects, resource efficiencies and costs. In Figure 11 the seven different district heating supply options are illustrated in the recommended 55% district heating scenarios with ambitions heat savings. These heat supply options have been analysed in combination with all district heating levels and all the refurbishment levels.

The upper limit in the system to integrate waste heat and renewable heat sources is ~73% as indicated by the scenarios to the right with the maximum heat uptake. In the recommended scenarios 54% renewable and waste heat is used in a mix of all heat sources, representing a more balanced manor that reflects that local conditions vary and may not enable an implementation of all options. To go from 54% to 73% requires waste or renewable heat to be present in all district heating areas only needing in parts of the winter to operate heat pumps and boilers. In practise some areas would only be supplied by large-scale heat pumps and boilers. With our geographical knowledge of the sources and the prioritisation to lower cost higher temperature sources the 54% represents sources we know with certainty is in the proximity of current heat demands. In our scenario however we have included datacentres and electrolyses heat even though these are not there to a large extend today. To ensure that the 54% is a realistic level of coverage, these source in the recommended scenario, replace low temperature industrial waste heat we know currently to be located in areas with district heating potentials.

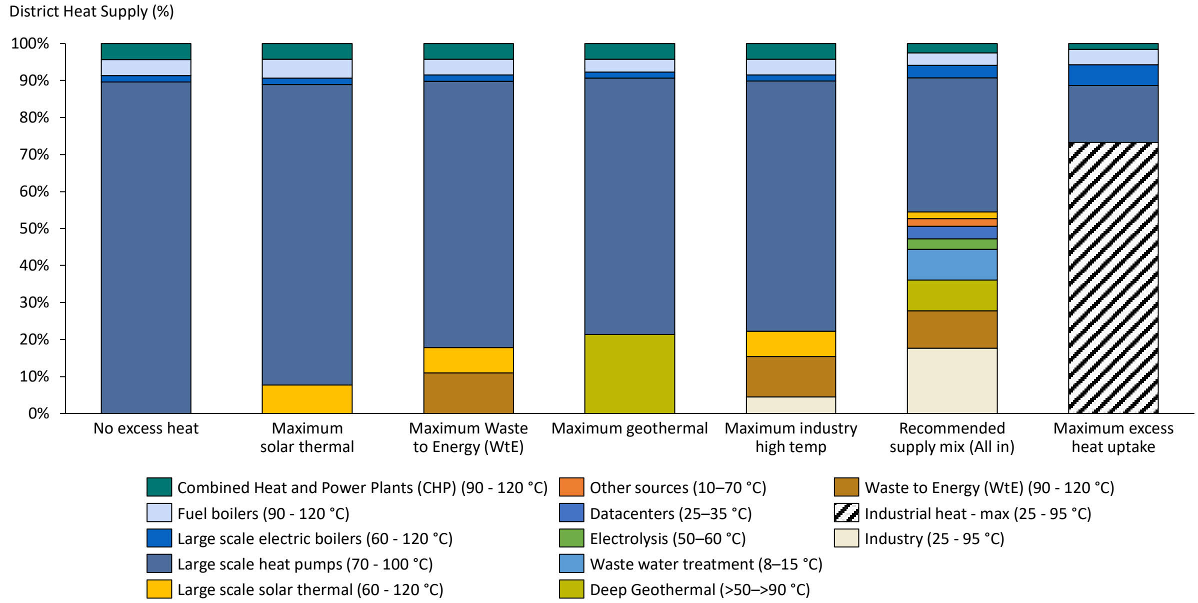

Figure 11. District heating supply options analysed with 55% district heating market share.

In the other extreme to the left a heat supply options with no utilisation of waste heat has been analysed in which large-scale heat pumps will play a significant role. In between those scenarios solar thermal, waste heat from WtE, geothermal, and high temperature heat from industry have been allowed to play the maximum possible role taking into account geographical and temporal constraints. In the recommended scenario each geolocated source has been used in the analyses behind. This means it is a realistic scenario also with less heat from data centres and electrolyses which is not yet implemented and thus cannot yet be geolocated. In some cases heat from industry will eliminate the need for e.g. geothermal and also the highest temperatures are prioritised which in some cases leave lower temperature heat sources and geothermal unused. This also represents a situation where the lowest cost local heat source is utilised first.

Robust price and lower cost heating systems

To identify the most feasible pathway to a decarbonised European heating sector by 2050, several alternative **heat-supply scenarios** have been analysed. The scenarios vary by:

- **district heating market share**; 5 - 65 % and beyond from the current ~13%,
- **building-refurbishment level**; three savings levels,
- **heat-supply configuration**; seven distict heating options plus efficient individual heat pumps

The analysis links final heat-demand reduction with investment requirements, system-level costs, and resource efficiency. Across all configurations a **55 % district heating market share** combined with **≈ 43 % refurbishment** with **4th generation low-temperature grids** emerges as the most robust and balanced target for 2050.

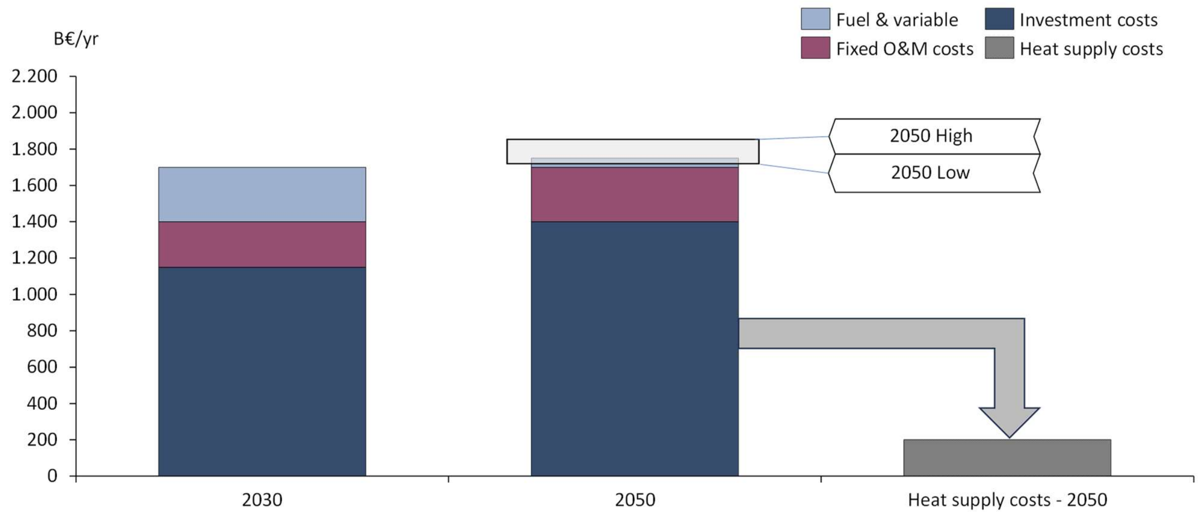

Figure 12. The total annual energy system costs including electricity, heating, transport and industry of the future energy systems in 2030 and 2050 as well as the total 2050 heat system costs as a part of the total system costs. The bar represents the highest and the lowest costs of the heating systems analysed.

The overall cost structure of the future decarbonised energy system is significantly different from today. The expenses going towards investments instead of paying for fuel. In 2024 countries in EU spent about 360 B € on mainly fossil fuel impots (Eurostat, 2025). In the future energy system this will be reduced significantly. Looking at the heating sector in the 2050 energy systems analysed the heat supply share constitutes about 13% of the total investment costs. In Figure 11 the cost structure of the overall energy system including heating, cooling, transport and industry is illustrated together with the costs of the heat supply excluding the refurbishment costs. The overall costs of the system increase slightly due to higher demands. The figure illustrates how the cost structure changes going from 2030 to 2050 leaning towards more investments in energy infrastructure rather than fuels for operation. In Table 2 the disaggregation of energy systems costs is listed into different components.

It can be seen that the heating sector investments reach 2,8 T€ by 2050 excluding refurbishment measures, corresponding to annual investment costs of ~200 B€/yr. This represents around 13% of total investments – when building refurbishment costs are excluded, compared to 18,1 T€ (1.495 B€/yr) for other system components. Within heating, district heating expansion and individual heat pumps constitute the largest shares, while in the wider system transport electrification, building renovation, and renewable power generation dominate. The figures highlight that although heating forms a smaller share of overall costs, its configuration between collective and individual solutions has important implications for total system expenditures and end-user heating costs.

Table 2. Overview of investments annual system costs for major components in the energy system from 2030 to 2050 in EU-27.

	Investment cost 2030 (B€)	Annual cost 2030 (B€/yr)	Investment cost 2040 (B€)	Annual cost 2040 (B€/yr)	Investment cost 2050 (B€)	Annual cost 2050 (B€/yr)
Heating components						
District heating expansion and 4G district heating	359	16	636	28	1156	51
Large heat pumps	37	9	63	12	61	4
Individual heat pumps	477	48	407	59	898	87
Combined heat and power plants	316	29	61	6	70	6
Large scale boilers	14	-	179	16	294	27
Individual boilers	477	-	407	5	94	11
Solar heating, surplus heat, and heat storage	85	-	144	27	84	4
Individual solar thermal	38	3	58	17	111	8
Geothermal energy	16	-	16	-	18	-
Total	**1819**	**109**	**1971**	**171**	**2786**	**200**
Other system components						
Offshore and onshore wind turbines	660	44	1575	109	2465	170
Solar photovoltaic (PV)	416	24	682	40	980	57
E-vehicles (incl. e-roads)	7808	834	8265	884	10317	989
Industry (savings and electrification)	28	2	206	15	206	15
Biogas plants	86	16	135	26	135	26
Nuclear	680	49	385	30	95	7
New gas-fired power stations	195	18	318	29	370	34
Charging points, electricity grid and ITS	3108	121	3453	124	56	5
Electrolysis and hydrogen storage	38	5	198	22	140	17
Wave power	121	6	118	7	-	-
Gasification, pyrolysis and electrofuels	107	11	121	13	124	12
Smart, flexible electricity requirement	-	-	161	-	345	16
Hydro	1215	64	837	47	911	51
Building renovation	784	38	1365	66	1997	96
Total	**15246**	**1233**	**17819**	**1414**	**18141**	**1495**

Regarding the source, comprehensive set of technology data and cost data is used drawing from several sources and developed to support the analysis. It integrates the current and the projected costs from sources like the Danish Energy Authority's technology catalogue and the extra elements used in the projects sEEnergies and IDA's Climate Response 2045 (Lund, Henrik et al., 2021; Maya-Drysdale et al., 2022). The costs data represents investments, installation capacities, cost development over time as well as maintenance and operational costs. A 3% discount rate in energy system analyses is used for political decision support, helping identify the most feasible long-term options and guide market design. The energy demand reduction entails some costs which are basically based on refurbishment measures in residential and service buildings which costs account for country-specific factors like labour and materials costs as well as building typologies from the sEEnergies project (Reiter et al., 2021). Finally, the grid cost estimates are calculated here considering the distribution in urban areas and depending on building typologies and heating demand.

This level remains robust across both lower and higher refurbishment rates. In some of the scenarios analysed, district heating shares above 60% may feasible and possibly achievable, particularly when refurbishment is higher, as the high unit costs of individual heat pumps make district heating comparatively more attractive. Overall, a 55% share of district heating is considered a realistic and balanced target, reflecting both the uncertainties in refurbishment levels and the cost variations between individual and collective heating solutions. Such a share is also attainable given the availability of waste heat and renewable heat sources. These trends are evident in both 3rd and 4th generation district heating, although the latter provides slightly larger economic benefits and resource efficiency.

The current final heat demand in the EU-27 is about 2,8 PWh per year (2015 baseline), covering space heating, domestic hot water, and service-sector heat. The Frozen-efficiency level (≈ 2.8 PWh per year) shown in Figure 13 represents a situation with minimal renovation and efficiency progress, but it does include the effect of a growing building stock. In 2050 about 90% of the existing building stock would still be present and between 2015 and 2050 the total heated floor area in the EU27 is expected to increase by roughly 30 %, corresponding to 25–30 % growth in the residential sector and 35–40 % in the service sector. Thus, the frozen demand of 2,8 PWh already entails some efficiency improvement per m², since total floor area rises while overall demand remains almost constant. It therefore serves only as a reference baseline, not a true "no-change" case but a situation with no new policies or a "no-action" path inconsistent with EU decarbonisation goals.

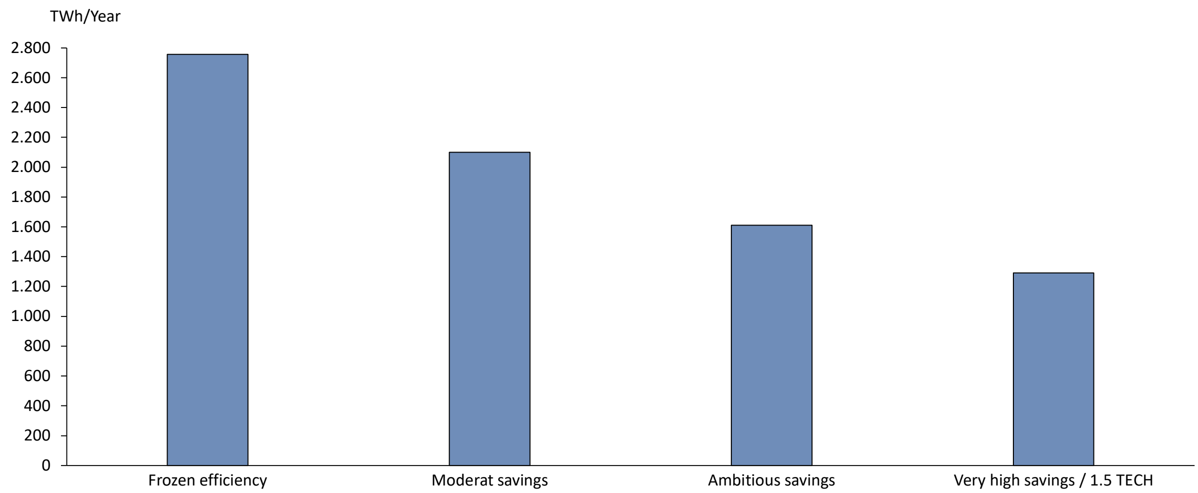

Figure 13. Development of the overall EU heat and hot water demands with difference refurbishment in towards 2050.

Under the ambitious refurbishment level the specific heat consumption declines to 60–80 kWh /m² ·year in 2050, yielding about 43 % end-use savings and a total heat demand near 1,6 PWh per year. A deeper very-high savings pathway (≈ 1.1 PWh per year) corresponds to the 1.5 TECH scenario of *A Clean Planet for All* and assumes almost complete renovation to near-passive standards (≈ 40–55 kWh /m² ·year), but at rapidly increasing marginal cost. Overall, even as total heated area grows by about one-third, total EU heat demand pr. square meter can fall through comprehensive refurbishment, improved building envelopes, and widespread adoption of low-temperature heating. In Figure 14 the pr. country heat and hot waster demands are illustrated.

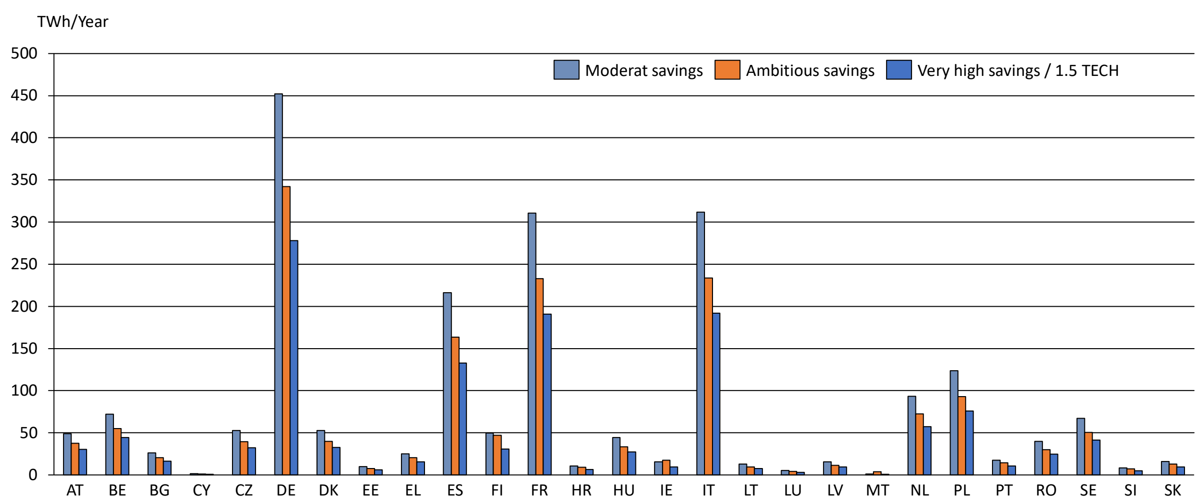

Figure 14. Development of the country level EU heat and hot water demands with difference refurbishment levels in 2050.

The moderate and ambitious savings cases (≈ 2,0 PWh and 1,6 PWh / year) represent realistic outcomes based on broad implementation of national renovation strategies and the EU Energy Performance of Buildings Directive. The very-high savings and the other two saving levels all correlate with a gain from an expansion of district heating. The question is which level is feasible when including the costs and energy system effects of the refurbishment levels. There can be at least three parameters to evaluate the savings levels: costs, primary energy supply and fuel or biomass consumption.

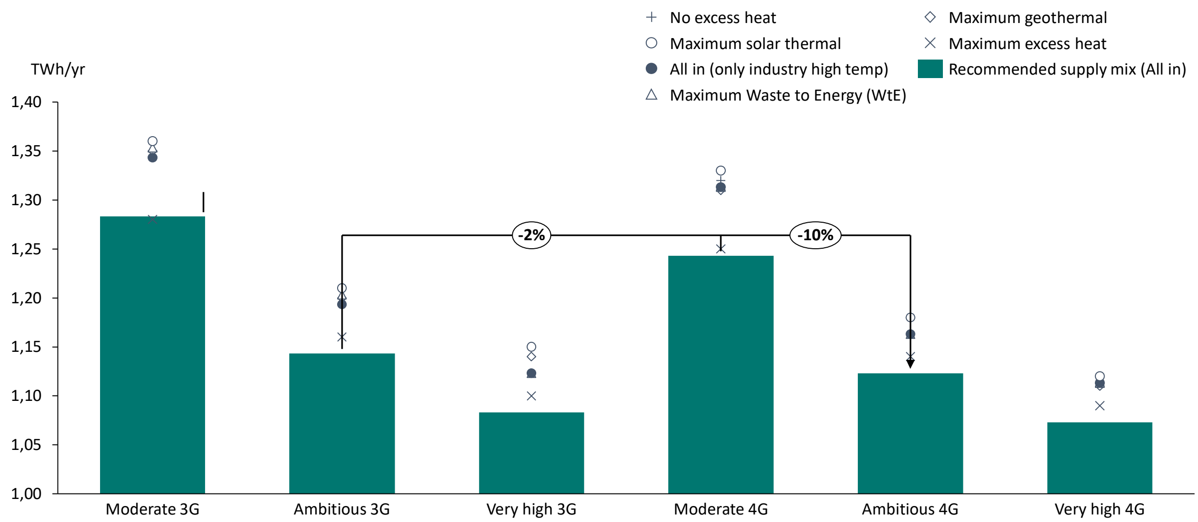

Figure 15. Biomass consumption of the different saving levels combined with the heat supply scenarios with 55% district heating for both 3rd and 4th generation district heating solutions in EU27.

In a fully decarbonised energy system, **biomass should be considered a limited resource**, alongside the continued phase-out of fossil fuels. Therefore, the evaluation of future heat-saving strategies must go beyond direct cost indicators. Figure 15 presents the biomass consumption associated with the different building-energy-saving levels, combined with the corresponding heat-supply scenarios for an EU27 system configuration with 55% district-heating share, representing both **third-generation (3GDH)** and **fourth-generation (4GDH)** district-heating solutions. The comparison shows that:

- Higher saving levels (ambitious and very-high) result in substantial reductions in total biomass consumption, even though total heat demand decreases less steeply in relative terms.
- The transition from 3GDH to 4GDH further reduces biomass needs due to lower supply temperatures, improved heat-source efficiency, and better integration of waste and renewable heat sources.
- Under a 55 % district-heating share, **biomass consumption drops by around 10 %** when moving from moderate to ambitious heat savings and a further 2% with a move to low-temperature district heating the ambitious savings case and by **2 %** in the very-high-savings scenario.
- These reductions indicate that a **fundamental energy system re-design is needed** to harvest the 2.0 energy efficiency potentials and that **technological advancement in district-heating generations** complements end-use savings.
- Going towards very high savings would decrease the biomass consumption by 5% compared to the ambitious 4DGH level, but is connected to a significant jump in the overall costs.

When considering the available heat-supply options, **the recommended scenarios represent a balanced and realistic mix** of technologies that optimise both cost and resource efficiency. The results indicate that the fuel-efficiency improvements achieved through energy savings and expansion of district heating with waste or renewable heat sources is far more decisive than the exact composition of the heat supply or the distinction between third- and fourth-generation district-heating systems. In other words, the level of heat savings, and the resulting reduction in total fuel and biomass demand, has a stronger influence on overall system performance than whether the supply mix includes slightly more solar thermal, large-scale heat pumps, or waste heat. The recommended configuration therefore strikes a **technically and economically feasible balance**, maximising the use of renewable and waste heat sources while **avoiding excessive reliance on any single technology or limited resource**. This underlines that coordinated heat planning, focusing on achievable renovation rates and efficient district-heating infrastructure, delivers the greatest system-wide benefits, ensuring fuel efficiency, manageable costs, and the flexible integration of future renewable and waste-heat potentials. Having said that, there is a clear indication that every system that is able to use a low cost waste or renewable heat source is an advantage cost wise and resource wise on the system level as well.

Figure 16 and Figure 17 illustrate the unit costs of delivered heat (€/MWh) for district heating and individual heating across three building-renovation levels and several market-share scenarios. Here the recommended supply mix is only illustrated. The three panels correspond to the renovation levels - *moderate*, *ambitious*, and *very-high savings* - each shown in a separate panel. The horizontal axis indicates the district-heating market share, while the vertical axis shows the average cost of heat supply, excluding refurbishment costs. Each point represents the average cost of all heat supplied under that specific market share. Thus, movements between points reflect not only marginal connections but also the combined system effect of connecting new consumers and changing the mix of supply technologies.

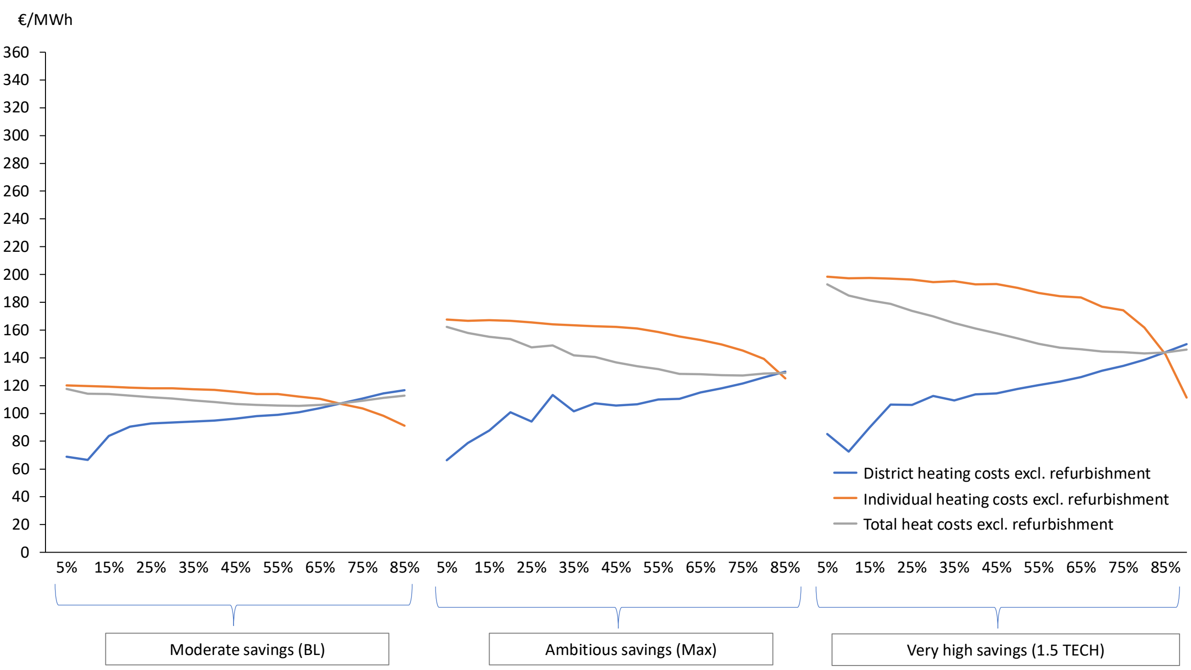

Figure 16. Costs pr. energy unit divided into district heating and individual heating, spread out on different market shares as well as on the three renovation levels included, but excluding refurbishment costs.

The results clearly demonstrate that district heating remains systematically cheaper than individual heating for most market-share levels and renovation scenarios, particularly in dense and semi-dense urban areas. However, as district heating expands into lower-density zones, its average cost gradually increases due to longer pipe networks, higher distribution losses, and lower heat densities. In summary, **deeper renovation generally strengthens the competitiveness of district heating** in core and medium-density areas, while limiting its economic reach into the most sparsely populated regions. In Figure 16, noting these costs are without refurbishment costs, the key results are:

- **District heating remains economically advantageous** across all renovation levels up to at least ~55% market share, and often considerably beyond, especially in moderately or ambitiously renovated areas.
- **Individual heating solutions become slightly cheaper** only in rural or very-low-density areas, where expanding district heating would require costly network extensions.
- **Unit costs for individual heating rise with deeper renovation**, since each dwelling's annual heat consumption decreases, making equipment and maintenance costs high per delivered MWh.
- **District heating maintains stable and relatively low average costs** because fixed and capacity-related costs are shared across many consumers, and system capacities can be adjusted dynamically.
- **At higher renovation levels**, district heating's **flatter seasonal demand** improves the utilisation of **renewable and waste heat sources**, while **individual units** remain bound by fixed capital costs per dwelling.

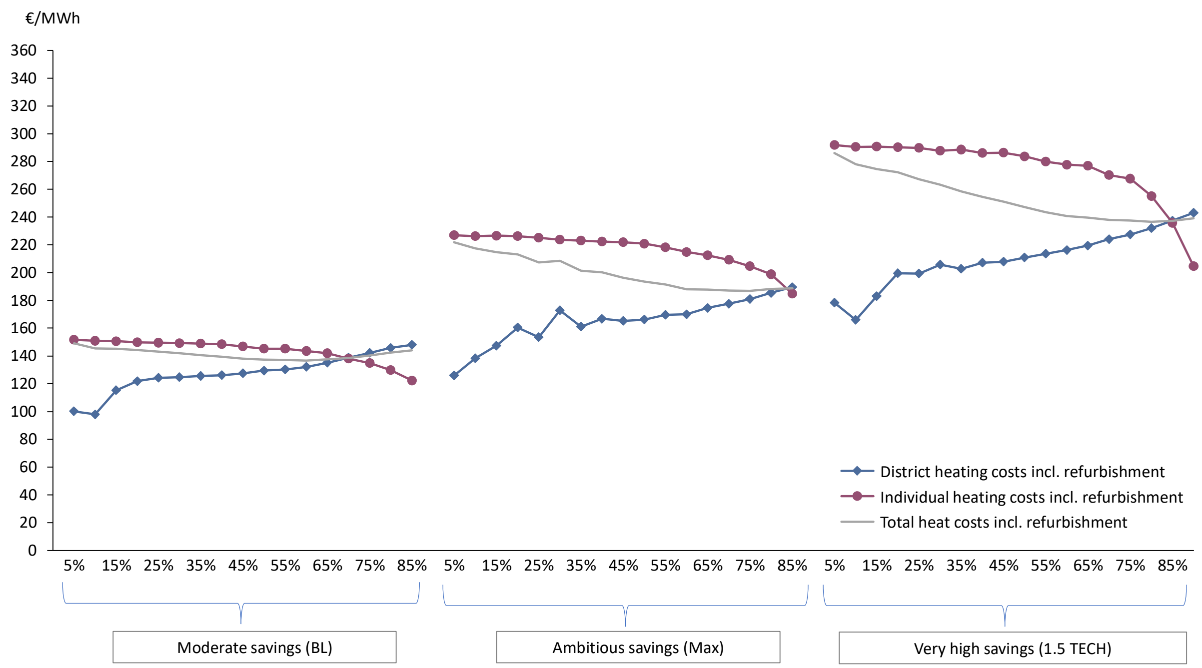

Figure 17. Costs pr. energy unit divided into district heating and individual heating, spread out on different market shares as well as on the three renovation levels included, but including refurbishment costs.

Figure 17 extends the analysis by including refurbishment costs in the unit cost of delivered heat (€/MWh) for both district heating and individual heating. As in Figure 16, the three panels correspond to the renovation levels - *moderate*, *ambitious*, and *very-high savings* - each showing how total costs evolve with increasing district-heating market share.

When refurbishment costs are included, the absolute unit costs rise significantly, especially in the high-savings scenario, because deep renovation requires large investments per square metre. Nevertheless, the relative difference between district and individual heating remains consistent: district heating continues to provide lower total heat-supply costs in the majority of cases. Including refurbishment costs changes the overall interpretation in several ways:

- **Total unit costs increase with deeper renovation**, as capital investments in the building envelope dominate, particularly for very-high savings scenarios.
- **District heating remains the lowest-cost solution** in dense and semi-dense areas.
- **Individual heating options become comparatively more expensive** once refurbishment costs are internalised, since each dwelling bears the full expense of both the building improvements and the heating unit.
- The total costs for the total heat market pr. unit **heat cost decreases 10-20%** across different scenarios. Please note that this reduction can give some district heating customers significantly higher cost reductions as this represents the over average included individual heating options.

When refurbishment levels and thus costs are included and increases, renovation costs becomes the cost driver. District heating remains robust and cost-efficient, but the total cost per unit heat increases with the level of building renovation.

Figure 18 shows how total energy-system costs (B€/yr) evolve with increasing district-heating market share across three different heat-saving levels—moderate, ambitious, and very-high savings for the recommended district heating supply mix. The figure captures the full system costs, including investments and operations across all energy sectors, rather than the cost per MWh of delivered heat. The moderate savings level represents a renovation depth that reduces heating demand significantly while still maintaining high heat density in urban and suburban areas. At this level, building improvements lower total energy use and peak loads, allowing for smaller generation and network capacities. The remaining heat demand, however, is still large enough to fully utilise district-heating infrastructure, meaning fixed investment costs are distributed efficiently over many delivered MWh. This balance between reduced demand and network utilization minimises total system costs. As the figure shows, costs fall steadily as district heating expands up to around 55–60%, reflecting economies of scale, shared infrastructure, and access to low-cost renewable and waste heat. Beyond this range, the cost curve flattens and eventually rises slightly because additional connections must be made in lower-density areas, where network investments per MWh become significantly higher. In contrast, at ambitious and very-high savings levels, total demand declines further but at the expense of heat density each kilometre of district heating pipeline delivers less heat, increasing unit network costs. This means that, even though energy demand is lower, total system costs are not always reduced proportionally. It is clear however that district heating is an advantage under any circumstance up to a certain market share, and that with increased savings the feasible market share may be higher that with low saving levels.

While moderate savings with ~55–60% DH mark the point of minimum total system costs, the ambitious savings scenario offers substantial system-level and resource benefits at only slightly higher cost.

- Across scenarios, more district heating proved **system level costs reductions of 2,5-3,1% or 40-50 billion €**.
- Ambitious savings lead to **larger absolute reductions in primary energy use**, particularly biomass, which is a limited resource in a decarbonised energy system.
- This improves **energy security**, and free renewable resources for harder-to-electrify sectors such as **transport, industry, and aviation fuels**.
- The lower heating demand enables **more flexible and lower-temperature district heating operation**, which supports the integration of **waste heat, geothermal, and large-scale heat pumps**, further strengthening the renewable share.

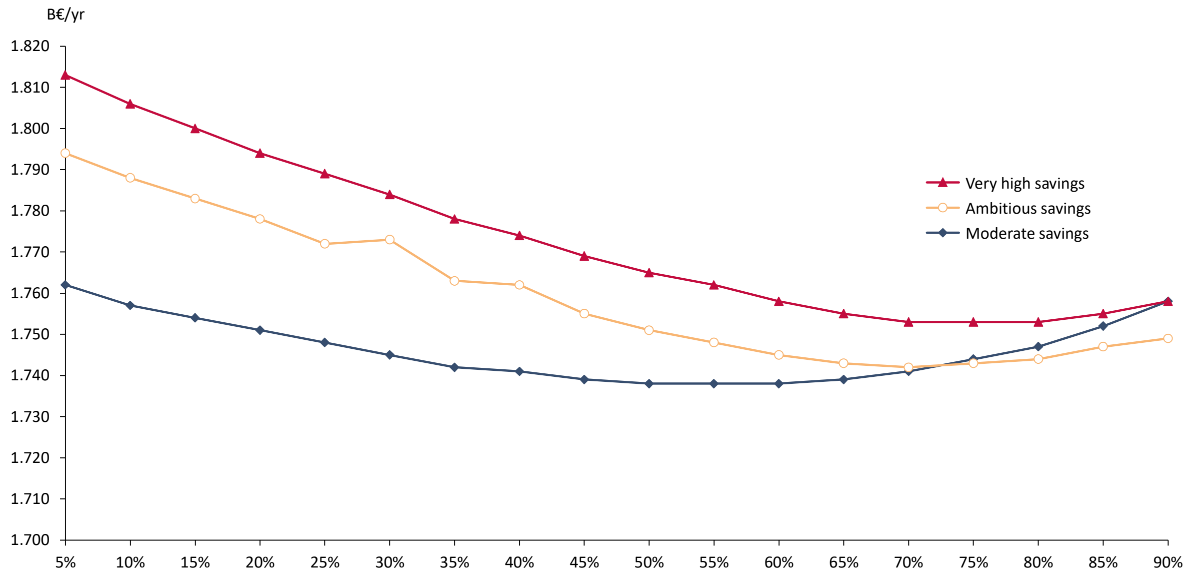

Figure 18. Development of total system costs as a function district heating market shares and across the three heat saving levels.

The overall cost structure and system efficiency has to be considered based on the above and considered across the interaction between heat savings, district-heating expansion, and the use of renewable and waste heat in the pathways for a decarbonising the European heat sector.

- District heating consistently provides lower unit costs of delivered heat than individual heating across most renovation levels and market shares, even when refurbishment costs are included. The advantage of district heating remains particularly strong in dense and semi-dense areas, where shared infrastructure and access to low-cost renewable and waste heat sources enable substantial efficiency gains.
- Higher building renovation levels and improved district-heating technologies (4GDH) significantly reduce biomass consumption and primary-energy demand. This is a crucial result, as biomass is a limited resource in a fully decarbonised energy system.
- District heating reduces total energy-system costs decline as heat savings increase and as district heating expands up to a certain level. The system-cost minimum occurs under moderate savings with around 55–60 % district heating, where both renovation and network utilisation are balanced. However, the ambitious savings level, though slightly more expensive in absolute terms, achieves significantly larger reductions in primary energy and fuel use, offering clear long-term strategic advantages.
- While in some cases more that 55% district heating may seem feasible it is also worth considering that going higher with regards to district heating increases the uncertainty due to lack of local knowledge in top-down, bottom-up modelling. It is also clear that district heating represents a "no-regrets" option – robust with several different district heating supply options and refurbishment levels.

When considering the full energy system, the integration of **district heating with renewable and waste heat sources** results in **total system costs approximately 2,5-3,1% or 40-50 billion € lower** than those of scenarios dominated by individual heating solutions. Focusing on the heating sector alone, the cost reduction is even greater, around **10 - 20 % or 10-30 billion,** reflecting the higher efficiency, shared capacity utilisation, and system-integration benefits of collective heat supply. Not that the 10 - 20 % cost reduction in the heat market represents an average including the individual heating costs, meaning that many will experience higher **cost reductions of 30-35% with district heating** connected.

District heating grid coverage

In order to achieve the market share of district heating the number of required start-up of new district heating systems in the EU27 and the associated investment costs is estimated. Figure 19 illustrates the estimated number of new systems needed to be installed each year. The corresponding investments needed including refurbishment of existing systems is illustrated in Figure 21. The estimates build upon geographical modelling of district heating potential areas and cost distinguishing between 3rd- and 4th-generation technologies.

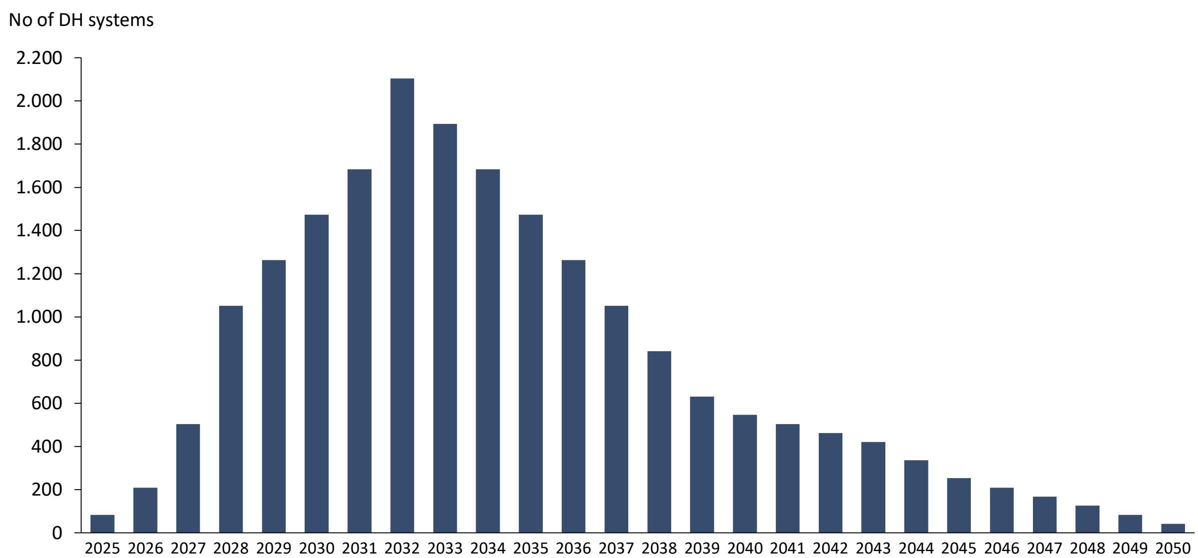

Figure 19. New prospect district heating systems by year.

The implementation pattern suggested here reflects an early phase of rapid expansion, including extensions into dense urban cores where grid costs may prove higher combined with smaller systems in smaller urban areas. This indicates a peak in new installations around 2032, after which a gradual decline occurs as market saturation increases, and the remaining unserved areas become smaller or more expensive and time consuming to connect. To reach a 55% district heating market share by 2050, up from roughly 13% in 2023, the required growth rate is about 7% per year until 2030, followed by a stabilisation at roughly 5% per year thereafter. Such acceleration is technically achievable: France and Germany have both realised annual district heating growth rates at 6% in recent years (2019–2023), while the EU-average expansion rate has been about 2,3% per year. An acceleration is required to expand the infrastructure throughout the 30'ties and 40'ties.

The methodology used for estimating how many district heating systems would be needed to achieve higher district heating shares assumes that the smaller district heating areas with final heat demand lower than 1 PJ would consist of one individual system each, then areas with a final heat demand ranging higher would be counted at up to five new systems. Considering a household heat demand of 15 MWh 1 PJ would be equivalent to about 18.000 households. The household demands vary across countries. In practice there may be large consumers (e.g. as well as buildings used in services and the commercial sectors, so the cities may go down to about 10.000 inhabitants. In practice district heating may be feasible in smaller plants from 100 or 200 households using waste heat or heat pumps combined with suitable thermal storages.

In Figure 20 the grid costs are illustrated dependent on the market share. The model identifies potential district heating areas based on two conditions: the average distribution grid costs in the area are below a predefined cost ceiling per country, and the annual heat demand in the area is above a predefined threshold.

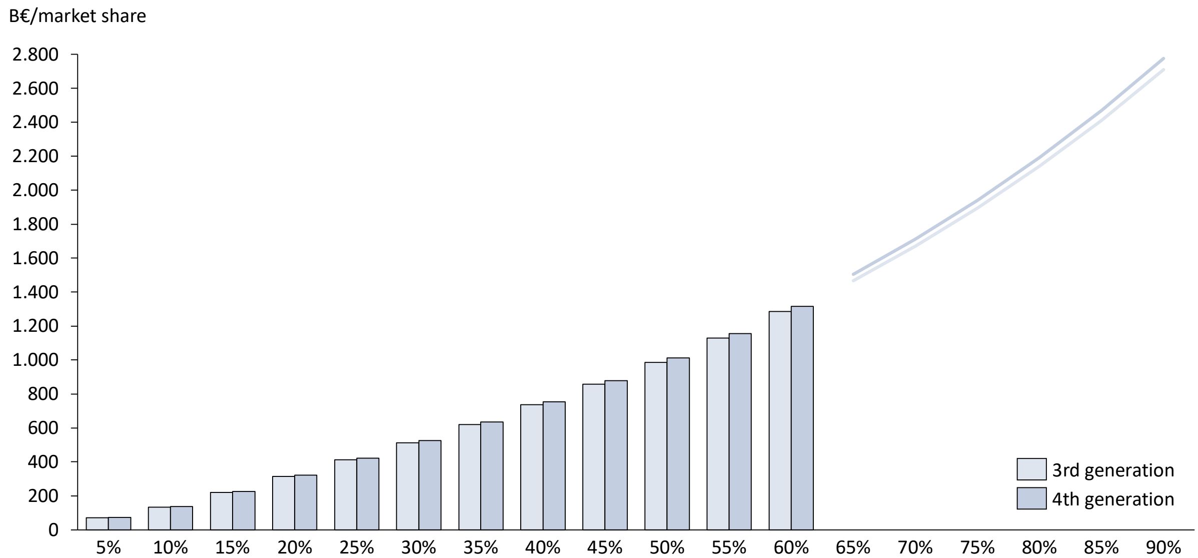

Figure 20. District heating grid costs as a function of market share for EU 27 for both 3rd and 4th generation district heating.

A possible implementation strategy with a large number of new plant combined with refurbishment of some of the existing networks entails high upfront investment costs, particularly during 2025–2040. Investment activity peaks between 2030–2040. The pattern in such an implementation strategy reflects the initial surge in installations, also included new systems in the centre of cities where networks may be more expensive than in areas with single family houses which the district heating may gradually spread to. The total required infrastructure investments (including replacement of ageing grids) are estimated at **1,13 – 1,16 trillion € by 2050** depending on the generation. This could be distributed as suggested in Figure 21 and distributed as follows:

- € 320 billion (2026–2030)
- € 540–610 billion (2030–2040)
- € 230–300 billion (2040–2050)

This corresponds to an investment approaching **70 billion € annually by 2030**, sustaining a 7 % yearly increase until that time. For comparison, we have estimated the current grid-replacement costs amount to about € 190 billion, which are included in the totals above. An average 40-year technical lifetime is assumed, while some may have a substantially longer span. The expansion of 4th generation, low-temperature district heating systems may be through first implementing 3rd generation, but ensuring investments are "4th generation ready" as refurbishment measures are implemented. This requires attention to heat exchanges and grid layout. In some areas, e.g. in old centers of cities, 3rd generation district heating may be the only feasible option, having in mind that not all buildings are able to be refurbished to the same extent. To reach the 55% share by 2050 (≈ 0,9 PWh of heat and hot-water demand) a staged milestones of **20 % by 2030** and **33 % by 2040** is consistent to reach the long-term target.

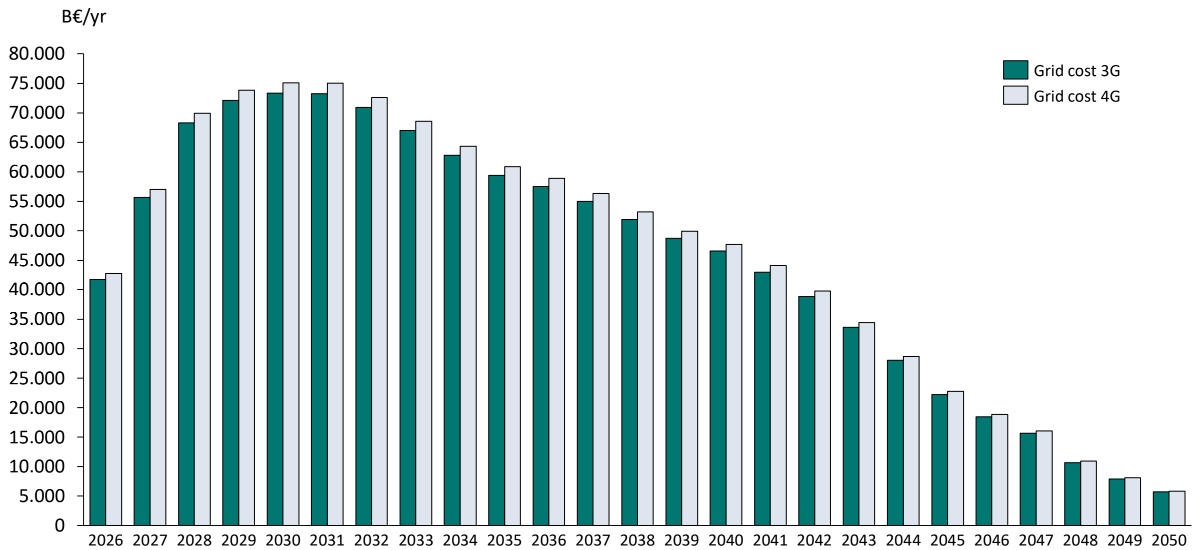

Figure 21. Distribution of grid costs for new district heating systems by year for 3rd and 4rth generation systems.

Figure 22 illustrates the minimum district heating share recommended in each member state to achieve a 55 % EU-wide market share by 2050, together with current and modelled levels. The comparison highlights the magnitude of effort required in countries where district heating is presently marginal or far from the full potential, particularly **Spain, Germany, the Netherlands, Belgium, Portugal, and Greece.** Conversely, countries such as **Finland**, **Denmark**, and parts of **Central and Eastern Europe** are already close or at the recommended levels. The analysis provides a country-level benchmark for national strategies. It should be noted that the actual achievable and feasible level should be assessed locally in communities. The recommended levels in Figure 22 are assessed looking across the current and modelled shares in the different member states.

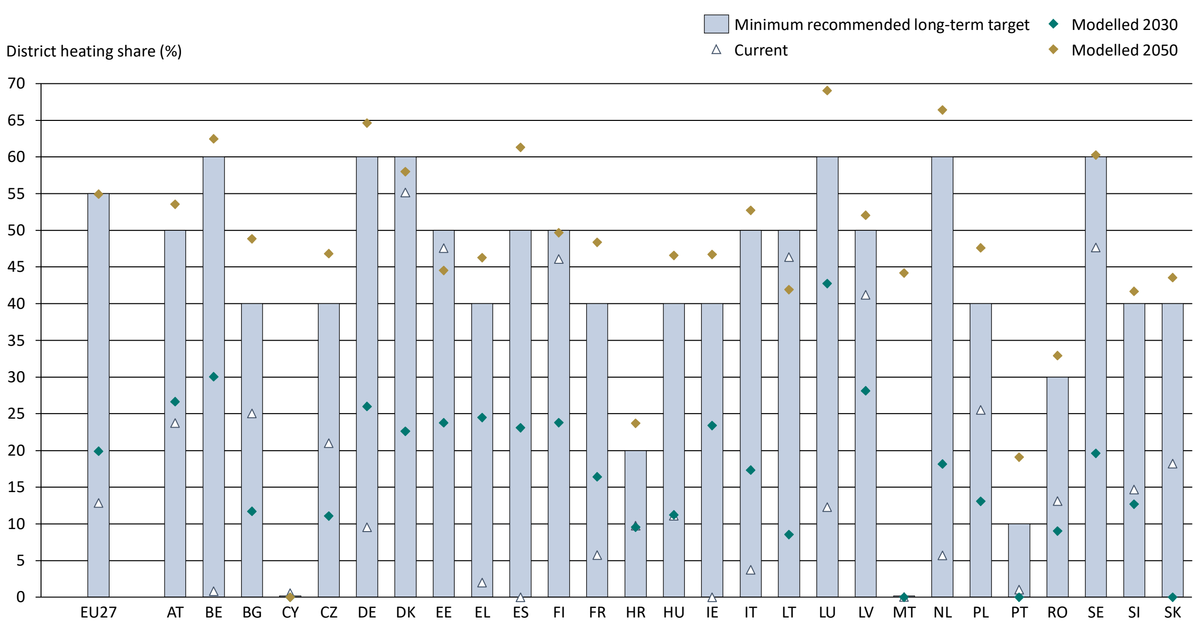

Figure 22. Country divided recommended district heating market shares (%) as well as the current (2023) and modelled shares.

Fact Box III. XXL Thermal Solar District Heating in Leipzing

Case: Leipzig Large-Scale Solar thermal plant

Location: Leipzig, Germany (approx. 630.000 people)
Technology: Large-scale solar thermal

From 2026 Leipzig will be fed heat from Germany's largest new solar thermal plant.

District heating in Leipzig represents 30% of the heat supply, with a network of 500 kilometres across the city. The system could supply 50% of the population by 2045 with green heat according to a scenario developed by the operator, which is the basis for the communal heating plan.

The solar thermal plant under development is the largest in Germany, with a peak capacity of 41 MW and a heat supply of 26 GWh/a. The solar panels will be set in 14 hectares of fields close to the city and provide heat with a temperature over 100 °C, covering around 20% of the district heat supply in the summer, and 2% over the year. The project is nearing completion, with commissioning due at the end of 2025/early 2026. Alongside other investments in renewable and waste heat projects, the deployment of solar thermal will accelerate Leipzig's heat transition and support the planned phase-out of fossil fuels by 2038.

Key Features:

- Covering 20% of Leipzig's heating needs every day
- 41MW of peak capacity
- 14 hectares of fields
- Feeding 26 million kWh of heat into the grid each year.
- Saving 7.160 tons of CO_2 per year.
- Planting fruit trees, hedges and other green areas to create species-rich habitats.

Mapping optimal cities in EU27 for district heating deployment and waste heat integration

Several heat sources have been mapped in this project in order to assess the geographical feasibility of the use of waste heat in district heating. While the full potential can cover up to ~130% of the full current heat and hot water demand from a theoretical viewpoint, it is obvious that 1) several sources rule out each other as they are placed in the same areas and 2) they are unable to be exploited due to the temporal aspects of the heat demands. In Figure 23 and Figure 24 European and selected country level future waste heat and geothermal sources is mapped. Please note that in addition we may see new sources not currently geolocated from e.g. datacentres and electrolyses plants.

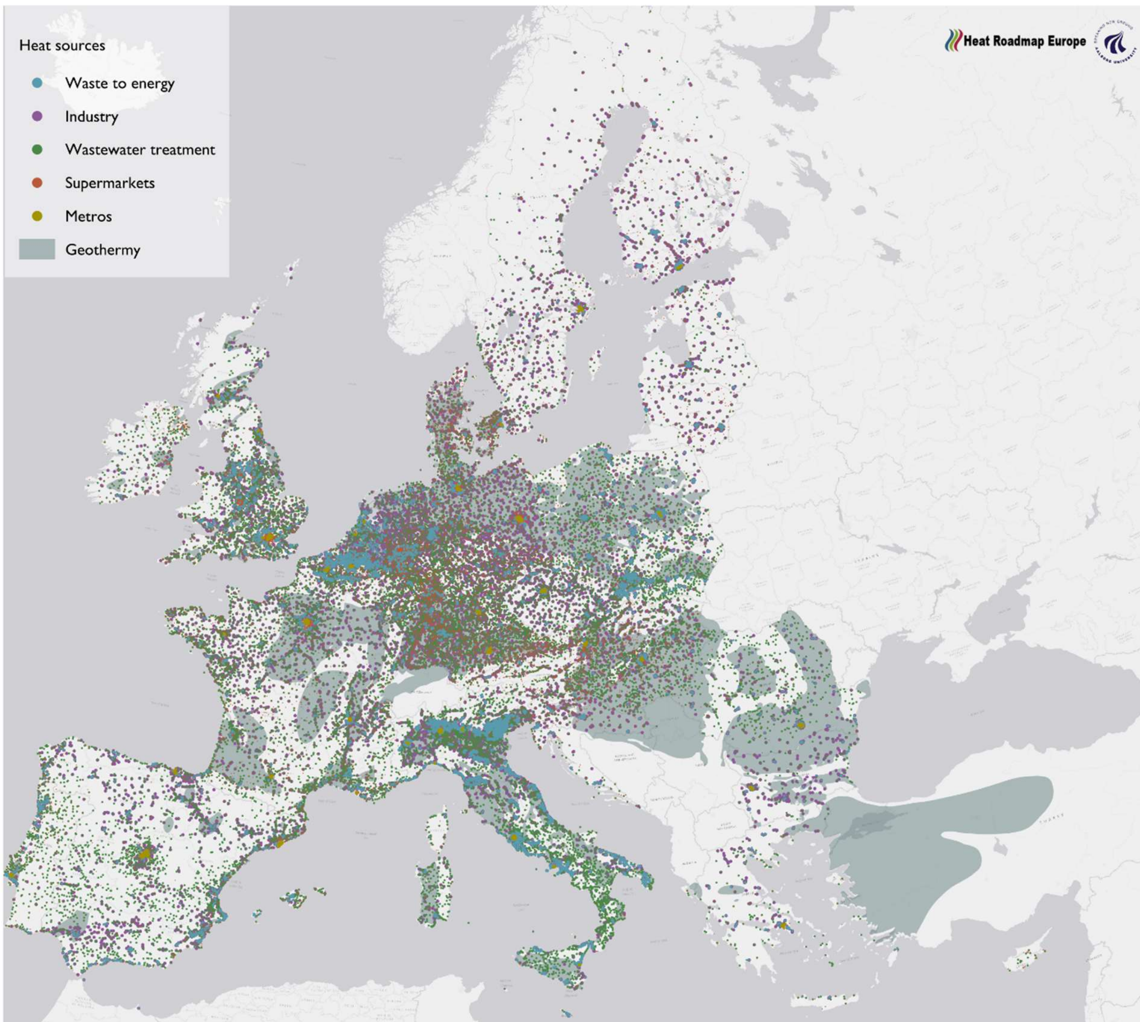

Figure 23. Illustration of the heat sources mapped in this Heat Roadmap Europe study.

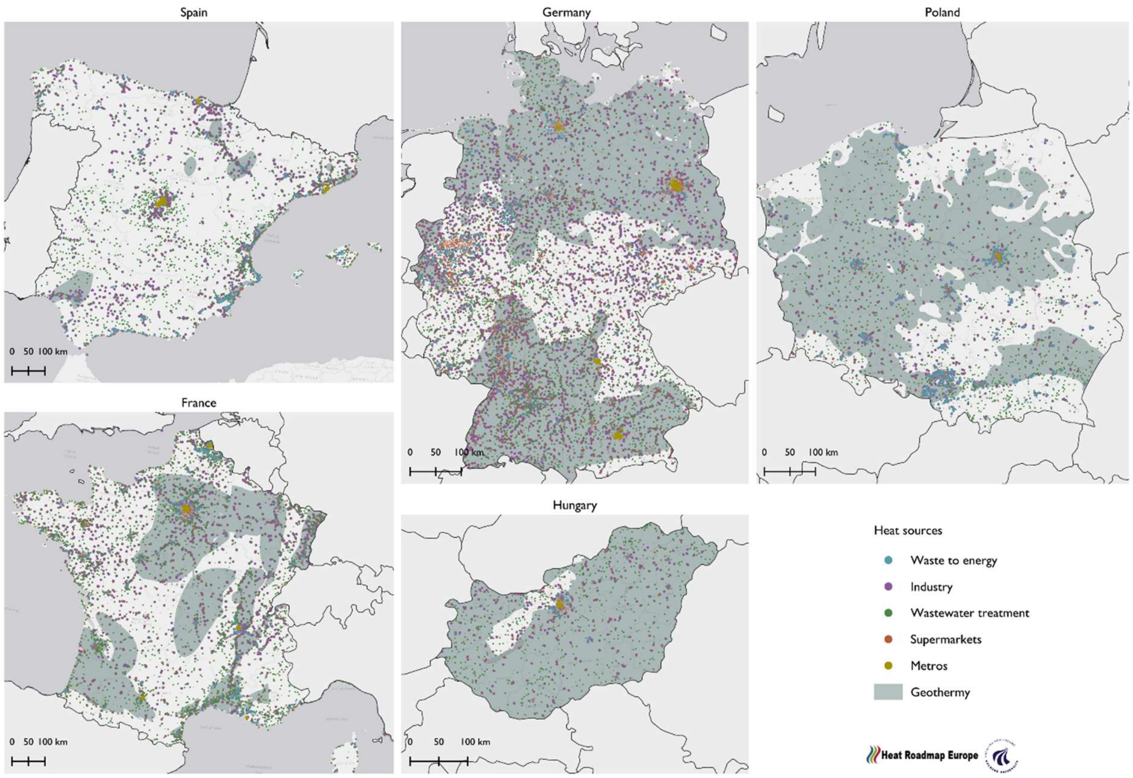

Figure 24. Illustration of the heat sources mapped in this Heat Roadmap Europe in the five investigated countries.

Locating the areas where district heating can be a priority is a decision based on economic feasibility and various factors. Cities across Europe differ in terms of their urban landscape and population density, and therefore their heat demand. In addition, their proximity to different renewable and waste heat sources varies. For this reason, the report presents a series of maps and tables of the different potentials that different cities can recover, taking into account the size of the city and its district heating system, but also the associated investment costs for district heating and the amount of heat that can be recovered.

Figure 25 illustrates the locations of cities where **high-temperature industrial heat potential** can be recovered in their district heating system relative to their demand. High-temperature heat recovery can be considered the most urgent to have implemented. The size of each bubble reflects the proportion of heat demand covered by the corresponding waste heat source, with larger bubbles representing coverage levels greater than 75% of the heat demand. The bubble colours indicate the population size of each city, providing an additional level of insight. For example, cities where high-temperature industrial waste heat can meet the majority of their district heating system demand, are: Thessaloniki in Greece, Le Havre in France, Linz in Austria, Duisburg in Germany, Ostrava in the Czech Republic, Mestre in Italy, and Gijon and Malaga in Spain and Valletta in Malta.

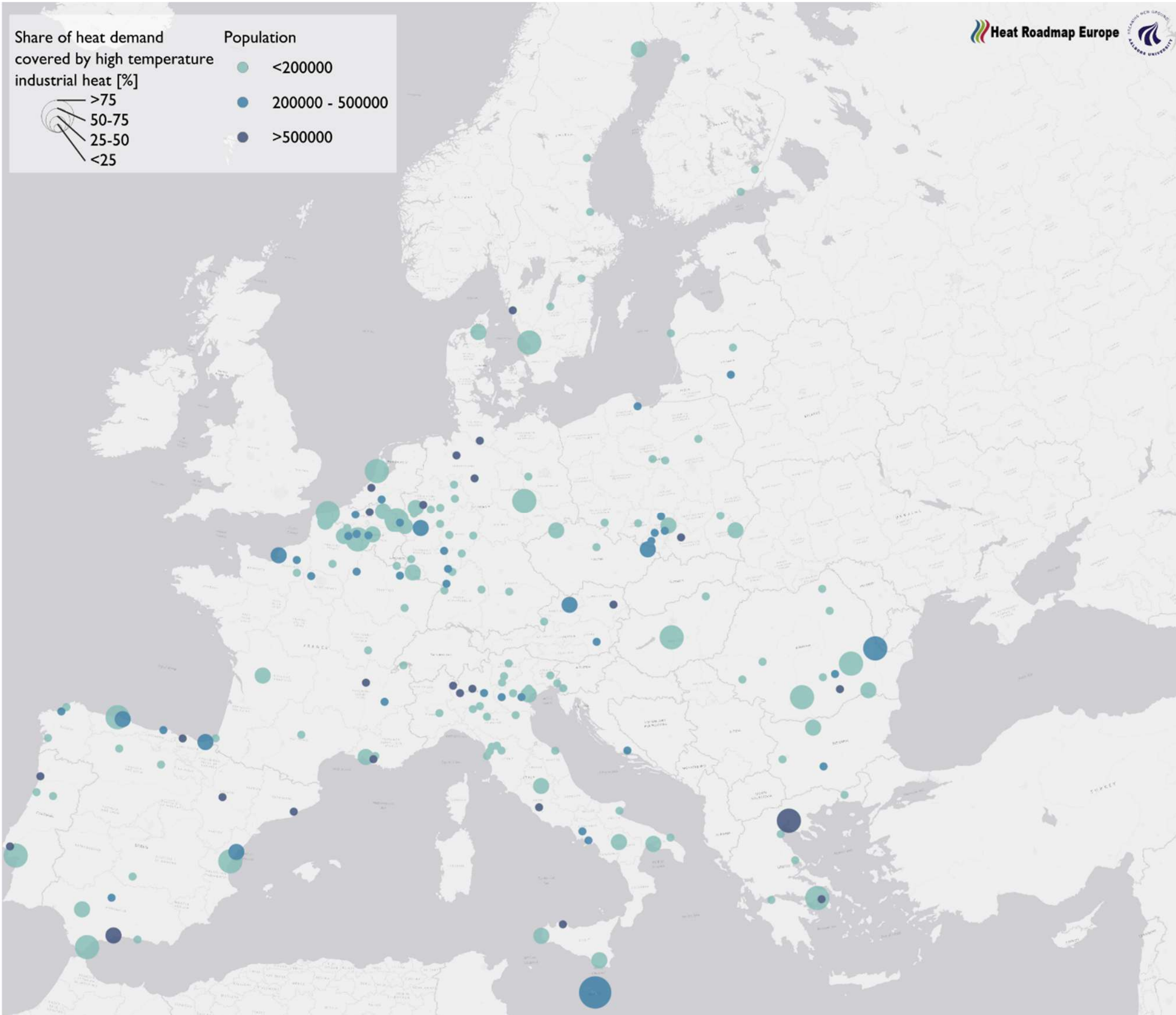

Figure 25. Mapped share of heat demand covered from high-temperature industrial sources in comparison to the city's population.

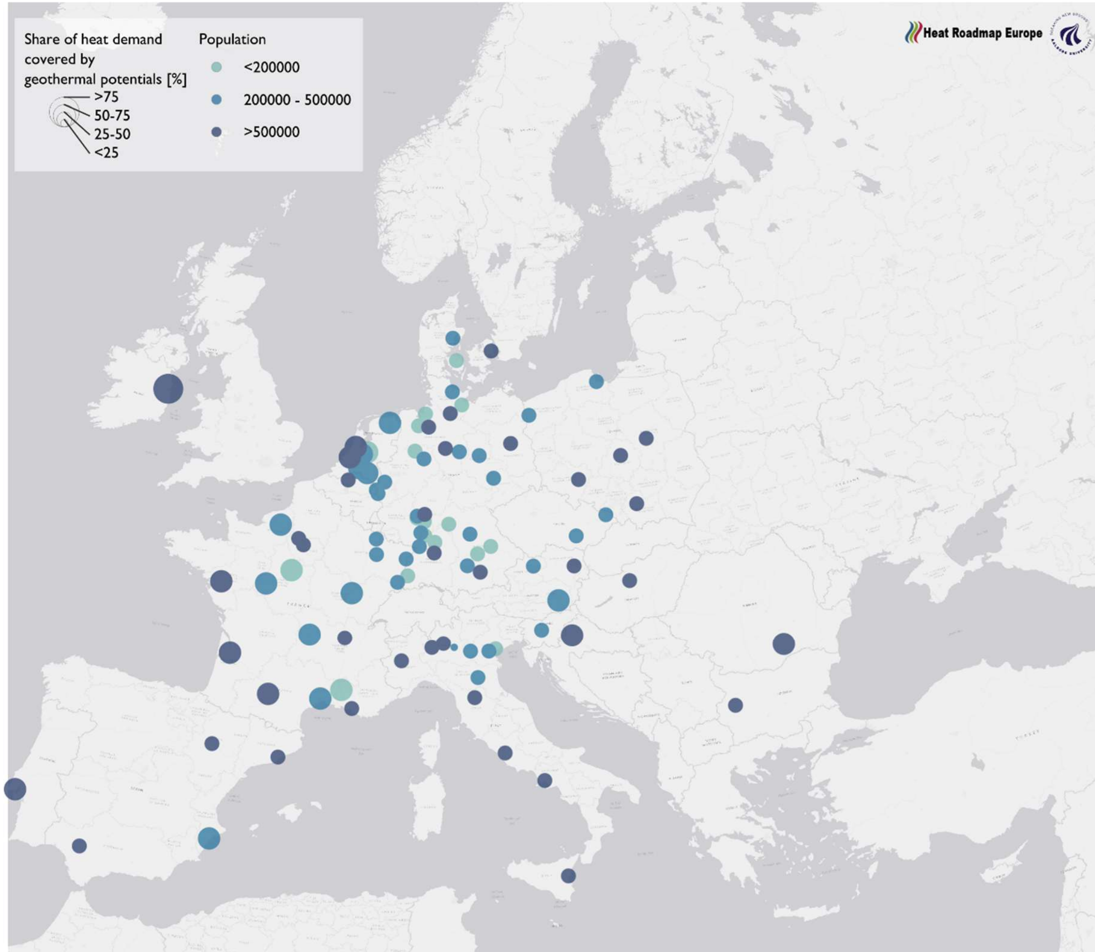

Figure 26. Mapped share of HD covered from geothermal potential in comparison to the city's population.

Similarly, the map in Figure 26 shows the locations of cities where **geothermal potential** can be recovered in their district heating system relative to their demand. Geothermal energy is an unlimited source of heat in theory, but with high initial investment costs. Thus, it is prioritised in cities with high heat demands. The size of each bubble in this map reflects the proportion of heat demand covered by geothermal energy, with larger bubbles representing coverage levels greater than 75% of the heat demand. The bubble colours indicate the population size of each city, providing an additional level of insight. For example, cities with high heat demand that can be met through geothermal potentials are Dublin in Ireland, Amsterdam, Antwerp and the Hague in the Netherlands, Lyon in France, Bremen in Germany. Capital cities with even higher heat demands, such as Berlin and Paris could also benefit be geothermal energy that could cover up to 47% of their needs. Paris already currently exploits this potential partly.