Heat Roadmap Europe: Towards a sustainable, resilient and competitive heating sector by 2050 – Main report

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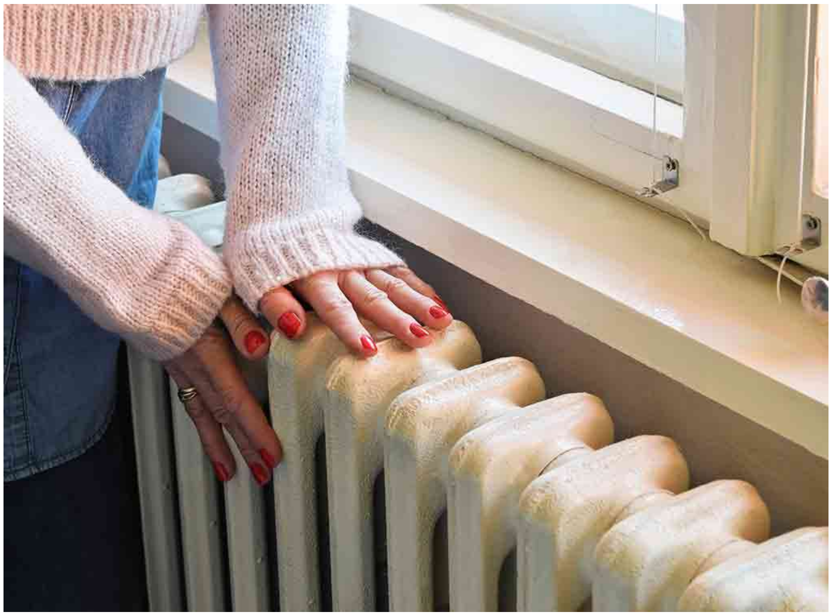

Heat Roadmap Europe

Towards a sustainable, resilient and competitive heating sector by 2050 – Main report

This report shows how ambitious heat savings, large-scale district heating expansion to a 55% market share, and smart electrification can reduce EU primary energy use, eliminate reliance on fossil fuels, and enhance competitiveness. More than 3 PWh of waste and renewable heat potentials have been identified, of which at least 650 TWh are assessed as usable. By integrating renewable and waste heat into adaptive, low-temperature networks, supported by large-scale heat pumps and thermal storage, Europe can achieve a sustainable and resilient heating sector by 2050. Smart electrification and district heating go hand in hand. The report focuses on the EU level but also provides exploitable country-level results.

By Brian Vad Mathiesen, Enric Gonzalez, Marina Georgati, Steffen Nielsen, Jelena Nikolic

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This report builds primarily on analyses conducted within the EU-funded project *sEEnergies* (Grant Agreement No 846463). It was prepared with support from Euroheat & Power and carried out in 2024–2025. The report forms part of the Heat Roadmap Europe project series and is the fifth in the series (heatroadmap.eu). It consists of a main report and a supplementary report, which complements the main report by providing additional EU-level and country-level data on primary waste-heat potentials, as well as downloadable maps in PNG format.

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, 2025a) 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 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 (Mathiesen, B. V. et al., 2015). 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., 2022).

- **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 member state levels, considering multiple district heating market share scenarios as part of a fully decarbonised energy system by 2050. Where possible results for the United Kingdom has been included.
- **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 EU27 level and to some extend for Germany, Spain, France, Hungary and Poland as well as for district heating grid costs and waste heat estimations for the all 27 EU member states.

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.

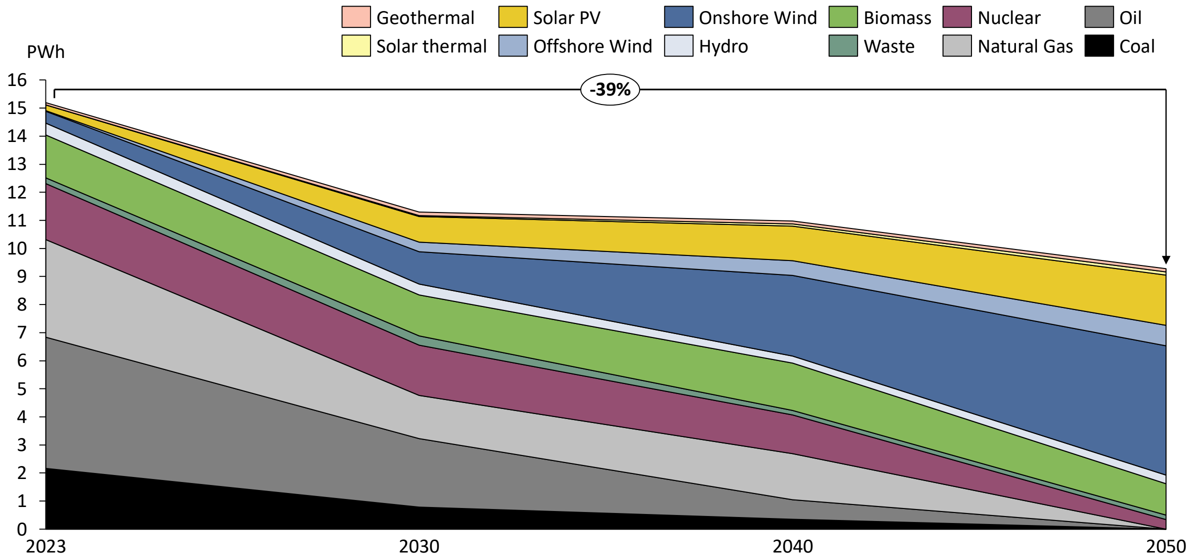


Figure 1. Primary energy supply in 2023, 2030, 2040 and 2050 for all sectors in EU27.

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 per 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.

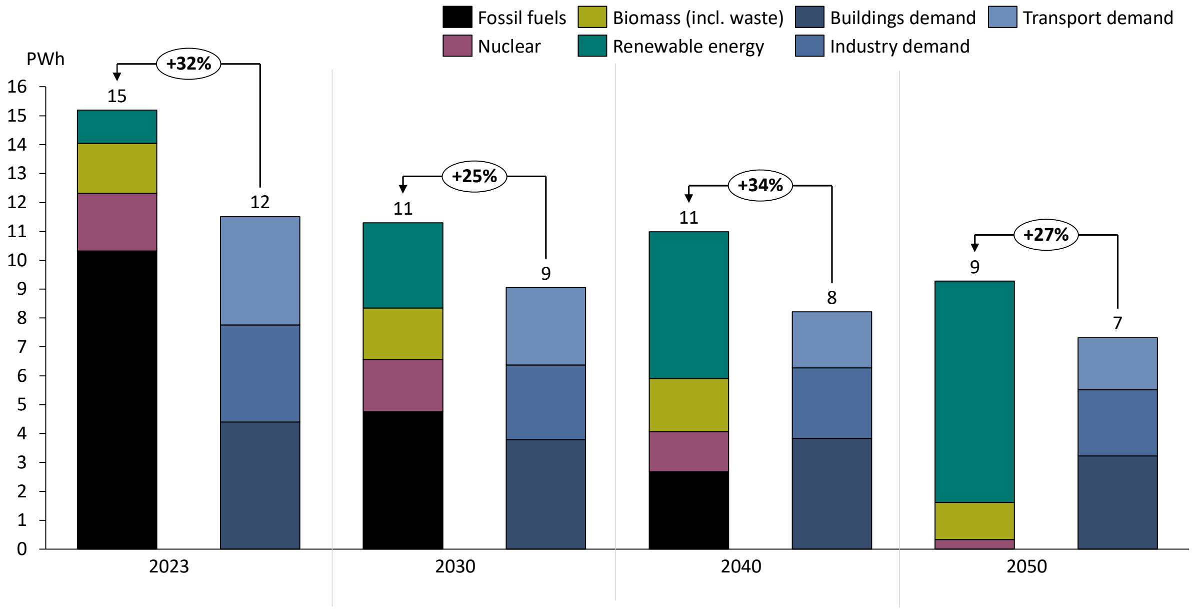


Figure 2, Primary energy supply and end demand development per sector towards 2050.

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.

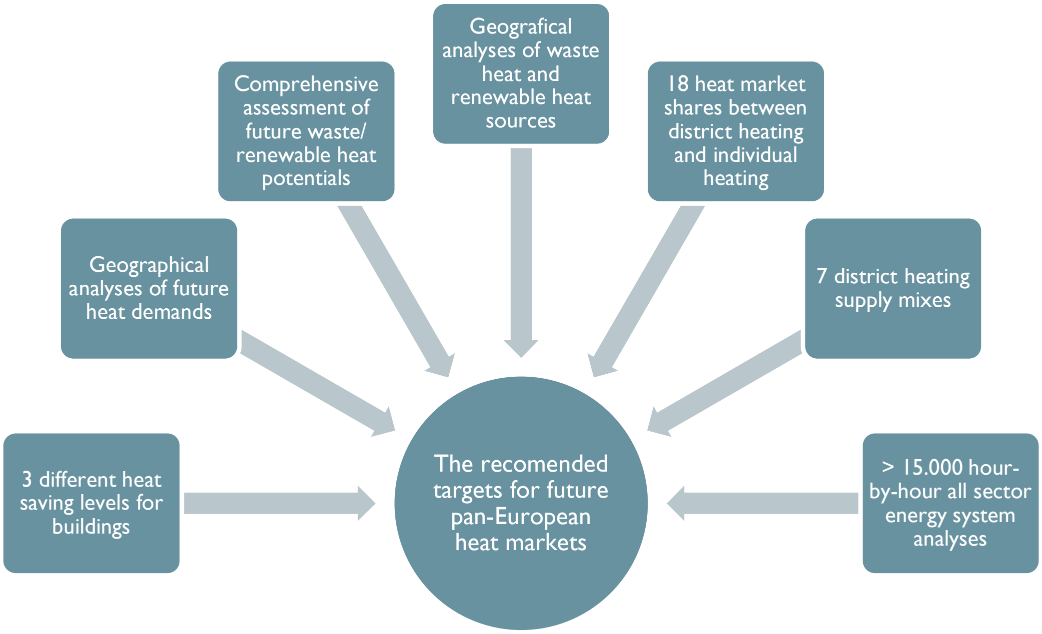


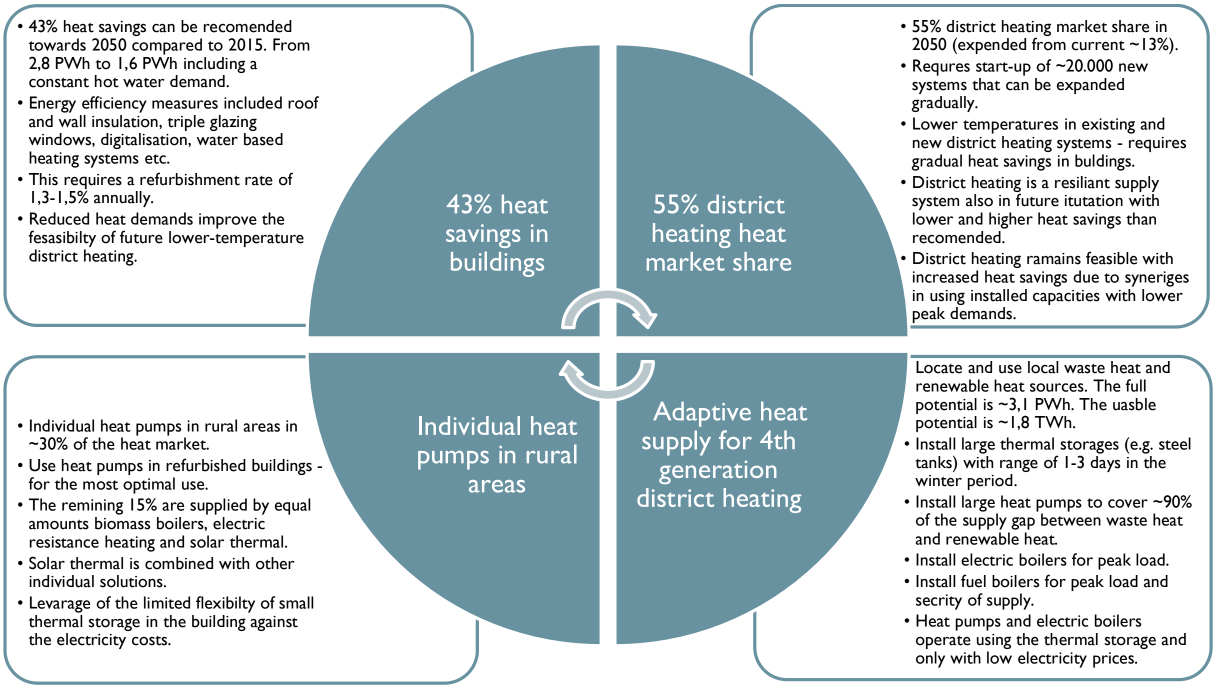
Figure 3, Simplified illustration of the inputs and analysis to reach a recommended 2050 energy system and a future heat market and layout.

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.

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 3,1 PWh, out of which 1,2 PWh is renewable heat and 1,6 PWh are traditional and unconventional heat sources and 0,6 PWh stems from power production plants. Approximately1,8 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.



- 43% heat savings can be recomended towards 2050 compared to 2015. From 2,8 PWh to 1,6 PWh including a constant hot water demand.
- Energy efficiency measures included roof and wall insulation, triple glazing windows, digitalisation, water based heating systems etc.
- This requires a refurbishment rate of 1,3-1,5% annually.
- Reduced heat demands improve the fesasibilty of future lower-temperature district heating.

- 55% district heating market share in 2050 (expended from current ~13%).
- Requres start-up of ~20.000 new systems that can be expanded gradually.
- Lower temperatures in existing and new district heating systems - requires gradual heat savings in buldings.
- District heating is a resiliant supply system also in future itutation with lower and higher heat savings than recomended.
- District heating ramains feasible with increased heat savings due to syneriges in using installed capacities with lower peak demands.

- Individual heat pumps in rural areas in ~30% of the heat market.
- Use heat pumps in refurbished buildings - for the most optimal use.
- The remining 15% are supplied by equal amounts biomass boilers, electric resistance heating and solar thermal.
- Solar thermal is combined with other individual solutions.
- Levarage of the limited flexibilty of small thermal storage in the building against the electricity costs.

Locate and use local waste heat and renewable heat sources. The full potential is ~3,1 PWh. The uasble potential is ~1,8 TWh.
- Install large thermal storages (e.g. steel tanks) with range of 1-3 days in the winter period.
- Install large heat pumps to cover ~90% of the supply gap between waste heat and renewable heat.
- Install electric boilers for peak load.
- Install fuel boilers for peak load and secrity of supply.
- Heat pumps and electric boilers operate using the thermal storage and only with low electricity prices.

Figure 4. Main structures in future decarbonised heat market.

Further, given the geographical and temporal constraints, energy system analyses, heat savings in buildings and energy supply technology costs 0,7 PWh of the full available potential is considered usable. This is 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.

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 6%, Ambitious 43% and Very high 53%. The 53% savings being equal to the level in the report *"A Clean Planet for All"* (European Commission, 2018).

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[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.

- 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 enables 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.

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.

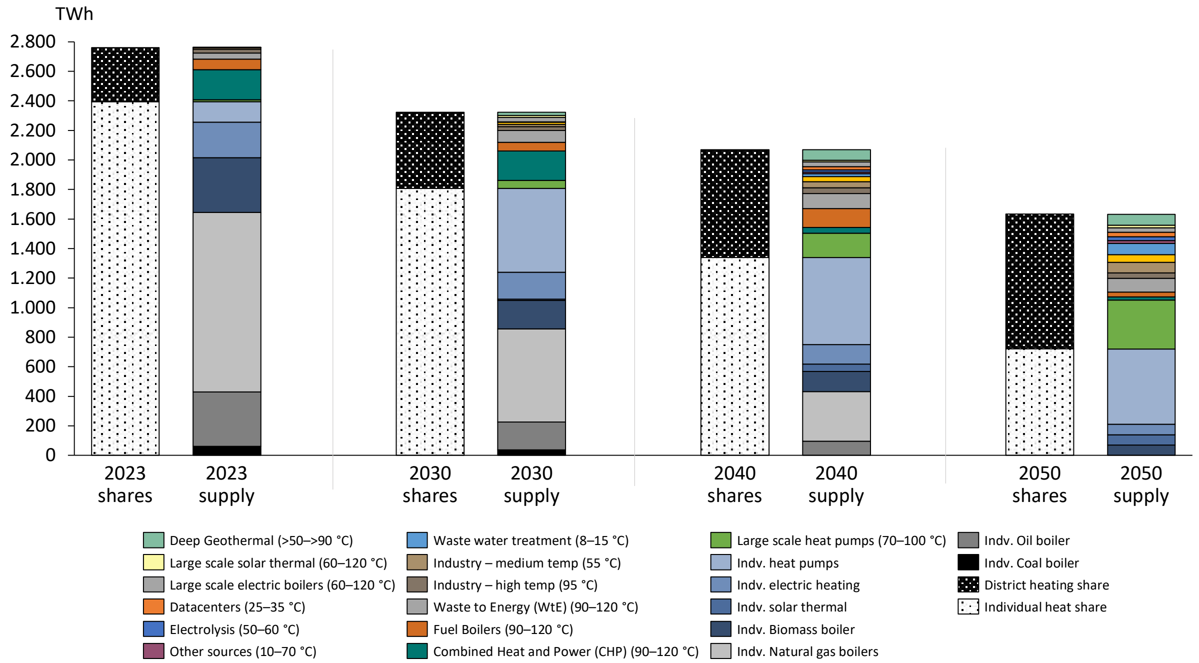

Figure 5, The development of the heat market, i.e. heating and hot water. Supply technologies and division between district heating and individual solutions. Industry sources, wastewater treatment, supermarkets and in some instances geothermal need large scale heat pumps. In this figure these sources 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% per 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% per 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% per 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

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[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)

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 at least 200 TWh technical heat potential from data centres is utilised covering 3% (40 TWh) and 20% of the electrolysis waste heat is used converting 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, 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 61 billion € in 2050.
- **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.

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[3] GW_e capacity on the electricity input side.

  - **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 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.

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.

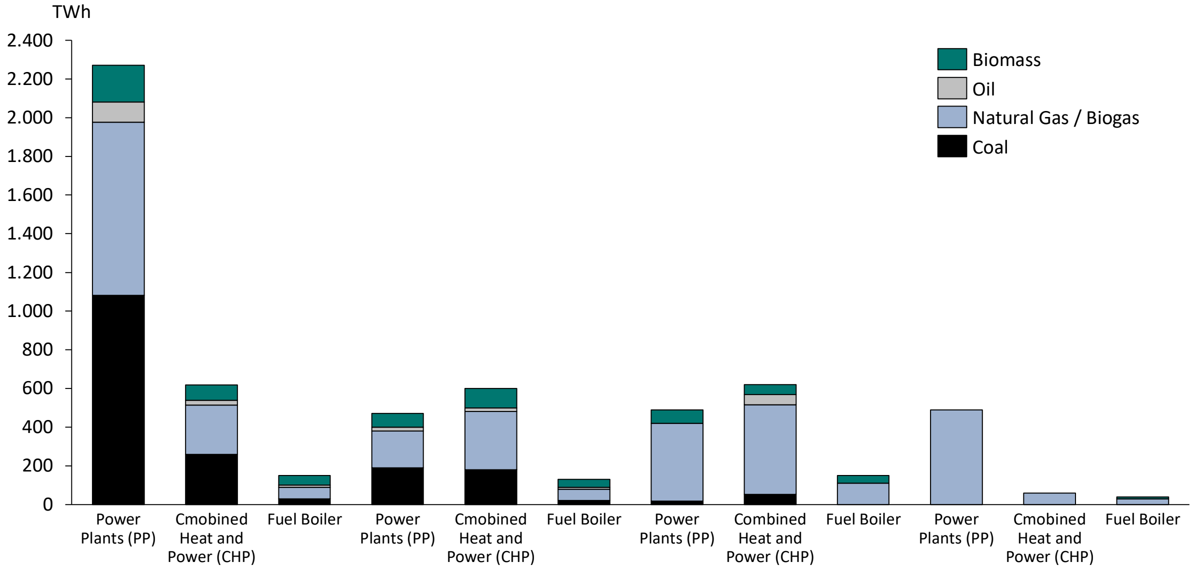

Figure 6, Estimated scenarios for fuel consumption in power plants, CHP plants and fuel boilers towards the recommended scenario in 2050.

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.

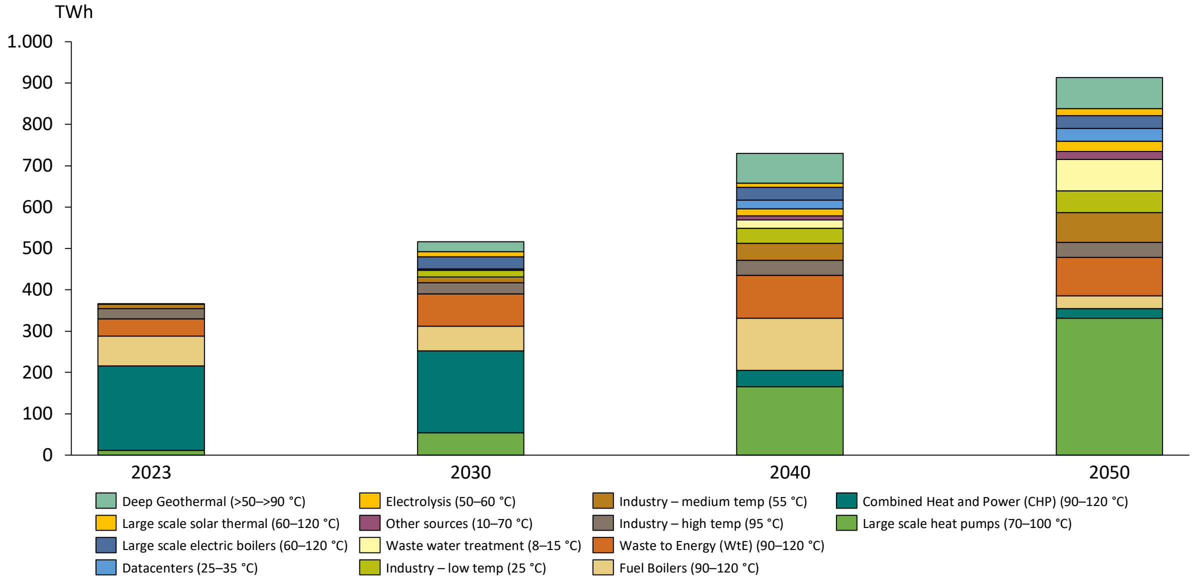

Figure 7. District heating supply mix from 2023 until 2050 excluding grid losses in the recommended mix and share.

Fact Box 1. The World's largest natural refrigerant seawater heat pump w. thermal storage

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

Location: Aalborg, Denmark (approx. 200.000 people)
Aalborg is transitioning from conventional heat production to a highly electrified, flexible district heating system, centred around what will be the world's largest seawater-based heat pump installation for district heating using natural refrigerants. The Norbis Park Seawater Large-scale heat pump plant enables large-scale integration of renewable electricity, operating primarily when electricity prices are low and thereby reducing reliance on fossil fuels and biomass. The seawater heat pump plant is designed as a core system asset rather than a stand-alone unit. In combination with large thermal storage, it provides substantial operational flexibility, allowing heat production to be decoupled from real-time electricity prices. During periods of high electricity prices, stored heat can cover demand for several days, while in low-price periods the system ramps up heat production. At full operation, the plant is expected to deliver around one third of Aalborg's total district heating demand. The remaining heat supply is provided by industrial waste heat (primarily from cement production at Aalborg Portland) and waste-to-energy (WtE), forming a diversified and resilient supply mix consistent with the recommendations in this study and with Energy Efficiency 2.0 principles.

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 district heating 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 m^3 thermal storage integration enables system balancing and sector coupling (including the existing 50.000 m^3) 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 m^3 thermal storage tanks in Aalborg.

The vast renewable heat and waste 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 EU27 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 (CHP) 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.

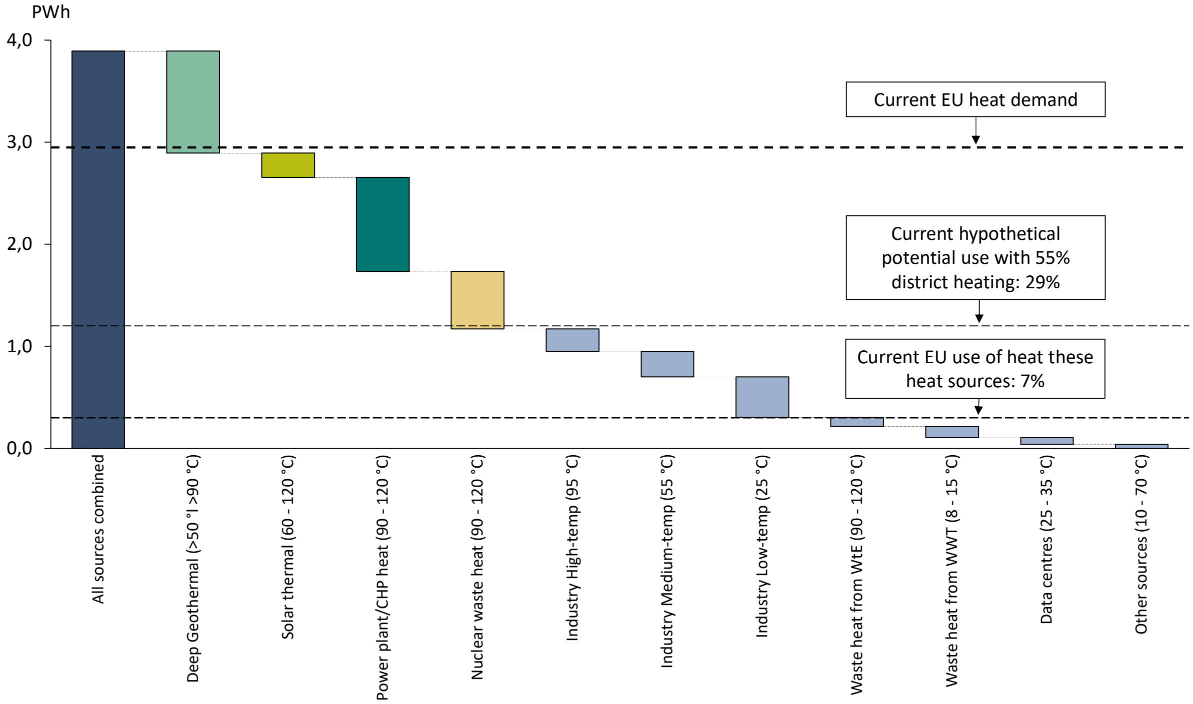

Figure 8. Diagram of the current EU27 heat sources combined and divided into sources. The sources are compared to the current heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands. WWT: wastewater treatment. WtE: waste-to-energy, 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 a potential future 55% district heating coverage, renewable heat and waste heat can cover up to 73% of the district heating production, utilising about 29% of the technical 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.

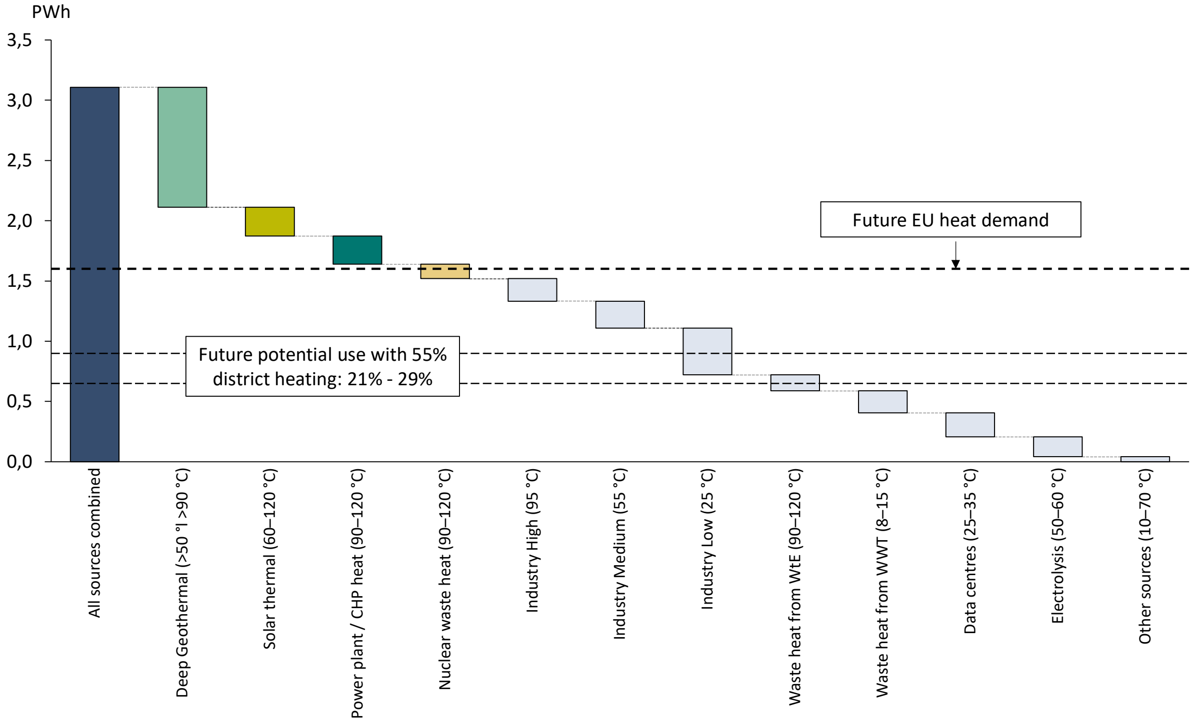

Figure 9. All future EU27 heat sources combined is illustrated as well as divided into sources. The sources are compared to the future heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands except data centres and electrolysis. 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 baseload 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 baseload heat demand equivalent to cities with about 100.000 inhabitants. If sources are certain and readily available geothermal may be applicable in smaller cities to. 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).

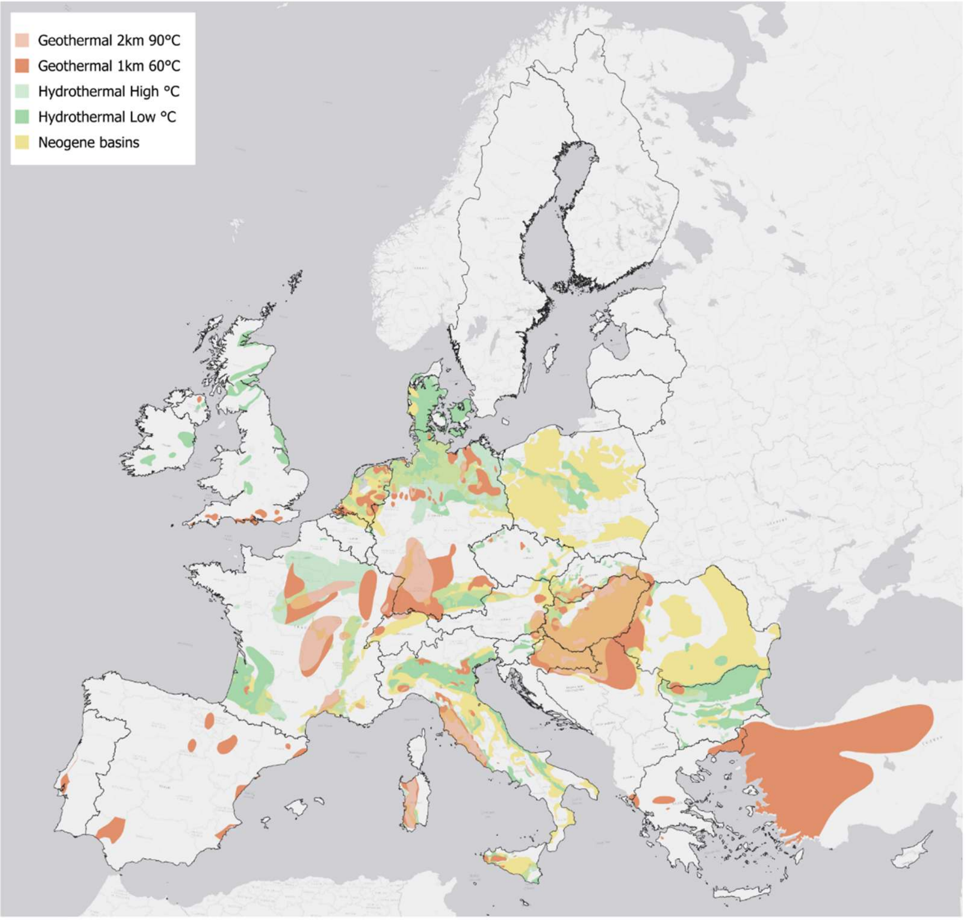

Figure 10, Areas with geothermal potentials in Europe.

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 potential 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). Solar thermal is considered in cities with less than 50.000 inhabitants where it most likely could cover 5% of the district heating supply mix, due to the likely scarcity of space for large diurnal, weekly of seasonal storage. In cities with e.g. 1.000 inhabitant may have a coverage of up to 50%, if land is available. Solar thermal is therefore primarily positioned as a supplementary baseload technology, particularly relevant in smaller and medium-sized systems where large seasonal thermal storage can be deployed and where competition from industrial waste heat is limited.

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 due to temporal aspects and other waste heat and renewable heat sources. **Nuclear waste heat** is only utilized in few cases for district heating currently in small towns or villages; however, it remains a source which is in principle useable if the geographical location is in closer vicinity to heat demands. Nuclear waste heat is expected also to be present in the future, but to a smaller extent compared to today considering the current development. The largest potentials for nuclear wate heat in 2050 are found in France 83 TWh/y, Czech Republic 12 TWh/y, Finland 9 TWh/y, but potentials are also expected in Bulgaria, Romania, Slovakia and Poland, however the planned plant in Poland is not included in the listed sources in this project. Together, these countries pose a total a potential of 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 the usable heat would be depending temporal aspects of heat demands locally, temporal aspects of other potential waste heat and renewable heat sources, i.e. the usable heat may be a baseload or may be limited to the wintertime i.e. about 40-50% of the potential depending on the context.

Fact Box II. Recovery of waste heat from industry and data centres

Case: Brescia's heat pump and multi-source waste heat integration

Location: Brescia, Italy (approx. 200.000 people)
Brescia operates one of Europe's most advanced district heating systems, with approximately 684 km of network supplying over 22.000 substations. The system integrates multiple waste-heat sources, with industrial waste heat from steel production forming the backbone of supply, complemented by newer low-temperature sources. A flagship project recovers waste heat from a local steel mill, upgraded through large-scale heat pumps and delivered to the district heating network at temperatures up to ~105 °C, providing around 50 GWh/year. In parallel, the Qarnot data centre project demonstrates the integration of low-temperature waste heat (~65 °C), reaching up to ~16 GWh/year in later phases. Together, these projects illustrate how diverse waste-heat streams can be combined in large urban district heating systems, in line with the system-integration principles outlined in this study.

Key features:

- 6 MW_{th} systems that recovers waste heat and sends water temperatures up to 105°C.
- COP, coefficient of performance, of 8,46
- Saving 178 tons of CO_{2}-eq in the 2025 heating season

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.

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 about 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), Spain (12 TWh/y), Italy (10 TWh/y), and the Netherlands (9 TWh/y). Together, these countries contribute about 70% of the EU27 potential in 2050. The heat from WtE however is distributed very differently compared to today.

The **waste heat from datacentres** is projected here to increase to at least 200 TWh/y towards 2050. The largest technical potentials for datacentre waste heat in the base case are in Germany ~50 TWh/y, France ~35 TWh/y, Ireland 19 TWh/y, the Netherlands ~17 TWh/y, and Italy 16 TWh/y. Together, these five countries account for about 135 TWh/y, which is more than half of the EU27 total technical potential by 2050. The potential has been estimated in this project using the latest forecast including expected gradual efficiency gains. The use of these waste heat sources is depending the readiness and type of data centre, on the location of the data centre as well as on the EU27 and member state level shares of electricity consumption in data centres – and of course - the deployment of district heating grid.

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 1 the percentages of the use of the heat sources are listed as well as the mix. In between the technical potential with 55% district heating and recommended use scenario, geographical analyses are 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 (TWh)	Recommended use, 55% DH	% of DH supply 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%
Waste heat sources	**1517**	**948**	**527**	**44%**	**422**	**35%**	**56%**
Renewable and waste heat sources	**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%**
Waste heat , incl Power plants/CHP	**1876**	**1196**	**557**	**47%**	**639**	**30%**	**47%**
Renewable and waste heat incl. PP/CHP	**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.

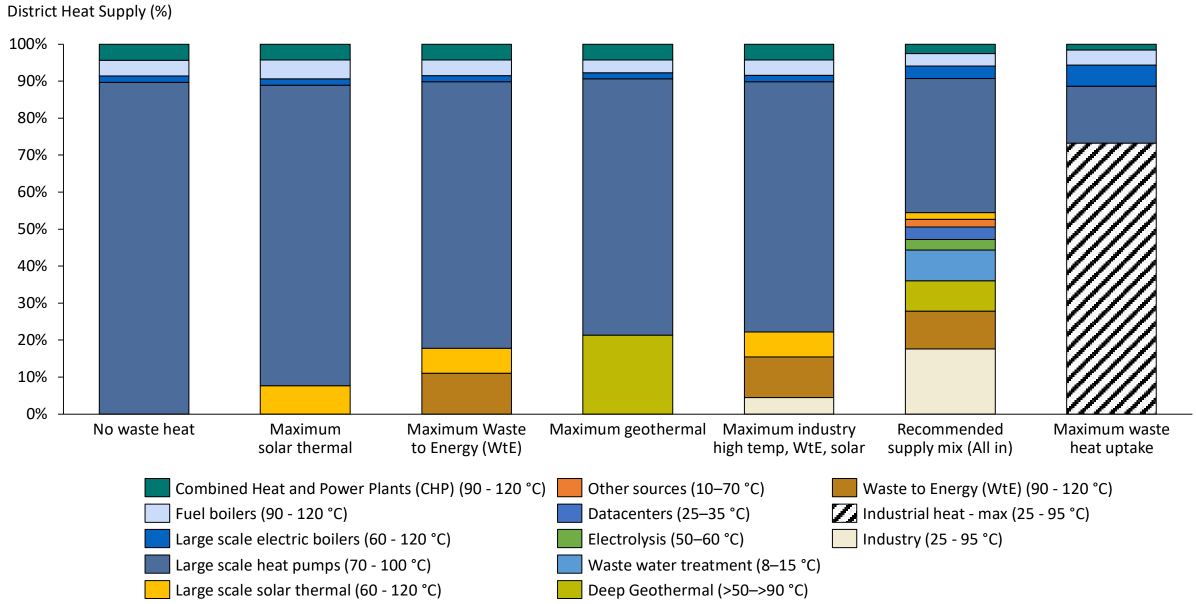

Figure 11, District heating supply options analysed with 55% district heating market share combined with ambitious savings and 4th generation district heating.

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.

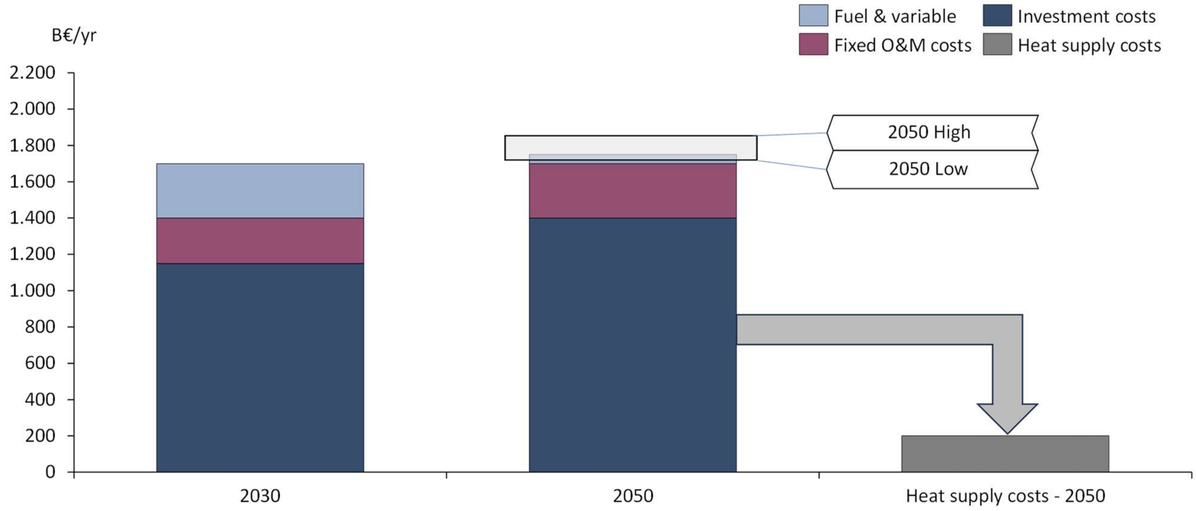

Figure 12, The total annual energy system costs including electricity, heating, transport and industry of the future energy systems in 2030 and 2050 as well as the total 2050 heat system costs as a part of the total system costs. The bar represents the highest and the lowest costs of the heating systems 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 12 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 20,8 T€ (1.700 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.

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.

Table 2. Overview of investments and annual system costs for major components in the energy system from 2030 to 2050 in EU27.

	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	1.156	51
Large heat pumps	37	9	63	12	61	4
Individual heat pumps	477	58	407	97	898	87
Combined heat and power plants	316	29	61	6	70	6
Large scale boilers	14	-	179	16	294	27
Individual boilers	477	49	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	1	16	1	18	1
Total	**1.819**	**165**	**1.971**	**209**	**2.786**	**199**
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)	7.808	834	8.265	884	10.317	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
Electrolysis and hydrogen storage	38	5	198	22	140	27
Gasification, pyrolysis and electrofuels	107	11	121	13	124	12
Smart, flexible electricity requirement	-	-	161	6	345	16
Hydro	1.215	64	837	46	911	51
Building renovation	784	38	1365	66	1.997	96
Total	**13.836**	**1.270**	**16.219**	**1.495**	**20.871**	**1.699**

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 EU27is 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.

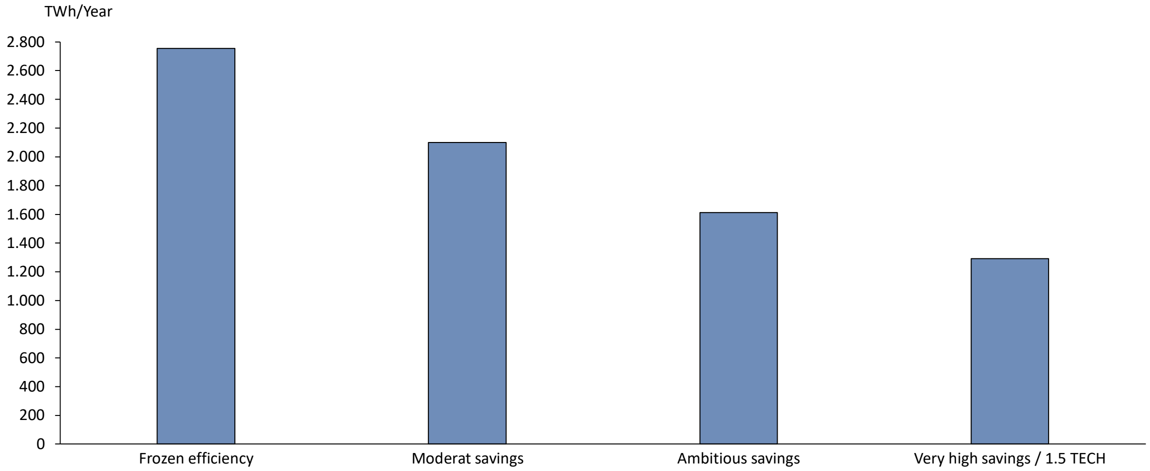

Figure 13, Development of the overall EU heat and hot water demands with difference refurbishment in towards 2050.

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 per square meter can fall through comprehensive refurbishment, improved building envelopes, and widespread adoption of low-temperature heating. In Figure 14 the per country heat and hot waster demands are illustrated.

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.

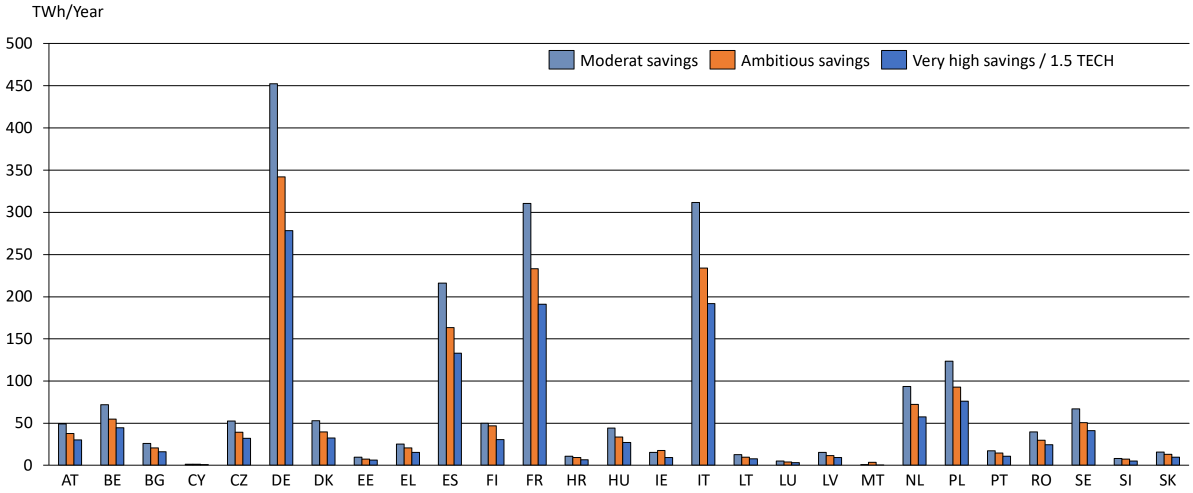

Figure 14, Development of the country level EU heat and hot water demands with difference refurbishment levels in 2050.

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 (Lund, Henrik et al., 2014). 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. However the moderate savings level in the 4th generation district heating supply option may not be possible due to the higher temperature needs. If the comparison is made between the moderate savings 3rd generation district heating and the ambitious savings 4th generation, the biomass savings are 12%.
- 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.

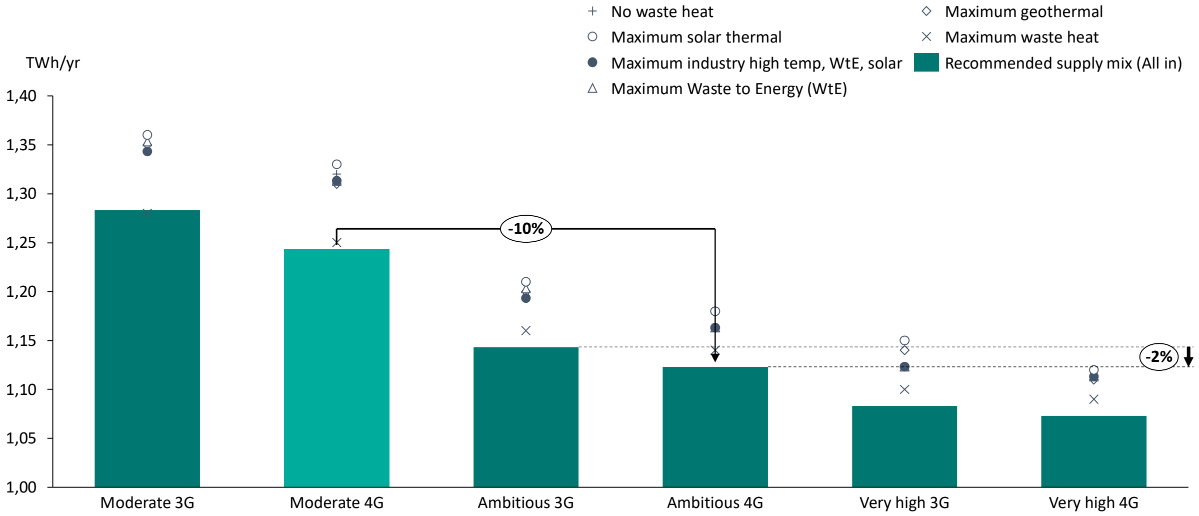

Figure 15, Biomass consumption of the different saving levels (moderate, ambitious and very high) combined with the seven heat supply scenarios with 55% district heating for both 3rd and 4th generation district heating solutions in EU27.

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 two building-renovation levels in the 4th generation district heating portfolio and several market-share scenarios. Here the recommended supply mix is only illustrated. The two panels correspond to the renovation levels - *ambitious*, and *very-high savings*. 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.

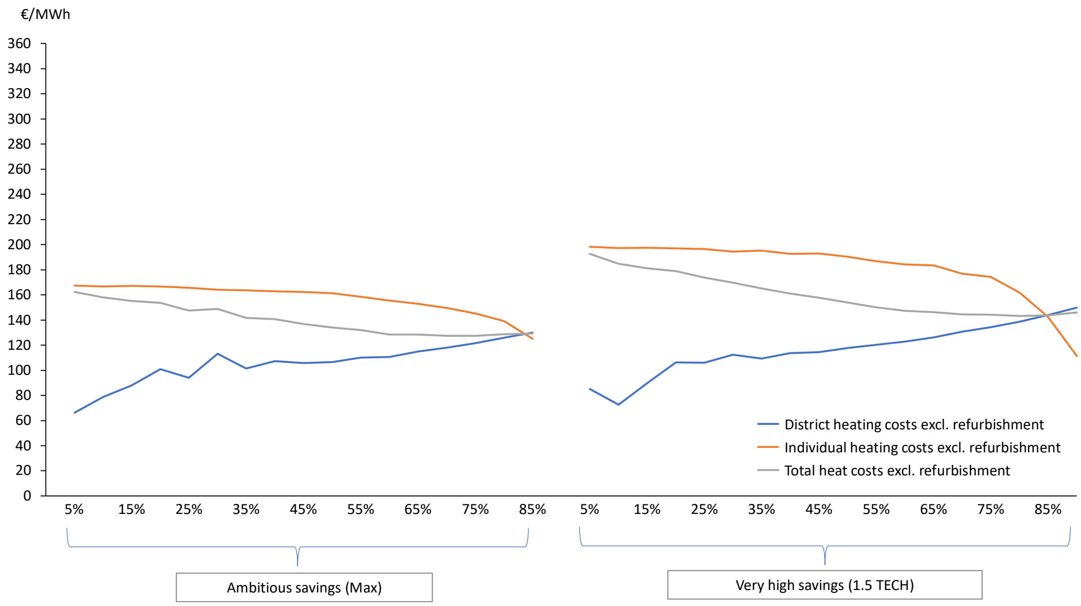

Figure 16, Costs per energy unit divided into district heating and individual heating, spread out on different market shares as well as on two renovation levels, but excluding refurbishment costs. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

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.

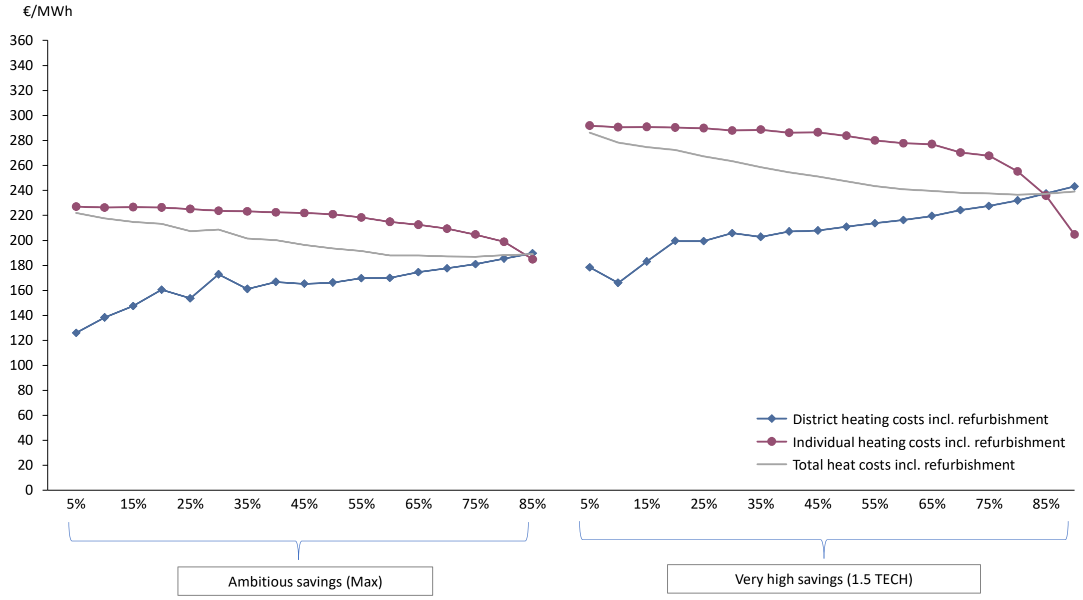

Figure 17, Costs per energy unit divided into district heating and individual heating, spread out on different market shares as well as on two renovation levels, but including refurbishment costs. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

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 two panels correspond to the renovation levels - *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 per 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 combined with 4th generation district heating. For comparison the 3rd generation district with the recommend supply mix and moderate savings are included. 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% district heating mark the point of minimum total system costs in the 4th generation district heating system, the ambitious savings scenario offers substantial system-level and resource benefits at only slightly higher cost. In Figure 18 the moderate savings scenario is shown as a dotted line in order to highlight that it is uncertain whether the low temperatures can be achieved with only the moderate savings level. In some local conditions this may be the case. In others it is not. The costs with moderate savings and 3rd generation district heating is shown for comparison.

- 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. It temperature levels cannot be reduces with only moderate savings, the comparison of the ambitions savings with 4th generation district heating should be with the 3rd generation district heating moderate savings.
- 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.

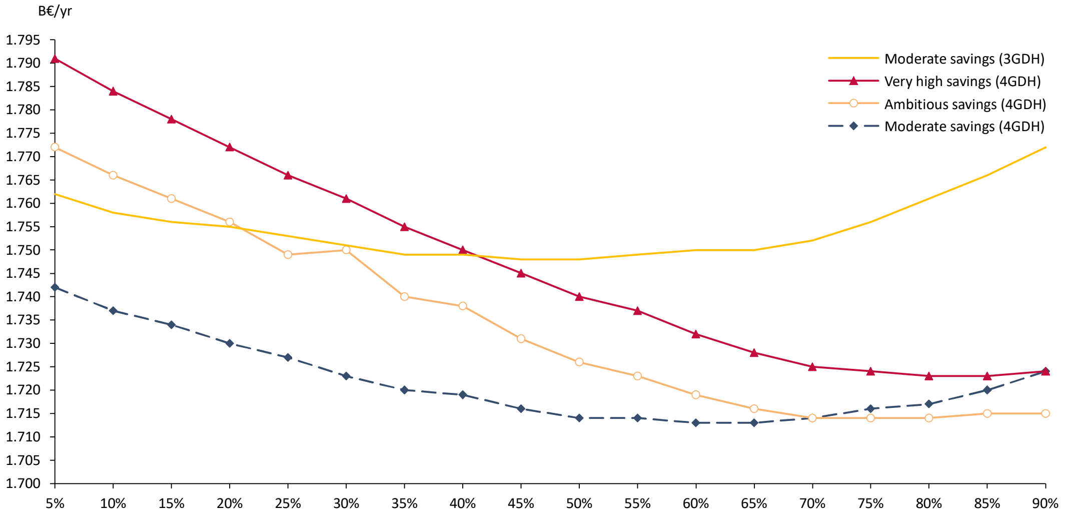

Figure 18, Development of total system costs as a function district heating market shares and across the three heat saving levels for the recommended district heating supply mix combined with 4th generation district heating and for the moderate savings also for the 3rd generation district heating. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

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 in percentages, 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.

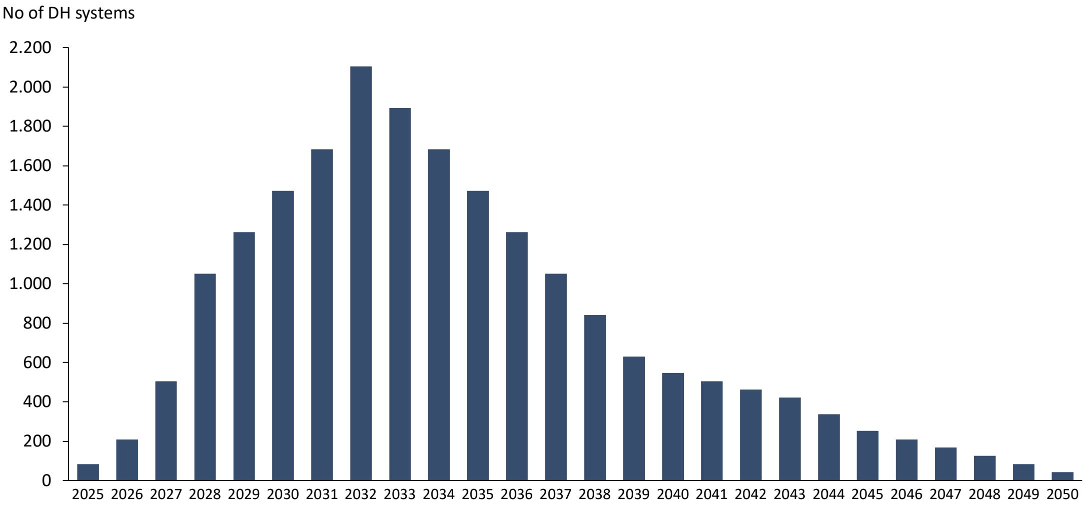

Figure 19. New prospect district heating systems by year.

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 approach to estimate how many district heating systems are needed for higher district heating shares assumes one system in small district heating areas with final heat demands below 1 PJ, while larger areas are counted as requiring up to five systems. As a rule of thumb, 1 PJ ≈ 18.000 households at 15 MWh/household (though household demand varies by country). In practice, the threshold depends on local conditions: large non-residential loads can reduce the population needed to roughly 10.000 inhabitants, and in reality district heating can also be viable in much smaller villages (~100–200 households) depending on heat densities and local sources.

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 villages 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.

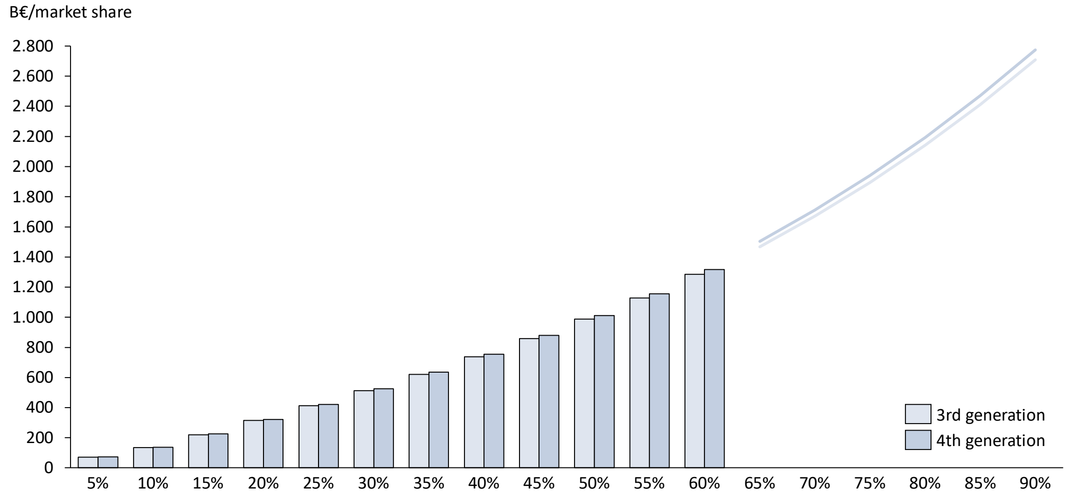

Figure 20, Accumulations cistrict heating grid costs as a function of market share for EU27 for both 3rd and 4th generation district heating. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

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:

- € 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.

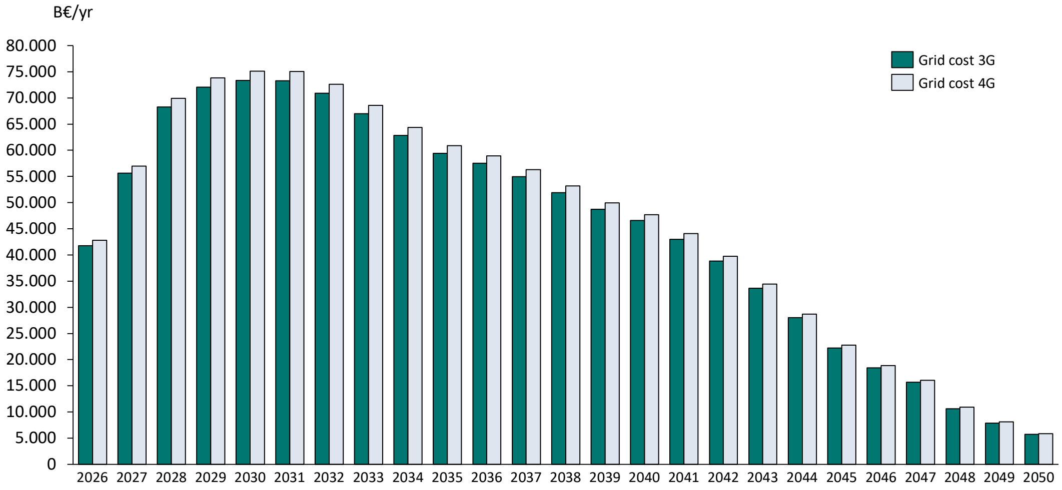

Figure 21. Distribution of grid costs for new district heating systems by year for 3rd and 4rth generation systems.

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.

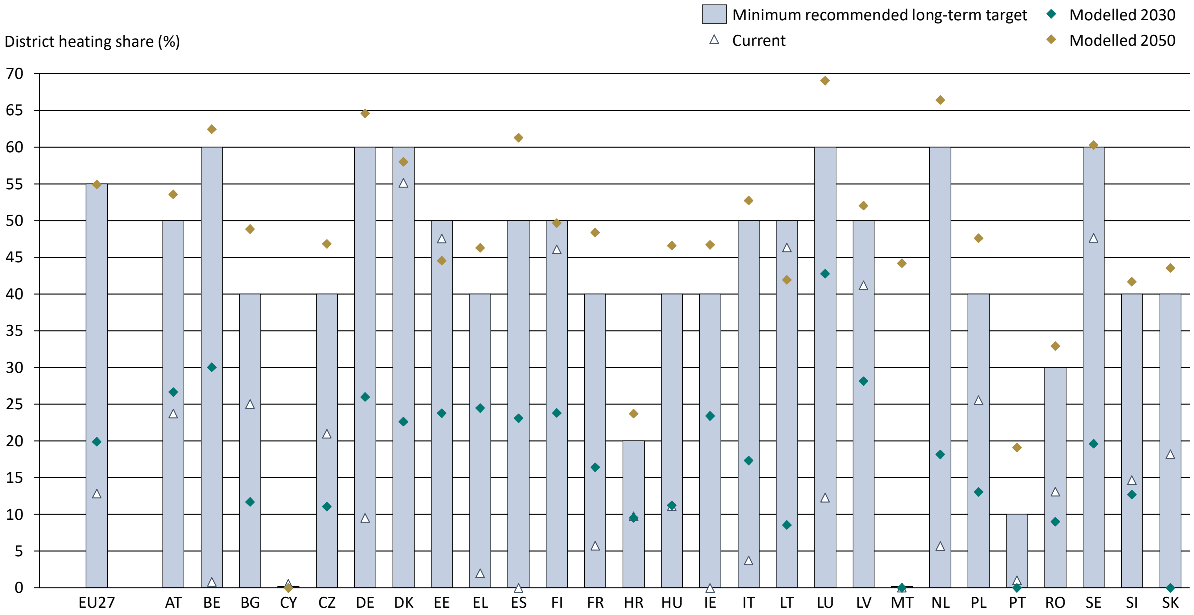

Figure 22, Country divided recommended district heating market shares (%) as well as the current (2023) and modelled shares.

EU27 district heating deployment "hot spot" cities using waste-, and renewable heat sources

Several heat sources have been mapped in this project 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.

Locating and prioritizing the development of district heating networks can be a difficult choice and is based on various parameters. This analysis emphasizes large urban centers, focusing on cities with more than 45.000 inhabitants, where the implementation of district heating systems is more feasible and economically viable. As each city and country presents its own unique opportunities for district heating development, we present the results of our analysis, which reflects the selection of the most suitable cities, based on investment costs and then based on the availability and size of waste and renewable heat sources both at EU27 and national level for the examined countries.

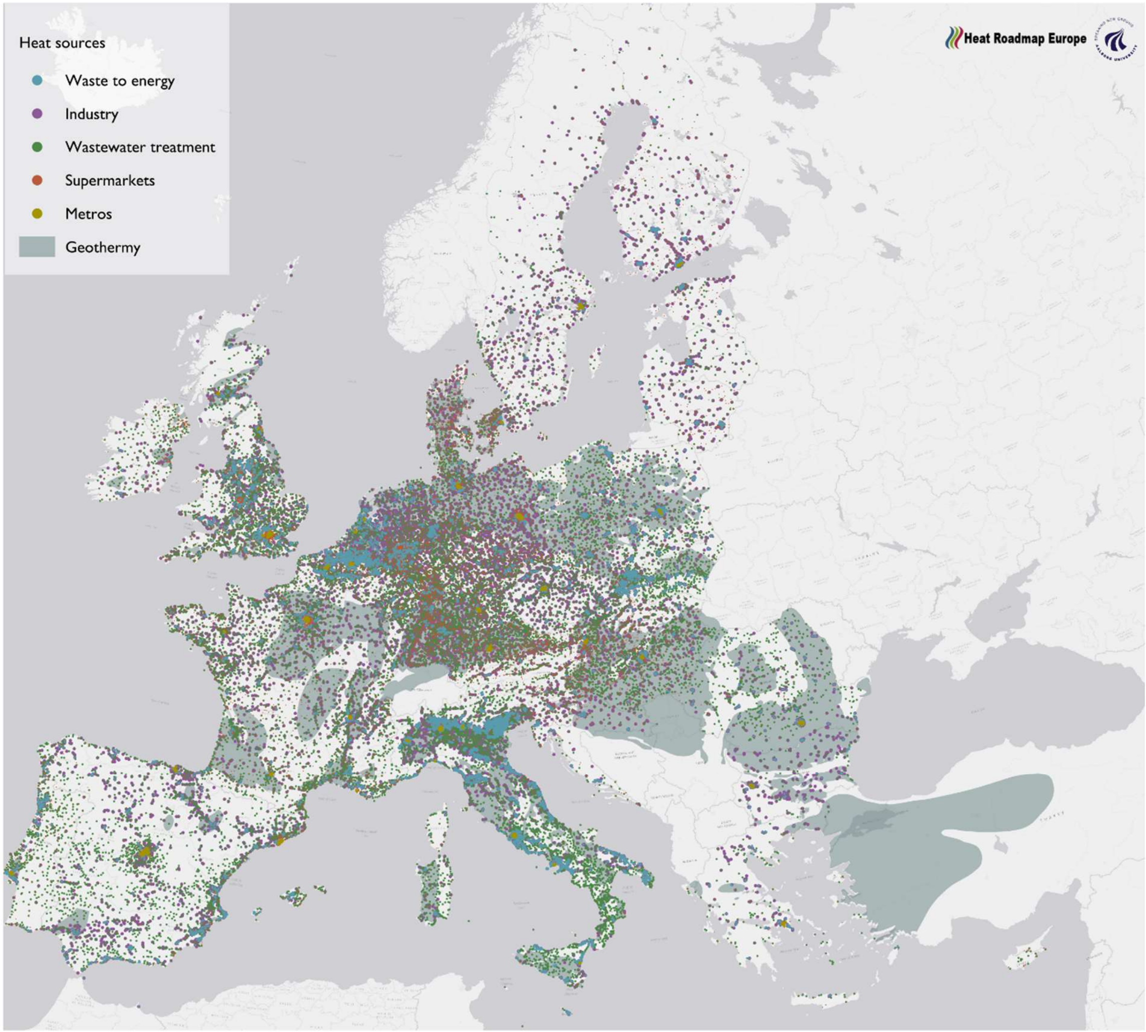

Figure 23, Illustration of the heat sources mapped in this Heat Roadmap Europe study.

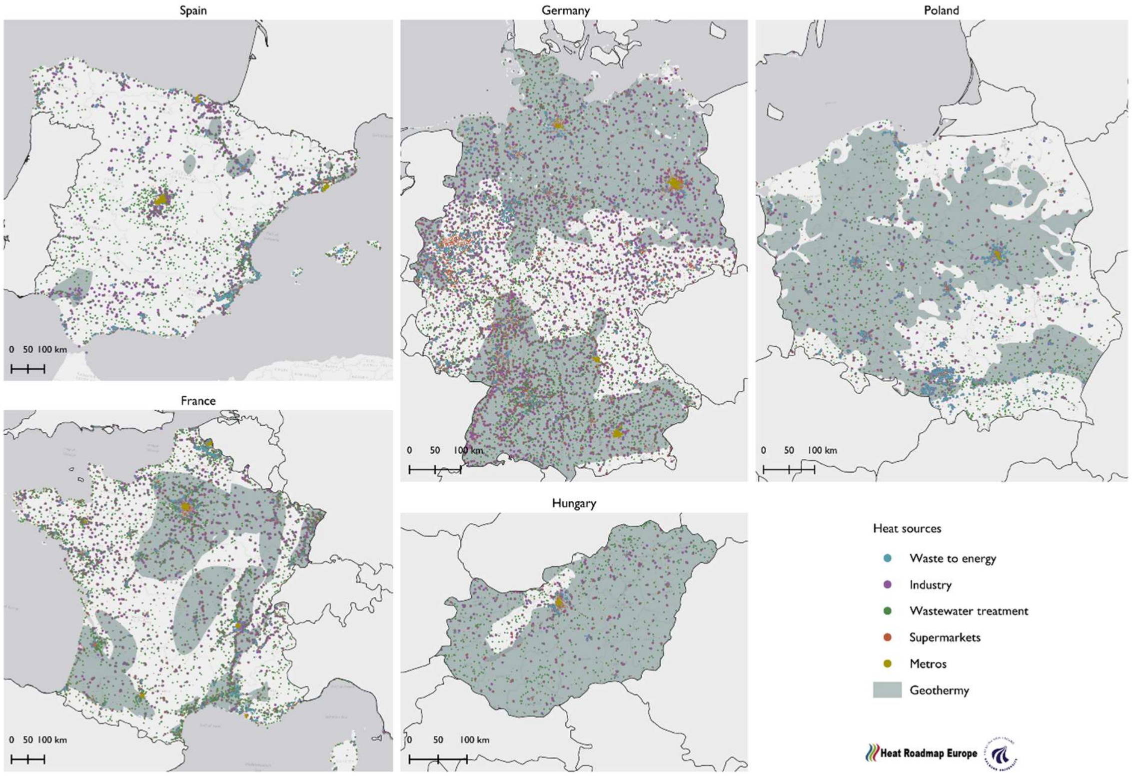

Figure 24, Illustration of the heat sources mapped in this Heat Roadmap Europe in the five investigated countries.

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 "hot spot" 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, Le Havre, Linz, Duisburg, Ostrava, Mestre close to Venice, Gijon, Malaga as well as Valletta in Malta.

There are vast parts of Europe with no or very few high-temperature sources. However, there are many other potential sources that create "hot spot" cities. In Figure 26 "hot-spot" cities with large **low-, and medium-temperature industrial waste heat potentials** are illustrated. Many of the sources are co-located with high temperature sources but it is clear from the results pr. country in this report and in Figure 26 that these sources are more distributed compared to the high-temperature waste heat.

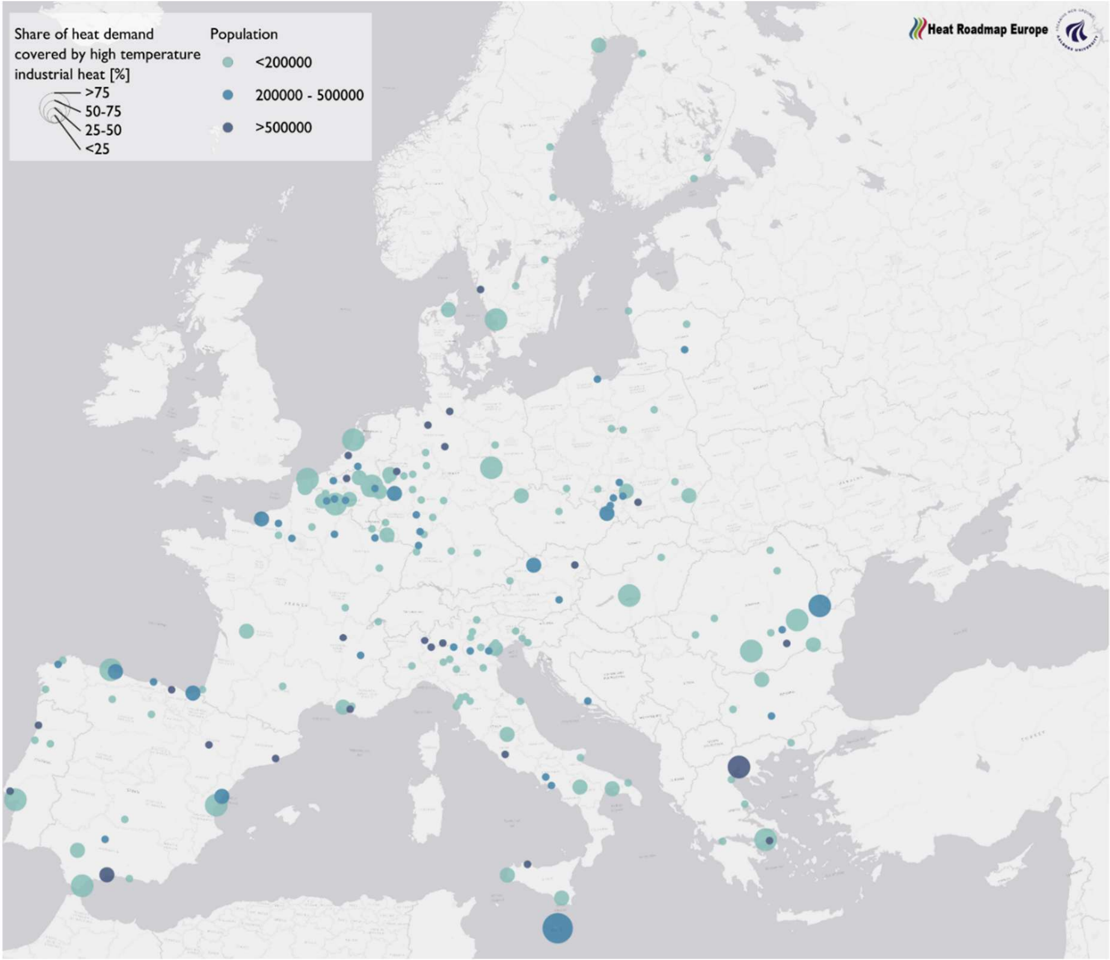

Figure 25. Mapped "hot spot" cities where high shares of heat demand potentially can be covered by high-temperature industrial waste heat sources in comparison to the city's population.

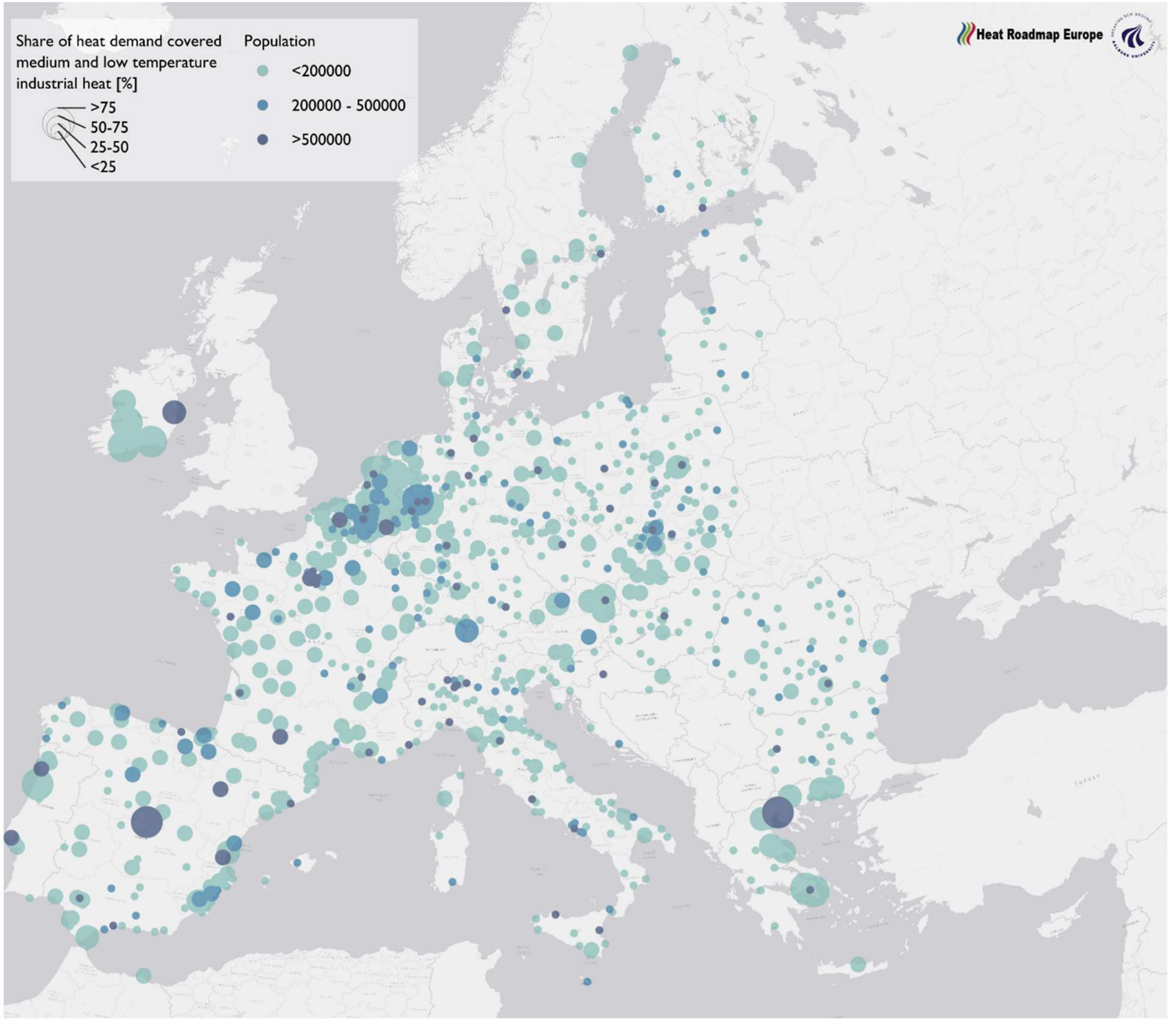

Figure 26, Mapped "hot spot" cities where high shares of heat demand potentially can be covered by low-, and medium-temperature industrial waste heat sources in comparison to the city's population.

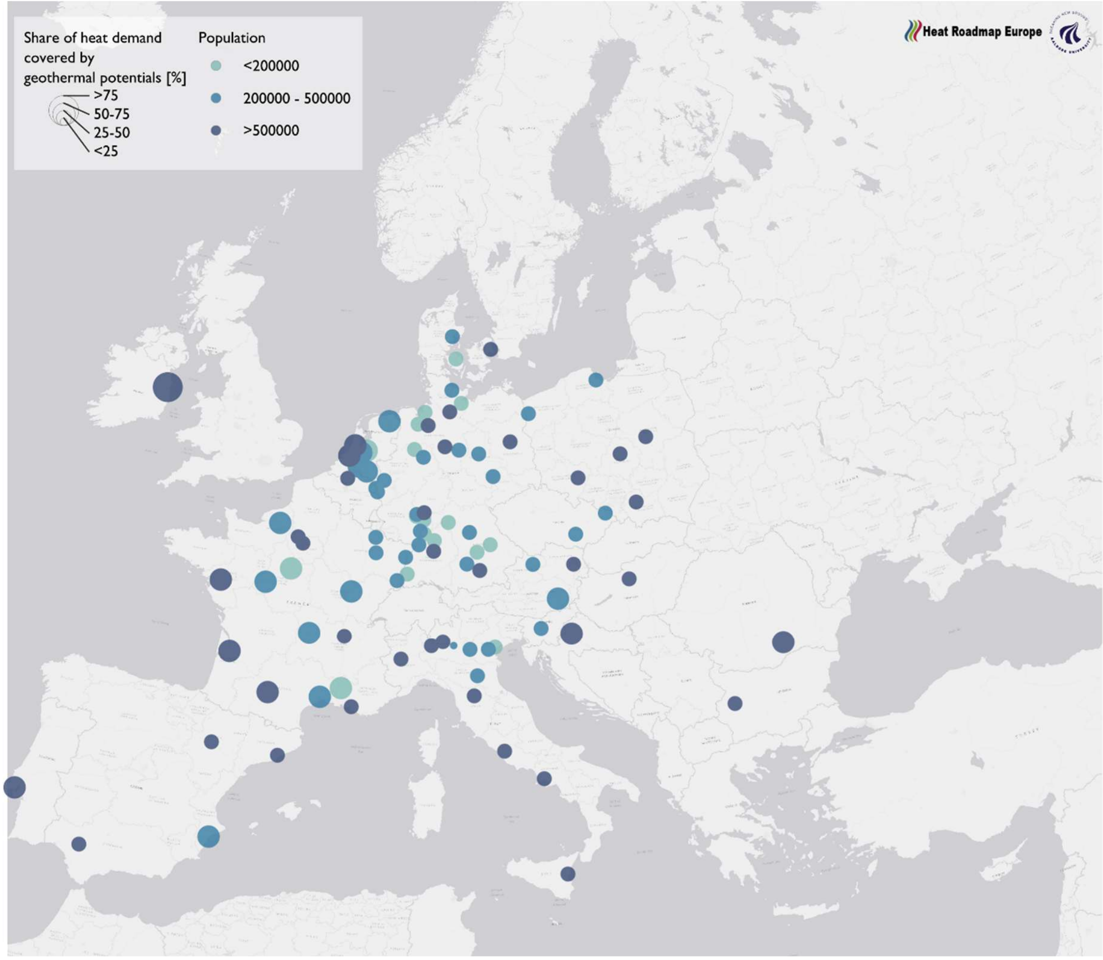

Figure 27. Mapped "hot spot" cities where high shares of heat demand potentially can be covered by geothermal heat sources in comparison to the city's population.

Figure 27 illustrate the "hot spot" cities with large **geothermal heat potentials**, relative to their demand, which can be exploited in district heating system. 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 and in cities that do not have large amounts of other sources. Again, 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 and Paris already currently exploits this potential partly.

In the associated "Data and Country profiles" report illustrations of waste heat from high-, medium- and low temperature industrial, waste heat from WtE, supermarkets, waste heat from WWT and metros, along with the correlating heat demands. In Figure 28 the three sources included in this section are compared for selected countries. There is high variation among the countries, their sources and the amount of the potentials, as the cities, their sizes and demands also differ respectively, which highlights the need for local heat planning.

Figure 28, "Hot spot" cities for selected countries where high shares of heat demand potentially can be covered by high-temperature waste heat (left), medium-, and low-temperature waste heat (middle) as well as geothermal heat sources (right) in comparison to the city's population.

Table 3, 10 "hot spot" cities where high shares of heat demand potentially can be covered by high-temperature industrial waste heat sources. Listed are heat demands, estimated district heating network investment needs, heat potentials of the source and share which in theory can be covered as well as the availability of geothermal and knowledge about the availability of a current district heating network.

City	Country	Heat demand 2050 [TWh]	Estimated network investment cost [EUR/MWh]	High temp waste industry heat [TWh]	Share of heat demand covered by high temp industrial waste heat	Available district heating	Available geothermal
Valletta	Malta	1,7	310,2	2,1	122%	No	No
Thessaloniki	Greece	2,0	863,1	1,2	62%	No	No
Le Havre	France	2,0	699,3	1,0	50%	Yes	No
Bonn	Germany	2,9	654,5	1,4	47%	Yes	No
Linz	Austria	2,8	557,9	1,3	47%	Yes	Yes
Duisburg	Germany	1,6	546,2	0,7	46%	Yes	No
Ostrava	Czechia	1,8	521,0	0,8	43%	Yes	Yes
Mestre	Italy	1,5	548,0	0,6	40%	No	Yes
Gijon	Spain	1,3	513,0	0,4	32%	No	No
Malaga	Spain	1,6	666,3	0,5	28%	No	No

Table 4, 10 "hot spot" cities where high shares of heat demand potentially can be covered by medium- and low-temperature industrial waste heat sources. Listed are heat demands, estimated district heating network investment needs, heat potentials of the source and share which in theory can be covered as well as the availability of geothermal and knowledge about the availability of a current district heating network.

City	Country	Heat demand 2050 [TWh]	Estimated network investment cost [EUR/MWh]	Medium- and low temp waste industry heat [TWh]	Share of Heat demand by M+L temp sources	Available district heating	Available geothermal
Limerick	Ireland	801,9	859,1	669,6	83,5	No	No
Thessaloniki	Greece	1.973,7	863,1	1.536,6	77,9	No	No
Cork	Ireland	1.009,8	974,6	761,2	75,4	Yes	No
Wels	Austria	802,0	738,4	581,1	72,5	Yes	Yes
Beringen	Belgium	841,9	1.138,1	536,9	63,8	No	No
Dublin	Ireland	6.807,5	886,4	4.325,2	63,5	Yes	Yes
Hasselt	Belgium	1.406,7	900,3	817,4	58,1	No	Yes
Feldkirch	Austria	1.011,6	1.077,4	551,9	54,6	Yes	Yes
Heist-op-den-Berg	Belgium	949,6	1.035,3	474,7	50,0	No	No
Herve	Belgium	813,2	970,9	395,9	48,7	No	No

Table 3, Table 4 and Table 5 list 10 selected cities respectively with high potentials of high-, medium-, and low-temperatures waste heat as well as heat from geothermal. In the associated "Data and country profiles" report the top 50 cities are listed, while country-level maps with the potentials of each source investigated is also included. Lastly, scatterplot diagrams associating the share of heat demand that can be covered by the corresponding sources to the investment cost are included in the country report.

Table 5, 10 "hot spot" cities where high shares of heat demand potentially can be covered by geothermal heat sources. Listed are heat demands, estimated district heating network investment needs and share which in theory can be covered. Note that in most cases the geothermal sources is combined with large-scale heat pumps, thus expanding the potentials of the sources listed.

City	Country	Heat demand 2050 [GWh]	Estimated network investment cost [EUR/MWh]	Geothermal energy [%, >70MW]
Dublin	Ireland	6.807,5	886,4	79,7
Amsterdam	Netherlands	8.418,8	986,8	56,1
The Hague	Netherlands	13.080,9	942,2	54,2
Lyon	France	7.580,6	782,9	49,9
Bremen	Germany	5.167,3	596,9	47,6
Antwerp	Belgium	10.278,4	611,6	46,7
Berlin	Germany	24.588,5	516,4	46,3
Paris	France	44.389,2	566,8	46,2
Hamburg	Germany	16.006,0	587,0	45,4
Hanover	Germany	6.169,3	532,0	45,1

Content

Further information and data: *Additionally, to this report there is a supplementary report containing "Data and Country profiles", which presents a comprehensive assessment of waste heat and renewable heat sources and district heating opportunities across the EU27, each member state and for the United Kingdom in the cases where data has been available for the analysis. The report compiles technical district heating potentials (TWh/y), waste heat from waste-to-energy (in million tonnes) potentials and waste heat from wastewater treatment plants for 2020–2050, data-centre waste-heat potentials, nuclear waste-heat estimates for 2023 and 2050, and aggregated industrial waste heat at 25°C, 55°C, and 95°C – all in (TWh/y) and for different district heating levels.*

National level district heating network costs are provided, along with an identification of the 50 most promising cities (population 45.000+) for district heating expansion based on spatial analyses of the waste heat and renewable heat sources. These cities are ranked based on investment requirements (M€) and the availability of nearby heat sources (TWh/y).

Country-specific chapters summarise potential district heating shares, mapped waste-heat potentials, and the spatial distribution of major heat sources, including geothermal (>40 MW and >70 MW), industrial heat (low/medium/high temperature), waste-to-energy plants, wastewater-treatment facilities, supermarkets, and metro systems. Selected figures compare scenario outcomes on maps. For France, Germany, Hungary, Poland and Spain specific system analyses have been conducted in which is also presented in this report.

A dedicated methodology section explains the spatial modelling of heat demand (TWh/y), which draws on building-stock and population datasets; the district-heating potential model using heat-demand and floor-area grids (excluding efficiency effects and omitting grid cells <400 m²); the EU-level estimation of district-heating market shares; and the mapping of future heat-source potentials (TWh/y), covering geothermal, solar thermal, industrial heat, waste-to-energy, wastewater treatment, supermarkets, metro systems, and nuclear energy.

The report further describes the scenario-based prioritisation framework used to allocate heat sources sequentially to baseload demand. Solar-thermal contributions are evaluated separately under two capacity assumptions before being integrated into the scenario stack. Six scenarios (A–F) are assessed in total, with detailed results provided for scenarios A, C, and D. Lastly, the report includes key EnergyPLAN inputs, costs, capacities, and scenario-specific parameters, intended to support subsequent system-modelling activities.

1 Context, main methodological principles and research design

Considering the need for more attention on energy efficiency the aim of this report is to provide a deep understanding of the possibilities by fundamentally changing the heat markets in EU. The main principles for addressing the climate crisis, competitiveness, furthering biodiversity and European autonomy and resilience are in focus. The analysis targets a 25-year span until 2050 and focuses on reducing the Primary Energy Supply (PES) to sustainable levels taking into consideration the overall system level costs and limitations in the renewable energy sources. This requires in addition to consider the local limitations in the deployment of renewable energy sources, the need for power plants, heat pumps, assessments of feasible refurbishment levels to assess future heat demands with. The context of the energy system and heat markets is also influenced by potential developments in the efficiency and electrification of industry and transport. In this chapter, we outline contexts considered in the analyses and the main principles in the methodology. For further information we refer to appendixes where applicable.

1.1 Research design

The research design builds on hundreds of data sources as well as on several different types of modelling tools. In the following chapters the specific methods and approaches applied are elaborated. In Figure 29 the overall methodological approach is illustrated.

In the first step the heat demands are established. The heat demands as well as the energy system contexts are based on the *sEEnergies* project (Mathiesen, Brian Vad et al., 2022). Three different future heat demands have been used in the modelling approaches which builds on data from the FORECAST tool. Using the heat demand data, several thousand potential district heating areas are modelled in GIS analyses up to a coverage of more than 60% district heating market share. This has been done in order to enable analyses of different levels of district heating from very little district heating to a large coverage. In the energy system analyses the three different refurbishment levels are analysed in combination with district heating levels. In the energy system analyses this is combined with different potentials for renewable heat and waste heat from both conventional and unconventional sources. The heat sources are assessed both in a current situation and in a future situation. For the EU the levels are in 5% intervals while for the five selected countries in the analyses have a 10% interval.

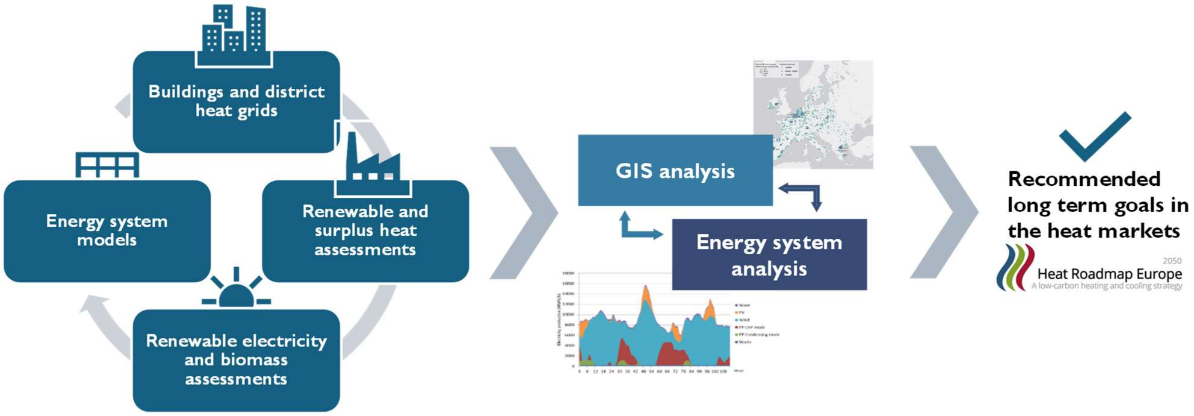

Figure 29 Overall methodological approach.

Going towards 2050 several different other changes will arise due to the EU level climate neutral goal. The electricity system will be dominated by onshore wind power and solar PV as well as lifetime extensions or newly established nuclear power plants. The future energy system context will change. Mobility will be electricified and power2X will provide major parts of the fuels for heavy duty transport. Industry will also be electrified, although smaller parts of high temperature needs in industry will be supplied with hydrogen or bioenergy. In the *sEEnergies* project this has been assessed using the TransportPLAN and IndustryPLAN tools. The significance of the changes for the heat markets are the changes in efficiency and thus changes in the possible waste heat sources due to the energy system design.

The heat markets will change also towards the future. It is assumed that the main decarbonization technology is individual heat pumps as well as district heating. In this project the idea is to identify a feasible long-term balance between the level of refurbishment, the use of renewable heat and waste heat as well as the main individual heat supplies using individual heat supply. It is pivotal to understand that the long term 2050 context are decarbonised solutions competing with each other, i.e. individual heat pumps combined with smaller shares of electric heat pumps, biomass boilers and solar thermal compete with different supply systems with district heating. In some cases geothermal may be outcompeted by other waste heat sources and heat pumps may be less relevant with very high temperature waste industrial heat. Here these sources are priorities and suggestions are made for balances for savings, supply systems and sources.

The goal is to assess the impact of the "energy efficiency first" principle in both current and future energy systems and both in the context of energy efficiency 1.0 and energy efficiency 2.0. For results related only to GIS all EU27 countries are included as well as the United Kingdom in most cases. In the scenario modelling using hour-by-hour energy system analyses methodologies EU27 is in focus.

1.2 Principles for the assessment of refurbishment cost and heat saving scenarios

The heat-demand projections and refurbishment-cost assumptions applied in this assessment are based on the harmonised modelling framework developed in the EU Horizon 2020 *sEEnergies* project (Reiter et al., 2021). The building stock is modelled as heated floor area time series (2015–2050) for the residential and service sectors, disaggregated by building type (single-family and multi-family houses), construction period, and refurbishment measure. Typologies and baseline thermal characteristics are calibrated against TABULA/EPISCOPE archetypes and Eurostat building statistics, while renovation potentials are represented for key envelope components (walls, roofs, windows, floors) and where included associated technical measures. Refurbishment costs are calculated using country-differentiated parameters reflecting labour costs, material prices and prevailing construction practices, and are aggregated into cost curves that link incremental reductions in final heat demand (kWh/m²) to cumulative investment needs; diminishing marginal returns are explicitly captured at higher renovation depths. To support energy-system integration analysis, the annual heat-demand projections are translated into hourly heat-demand distributions at country level using an empirically derived relationship between observed heat consumption and heating degree days.

1.3 Identification of district heating grid costs and number of new systems needed

In Europe the data about the current market share of district heating as well as the knowledge about the exact coverage of existing district heating grids is spears. Despite the lack of surveys or inventories of the existing district heating systems in Europe, this report elaborates on the potential of the district heating network expansion costs to move from the current ~13% district heating market share. Previous investigation based on the Halmstad University District Heating and Cooling database have documented there are more than 4.000 recorded district heating systems across Europe. Of these, about 2.800 are in cities with more than 5.000 inhabitants, indicating that a substantial share of mapped systems are associated with larger settlement (Connolly et al., 2012).

To identify the market share for district heating costs for EU27 as well as for the member states and the United Kingdom the current and future heat demands must be connected to the district heating costs. Thus, the first step is to establish the connection with the heat demand densities and the costs of thermal grids. As a result, the district heating grids costs can be estimated for EU27 and on the national level. Please note that the levels of district heating for e.g. 30% coverage in EU27 is not the same as a 30% market share in an individual country. This is due to different heat densities and hence different costs across an EU market share and a country level market share. In the following sections the methodologies are outlined.

1.3.1 Connections between heat demands and the grid assessment including cost

The outset of the heat densities are national level heat demands. The downscaling of national heat demands to local-level estimates is based on research for EU27, member states and the United Kingdom previously done in the *sEEnergies* project (Maya-Drysdale et al., 2022; Persson et al., 2021). The approaches for estimating district heating potentials is based on the methodology described in (Fallahnejad et al., 2024) and calculated using the module available in (Fallahnejad, 2022). The module can run the calculation by using a heat demand in the beginning and another heat demand at the end of the year, representing, e.g. implementing energy efficiency measures in buildings and lowering the demand over time.

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. We have adjusted the original model to additionally estimate investment cost estimates and heat losses separately for 3rd and 4th generation district heating. The calculations for 4th generation district heating were done in a simplified way, based on the results from Heat Plan Denmark 2021 (Mathiesen, B. V. et al., 2021), where the 4th generation district heating heat loss was on average 3,1% lower than 3rd generation and the investment cost was on average 2,41% higher. The same averages have been applied in this model.

The aim of the analysis is to be able to identify potential district heating areas and create district heating cost curves per country to be used in the energy system analysis; in this aspect, we want to find the maximum district heating potential and afterwards decide on how much district heating is feasible based on the energy system analysis. Therefore, in the mapping of district heating potentials, we only remove areas that would most likely never be relevant for district heating, while we keep areas that could have a potential if e.g. there are a lot of cheap heat sources.

The approach is used in this report to estimate the EU27 potential for 2050. The specific dataset used is the future district heating areas dataset, which includes the aggregated heat demand for 47.711 modelled areas and is further used to:

(i) estimate the most suitable cities for district heating development,
(ii) potential integration of waste and renewable heat sources,
(iii) assess the future district heating expansion shares and costs.

This analysis assesses the future market shares of district heating in the EU27 countries, based on the systems needed to meet the 2050 targets. It aggregates and ranks district heating systems according to the ratio of specific energy costs to heat demand within each area. A cost ceiling of 50 EUR/MWh is applied in the model, which restricts the inclusion of high-cost areas and thereby limits the technically feasible district heating market share at 63,74% of total heat demand. In addition, a minimum annual heat demand threshold of 1 GWh is used to ensure that even relatively small areas can be considered in the modelling. In this way, this approach focuses on larger areas with higher heat demand, even if costs are relatively higher, as these are more cost-effective to invest in.

District heating systems are grouped into 5% intervals based on the heat density shares at the EU27 level, with grid costs accumulated at each step. The main effect of this assumption is noticeable in low district heating market shares, where the cost for the first 5% of areas is larger than for those between 5% and 10%.

The model allows for varying district heating connection rates over time, enabling a transition from an initial to a final connection level. In this analysis, however, this functionality is only used to a limited extent. A high connection rate is assumed throughout, increasing marginally from 88% at the beginning of the modelling period to 90% in the final year for all countries and areas. This assumption reflects a focus on identifying the technical potential of district heating. Lower initial connection rates would increase the specific cost per MWh in early years, as fixed infrastructure costs would be distributed over smaller delivered heat volumes, thereby underestimating the long-term system potential and not reflect the real costs.

The estimation of distribution grid costs is based on the cost formulation developed in the *sEEnergies* project, where the linear heat density of each potential district heating area is multiplied by a pipe investment cost Fallahnejad et al. (2024) includes a detailed description of the methods. In this framework, pipe investment costs are expressed as a linear function of pipe diameter:

$$C = c_1 + c_2 \cdot D$$

where *C* the cost per metre of pipe in EUR/m, *D* is the average pipe diameter [m], and c_1 and c_2 are cost parameters representing a fixed component and a diameter-dependent component, respectively. In this analysis, the values are set to c_1 = 664 EUR/m and c_2 = 2.610 EUR/m^2 based on updated German cost data from the *sEEnergies* project. For example, for a pipe diameter of 0,15 m, this corresponds to a cost of approximately 1,055 EUR/m. Although pipe costs vary between countries and urban contexts, a harmonised cost assumption is applied across all countries to ensure consistency with the broader energy system modelling framework. Figure 30 illustrates typical cost ranges across selected European countries, where the updated German cost level (2020) is used as the reference in this study. Additional cost curves and country-specific variations are documented in detail in the *sEEnergies* project report. (Sánchez-García et al., 2022)

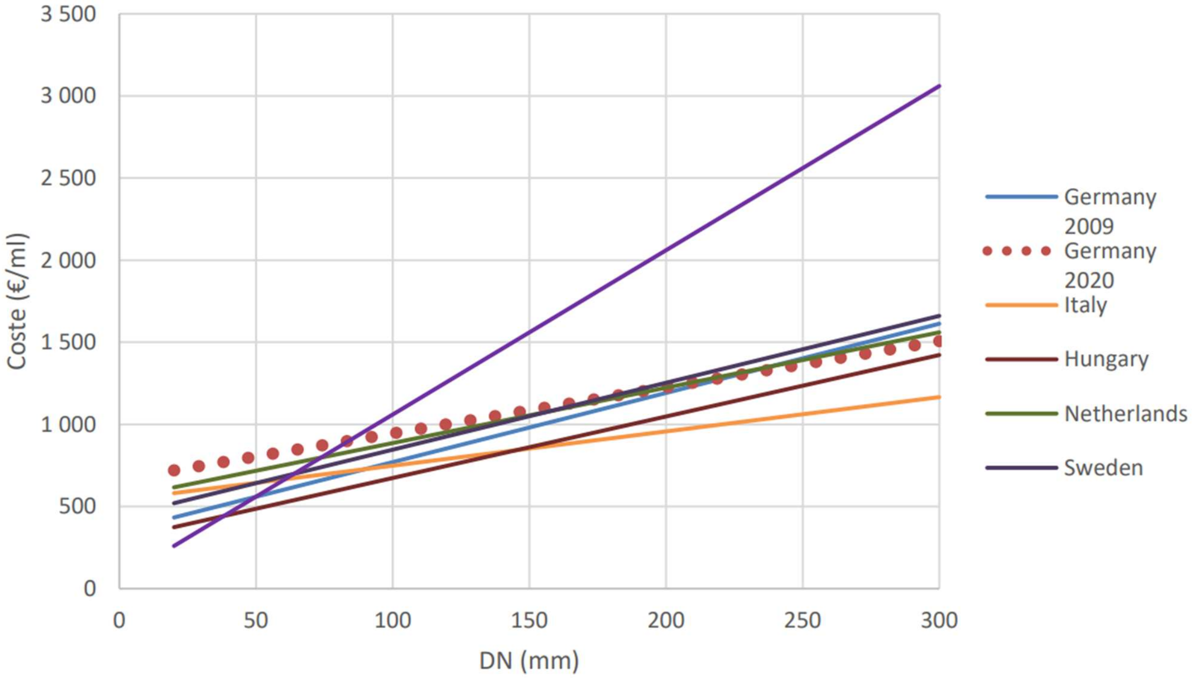

Figure 30, Construction costs of district heating pipes for different diameters in various European countries (Sánchez-García et al., 2022).

1.3.2 Assessment of the number of district heating plants

In the absence of good quality data on the geographical coverage of existing district heating systems in Europe, it is difficult to estimate the number of plants and investment costs that are required in the district heating grid expansion networks. While the exact location and extent of district heating is not available, national figures for district heating coverage are, that allow an approximation in this report on the estimation of expansion costs. An estimate of the expected number of new district heating plants been calculated towards 2050. 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 one individual system each, then areas with a final heat demand ranging from 1 to 10 PJ would develop 3 district heating plant per PJ, while the areas with a final heat demand between 10-20 PJ and over 20 PJ need to develop 4 and 5 district heating plant per PJ respectively. Considering a household heat demand of 15 MWh 1 PJ would be equivalent to about 18.000 households. In practice there may be large consumers 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 villages – even from 100 or 200 households depending on local sources or costs of fuel boilers, large-scale heat pumps, thermal storage, solar thermal as well as heat demand densities.

1.3.3 Identification of optimal cities for district heating development

This analysis also identifies the most suitable cities for the development of district heating based on two factors. The first is the ratio of specific energy costs to heat demand within each area. In this way, this approach focuses on larger areas with higher heat demand, even if the costs are relatively higher, as these are more cost-effective for long-term investments. Second, by integrating high levels of waste heat from different sources, with a focus on large urban areas. As shown in the next section, this report provides a new assessment of the major untapped existing and potential future sources of waste and renewable heat. In general, the sources are large, but the ability to exploit this potential varies due to geographical constraints, regional economics and proximity to suitable infrastructure, such as district heating networks, which are critical to the use of such sources. Consequently, the analysis prioritizes cities with significant potential for high, medium and low temperature industrial waste heat, geothermal and solar energy. By aggregating heat demand and waste heat potential from individual district heating areas into city level zones, the analysis simplifies data entry and improves clarity at both EU and national levels. The study focuses on cities with more than 45.000 inhabitants, where the implementation of district heating systems is more feasible.

1.4 The renewable heat and waste heat funnel

A central objective of this study is to systematically assess how renewable heat and waste heat sources can be utilised within future European district heating systems. The analysis covers a broad portfolio of heat sources, including geothermal and solar thermal energy; industrial waste heat at different temperature levels; waste heat from WtE plants; data centres; sewage and wastewater treatment plants; metro stations; supermarkets; electrolysis; nuclear power plants; and combined heat and power (CHP). These sources differ fundamentally in their spatial characteristics, capacity constraints, temporal availability, and integration requirements. Some sources are limited in capacity and vary significantly over time, while others are theoretically continuous and dispatchable.

The assessment distinguishes three successive potential levels: full potentials, technical potentials, and utilisation potentials. Full potentials represent the total recoverable heat from all identified sources, regardless of spatial, heat demands or system constraints. Several sources overlap spatially, compete for the same demand, or are poorly aligned temporally with heat consumption patterns. Consequently, only a fraction of the full potential can be realistically utilised.

Technical potentials capture the subset of heat that can be recovered within modelled district heating areas after applying spatial matching and technical feasibility constraints, namely a baseload heat supply approach. Utilisation potentials further refine this by introducing system-level prioritisation. In the utilisation step, heat sources are ranked according to their suitability for district heating development under the proposed market share scenario, considering specific expected energy costs relative to local heat demand. Figure 31 illustrates the overall workflow used to identify, process, and assess renewable and waste heat sources across Europe.

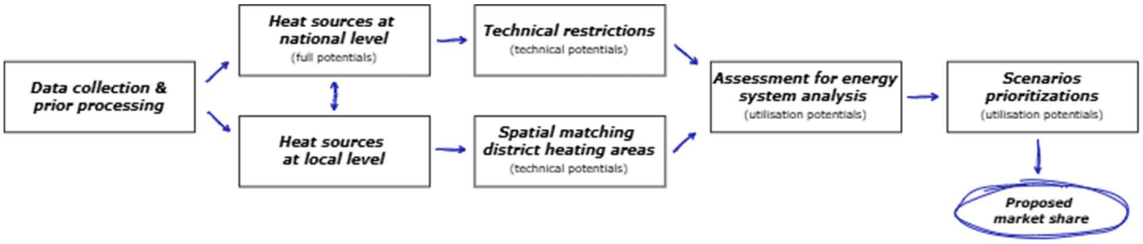

Figure 31, Workflow for waste and renewable heat sources.

1.4.1 Assessment of the full potential renewable heat and waste heat sources

Because of this heterogeneity, a single assessment method is not sufficient. Instead, source-specific data processing and evaluation procedures are applied. A fundamental first step is the production, collection, and harmonisation of datasets describing current and future heat source capacities. These datasets form the basis for estimating full (theoretical) potentials, defined as the total amount of heat that could in principle be recovered from a given resource. Examples include the total waste heat generated by industrial processes or the theoretical solar thermal yield under given climatic conditions.

However, full potentials are rarely realisable in practice. Their exploitation is constrained by technical limitations such as temperature levels, load profiles, and process-specific recovery limits as well as by geographical factors, most notably the distance between heat sources and suitable heat demands in district heating areas. To address these constraints, national-level estimates of full potentials are combined with technical screening and spatial matching to derive technical potentials, representing the share of heat that can realistically be recovered within the modelled district heating areas.

1.4.2 Assessment of the technical potential renewable heat and waste heat sources

After establishing national full potentials, these estimates are spatially matched to the modelled district heating areas wherever sufficiently granular data are available. The spatial assessment includes industrial waste heat disaggregated by temperature level, waste-to-energy plants, sewage and wastewater treatment facilities, metro systems, geothermal resources, and solar thermal potential. For these sources, explicit geospatial datasets allow a direct or semi-direct coupling to district heating areas.

A top-down approach is applied for waste heat from industrial activities and waste heat from WtE, whereby national estimates are downscaled to the local level based on the spatial distribution of industrial facilities across Europe and subsequently linked to district heating areas. Medium- and low-temperature waste heat sources available as point datasets such as wastewater treatment plants and metro systems are directly spatially matched to district heating networks.

Other sources, including CHP plants, electrolysis, and data centres, are assessed primarily through technical constraints and energy system analyses, as consistent and sufficiently granular geospatial data are not available across countries. These sources are therefore allocated at national level or represented through scenario-based developments rather than explicit spatial matching to individual district heating areas. Nuclear waste heat is treated as a special case, with a dedicated spatial assessment focusing on proximity to existing or potential district heating networks.

Although CHP, electrolysis, and data centres are not explicitly spatially modelled, they are still implicitly accounted for in the analysis. This is because many modelled district heating areas do not coincide with any of the spatially mapped heat sources, thereby representing available system capacity where such sources could plausibly be located. In this way, the assessment captures not only currently identified heat sources, but also the potential integration of future heat supply options within suitable district heating areas.

Geothermal and solar thermal resources follow a distinct methodology, as their theoretical potentials are not constrained by point locations. For geothermal energy, technical potential within each district heating area is determined by the spatial intersection with identified geothermal zones and the allocation of base load heat demand, if continuous geothermal supply can meet this demand where accessible. Solar thermal potential is similarly linked to base load demand, reflecting system integration constraints rather than resource scarcity. Further details on data sources and spatial processing are provided for each renewable heat and waste heat source.

Figure 32 provides a Europe-wide overview of all mapped future waste and renewable heat sources, excluding CHP and nuclear plants. In addition to currently known sources, this perspective anticipates the emergence of new heat streams from electrolysis, data centres, and potentially gasification facilities. Due to heat demand densities reducing rapidly beyond this threshold, the modelled district heating areas represent 63,74% of the EU heat market, the results for the potential heat sources are extrapolated proportionally to estimate full EU27 potentials at 100% market coverage where applicable.

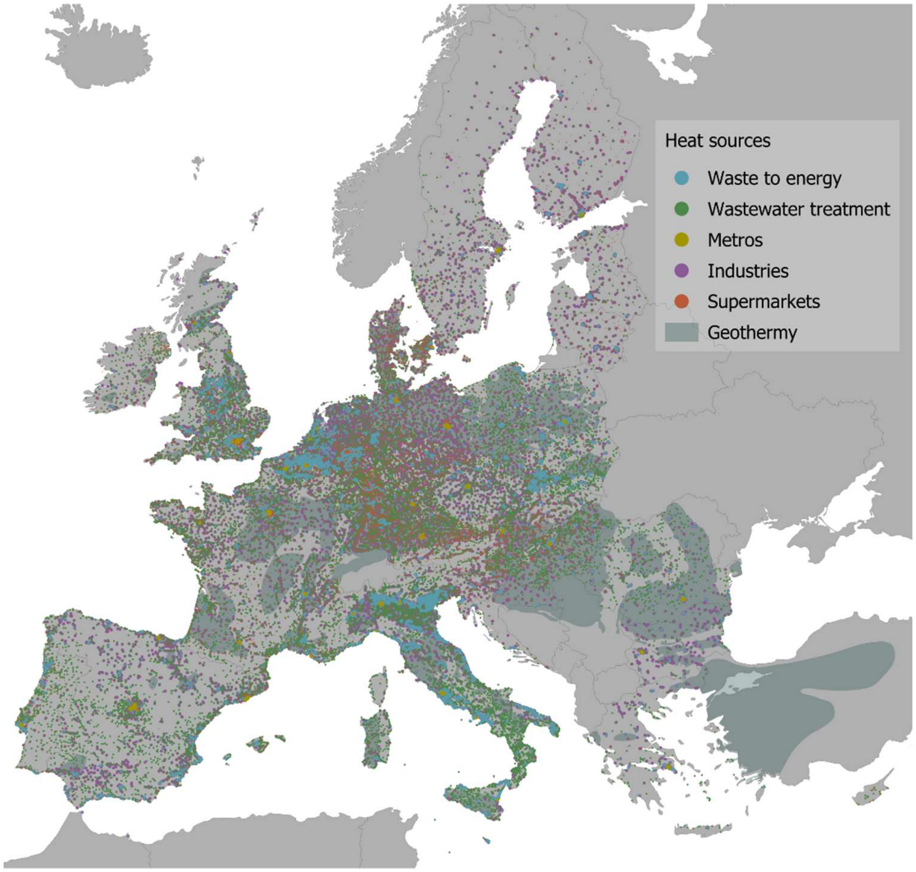

Figure 32, Illustration of the heat sources which are spatially mapped in this Heat Roadmap Europe project to form the potential of renewable heat and waste heat.

1.4.3 Assessment of the utilisation potentials for renewable heat and waste heat sources

This combined approach results in a second harmonised dataset: the technical potential dataset, which serves as the input to the energy system modelling. Figure 33 illustrates the "renewable and waste heat funnel," showing the transition from full potentials to technical potentials, and subsequently to utilisation potentials under different district heating market share scenarios considering that these sources are limited to supply a "baseload" level of the district heating demand. A key methodological step for the technical potentials is the estimation of base load heat demand, reflecting the continuous heat requirement that e.g. industrial waste heat or geothermal systems are best suited to supply. Baseload is calculated by combining industrial heat demand within district heating areas, domestic hot water demand, and district heating network losses, and applying a factor of 1,1 to account for additional load considerations. Domestic hot water demand is assumed to represent 20% of residential and service-sector heat demand in most countries, increasing to 25% in southern European countries.

While detailed assumptions vary by source, this funnel structure provides a consistent conceptual framework across all technologies and countries. The final step of the analysis translates technical potentials into utilisation potentials under difference district heating supply scenarios and difference levels district heating market shares. Through this structured funnel, from full potentials, via technical screening, to prioritised utilisation, the analysis ensures that estimated renewable and waste heat contributions are not only physically plausible but can also provide a set of renewable heat and waste heat potentials as an output of this project but also as inputs for energy system analyses in this project. The data are provided for the EU27, each member state, and the United Kingdom and for different district heating market shares.

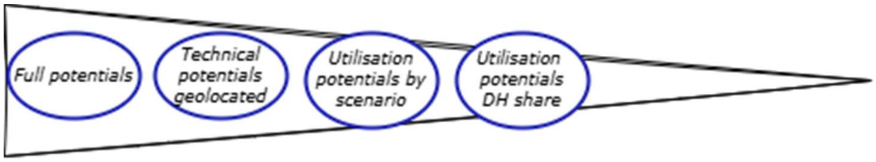

Figure 33, Renewable heat and waste heat funnel for identifying the potentials pr source for 1) the levels in the funnel, 2) different levels of for different district heating shares and 3) for EU27 for each member state and the United Kingdom.

1.5 The energy system analysis modelling approach

To manage the large combinatorial space of heating and energy system configurations, the analysis applied a matrix method as a structured processing and scenario generation layer prior to running EnergyPLAN. The matrix formalises the relationships between the heat demand levels (three), district heating market shares (18 different) and on the other side balancing heat supply and electricity supply.

1.5.1 The advanced energy system analyses tool EnergyPLAN

The tool used for the analyses of the sectors in the energy system and the heat markets in the context of the energy system is the advanced energy systems analyses tool EnergyPLAN in combination with GIS-based inputs and additional bottom-up tools for industry and transport characterisation. EnergyPLAN is a deterministic, hourly simulation model that performs hour-by-hour energy balance calculations across all major sectors: electricity, heating, cooling, gas, transport and industry. It explicitly represents the operational coupling between sectors via conversion technologies and storages e.g., power plants and CHP, boilers, large-scale heat pumps and electric boilers, electrolysers, hydrogen storage, gas storage, and thermal storage (Lund, H. et al., 2021). In each hour, EnergyPLAN balances demands and supplies subject to technical constraints and user-defined operational strategies, thereby capturing the system wide implications of variability in wind/solar generation, seasonal heat demand, and the need for flexibility. For this work, the modelling was conducted using EnergyPLAN version 16.3 (released February 2024). The tool is widely applied as a full energy system simulation tool for high renewables transitions and analyses of integration of intermittent resources as well as a large focus on the use of thermal grids and the possibilities for a district heating supply. The tool has been continuously development since 1999 and has formed the basis for several hundred research papers. The tool enables investment optimisations by defining exogenously alternative energy system designs. It is a simulation tool rather than an investment endogenous optimisation tool that enables fast "what-if" comparisons of coherent system configurations. The tool is a freeware tool openly available.

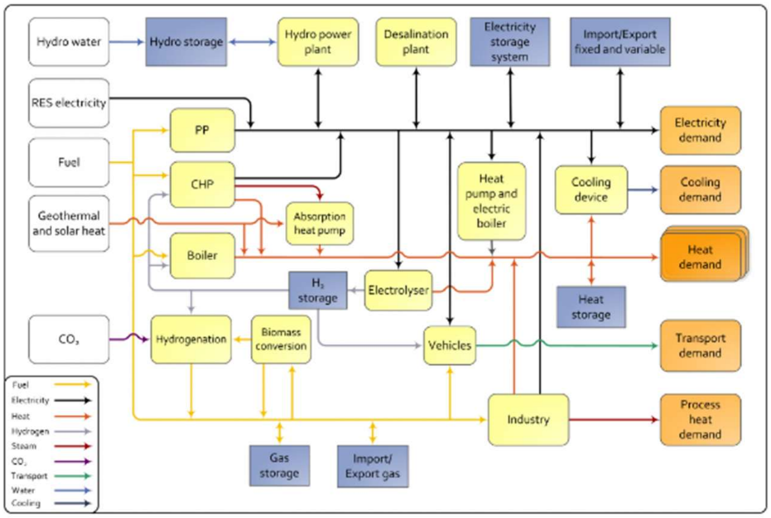

Figure 34. EnergyPlan model tool. (Lund, H. et al., 2021)

Figure 35 illustrates the EnergyPLAN modelling concept: sector demands (electricity, heat, cooling, transport and process heat) are met through an integrated set of supply technologies, conversion pathways and storages, enabling consistent accounting of energy flows, fuel use, and cross-sector interactions. The model outputs include hourly dispatch by technology, annual energy balances, primary energy supply, fuel consumption by carrier, system costs (including investments and operational expenditures where specified), and emissions which allows direct comparison of scenarios and identification of key drivers of cost and flexibility.

A limitation of EnergyPLAN is that it does not natively allocate demand and supply spatially within a country or region. In the context here, this is handled through external spatial analyses performed using GIS and in other bottom-up inputs e.g. heat-demand densities, suitable district heating areas, local waste heat point sources limited by the local heat demand. These spatially derived inputs are then aggregated into the non-spatial EnergyPLAN representation, ensuring that the national energy-system simulations remain grounded in geographically informed assumptions.

1.5.2 Application of the matrix method as a scenario generator using GIS inputs and EnergyPLAN

The matrix approach constitutes a central methodological component of the modelling framework and is applied prior to the EnergyPLAN simulations. The method combines technology sizing rules and ensures automatically consistent sets of inputs for each scenario variant. It functions as a structured translation layer between high-level scenario definitions, such as district heating market shares, energy savings, electricity demand developments, and the availability of waste and renewable heat, and the detailed, technology specific inputs required for simulation. In doing so, it ensures internally consistent energy balances and coherent interactions between technologies across sectors, which is essential in a modelling context where sector coupling and temporal dynamics significantly influence system performance. The matrix also enables a direct linkage to the spatial analyses (GIS) of heat demand and supply potentials

The three heat saving levels are combined with district heating market shares in 18 increments of 5% starting from 5% district heating and 95% individual heating solutions. For each increment, the remaining individual heat demand is allocated through a fixed, rule-based technology hierarchy: where individual heat pumps is adjusted while household level electric boilers, biomass boilers and solar thermal are kept constant at each 5% fix market share of the total heat market. The matrix approach combines the variables about with two performance and cost assumptions for technologies used to provide heat in 3rd and 4th generation district heating. These scenarios are combined with 6 different district heating supply mixes based on bottom-up spatial analyses, combined with large-scale heat pumps and more, to have a balanced heat supply. In all scenarios the resulting cost changes, primary energy supply changes and system dynamics in the heat supply is generated.

Finally, the matrix approach supports a continuous calibration of renewable system consistency by iterating system configurations to meet a defined Critical Excess Electricity Production (CEEP)[4] constraint as a percentage of the electricity production. In practice, this is implemented as repeated modelling simulations for each scenario to adjust renewable capacities. The resulting matrix therefore functions as a coherent scenario engine that (i) guarantees internally consistent technology sizing across sectors, (ii) enables systematic comparisons across heat saving levels, district heating design shares and supply mixes, and (iii) produces EnergyPLAN-ready inputs for large-scale hourly cross-sector simulations.

After defining the relevant variables, technology assumptions, constraints and threshold values, the energy-system results are assessed through the comprehensive, cross-sector simulation. The evaluation criteria are based on system cost comparison, heat market cost comparisons as well as the ability to cost-efficiently use biomass and renewable electricity sources in a climate neutral EU27. For the modelling the sustainable levels of residual biomass use levels are met and it assumes lifetime extension of nuclear power plants, including the already decided new nuclear power plants under construction. For renewable electricity sources each country's level of potential is identified for e.g. onshore wind power, solar PV and offshore wind power.

The construction of the matrix is based on a set of core parameters, including heat demands and refurbishment costs, the share of district heating versus individual heating, electricity demand levels, and technology-specific efficiencies and the associated cost assumptions. These parameters are defined consistently across all countries and scenarios, while allowing for national differences in resource availability, demand structure, and renewable potentials.

In addition to energy-related parameters, the matrix incorporates a range of techno-economic inputs required for the EnergyPLAN simulations. These include investment costs, operation and maintenance costs, efficiencies, and lifetime assumptions for all technologies.

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[4] Critical Excess Electricity Production (CEEP) is the portion of electricity generation that cannot be absorbed by the electricity system in the hour it is produced. Using e.g. large-scale heat pumps in combination with thermal storages and stopping the operation of combined heat and power plants are signs of a system designed to integrate more low-cost renewable electricity. In EnergyPLAN terminology, CEEP is "critical" because it represents surplus electricity that would otherwise need to be curtailed. It should be noted that a certain level of curtailed electricity is economically feasible.

2 Heat demands and refurbishment

The heat-demand projections and refurbishment-cost estimates applied in this assessment are derived from the *sEEnergies* project (Horizon 2020, Grant Agreement No. 846463), which established a harmonised modelling framework covering all EU27Member States. The building heat-demand modelling integrates several datasets and analytical stages developed primarily within Work Package 1 (Buildings) and Work Package 4 (Energy Grids) (Reiter et al., 2021).

The modelling framework is anchored in a detailed representation of the building stock, including time series of heated floor area for the period 2015–2050 by country and sector (residential and service). Buildings are disaggregated by construction age classes and typologies, calibrated against TABULA/EPISCOPE building archetypes and Eurostat building statistics. For each category, the model incorporates specific heat-demand intensities per square metre, renovation potentials for envelope components (walls, roofs, windows) and technical systems, as well as country-specific cost parameters reflecting labour costs, material prices, and prevailing construction practices.

The model assumes that approximately 90 % of the 2015 building stock remains in place in 2050, reflecting long building lifetimes, while total heated floor area increases by around 30 % over the same period (approximately 27 % in the residential sector and 35 % in the service sector). These developments are driven by demographic, economic, and activity projections consistent with Eurostat scenarios.

The building stock is represented using a structured typology that combines building type, construction period, and energy-refurbishment measure, allowing a differentiated assessment of energy savings and investment pathways across heterogeneous buildings. Two building types are distinguished: single-family houses (SFH) and multi-family houses (MFH). These categories capture fundamental differences in building geometry, surface-to-volume ratios, renovation economics, and feasible energy-efficiency measures. Single-family houses typically offer greater flexibility for envelope refurbishment but exhibit higher specific heat losses, whereas multi-family houses benefit from shared walls and lower specific demand but may face organisational and ownership-related constraints.

The building stock is further classified into five construction age classes, reflecting historical building standards and regulatory regimes: buildings constructed before 1961, 1961–1990, 1991–2008, 2009–2020, and after 2020. These age classes differ substantially in baseline thermal performance, material composition, and marginal potential for energy savings. Pre-1961 buildings generally exhibit the highest specific heat demand and refurbishment potential, while post-2009 buildings already comply with stricter energy codes and therefore show limited additional savings potential.

Energy-efficiency interventions are represented through sixteen discrete energy-refurbishment measures, spanning from very shallow to deep renovation levels. Measure 1 (facade painting) represents a non-energy or negligible-impact baseline intervention. Measures 2 to 5 reflect progressively deeper renovation packages covering combinations of windows, walls, roofs, and floors at low to high performance levels. Measures 6 and 7 build on the comprehensive package of Measure 5, assuming higher and highest insulation and performance standards, respectively, while Measure 8 represents a deep renovation consistent with passive-house level performance. Additional targeted combinations (Measures 9–16) represent partial but higher-quality refurbishments of specific envelope components, such as advanced window replacement, roof and floor insulation, or combinations thereof.

Two main renovation pathways are modelled to reflect observed and plausible decision behaviour among building owners. First, buildings that already undergo energy-improving renovations in the baseline scenario (initially assigned to Measures 1–5) are assumed to have a higher likelihood of adopting more ambitious refurbishment packages over time. In the model, this is implemented by redistributing shares of these buildings from baseline packages towards higher-performance measures (Measures 2–16), reflecting path dependency and renovation momentum. Second, buildings that do not initially implement energy-efficiency measures are assumed to be driven towards simple, low-cost interventions, particularly shallow measures with favourable cost-effectiveness and low disruption.

This combined typology of building type (SFH/MFH), construction period, and refurbishment measure provides the structural basis for calculating heat-demand reductions, investment needs, and system-level impacts in the energy-system analysis. It ensures consistency between building-stock dynamics, renovation pathways, and the broader modelling of heat demand, district heating expansion, and electrification pathways.

2.1 Refurbishment levels analysed

Using the underlying building-stock dataset, cost curves for building-envelope improvements are constructed by aggregating renovation costs across predefined refurbishment packages. Each cost curve links incremental reductions in final heat demand (expressed in kWh/m²) to total renovation costs. These costs include investments in insulation measures, window and glazing replacement, and - in relevant packages - heating-system upgrades. Country-specific multipliers are applied to reflect differences in labour costs, material prices, and prevailing construction practices, while diminishing marginal returns are explicitly accounted for at higher renovation depths.

The refurbishment costs applied in the heat-demand scenarios are therefore based on country-weighted averages derived from the *sEEnergies* project. Within this framework, three levels of energy savings are distinguished. The moderate, ambitious, and very high savings levels correspond to reductions in building energy intensity of approximately 16 %, 43 %, and 53 %, respectively. The ambitious savings level represents a substantial acceleration compared to current renovation trends, while the very high savings level is consistent with the 1.5 TECH scenario in *"A Clean Planet for All"* (European Commission, 2018; Reiter et al., 2021).

Building energy savings are a key driver of final heat demand in the energy-system analysis. These savings originate from refurbishment measures ranging from simple, low-cost interventions such as roof insulation or window replacement to comprehensive deep renovations of the entire building envelope, including passive-house–level refurbishments. While deeper renovations significantly reduce heat demand, they also increase total system costs, as refurbishment investments are treated as additional investment cost within the energy-system framework.

For modelling purposes, all three savings levels are applied relative to a Frozen Efficiency reference scenario for 2050, representing a situation with no additional energy-efficiency policies beyond those already implemented. In this reference case, no further improvements in building energy performance are assumed, and renovation activity remains at a minimal level. The moderate savings level can therefore be interpreted as a continuation of insufficient baseline policies, whereas the ambitious and very high levels reflect progressively stronger policy intervention.

The current final heat demand in EU27buildings is approximately 2,8 PWh per year, covering space heating and domestic hot water in the residential and service sectors. In the Frozen Efficiency scenario, total final heat demand in 2050 remains close to this level. This outcome already incorporates the effect of a growing building stock: around 90% of the 2015 building stock is assumed to remain in use in 2050, while total heated floor area increases by roughly 30% between 2015 and 2050 - approximately 25-30 % in the residential sector and 35-40 % in the service sector. As a result, the frozen-demand level implicitly includes some efficiency improvement per square metre, since total floor area grows while aggregate heat demand remains nearly constant. The Frozen Efficiency scenario therefore serves only as a reference case, not a true "no-change" scenario, and represents a development path that is inconsistent with EU decarbonisation objectives.

Energy-savings assumptions are applied exclusively to residential and service-sector buildings. Industrial heat demand is not affected by refurbishment measures. The Moderate and Ambitious savings cases correspond to total EU27final heat demands of approximately 2,0 PWh/year and 1,6 PWh/year, respectively, reflecting increasingly stringent implementation of national renovation strategies and the Energy Performance of Buildings Directive. Under the Ambitious savings level, average specific heat consumption declines to approximately 60–80 kWh/m^2·year by 2050, yielding end-use heat savings of around 43% relative to 2015.

A deeper Very High savings pathway reduces total heat demand further to approximately 1,1 PWh/year, consistent with the 1.5 TECH scenario in *A Clean Planet for All*. This pathway assumes near-complete refurbishment of the building stock to near-passive standards, with specific heat consumption falling to approximately 40–55 kWh/m^2·year. Hot water consumption is assumed to remain broadly constant across all scenarios, implying that progressively larger reductions must be achieved through improvements in the building envelope. As a result, marginal refurbishment costs increase rapidly at higher savings levels.

Despite an increase in total heated floor area of roughly one-third between 2015 and 2050, comprehensive refurbishment, improved envelope performance, and the widespread deployment of low-temperature heating systems enable a substantial reduction in average heat demand per m^2 across all scenarios. Table 6 summarises the four refurbishment levels considered, their corresponding total EU27heat demands, and indicative ranges of specific annual heat consumption.

Table 6, Overview of the four levels of refurbishment and heat demands in EU27.

Scenarios	**Description**	**Estimated specific heat consumption (kWh/m^2·yr)**	**EU27total heat demand (PWh/yr)**
Frozen efficiency	No new policies, only natural stock turnover	≈ 165 - 180	≈ 2,8
Moderate savings	Current national strategies (EPBD compliance)	≈ 110 - 120	≈ 2,0
Ambitious savings	Strong renovation wave (Renovation Wave / EED targets)	≈ 60 - 80	≈ 1,6
Very-high savings / 1.5 TECH	Deep refurbishment, near-passive standards	≈ 40 - 55	≈ 1,1

The question is which level is feasible when including the costs and energy system effects of the refurbishment levels. In the energy system analyses here three parameters are used to evaluate savings levels: costs, primary energy supply and as part of that the fuel or biomass consumption. When analysing the energy system effects of the Very high saving level and the other two saving levels they all correlate with a gain from an expansion of district heating. In Figure 35 the per country heat and hot water demands are illustrated per savings level.

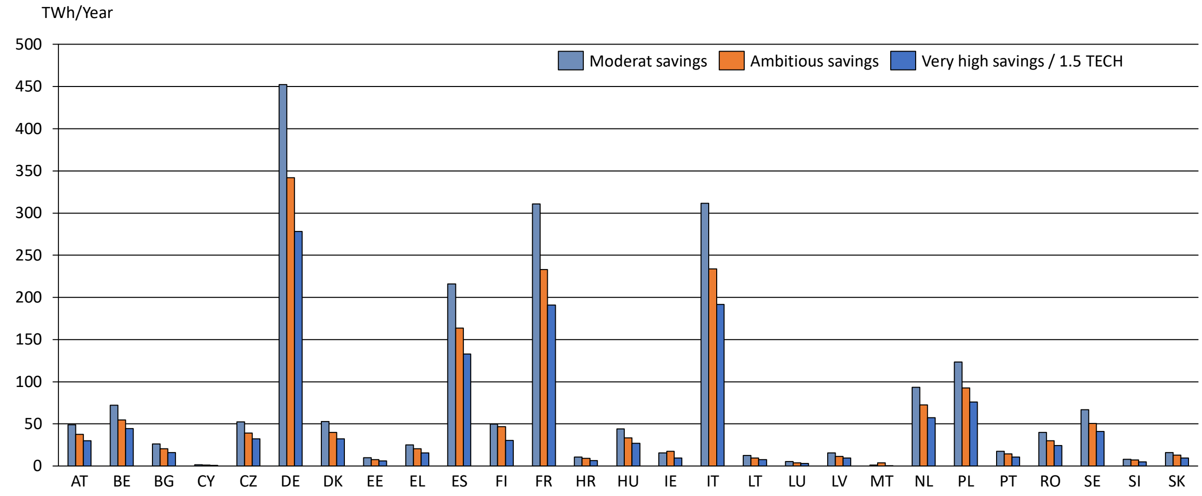


Figure 35, Development of the country level EU heat and hot water demands with difference refurbishment levels in 2050.

2.2 Refurbishment costs

Refurbishment costs associated with each savings level are derived from the *sEEnergies* project and represent additional upfront investments required to implement the corresponding building-efficiency measures. Costs are calculated separately for residential and service buildings and aggregated at national and EU level. They include investments in envelope components (walls, roofs, floors, windows), adjusted using country-specific cost factors reflecting labour costs, material prices, and construction practices.

Total refurbishment investments increase across savings levels in a non-linear manner. The transition from Frozen Efficiency to Moderate savings involves relatively large initial investments but delivers substantial reductions in heat demand. Subsequent transitions to Ambitious and Very High savings levels yield progressively smaller incremental demand reductions at increasing marginal cost, reflecting diminishing returns of deep renovation measures. This is consistent across most countries and is visible both at EU27 level and in national results, see Figure 36 and Table 7.

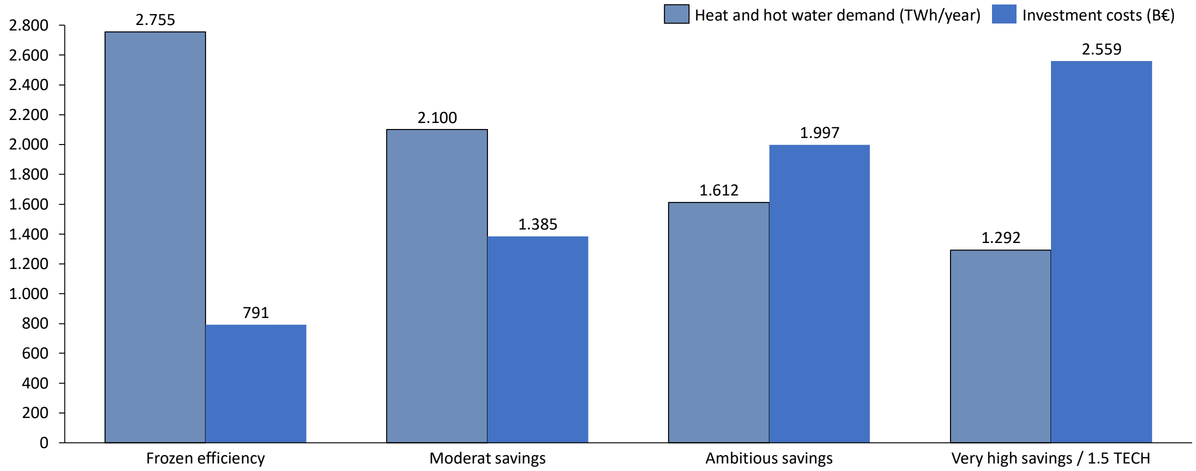


Figure 36, Development of the overall EU heat and hot water demands with difference refurbishment in towards 2050 as well as the associated upfront refurbishment costs.

Achieving higher levels of heat-demand reduction in buildings requires substantial and unevenly distributed refurbishment investments across countries, reflecting differences in building-stock size, age structure, construction practices, and baseline energy performance. Across the EU27, cumulative additional refurbishment investments required up to 2050 amount to approximately 1,4 trillion € under the Moderate savings scenario, 2,0 trillion € under the Ambitious savings scenario, and 2,6 trillion € under the Very High savings scenario. The Ambitious pathway is the recommended scenario, corresponding to a 43% reduction in building heat demand by 2050 compared to 2015 (with interim reductions of approximately 8% by 2030 and 25% by 2040).

The country-level results in Table 7 illustrate that refurbishment investment needs scale primarily with the size and composition of national building stocks. Large Member States with extensive residential and service-sector floor areas - most notably Germany, France, Italy and Spain account for the largest absolute investment volumes across all savings levels. Germany alone requires cumulative investments of approximately 343 billion € under the Moderate savings scenario and 470 billion € under the Ambitious scenario, increasing to around 565 billion € under the Very High savings pathway. Smaller Member States exhibit much lower absolute investment volumes but often display steeper relative increases between savings levels. This pattern reflects both a higher share of older, less efficient buildings and more limited opportunities for low-cost initial improvements e.g. Bulgaria, Romania, Croatia, and Cyprus when moving from Moderate to Ambitious or Very High savings levels.

The transition from the Frozen Efficiency reference case to the Moderate savings scenario generally entails the largest marginal reduction in heat demand per euro invested, as it captures cost-effective and technically straightforward measures such as roof insulation, window replacement, and basic envelope upgrades. Subsequent transitions to Ambitious and Very High savings levels deliver progressively smaller incremental demand reductions at increasing marginal cost, reflecting the need for comprehensive envelope refurbishment and near-passive building standards.

Table 7, Estimated cumulative refurbishment investments in billion € by country for residential and service-sector buildings under four building energy-efficiency scenarios (Frozen Efficiency, Moderate, Ambitious, and Very High savings), aggregated over the period 2015-2050. Values represent additional upfront investments required to achieve the corresponding heat-demand reductions.

Billion € investment cost per country	Frozen Efficiency	Moderate	Ambitious	Very High
Austria	30.168	51.149	72.392	92.464
Belgium	21.195	43.020	54.085	69.108
Bulgaria	2.456	10.463	19.533	26.382
Croatia	266	1.975	3.396	3.688
Cyprus	305	1.339	1.928	2.538
Czechia	6.220	9.651	18.309	24.039
Denmark	33.053	50.950	71.172	95.191
Estonia	843	1.507	3.041	3.742
Finland	21.397	35.494	56.971	72.673
France	152.842	297.578	358.025	453.854
Germany	186.687	342.559	469.760	565.267
Greece	9.137	13.585	17.993	24.320
Hungary	5.543	12.014	20.897	27.845
Ireland	15.270	29.956	36.691	44.266
Italy	115.665	150.394	240.545	331.878
Latvia	1.139	1.764	3.486	4.274
Lithuania	2.667	4.703	7.437	8.623
Luxembourg	519	2.975	3.900	4.437
Malta	146	751	1.117	1.518
Netherlands	43.196	74.292	92.197	119.716
Poland	15.621	30.989	64.431	85.250
Portugal	7.678	13.036	18.288	25.521
Romania	2.396	5.612	14.309	18.484
Slovakia	3.179	6.985	11.333	13.377
Slovenia	1.087	2.247	3.510	3.834
Spain	68.532	107.776	199.164	262.649
Sweden	44.013	82.583	132.589	174.178
EU27	791.221	1.385.347	1.996.501	2.559.116
United Kingdom	169.046	289.206	400.889	500.884
EU27 + UK	960.268	1.674.553	2.397.390	3.060.001

2.3 Heating and heat demand distributions

From an energy-system perspective, all three energy-savings pathways - Moderate, Ambitious, and Very High - exhibit a consistent increase in system value when combined with an expansion of district heating. Higher refurbishment levels reduce peak heat demand, enable lower-temperature operation of district heating networks, and improve the economic feasibility of utilising waste heat and large-scale heat pumps.

A central element of the heating-system analysis is the construction of hourly heat-demand distribution profiles for each country, capturing seasonal and intra-day variability over a full year. These distributions are required to assess system integration, peak loads, and the interaction between heat demand, electricity supply, and flexibility options. The methodology builds on a data-driven relationship between observed heat consumption and climatic conditions, expressed through heating degree days (HDD).

Observed district heating consumption data for Copenhagen in 2014, sourced from *Fremtidens Fjernvarme* projections, are used as the empirical reference for heating-demand behaviour (Fremtidens Fjernvarme, 2022). Heating degree days are obtained from the Renewables.ninja platform, which provides hourly climate data based on satellite observations (*Renewables.ninja,* 2024). A correlation between hourly heat consumption and HDD is first established for Copenhagen and subsequently extrapolated to other European countries using their respective HDD profiles. For each country, household space-heating demand is calculated by scaling the Copenhagen reference profile according to the ratio of national to Danish heating degree days:

$$HD_{hh} = \left(\frac{HD_{CPH}}{DK_{HDD}}\right) * Country_{HDD}$$

where HD_{hh} is household heating demand, HD_{CPH} is observed heat demand in Copenhagen, HDD_{DK} is Danish heating degree days, and $HDD_{country}$ represents country-specific heating degree days. All HDD values are calculated on an hourly basis to preserve temporal variation.

Total district heating demand at any hour is defined as the sum of household heating demand, industrial heat demand, domestic hot water demand, and distribution losses:

$$HD = HD_{hh} + HD_{ind} + HD_{hw} + HD_{dl}$$

Industrial heat demand supplied by district heating is derived using country-specific shares from the *sEEnergies* project. Based on the relative contribution of industry and households to total district heat consumption can be calculated:

$$HD_{ind} = HD_{hh} * \frac{Ind_{\%}}{hh_{\%}}$$

The same proportional approach is applied to estimate domestic hot water demand and network losses. Domestic hot water demand is assumed to account for approximately 20% of total heat demand in most countries and 25% in southern European countries such as Spain, Italy, and Malta. Both domestic hot water demand and distribution losses are treated as constant over time, reflecting their weak dependence on outdoor temperature. For buildings not connected to district heating, individual heating demand is calculated as the sum of household space heating and domestic hot water demand:

$$HD_{ih} = HD_{hh} + HD_{hw}$$

Future scenarios are implemented by adjusting household heating demand in accordance with the assumed energy-efficiency improvements under each savings pathway. This approach ensures that reductions in final heat demand are consistently reflected in hourly profiles while preserving realistic temporal patterns. Overall, the methodology enables a country-specific, hour-by-hour representation of heating demand that integrates climate variability, structural differences in heat supply, and long-term efficiency improvements. The analysis supports a detailed assessment of 2050 heating-system configurations across the EU27, including the interaction between demand reduction, waste heat utilisation, and district heating expansion.

Figure 37 illustrates the indexed hourly heat demand distributions for the EU27 under three different building heat-saving levels: moderate, ambitious, and very high savings. The profiles are shown as indexed curves, meaning that each distribution is normalised to its respective annual heat demand. As a result, absolute heat consumption in TWh is lower at higher saving levels, while the relative shape of the annual load profile can be directly compared across scenarios. The figure shows that increasing building insulation and efficiency leads to a progressively flatter heat demand profile over the year. In particular, higher saving levels reduce the magnitude of winter peak loads, while summer heat demand remains at a relatively similar absolute level due to domestic hot water demand. This results in a higher share of the annual heat demand being covered by base-load operation, even though the total delivered heat is lower in absolute terms. Note that the summer demands in principle should be the same, so the curve represents that a lower annual demand is distributed differently.

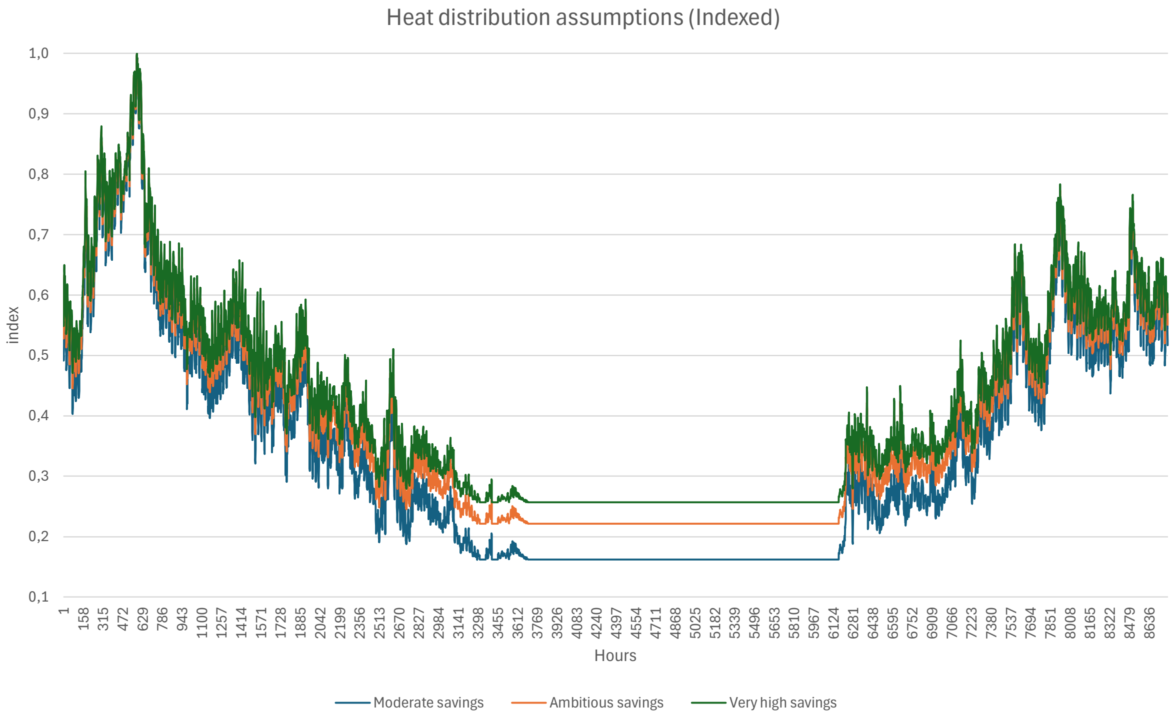


Figure 37, Heat distribution files for EU27 for the three different saving levels.

With more efficient buildings higher percentage of the total demand can be served by continuous, base-load heat sources such as industrial waste heat, geothermal energy, or waste heat from WtE. At the same time, the reduction in peak demand has significant system implications, as it lowers required investment in peak heat production capacity and network dimensioning for district heating systems.

2.4 Cooling demands and district cooling potentials

Cooling demand is becoming an increasingly relevant component of Europe's energy system in the context of climate change, public health, and urban resilience. Globally, space cooling and electric fans accounted for nearly 20 % of total building electricity consumption in 2018 (IEA, 2018). In Europe, cooling demand has historically remained well below heating demand, even in southern regions; however, recent years characterised by prolonged and more frequent heatwaves have accelerated the uptake of cooling technologies.

In line with previous *Heat Roadmap Europe* assessments, cooling is identified as the fastest-growing segment of the heating and cooling sector, although it is not expected to exceed 20% of total heating and cooling demand by 2050 (Mathiesen, Brian Vad et al., 2019; Paardekooper et al., 2018). Current estimates indicate that cooling demand in Europe amounts to approximately 200 TWh per year, corresponding to around 5-10% of total heating and cooling demand, excluding domestic hot water. Towards 2050, total cooling demand is expected to increase substantially, reaching approximately 450 TWh per year, while the heating sector remains dominant in absolute terms.

Cooling demand differs structurally from heating demand in that it is dominated by the service and industrial sectors, including offices, hospitals, schools, commercial buildings, and industrial processes. The service sector in particular exhibits a substantial theoretical potential for district cooling, due to high demand densities, relatively uniform load profiles, and proximity to suitable cooling sources. Industrial process cooling is expected to grow more moderately and to account for approximately 4% of total heating and cooling demand by 2050 (Mathiesen, Brian Vad et al., 2019).

It is important to emphasise that cooling demand and district cooling supply are not explicitly modelled in this study. The figures cited above are based on earlier Heat Roadmap Europe analyses (HRE4) and related literature, rather than on a detailed spatial or temporal modelling framework comparable to that applied for heating. Existing spatial analyses suggest that district cooling currently represents less than 5% of the European cooling market; however, these estimates are subject to considerable uncertainty. The spatial modelling of cooling networks and cooling-demand densities is less mature and less robust than that developed for district heating, and the projected cooling demand of around 450 TWh in 2050 is therefore likely to represent a conservative estimate of the long-term potential (Paardekooper et al., 2018).

Nevertheless, earlier Heat Roadmap Europe work has identified significant opportunities for district cooling based on free cooling, particularly where deep water from lakes, rivers, or seas is available, as well as through the utilisation of waste heat and waste cold sources using absorption technologies or integrated energy infrastructures, including LNG terminals. When combined with thermal storage, district cooling systems could contribute to peak-load management, enhance electricity-grid stability, and facilitate the integration of variable renewable electricity in highly electrified urban systems.

A comprehensive assessment of cooling demand, district cooling infrastructures, and their interaction with heating and electricity systems is therefore identified as an important topic for future research, but it lies beyond the modelling scope of the present analysis.

3 Available waste heat and renewable heat sources

A central premise of the Energy Efficiency 2.0 principle is that decarbonising heat is not only a matter of reducing demand, but equally of transforming how the remaining heat demand is supplied. In the literature, three closely related terms are often used: *waste heat*, *excess heat*, and *surplus heat*. *Waste heat* refers broadly to heat generated as a by-product of a process and normally rejected to the environment. *Excess heat* is the share of waste heat that exceeds internal needs and is therefore in principle available for external use, while *surplus heat* denotes waste or excess heat that remains unused due to spatial, temporal, or economic constraints. In this report, only the term "waste heat" is used, and it consistently refers to heat that could in principle be recovered for useful purposes, subject to real-world constraints. These constraints are decisive: heat resources must be close enough to demand, available at the right times of year, and technically compatible with the temperature requirements of district heating systems - especially in low-temperature 4th generation district heating (4GDH), where large-scale heat pumps can upgrade low-grade heat to supply temperatures. Waste heat and renewable heat is also very suitable in 3rd generation district heating systems; however, they can be slightly more efficiently used in 4th generation systems.

Under the Energy Efficiency 2.0 framework, future district heating systems increasingly combine waste heat and renewable heat with smart electrification, large-scale heat pumps, and thermal storage. The resulting district heating mix is inherently local and resource-dependent: industrial regions may rely heavily on industrial waste heat, dense urban areas may exploit wastewater, data centres, and other urban sources, while geothermal and solar thermal contribute where geological and seasonal conditions allow. The objective of this chapter is therefore to assess the scale, structure, and usability of waste heat and renewable heat resources in Europe, and to clarify how much of these resources can realistically contribute to district heating in a future energy system with much lower heat demand due to building refurbishment.

3.1 Potential levels and interpretation

In this chapter and in the accompanying figures and tables, three distinct levels of potential are reported. The future full potential represents the gross theoretical annual heat resource available in 2050 from each source category, before considering spatial proximity, network feasibility, or seasonal mismatch. The technical potential with 55% district heating represents the subset of this resource that is geographically and structurally compatible with a district heating system covering 55% of building heat demand, i.e. sources that are sufficiently close to relevant demand areas and technically connectable. Finally, the recommended use reflects the share of the technical potential that is actually utilised in the cost-optimised recommended scenario, taking into account competition between sources, temporal alignment with demand, and system integration constraints such as storage requirements and heat pump operation.

The mapping of waste heat and renewable heat sources across EU27yields a *current* full potential of approximately 3,8 PWh/year and a future full potential of 3,1 PWh/year, combining geothermal and solar thermal, industrial waste heat at different temperature levels, waste-to-energy plants, power plants and CHP, nuclear waste heat, data centres, wastewater treatment plants, supermarkets, and metro systems. These sources are assessed geographically, i.e. in relation to current and potential future heat-demand areas, with the exception of data centres and electrolysis, whose future placement depends more strongly on planning and policy decisions. The current waste heat levels are compared to the current heat demands in buildings for EU27 in Figure 38. The may in the future be other energy system waste heat streams not accounted for here in elements such as CCU/CCS chains with capture and compression heat, solvent regeneration where applicable, CO_2 conditioning, synthetic fuel production (e-methanol, Fischer–Tropsch, ammonia and methanation), production of synthetic plastics as well as gasification biogas up-grade processes.

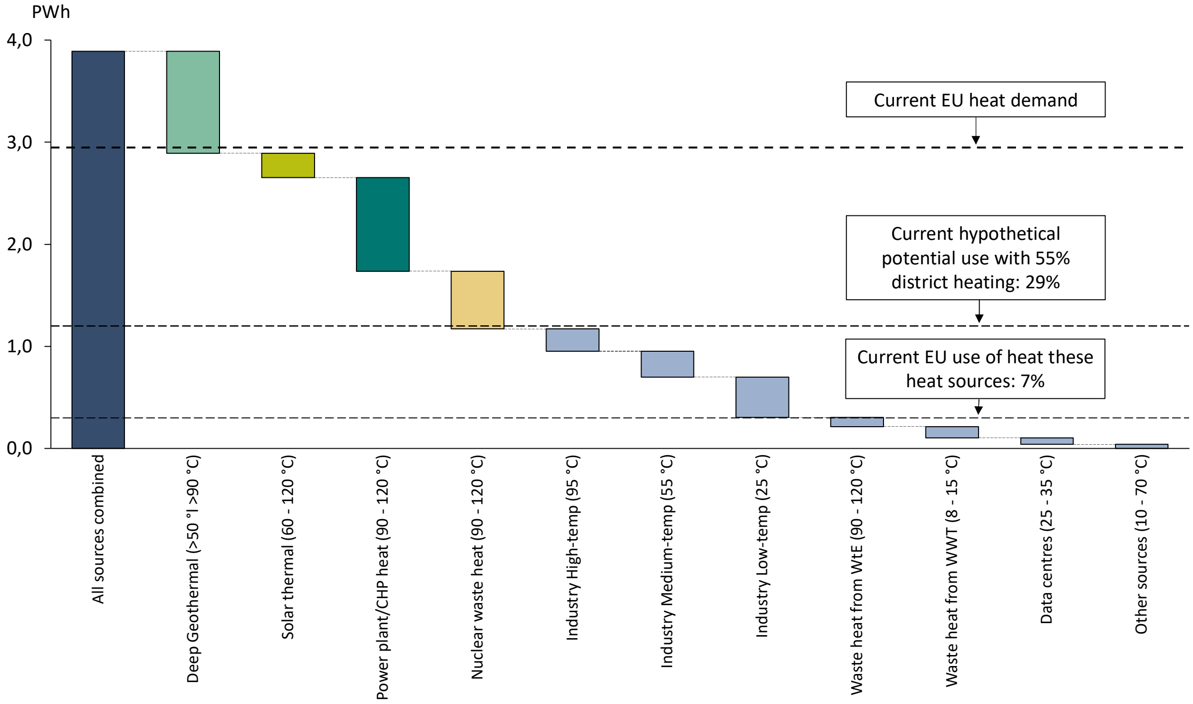


Figure 38. Diagram of the current EU27 heat sources combined and divided into sources. The sources are compared to the current heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands. WWT: wastewater treatment. WtE: waste-to-energy, other sources include supermarkets and metro stations.

While the full potential is very large, only a fraction is exploitable in practice. Spatial constraints limit access to sources that are distant from heat-demand areas, while temporal constraints arise because heat demand is highly seasonal whereas many waste heat sources are relatively constant over the year and renewable sources such as solar thermal are strongly summer-biased. When these constraints are applied in an energy-system context with 55% district heating coverage, renewable heat and waste heat together can supply up to 73% of district heating production, corresponding to the utilisation of roughly one-quarter of the mapped resource. In Figure 39 the potential future waste heat and renewable heat sources are illustrated. Depending on whether waste heat from power plants and CHP is included and on how temporal constraints are treated, this corresponds to approximately 21–29% of the future full potential. By comparison, current utilisation of waste heat in district heating is only about 7%, of which roughly 5% originates from CHP and 2% from mainly high-temperature industrial sources. In Table 8 the percentages of the use of the heat sources is listed as well as the mix in the recommended scenario. The table also shows the full technical potential for each waste heat and renewable heat category assuming the maximum level of district heating investigated at ~64%. There are several other supply mixes the recommended 55% mix in this Table 8 elaborated in section 5.4.

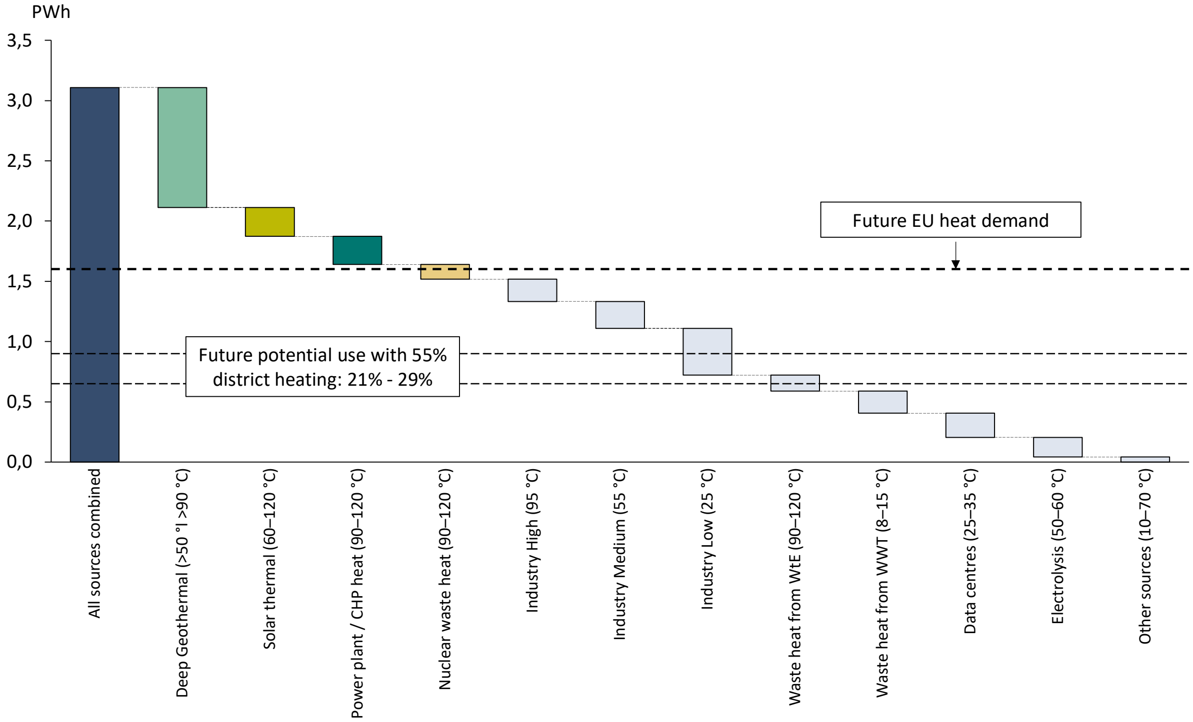


Figure 39. All future EU27 heat sources combined is illustrated as well as divided into sources. The sources are compared to the future heat demand in buildings. All heat sources are assessed from a geographical perspective and in the vicinity of current heat demands except data centres and electrolysis. 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

Table 8, 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 (TWh)	Recommended use, 55% DH	% of DH supply 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%
Waste heat sources	**1517**	**948**	**527**	**44%**	**422**	**35%**	**56%**
Renewable and waste heat sources	**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%**
Waste heat , incl Power plants/CHP	**1876**	**1196**	**557**	**47%**	**639**	**30%**	**47%**
Renewable and waste heat incl. PP/CHP	**3112**	**1569**	**676**	**57%**	**893**	**22%**	**43%**

In the appendix report containing data and country profiles, additional insights are provided. These include lists of potential renewable and waste heat sources based on the recommended 55% district heating market share, as well as scenarios ranging from 5% to 65% market shares. The data are presented both at the EU27 level and for individual EU countries and the United Kingdom. In addition, potential waste heat sources are categorized by temperature level (high, medium, and low). Furthermore, the identified heat sources have been geolocated and presented on maps at both the national level and for the EU27 as a whole.

The appendix report also identifies the 50 most suitable cities (with more than 45.000 inhabitants) for the development of district heating, based on investment costs, and provides the underlying data used to identify these cities.

3.2 Renewable heat sources

The full potential of renewable heat is very large and it covers 10% directly in the recommended supply mix for 55% district heating. This level could be about 30% if other waste heat sources prove less viable according to Table 8 and our system analyses in Section 1. The estimation of renewable heat potentials within district heating, specifically geothermal and solar thermal energy, differs fundamentally from the assessment of industrial and non-industrial waste heat sources. While waste heat sources are tied to specific point locations of activities and infrastructure, geothermal and solar thermal energy are spatially continuous resources. Their feasibility is therefore not strictly limited by the location of existing industrial processes but instead depends on the coincidence between renewable resource availability, heat-demand density, and system design conditions.

Consequently, the estimation of renewable heat potential is governed primarily by the size and structure of district heating demand, the geographical extent of suitable geothermal areas, and local climatic conditions. In addition, renewable heat sources are strongly affected by temporal constraints: geothermal energy can provide continuous base-load heat, while solar thermal production is inherently seasonal and concentrated in summer months. These characteristics fundamentally shape their technical and economic integration into district heating systems.

In this study, the estimation of geothermal and solar thermal potentials is explicitly tied to the baseload heat demand, reflecting the role of these technologies as predominantly "base-load supply options" within district heating systems. For geothermal energy, the potential is derived directly from the baseload heat demand of each district heating area. Consequently, the geothermal share of total district heating supply equals the baseload share, provided that (i) the city is located within an identified geothermal resource area and (ii) no competing baseload technologies, such as large-scale industrial waste heat or CHP are prioritised. I.e. geothermal and also solar thermal is placed in areas with competing baseload technologies that do not fully meet the baseload demand, the geothermal and solar thermal potential is estimated as the remaining baseload demand.

This approach reflects the fact that geothermal energy is, in principle, continuously available and dispatchable, but economically viable only when sufficient, stable year-round heat demand exists.

The baseload itself is calculated from future district heating demand, including network losses and hot water demands. While total heat demand varies across insulation scenarios, the baseload concept remains structurally independent of short-term demand fluctuations and is therefore well suited for geothermal assessment. To operationalise this approach, minimum baseload capacity thresholds are applied.

Overall, the baseload-based approach ensures internal consistency between geothermal and solar thermal assessments and the broader district heating system design and supply mixes in this report. It also provides a transparent link between city size, heat demand, and renewable heat feasibility. Geothermal is used in larger cities while solar thermal is mainly used in smaller cities the sizes of which is elaborated below.

For renewable heat sources as a whole, including geothermal and solar thermal, the future full potential is estimated at 1.237 TWh/year. When spatial and temporal constraints are applied in a system with 55% district heating coverage, only 374 TWh/year remains as technical potential. In the recommended scenario, 120 TWh/year of renewable heat is utilised, corresponding to approximately 32% of the technical potential and around 10% of the full potential. This reflects both the strong system value of renewable heat where conditions are favourable and the limitations imposed by demand patterns, competing waste heat sources, and cost considerations. In addition, solar thermal provides 5% of the heat in individual heating solutions. A full utilisation of the 374 TWh/year would make these sources cover 30% of the 55% district heating production.

3.2.1 Geothermal energy

Geothermal heating and cooling offer a local, reliable, and adaptable renewable energy source, contributing to a diversified heat supply and providing a hedge against volatile and rising fossil fuel prices. Geothermal resources are characterised by high availability and long lifetimes, making them particularly suitable for base-load heat supply in district heating systems. Globally, geothermal energy is already a strategic priority in countries such as the Philippines and Indonesia, and technological improvements, combined with cost reductions, are expected to enable geothermal energy to meet up to 15% of global electricity demand growth by 2050. For the heating sector, geothermal resources provide a continuous source of low- and medium-temperature heat, well suited for buildings and district heating networks (IEA, 2024c).

According to the Geothermal District Heating database, more than 240 geothermal district heating systems are already in operation worldwide, predominantly based on hydrothermal resources (GEODH, 2022). In Europe, geothermal district heating is currently concentrated mainly in France and Iceland, with ongoing and emerging projects in Austria, Germany, and Hungary. Despite this, geothermal heat today contributes less than 3% of total district heating supply in Europe, indicating a substantial gap between technical feasibility and current deployment. This situation is expected to evolve as policy support improves following the 2022 energy crisis and as district heating systems transition towards lower operating temperatures (IEA, 2024c).

A defining feature of geothermal energy is that its technical potential is not constrained in the same way as point-based waste heat sources. In theory, geothermal resources are virtually unlimited; however, their practical utilisation depends strongly on resource temperature, local geology, and the scale of heat demand. As illustrated in Figure 40, different geothermal temperature ranges correspond to distinct energy applications. Low-temperature resources (typically below 50–60 °C) are suitable for geothermal heat pumps, aquaculture, greenhouse heating, and low-temperature district heating. Medium-temperature resources (around 60–120 °C) are well matched to direct use in district heating networks, food processing, and other industrial heat uses. High-temperature geothermal resources enable industrial processes and, at even higher temperatures, electricity generation via binary or flash steam power plants (IEA, 2024c).

In practice, the dominant application of geothermal energy globally is heat, accounting for approximately 79% of total geothermal final energy use, while electricity generation represents around 21%. Within the heating sector, district heating is the second-largest geothermal heat application, representing roughly one third of global geothermal heat consumption (IEA, 2024c). This confirms the strong structural compatibility between geothermal resources and district heating systems, particularly in urban areas where geothermal is dimensioned only to cover the stable year-round demand, i.e. dimensioning the capacity to cover the summer load combined with a slight winter ramp up.

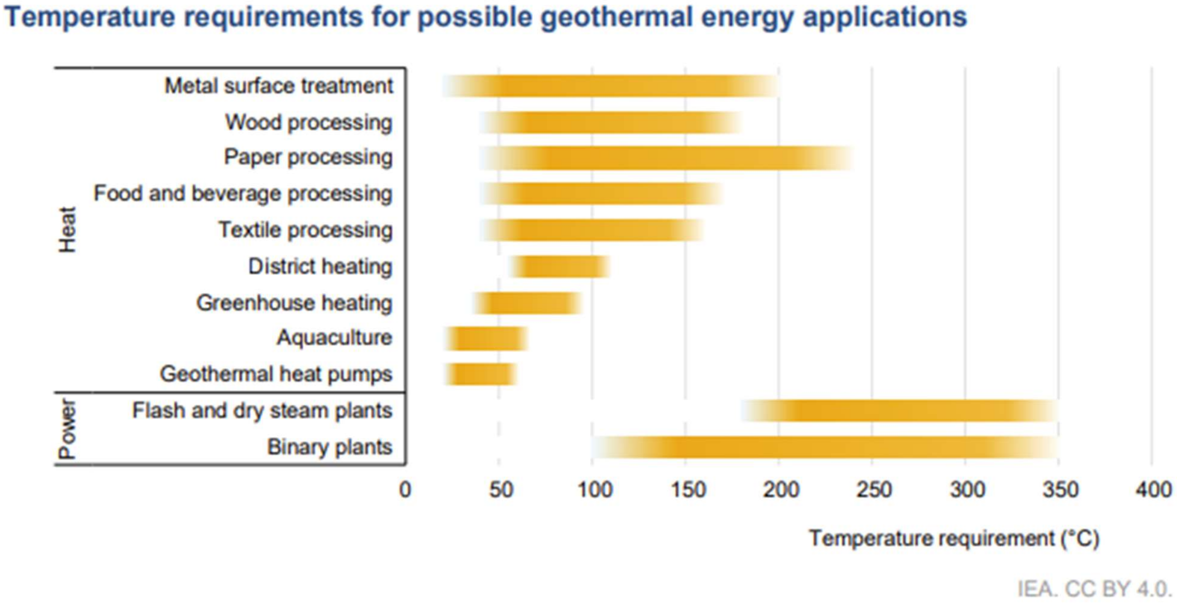


Figure 40. Temperature requirements for possible geothermal energy applications. *(IEA, 2024c)*

In the spatial analysis here, geothermal energy is explicitly assessed only for district heating applications, even though geothermal resources could also support industrial heat, cooling, or electricity generation depending on temperature levels. The estimation of geothermal potential, therefore does not rely on a simple aggregation of geological resources. Instead, it is based on a spatial intersection between identified geothermal zones and potential district heating systems, combined with an assessment of base-load heat demand. Geothermal zones are identified using the GeoDH database, including hydrothermal resources, deep and shallow geothermal areas, and Neogene basins (GEODH, 2022). To reflect economic feasibility, geothermal deployment is restricted to district heating systems of sufficient scale, as investments in geothermal drilling and infrastructure are not recommended for small systems due to high upfront costs and geological risk.

In this study, 40 MW and 70 MW baseload minimum thresholds are used to identify systems where geothermal investments are considered economically realistic. In many cases, several units will be deployed, as many cities exceed the minimum threshold for geothermal. These thresholds correspond, on average, to medium-sized and large cities, respectively. Empirically, cities with a baseload of around 70 MW typically correspond to populations of approximately 200.000 inhabitants and 40 MW to about 100.000 inhabitants, although these relationships vary with climate conditions and assumed heat savings. In the recommended scenario, a minimum base-load capacity of 40 MW is applied, ensuring that geothermal heat is prioritised in large and medium-sized urban systems where high annual load factors can be achieved.

Fact Box III. Geothermal district heating

Case: Szeged Geothermal

Location: Szeged, Hungary (approx. 162,000 people)
Szeged demonstrates how deep geothermal energy can supply baseload heat in a medium-sized European city with an existing district heating network. The municipally owned district heating company has replaced natural gas with geothermal heat by integrating deep geothermal wells into the city's district heating system as part of Szeged's heat decarbonisation strategy. The project confirms a core assumption in the present study: geothermal heat is economically viable where sufficiently large, stable baseload demand exists and where it can be integrated into an established network, with fossil boilers retained for peak and backup operation.

In Szeged, a wide range of buildings, including apartments, schools, kindergartens, and retail facilities, are supplied with heat by the local district heating operator, SZETÁV. The municipally owned company provides space heating and domestic hot water to approximately 27.000 apartments and more than 400 public buildings through a district heating network extending over about 250 km. The system delivers a total annual heat output of around 234 GWh, which historically relied on natural gas.

Key features:

- Geothermal wells: ~1,700–2,000 m depth, ~90 °C
- Emission reduction: ~60% of natural gas CO_2
- Role in system: Geothermal baseload, gas for peak/backup
- Cost reported ~70 M€, with ~23 M€ financed by EU cohesion funds

Under these constraints, the full geothermal heat potential across Europe is estimated at approximately 997 TWh/year, but only around 10% of this potential is practically usable within economically viable district heating configurations using waste heat sources before geothermal sources in the recommended scenario. This corresponds to 8% of the district heating production in the 55% scenario, but if waste heat is less available, geothermal could cover up to about 20%. As a result, geothermal energy in the recommended scenario plays a strategic but geographically concentrated role, primarily supplying base load in larger cities with high heat density. Examples of cities with particularly strong geothermal potential relative to their heat demand include Dublin, Amsterdam, Antwerp, The Hague, Lyon, and Bremen, while very large metropolitan systems such as Paris and Berlin could cover a substantial share of their demand through geothermal heat. Paris already exploits substantial levels of this potential today.

Geothermal will most likely have a sector integration component. Even where geothermal resources provide medium-temperature heat, large-scale heat pumps often play a complementary role by upgrading source temperatures to match network supply requirements and by enabling flexible operation in response to electricity-system conditions. In this context, geothermal heat functions primarily as a stable base-load input, while heat pumps provide temperature lift and operational flexibility, allowing the system to optimise electricity consumption during periods of high availability of low-cost renewable electricity.

3.2.2 Solar thermal

Today, the use of solar thermal is deployed mainly in countries like Denmark, Germany, Austria and Poland within district heating. There is still a large potential both in communities and large cities where solar thermal has the potential to substitute finite resources and increase the efficiency of systems during the summertime.

In large metropolitan systems with abundant waste heat, solar thermal is often outcompeted on a system-cost basis, despite its technical feasibility. Larger solar thermal integration is dependent on thermal storage, due to the pronounced seasonal mismatch between solar heat production and space-heating demand but is limited to smaller cities. Short-term storage (diurnal to weekly) allows solar thermal to contribute effectively to domestic hot water and service-sector demand, while large seasonal storage (e.g. pit thermal energy storage) is essential for extending the usability of solar heat into shoulder seasons. Pit thermal storage or larger storages require space however, and land costs and availability limit these options. In systems with adequate storage capacity, solar thermal can significantly reduce fuel use and peak-load operation of other heat sources, even if its annual utilisation remains limited. However, the capital intensity of large thermal storage means that solar thermal integration is most cost-effective in smaller and medium-sized district heating systems, where storage can be deployed at scale relative to demand and where competition from constant waste heat sources is more limited.

Solar thermal potential is estimated using a related but distinct methodology. While solar thermal is also linked to the baseload concept, its usable output is constrained by seasonality rather than resource availability. In these analyses, solar thermal production is calculated as the product of baseload capacity and an assumed number of full-load hours, which is approximately 1,100 hours per year for the selected representative cities. For example, a city with a 20 MW baseload yields a solar thermal potential of roughly 22 GWh/year. This approach captures the fact that solar thermal contributes primarily during summer and shoulder seasons and therefore cannot cover the full baseload throughout the year. A maximum city level of 20 MW is used, corresponding to around 50.000 inhabitants. In the analyses, all smaller systems identified as potential district heating areas are combined with solar thermal, subject though to the availability of other waste heat sources.

As a result of this methodology, the solar thermal share of total district heating demand appears relatively low in smaller cities. For example, in cities with an average baseload of 175 GWh/year (corresponding to approximately 20 MW), solar thermal contributes around 28 GWh/year, or about 7% of total heat demand. This is not an underestimation of the source but rather represents an average potential coverage in cities up to about 50.000 inhabitants. With cities of about 50.000 inhabitants the coverage is most likely 5%, due to the likely scarcity of space for large diurnal, weekly of seasonal storage, while cities of e.g. 1.000 inhabitant may have a coverage of up to 50%, if land is available. Solar thermal is therefore primarily positioned as a supplementary baseload technology, particularly relevant in smaller and medium-sized systems where large seasonal thermal storage can be deployed and where competition from industrial waste heat is limited.

In this analysis, two sets of solar thermal potentials are considered, with particular emphasis on smaller communities where large thermal storage can be deployed alongside solar fields. The maximum potential considering temporal aspects is estimated at 239 TWh/year, but only 10–20% of this is usable in practice, corresponding to 2-10% of the district heating supply mix with 55% district heating. In the recommended scenario, solar thermal represents 2% of the district heating fuel mix in 2050 and is utilised only where it does not compete unfavourably with other waste heat sources available.

Fact Box IV. Large thermal Solar District Heating in Leipzig

Case: Leipzig Large-Scale Solar thermal plant

Location: Leipzig, Germany (approx. 630.000 people)
Leipzig is expanding its district heating system with what will be Germany's largest new solar thermal plant, scheduled for commissioning in early 2026. District heating currently supplies around 30% of Leipzig's total heat demand, supported by a network of approximately 500 km. According to the municipal heat planning scenario developed by the system operator, district heating could supply up to 50% of the population by 2045, largely based on renewable and waste heat sources.

The new solar thermal plant has a peak thermal capacity of 41 MW and is designed to deliver approximately 26 GWh of heat annually. The installation covers around 14 hectares on the outskirts of the city and is capable of delivering heat at temperatures above 100 °C, allowing direct integration into the existing district heating network without extensive temperature upgrading.

In system terms, the plant plays a seasonal role, supplying up to around 20% of district heating demand during summer periods, while contributing roughly 2% of annual district heating supply. It complements other renewable and waste heat investments and supports Leipzig's strategy to phase out fossil heat supply by 2038, in line with German climate targets.

Key Features:

- Covering 20% of Leipzig's heating needs in the summer period
- 41 MW of peak capacity and 14 hectares of fields
- Feeding 26 million kWh of heat into the grid each year.
- CO_2 reduction: ~7.200 tCO_2/year

3.3 Waste heat sources

For waste heat sources excluding power plants and CHP, the future full potential amounts to 1.517 TWh/year, while the technical potential within a 55% district heating system is 948 TWh/year. In the recommended scenario, 527 TWh/year is utilised, corresponding to about 56% of the technical potential and 35% of the full potential. This relatively high utilisation rate reflects the strong spatial alignment of many waste heat sources with urban heat demand and their comparatively favourable cost characteristics. In this section each source is elaborated.

3.3.1 Industrial waste heat is also present in future decarbonised energy systems

Industrial waste heat represents a crucial yet still underutilised energy resource in Europe, particularly in urban and industrialised regions where large heat demands coincide spatially with energy-intensive activities. In combination with district heating systems, industrial waste heat offers a highly efficient pathway to decarbonise heat supply by recovering energy that would otherwise be released to the environment. The proximity of industrial facilities to densely populated areas create favourable conditions for capturing and reusing this heat to meet space-heating, hot-water, and, in some cases, cooling demands in nearby buildings and infrastructure.

Industrial processes generate waste heat at different temperature levels, which fundamentally determine how and where this heat can be utilised within district heating systems. In this Heat Roadmap Europe study, industrial waste heat is categorised according to three temperature thresholds:

- low-temperature heat above 25 °C,
- medium-temperature heat above 55 °C, and
- high-temperature heat above 95 °C.

This classification is critical, as temperature levels directly affect both the technical feasibility and the system value of waste heat integration. High- and medium-temperature waste heat can often be integrated directly into existing district heating networks, while low-temperature heat typically requires upgrading through large-scale heat pumps and benefits from low-temperature (4th generation) district heating infrastructures. Identifying the temperature range is therefore essential for determining both the utilisable share of waste heat and the required system adaptations.

In addition to temperature, industrial waste heat can also be classified by sector. Significant waste heat is generated across a wide range of industrial activities, including chemicals, iron and steel production, non-ferrous metals, non-metallic minerals (e.g. cement), paper and pulp, foundries, and a diverse group of other industries such as food processing, drinks, textiles, and engineering. The magnitude of waste heat potential varies substantially between sectors and countries, reflecting differences in industrial structure and geographic distribution. Countries with a high share of energy-intensive industries, such as Germany, France, Italy, Spain, Poland, Sweden, and Finland, exhibit particularly large industrial waste heat potentials. Detailed sector- and country-specific data underpinning this assessment are documented in the data and country report.

The industrial waste heat data used in this study builds on the comprehensive assessment developed in the *sEEnergies* project and is implemented through the IndustryPLAN framework. IndustryPLAN enables integrated analyses of industrial energy use and mitigation options, including electrification, best available technologies (BAT), material recycling, and waste heat utilisation, while ensuring consistency with renewable smart energy systems and district heating integration (Johannsen et al., 2023; Mathiesen et al., 2023). The methodology explicitly considers the spatial match between industrial facilities and district heating areas, recognising that only waste heat located sufficiently close to heat demand can be realistically recovered.

As with any system-level assessment, defined boundaries imply that some smaller or more diffuse sources are not fully captured. Smaller industrial facilities, activities with very low energy demand, and certain non-industrial sources, such as data centres or wastewater treatment plants, are therefore assessed separately in other sections. To quantify future developments, industrial waste heat is assessed using 2015 as a reference year and projected under three scenarios for 2030 and 2050. These include a Business-as-Usual (BAU) scenario with no major technological changes, and two scenarios based on best available technologies that are already commercially available today. One BAT scenario assumes high material recycling rates, while the other assumes no additional recycling. Although incremental efficiency improvements are expected over time, the core assumption is that the technologies required to recover industrial waste heat already exist.

Across these scenarios, we find here that in a future fossil-free European energy system, total industrial waste heat declines by only around 8% compared to today, remaining close to 800 TWh/year (≈ 2,900 PJ) across EU27 industries. This highlights that waste heat is not merely a fossil-fuel-related phenomenon but a structural feature of many industrial processes, including chemical reactions and mineral and metal processing, which continue to generate substantial recoverable heat even in electrified and decarbonised production systems. Where possible, industrial processes are electrified; where direct electrification is not feasible, low-carbon fuels such as biogas or hydrogen are assumed.

The sectoral and temperature-specific evolution of industrial waste heat between 2015 and 2050 is summarised in Table 9. The table shows that, across EU27, total industrial waste heat declines only modestly (≈8%), while the composition shifts substantially across sectors and temperature levels. In particular, high-temperature waste heat decreases more strongly than low- and medium-temperature sources, reinforcing the importance of large-scale heat pumps and low-temperature district heating systems.

EU27 industrial waste heat development (TJ)

Temperature	**Year**	**Chemicals**	**Foundries**	**Iron and steel**	**Non-ferrous metals**	**Non-metallic minerals**	**Others**	**Paper and pulp**	**Total**
25 °C	2015	212.736	31.624	194.505	123.794	335.879	423.731	102.025	1.424.294
	2050	214.761	32.274	111.572	98.611	323.333	501.899	109.100	1.391.551
	% ***comparison***	***101%***	***102%***	***57%***	***80%***	***96%***	***118%***	***107%***	***98%***
55 °C	2015	61.049	27.613	156.545	102.921	251.044	274.132	35.736	909.040
	2050	56.400	28.092	80.813	78.297	230.703	297.351	35.061	806.717
	% ***comparison***	***92%***	***102%***	***52%***	***76%***	***92%***	***108%***	***98%***	***89%***
95 °C	2015	39.024	26.326	136.831	98.647	218.868	237.419	27.805	784.920
	2050	32.773	26.717	66.580	74.081	194.413	247.054	26.528	668.147
	% ***comparison***	***84%***	***101%***	***49%***	***75%***	***89%***	***104%***	***95%***	***85%***
Total	2015	312.809	85.563	487.880	325.363	805.791	935.282	165.566	3.118.254
	2050	303.934	87.083	258.965	250.989	748.449	1.046.305	170.689	2.866.414
	% ***comparison***	***97%***	***102%***	***53%***	***77%***	***93%***	***112%***	***103%***	***92%***

Table 9: The industrial waste heat development (TJ) from 2015 to 2050, at each temperature level and by industrial process.

The decline in waste heat is uneven across sectors. Iron and steel production shows the strongest reduction, with waste heat roughly halved by 2050, while non-ferrous metals and non-metallic minerals also decline significantly. In contrast, chemicals, paper and pulp, and foundries remain relatively stable, and waste heat from other industries including food, drinks, textiles, and engineering, may even increase by up to 18%. High-temperature industrial waste heat (> 95 °C) decreases by about 15%, while medium-temperature (≈ 55 °C) and low-temperature (> 25 °C) sources decline by around 10% and 2%, respectively. By 2050, high-temperature waste heat represents only about 25% of the total industrial waste heat supply, underscoring the growing importance of large-scale heat pumps and low-temperature district heating networks.

Geographically, industrial waste heat is highly concentrated, as illustrated in Figure 41 and Figure 42, which show the available low-, medium-, and high-temperature industrial waste heat by country in 2050. Germany (≈ 128 TWh/year), France (≈ 95 TWh/year), Italy (≈ 75 TWh/year), Spain (≈ 70 TWh/year), and Poland (≈ 32 TWh/year) together account for roughly 400 TWh/year, i.e. about half the EU27 industrial waste heat potential in 2050. This concentration strongly shapes where industrial waste heat integration into district heating systems is most scalable and economically attractive.

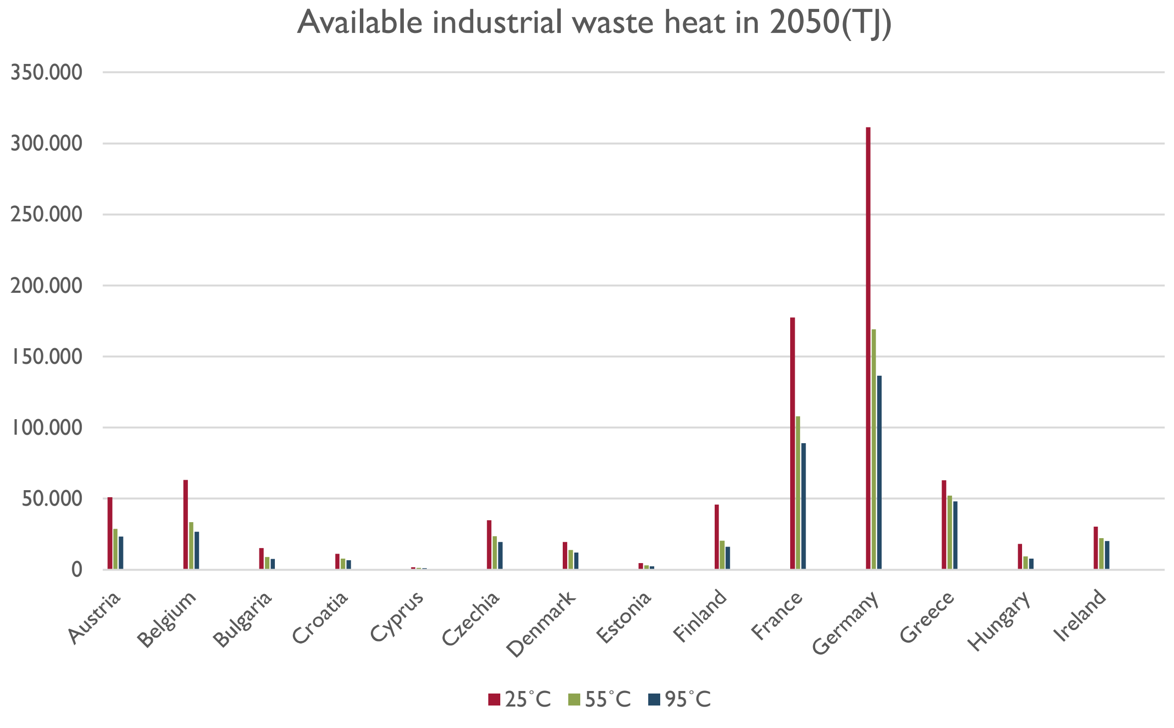


Figure 41, Available waste low-, medium- and high temperature heat in 2050 in the BAT scenario for EU27 (A to I).

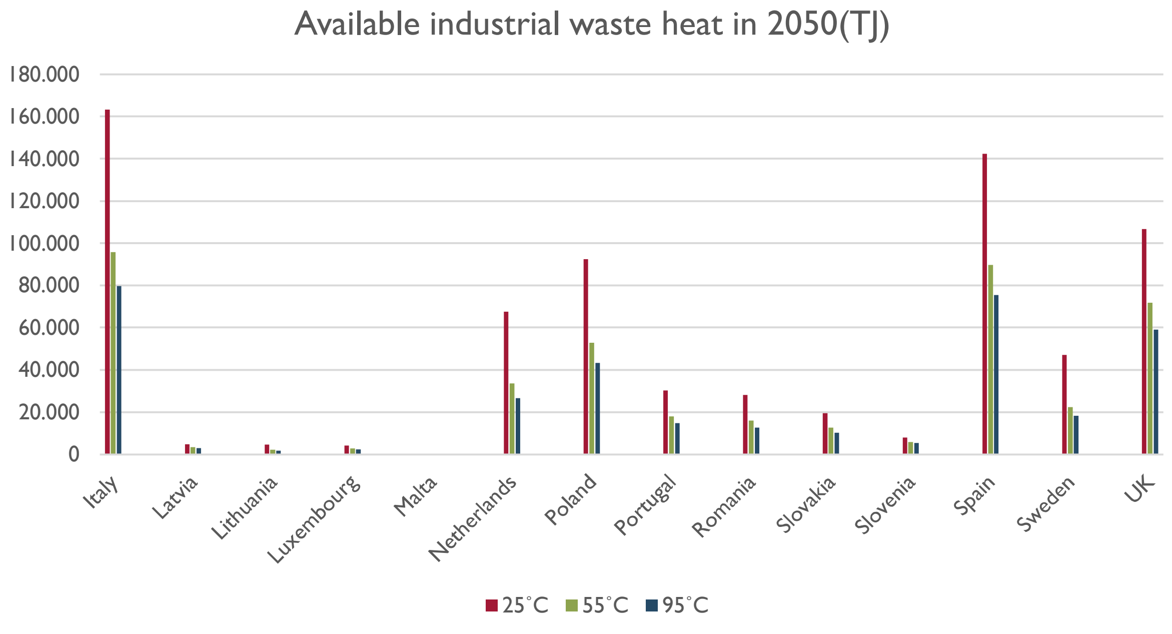


Figure 42, Available waste low-, medium- and high temperature heat in 2050 in the BAT scenario for EU27 (I to S) and the United Kingdom.

Industrial waste heat remains a substantially under-exploited energy resource in Europe. While many district heating systems draw on combined heat and power, waste incineration, or biomass, the share of heat derived from industrial residual streams is generally low relative to the technical potential documented in here. In a limited number of cases, systematic recovery of industrial residual energy contributes directly to urban heat supply.

Large-scale heat pump technology is emerging as a key enabler for integrating lower-temperature industrial waste heat into district heating systems. Deployments such as those documented in Vienna illustrate that heat pumps can be used to upgrade waste and secondary heat sources to district heating temperature levels, expanding the usable portion of available waste energy. In Hamburg, EU-supported initiatives are demonstrating reuse of industrial residual heat for climate-neutral district heating supply, underscoring how industrial heat streams can be embedded in district heating systems.

Although this study does not explicitly model cooling, related developments further demonstrate the value of integrating industrial energy streams. Case evidence such as the urban utilisation of residual cold from LNG regasification in Barcelona highlights opportunities to use process energy for low-carbon cooling and ancillary services. Taken together, these examples reinforce the conclusion that, even with substantial decarbonisation of industry, waste heat and industrial residual energy streams are critical components of cost-effective, low-carbon district heating systems.

Fact Box V. Recovery of industrial waste heat combined with thermal storage

Case: Hamburg – industrial waste heat integration from non-ferrous metals production

Location: Hamburg, Germany (approx. 1.9 million people)
Hamburg is Germany's second largest city and operates one of Germany's largest district heating systems, with nearly 900 km of network supplying a substantial share of the city's heat demand. As part of its heat transition strategy, Hamburg is replacing fossil-based heat production, most notably the Tiefstack coal-fired plant, with a portfolio of climate-neutral heating solutions, including industrial waste heat, renewable heat sources, large-scale heat pumps, and thermal storage.

A flagship element of this transition is the industrial waste heat partnership between Hamburger Energiewerke (the district heating operator) and Aurubis, one of Europe's largest non-ferrous metals producers. Large quantities of surplus heat from Aurubis' copper production processes are recovered and fed into the district heating network instead of being released unused to the environment. This integration reduces fossil fuel consumption in the heat system while making use of a stable, year-round industrial heat source.

Thermal storage plays a central role in the system, allowing recovered heat to be buffered and dispatched flexibly in line with district heating demand. The project is a cornerstone of Hamburg's strategy to decarbonise urban heat supply by 2030 and beyond, demonstrating how industrial waste heat can substitute conventional base-load heat production in large metropolitan systems.

Key features:

- Primary heat source: Industrial waste heat from Aurubis (non-ferrous metals production)
- Heat integration: Direct supply to Hamburg's district heating network via large-scale heat pumps
- Thermal storage w. pressure heat accumulator ~4 million litres at storage temp. up to ~105 °C
- Climate impact: Avoids up to ~100,000 tCO_2/year and provides carbon neutral heat for up to 20,000 households

3.3.2 Waste heat from waste-to-energy is expected to remain at the same level

While it should be emphasised that waste heat from waste-to-energy (WtE) plants is not a prerequisite for the expansion of district heating, it nevertheless constitutes a significant potential heat source in future energy systems, even under scenarios with very stringent requirements for waste prevention, recycling, and reuse. The utilisation of WtE heat must be understood in the context that waste-to-energy is a by-product of material consumption and residual waste management, rather than a heat-supply technology deployed to meet district heating demand as such.

In this project, waste heat from WtE is considered CO_2-neutral, based on the assumption that Europe meets its long-term climate targets either through the progressive removal of fossil-based materials, notably plastics, from the waste stream, or through the deployment of carbon capture technologies at WtE facilities. Carbon capture on WtE plants, or on other combustion-based sources, is not explicitly modelled in the present analysis; however, such solutions would further increase the potential contribution of WtE facilities as heat sources for district heating systems.

WtE constitutes one of the most mature and already utilised waste-heat sources for district heating in Europe. At present, the share of waste heat recovered from WtE plants is significantly below the theoretical potential, largely reflecting historical waste management practices and limited district heating coverage rather than technical constraints. With current landfill rates and waste streams, the theoretical heat potential from WtE exceeds present utilisation by a wide margin (Eurostat, 2025a, 2025b, 2025c).

WtE facilities are typically embedded in or located close to urban areas, reflecting the spatial coincidence between waste generation and heat demand. As a result, WtE plants already provide a stable base-load contribution to district heating systems in several member states, capturing heat that would otherwise be rejected to the environment in the absence of district heating infrastructure. WtE plays a dual role in European energy and waste systems. First, it contributes to the treatment of residual waste that cannot be prevented, reused, or recycled. Second, it enables energy recovery in line with the EU waste hierarchy, which prioritises waste prevention, reuse, recycling, and recovery over disposal (EU, 2024; The European Parliament & The European Council, 2008, 2018). Several member states have integrated WtE into their waste management strategies to phase out landfilling, while simultaneously supporting district heating development.

Policy context and waste system evolution to 2035

The future availability of waste heat from WtE plants is strongly shaped by European waste and circular economy policy. The EU Circular Economy Action Plan mandates minimum municipal waste recycling rates of 55 % by 2025, 60 % by 2030, and 65 % by 2035, alongside progressively stricter limits on landfilling (The European Parliament & The European Council, 2018). Achieving the 2030 recycling target alone implies a reduction in residual municipal waste of more than 50 million tons at EU level. These developments directly affect the waste input to WtE facilities and, consequently, the availability of recoverable heat for district heating systems. Eurostat data illustrate the current role of waste to energy within European waste treatment. In 2022, approximately 6,4% of municipal waste in the EU was incinerated with energy recovery, while only 0,4% was incinerated without energy recovery. Significant national differences exist.

Going beyond 2035: scenario-based assumptions

For the period beyond 2035, no binding EU recycling targets exist. Accordingly, recycling rates applied after 2035 in this study reflect scenario-based assumptions rather than legislative commitments. These assumptions are informed by circular-economy scenario analyses and waste-to-energy modelling frameworks developed by CEWEP, the Confederation of European Waste-to-Energy Plants (CEWEP, 2023). In this study this tool is used to assess the WtE potentials in an EU where demands for recycling and land fill are further tightened requirements towards 2050 beyond 2035.

This Heat Roadmap Europe study further advances earlier Heat Roadmap frameworks by explicitly integrating circular economy constraints and recycling developments and assessing waste heat from WtE on the country level towards 2050.

To translate European waste policy targets into energy system inputs, a three-step methodological approach is applied. First, policy-driven constraints on recycling rates, landfilling, and waste prevention are used to define national waste quantities over time, drawing on Eurostat data, EU policy and CEWEP projections until 2035 and here assumed prolonged and tightened into 2050. Second, these waste quantities are converted into energy inputs for waste-to-energy plants using technology-specific efficiencies, consistent with the Heat Roadmap Europe modelling practice. Municipal waste and commercial and industrial waste are treated separately but consistently across all member states. Third, the assessments are conducted pr. member state to be aligned with the overall EU27 targets. This approach allows waste-to-energy heat potentials to be assessed consistently across countries and scenarios, while ensuring that developments beyond 2035 reflect analytical scenario and country assumptions.

Some of the key assumptions for WtE in Heat Roadmap Europe towards 2050 include:

- Municipal waste and Commercial & Industrial (C&I) waste at the EU27 level: Based on the CEWEP calculation tool, municipal and C&I waste estimates have been made using a baseline recycling rate of 80% for commercial and industrial waste, which corresponds to a recycling target of at least 50% on a national level.
- Recycling and waste generation projections pr. country: Municipal waste estimates for each country are based on Eurostat's 2020 data and country-specific recycling rate developments, aligning with CEWEP's aggregated results and with the EU targets.
- Post 2035 assumed targets for 2050: Waste prevention going beyond 2035 assumed trends reflecting development slowly building on top of the 2035 targets. Recycling rates increase progressively over time, while landfilling is reduced to 5 percent or less. Residues from recycling processes are explicitly accounted for, with 15 percent assumed as recycling residues, of which 20 percent are sent to landfill, and the remainder treated as residual municipal waste available for further treatment. Of course, the EU targets will affect the shape and the development of the waste handling, for instance the share to landfill being 0 or the applicable recycling rate up to 75% in 2050 or the shift to recycling from landfilling up to 80% for 2050.
- Waste prevention and growth effects: In the modelling framework, waste prevention and efficiency improvements at member state level are assumed to offset the effects of population and economic growth. As a result, total waste quantities remain broadly similar to today's levels over time, while the composition and treatment of waste evolve in line with circular economy and recycling policy assumptions rather than changes in absolute waste generation.

While population historically is an important underlying driver for waste generation the goal is to change this in EU. Here, the effect of population and GDP growth on total waste quantities is neutralised by explicit modelling assumption. Real GDP growth is not translated into higher waste volumes. Instead, waste prevention, material efficiency, eco-design, and circular-economy measures are assumed to fully offset the waste-generating effects of economic and demographic growth. This is implemented in the model as a net zero effect of population and GDP growth on total waste generation (in tons). Importantly, this does not imply that growth pressures are absent; rather, it implies that prevention and efficiency gains continuously counterbalance them. The implied prevention effort is non-trivial:

- Under the Eurostat baseline population projection, maintaining constant total waste volumes between 2020 and 2035 requires a per-capita waste reduction of approximately 1% over the period.

Under the higher-migration projection, the corresponding required per-capita reduction rises to around 3% by 2035 (EuroStat, 2023).

- Similarly, if real GDP were to grow by 1% per year, holding total waste constant would require a cumulative reduction in waste intensity of roughly 15% by 2035. At 2% annual GDP growth, the implied reduction approaches 25–30%. These values are consistent with historical waste-intensity trends and scenario analyses reported by the European Environment Agency and the OECD, which indicate that sustained reductions of this magnitude require continuous policy intervention and structural change (EEA, 2025a, 2025b; OECD, 2019). Note – policies and implementation focuses are required to maintain such results.

Accordingly, the assumption of constant total waste quantities reflects a scenario-based representation of long-term circular economy progress rather than a continuation of historical trends. The results of these Heat Roadmap Europe assumptions are summarised in Table 10. Please note that this methodology provides the EU level targets, while in this Heat Roadmap Europe project we then translate that into country level assessments which are not proved by the EU or by using the CEWEP tool.

Table 10, Waste handling assumptions and targets going beyond 2035. Please note the assumptions for landfill and recycling in 2040 and 2050.

Municipal waste	**2030**	**2035**	**2040**	**2050**
Population growth model	EUROSTAT baseline	EUROSTAT baseline	EUROSTAT baseline	EUROSTAT baseline
Additional waste prevention (per anno)	0%	0%	0%	0%
Targets for EU27 + UK:	2030	2035	2035	2035
Share landfilling	None	10%	5%	5%
Applicable recycling rate (excl. Derogations)	60%	65%	70%	75%
Shift to recycling from landfilling	80%	80%	80%	80%
Considered exception for countries with high landfill	No	No	No	No
Residues from recycling:	15%	15%	15%	15%
Share of recycling residues sent to landfilling	20%	20%	20%	20%
Consider recycling residues as municipal waste	Yes	Yes	Yes	Yes
Commercial waste				
GDP Growth(real) per anno	0.00%	0.00%	0.00%	0.00%
Additional waste prevention (per anno)	0.00%	0.00%	0.00%	0.00%
Recycling rate commercial waste (input-based)	80%	80%	80%	80%
Landfill rate commercial waste (output-based)	6,3%	6,3%	3,4%	3,4%
Status quo (Current situation) - consider residues	Yes	Yes	Yes	Yes
Residues from recycling (C&I W):	15%	15%	15%	15%
Others				
Minimum total landfilling	0,5%	0,0%	0,5%	0,5%

Current waste available for WtE: development of tonnes

Applying these assumptions waste-to-energy remains a stable and geographically favourable source of waste heat, even under ambitious circular economy scenarios. Although increased recycling and waste prevention reduce the volume of residual waste compared to today, a substantial fraction remains available for energy recovery. At present, EU27 generates very large waste volumes, but only a limited share is used for energy recovery see Table 11. The total waste generation for EU27 amounts to approximately 2,15 billion tons pr. year, corresponding to about 4,8 tons pr. capita considering both municipal waste and C&I waste divided by:

- Around 1,04 billion tons are recycled or backfilled,
- 796 million tons are still disposed of through landfilling or other non-recovery routes,
- Only 129 million tons are treated through energy recovery (WtE),
- An additional ~10 million tons are incinerated without energy recovery.

Table 11, 2020 municipal and C&I waste and treatment allocation pr. type for EU27 & the United Kingdom(*Eurostat, 2025a, 2025b, 2025c*).

	Total waste generation		**Total waste treatment (mio. tons)**			
	Total waste (mio. tons)	Waste (t/capita)	Disposal - landfill and other	Recovery – recycling & backfilling	Recovery - energy recovery	Disposal - Incineration
Austria	68,9	7,7	29,6	33,3	2,8	0,9
Belgium	68,1	5,9	3,5	46,6	4,0	0,6
Bulgaria	116,4	16,8	100,8	8,5	0,7	0,1
Croatia	6,0	1,5	1,4	2,5	0,2	0,0
Cyprus	2,2	2,5	0,6	0,5	0,2	0,0
Czechia	38,5	3,6	3,9	30,0	1,4	0,1
Denmark	20,1	3,5	1,3	12,5	3,5	0,0
Estonia	16,2	12,2	6,0	9,0	0,3	0,0
Finland	116,1	21,0	94,7	11,7	6,2	0,1
France	310,4	4,6	77,4	188,4	22,5	4,2
Germany	401,2	4,8	67,4	267,4	45,1	2,0
Greece	28,4	2,7	14,1	7,1	0,4	0,0
Hungary	17,2	1,8	4,2	15,0	1,3	0,1
Ireland	16,2	3,2	4,1	8,8	1,2	0,0
Italy	174,9	2,9	15,6	122,7	8,1	0,7
Latvia	2,9	1,5	0,5	1,4	0,2	0,0
Lithuania	6,7	2,4	2,0	1,8	0,5	0,0
Luxembourg	9,2	14,6	2,2	7,2	0,3	0,0
Malta	3,5	6,8	0,3	3,0	0,0	0,0
Netherlands	125,1	7,2	51,2	60,2	9,4	1,2
Poland	170,2	4,5	34,8	97,9	3,7	0,3
Portugal	16,6	1,6	3,8	5,9	1,2	0,0
Romania	141,4	7,3	127,5	8,4	2,0	0,1
Slovakia	12,8	2,3	3,0	6,7	0,6	0,0
Slovenia	7,5	3,6	0,4	6,6	0,2	0,0
Spain	105,6	2,2	31,1	51,7	3,4	0,1
Sweden	151,8	14,7	114,3	21,1	8,9	0,1
EU27	2.154,0	4,8	796,0	1.036,1	128,9	9,8
UK	282,4	4,2	76,5	122,5	8,5	7,3

This table of the current situation highlights that WtE currently represents a relatively small share of overall waste treatment, despite its importance for district heating in several countries. Large differences exist between member states. Countries such as Germany, France, Italy, Sweden, and the Netherlands already operate substantial WtE capacity and recover significant amounts of heat. In contrast, several countries still rely heavily on landfilling and have very limited WtE capacity today, notably Romania, Bulgaria, Greece, Croatia, Cyprus, and parts of Central and Eastern Europe. These countries face a dual challenge: sharply reducing landfill use while expanding recycling and, where appropriate, energy recovery.

Future waste-to-energy heat potential

In this study, future waste availability for WtE is derived from a combination of EU-level CEWEP projections to 2050 and country-level modelling based on Eurostat data. The CEWEP Circular Economy Calculation Tool is used to ensure consistency with EU waste policy at the aggregate level, while country-specific distributions, as CEWEP does not provide national projections.

In Table 12 the future estimations for EU27 and pr. country is outlined. The projected residual waste quantities are broadly consistent with other CEWEP estimates, although some divergence occurs due to different treatments of recycling residues and national recycling trajectories when the aggregation of the country results are calculated especially in 2040 and 2050. The trajectory reflects tightening recycling targets: 55% by 2025, 60% by 2030, 65% by 2035 as well as 70% and 75% in 2040 and 2050. Landfill is also explicitly reduced to 5% in 2040 and 2050.

The aggregated country results for municipal waste (residual fraction) shows a decline overall, but it remains substantial due to less landfill: ~66 Mt in 2030, ~63 Mt in 2035, ~68 Mt in 2050. The differences relative to the modelled CEWEP results arise mainly from treatment of recycling residues and national recycling pathways.

The aggregated country results for commercial and industrial (C&I) waste remains broadly stable over time: ~70–76 Mt across 2030–2050. This is driven by the assumption of 80% recycling prior to residual treatment, with no additional waste prevention beyond existing trends.

The future distribution of WtE-relevant waste across countries is vastly different compared to today:

- Germany, France, Italy, Spain, the UK, Sweden, and the Netherlands together account for a large share of total WtE feedstock throughout the period.
- Several countries with currently low WtE capacity see strong growth in WtE-relevant waste volumes, driven mainly by landfill reduction requirements (e.g. Spain, Poland, Romania, Greece, Czechia).
- These countries will either need to expand WtE capacity, export residual waste, or achieve very rapid increases in recycling and waste prevention.

In Table 12 the waste for WtE plants is also translated into heat potentials pr. country pr. year as well as for EU27 and the United Kingdom. The total EU level waste heat from WtE is expected for be 133 TWh or at the same level as today. The largest potentials for WtE waste heat are in Germany (35 TWh/y), France (25 TWh/y), Spain (12 TWh/y), Italy (10 TWh/y), and the Netherlands (9 TWh/y). Together, these countries contribute about 70% of the EU27 potential in 2050. The heat from WtE however is distributed very differently compared to today. Despite declining residual waste volumes after 2035, it remains a significant heat source. For countries with limited WtE today but high landfill shares, the results indicate that meeting EU waste targets will require either rapid expansion of recycling and sorting capacity, new WtE capacity, or both.

Table 12, Projected WtE waste amounts and estimated heat production for EU27 and the United Kingdom.

	Total waste for WtE potential (mio. tons)					**Heat production (TWh)**				
Year	2020	2030	2035	2040	2050	2020	2030	2035	2040	2050
EU27	136,1	136,6	133,1	160,9	145,1	91,4	126,9	122,8	148,8	133,2
Austria	3,2	2,9	2,9	3,4	2,9	2,1	2,7	2,7	3,1	2,6
Belgium	4,5	3,4	3,2	4,2	3,6	3,0	3,2	3,0	3,8	3,3
Bulgaria	0,8	2,0	2,0	2,4	2,2	0,5	1,9	1,8	2,2	2,0
Cyprus	0,2	0,3	0,3	0,3	0,3	0,1	0,2	0,2	0,3	0,3
Czechia	1,4	2,4	2,2	3,0	2,6	1,0	2,2	2,1	2,8	2,4
Germany	44,9	35,2	36,4	42,3	38,5	30,2	32,7	33,6	39,1	35,4
Denmark	3,3	2,5	2,4	2,7	2,4	2,3	2,3	2,2	2,5	2,2
Estonia	0,3	0,8	0,8	0,9	0,9	0,2	0,8	0,7	0,9	0,8
Greece	0,4	1,9	1,8	2,4	2,0	0,3	1,8	1,6	2,3	1,9
Spain	3,5	11,9	11,3	14,6	13,1	2,4	11,1	10,4	13,5	12,0
Finland	5,9	4,3	4,2	4,5	4,2	4,0	4,0	3,9	4,1	3,9
France	26,7	25,4	24,4	29,9	27,4	17,9	23,6	22,5	27,6	25,1
Croatia	0,1	0,5	0,5	0,7	0,6	0,1	0,5	0,5	0,6	0,5
Hungary	1,4	2,0	1,8	2,3	2,0	0,9	1,8	1,7	2,1	1,9
Ireland	2,7	2,2	2,1	2,5	2,3	1,8	2,1	2,0	2,3	2,1
Italy	8,7	10,3	9,5	13,0	11,2	5,8	9,6	8,8	12,0	10,2
Lithuania	0,5	0,5	0,4	0,5	0,5	0,3	0,4	0,4	0,5	0,4
Luxembourg	0,3	0,2	0,2	0,3	0,2	0,2	0,2	0,2	0,2	0,2
Latvia	0,2	0,4	0,4	0,5	0,4	0,1	0,4	0,3	0,4	0,4
Malta	0,0	0,1	0,1	0,1	0,1	0,0	0,1	0,1	0,1	0,1
Netherlands	10,5	9,8	9,6	10,2	9,6	7,0	9,1	8,9	9,5	8,8
Poland	3,8	4,6	4,2	6,0	5,0	2,6	4,3	3,9	5,5	4,6
Portugal	1,2	1,7	1,5	2,2	1,8	0,8	1,6	1,4	2,1	1,7
Romania	2,0	3,1	3,0	3,7	3,3	1,4	2,9	2,7	3,4	3,0
Sweden	8,7	6,6	6,5	6,9	6,6	5,8	6,1	6,0	6,3	6,0
Slovenia	0,2	0,2	0,2	0,3	0,3	0,2	0,2	0,2	0,3	0,3
Slovakia	0,7	1,2	1,1	1,4	1,2	0,4	1,1	1,0	1,3	1,1
United Kingdom	16,2	16,3	15,9	19,2	17,3	10,9	15,1	14,6	17,7	15,9
CEWEP estimate for EU27 from 2020	134,2	146,3	134,7	138,0	126,3	90,1	136,0	124,3	127,5	116,0

3.3.3 Waste heat from data centres

Uncertainty about future data centre development is substantial. EU data centre electricity demand has become a strategic energy system topic because growth is driven by both "classical" cloud/storage and a new, highly power-dense layer of accelerated computing for AI. Notably, several pre-2020 projections already discussed potential AI-driven acceleration, but recent evidence suggests that both demand levels and efficiency trajectories remain highly uncertain.

The energy efficiency of data centres is commonly assessed using Power Usage Effectiveness (PUE), defined as the ratio between total facility electricity consumption and electricity used directly by IT equipment. A PUE of 1.0 represents a theoretical optimum in which all electricity is used exclusively for IT processes. AI has accelerated "data needs" and compute intensity, while at the same time observed PUE levels appear to have improved faster than earlier projections anticipated. Historically rapid improvements in computing efficiency were enabled by Moore's-law-era semiconductor scaling and associated advances in device design and architectures (Moore, 1965). As computing demand rose, ICT electricity use increased much more slowly because performance per watt improved quickly. Further gains are less certain today as transistor and voltage scaling has slowed, shifting progress toward architecture, software and system level efficiency (Leiserson et al., 2020). This report therefore combines observed trends and forward looking assumptions to construct a range of EU27 electricity demand and waste heat trajectories at EU and member state levels towards 2050.

State-of-the-art knowledge on data centre electricity consumption in EU27

Published estimates and projections for Europe and EU datacentre electricity consumption diverge, reflecting differences in geographic scope, system boundaries, and methods. Some past high-end projections appear to have overestimated near-term electricity demand relative to other more recent. Previously it was anticipated that the electricity consumption in and around the early/mid 20'ties would be 100 TWh or more (Dodd et al., 2020). An estimate based on 2018 data estimated the electricity consumption would increase from about 77 TWh (EU27+UK), corresponding to 2,7% of EU27 + UK electricity demand at the time, to 92,6 TWh in 2025 (Monteavecchi et al., 2020). S&P Global claimed in November 2025 anticipated usage of electricity in 2025 of 145 TWh increasing to potentially 235 TWh in 2030 (Grama, 2025). In January 2024 the IEA came out with a report claiming the level for Europe may rise to 150 TWh in 2026 within the EU alone and that the consumption in 2022 was 100 TWh (IEA, 2024b). In the same year however, the European Commission published a report that said 40 TWh in 2020 and 45-65 TWh in 2022 (Kamiya & Bertoldi, 2024).

The EU has established a database on data-centre performance, providing an increasingly valuable empirical snapshot of operational trends across EU member states, several with large data centre concentrations. For the latest reporting years (2023–2024), the dataset shows rising total electricity consumption alongside shifts in installed IT capacity and infrastructure performance. In 2023 14 reporting countries had a total electricity consumption of 10,2 TWh, with 11,5 GW of installed capacity and a weighted average PUE of 1,43. In 2024 9 reporting countries, reported electricity consumption increased to 20,1 TWh, with 3,5 GW of installed capacity and a weighted average PUE of 1,74. Changes between years partly reflect differences in reporting coverage, i.e. number of countries and facilities, and the dataset is therefore not yet a consistent trustworthy EU wide source (EC, 2025b). The database also monitors indicators related to water use and renewable energy sourcing, which are important for broader sustainability assessment. As reporting expands over time, this database can become a more robust reference point for tracking structural efficiency improvements.

Overall uncertainty remains high for both "current" consumption levels and forward projections, due to differences what is included in the data centre category and whether reported figures reflect Europe or EU27 (e.g. Norway and The United Kingdom or not). In Table 13 and Table 14 selected published estimates and projections of electricity demands and PUE levels are listed where available.

Table 13, Overview of electricity consumption (TWh) from different reports covering Europe or the EU from between 2020 and 2025. Values in TWh stem from the referenced reports while the annual increases in TWh and percentages are calculated here. Values in Italic indicate a future projection in the report.

Publication year / Organisation / Geography	**Unit**	**‘10**	**‘15**	**‘18**	**‘20**	**‘22**	**‘23**	**‘24**	**‘25**	**‘26**	**‘30**	**Reference**
2020	TWh	55	74		*104*				*134*		*160*	(Dodd et al., 2020)
JRC	TWh/y incr.		3,8		*6,0*				*6,0*		*5,2*	
EU27 + UK	% increase/y		6,1%		*7,0%*				*5,2%*		*3,6%*	
2020	TWh/y	52	67	76,8					*92,6*		*98,5*	(Monteavecchi et al., 2020)
EC	TWh/y incr.		3,0	3,3					*2,3*		*1,2*	
EU27 + UK	% increase/y		5,2%	4,7%					*2,7%*		*1,2%*	
2024	TWh/y				39,5	45–65						(Kamiya & Bertoldi, 2024)
EC	TWh/y incr.					2,8-12,8						
EU27	% increase/y					7-28%						
2024	TWh/y					100				*150*		(IEA, 2024b)
IEA	TWh/y incr.									*12,5*		
EU27	% increase/y									*10,7%*		
2025	TWh/y				57		66	68			*113*	(IEA, 2025)
IEA	TWh/y incr.						3,0	2,0			*7,5*	
Europe	% increase/y						5%	3 %			*8,8%*	
2025	TWh/y								145		*238*	(Grama, 2025)
S&P Global	TWh/y incr.										*18,6*	
Europe	% increase/y										*10,4%*	

The IEA report from 2024 focused broadly on electricity demand forecasts from 2024 to 2026 globally but subdivided into regions (IEA, 2024b). In April 2025 the IEA altered this picture in the “Energy and AI” report to 68 TWh in 2024 for Europe as a region (IEA, 2025). The IEA also assessed that the global electricity consumption of electricity for data centres was 416 TWh/year in 2024, implying Europe represents roughly one-sixth of global demand in that year. The European Union currently refers to the IEA report “Energy and AI” dedicated to electricity consumption in the data centre industry but is expecting to publish their own substantial data centre review in 2026. Based on this IEA report the EU reports an EU level consumption of 70 TWh for 2024 and an anticipated level at 113 TWh in 2030.

In this report we take the 70 TWh in 2024 as the point of departure. The 68 TWh is reported as a regional European level (not EU27) in 2024 (IEA, 2025), but given that several other sources indicate higher near-term levels for EU27 scopes, we use 70 TWh as the EU27 electricity consumption in 2024.

State-of-the-art knowledge on the development of PUE in EU27 data centres

The translation from IT workload growth to facility electricity demand is strongly influenced by PUE, but it is difficult to establish a single “true” EU average because PUE varies by geography, climate, and data-centre type. Nevertheless, multiple sources indicate that PUE has improved steadily and in some cases faster than earlier projections assumed.

Table 14 indicates that the PUE in European data centres has improved steadily over the past decade, and in several cases faster than earlier projections suggested. The European Commission study shows a reduction from 2,03 in 2010 to 1,71 in 2020, corresponding to annual efficiency improvements of ~1,1-2,5%/year. Savills Research (2022) reports a similar downward trend, reaching 1,25 by 2022, while perhaps the best-in-class operators report substantially lower values (e.g., Google reporting ~1,10 for its fleet average)(Google, 2025).

The IEA 2025 data centre focused report confirms continued progress, with European averages declining from around 1,57 to 1,45 in the early 2020s and a projected level near 1,29 by 2030 (IEA, 2025). Overall, the historical evidence suggests that improvements in PUE have generally materialised at the upper end of earlier expectations rather than stagnating.

Table 14, Overview of PUE from different reports covering Europe or the EU from between 2020 and 2025. PUE values stem from the referenced reports while the annual improvements in PUE and percentages are calculated here. Values in Italic indicate a future projection in the report.

Publication year	**Organisation**	**Geography / unit**	**'10**	**'15**	**'18**	**'20**	**'22**	**'23**	**'24**	**'25**	**'30**	**Reference**
2020	JRC	EU27 + UK / PUE									*1,5*	(Dodd et al., 2020)
2020	EC	EU27 + UK	2,03	1,89	1,75	*1,71*				*1,51*		(Monteavecchi et al., 2020)
		% improvement/y		-1,4%	-2,5%	*-1,1%*				-2,5%		
2022	Savills Research	Europe / PUE	1,50	1,40	1,35	1,25	1,25					(Savills Research, 2022)
		% improvement/y		-1,4%	-1,2%	-3,8%	0,0%					
2025	IEA	Europe / PUE				1,57		1,47	1,45		*1,29*	(IEA, 2025)
		% improvement/y						-2,2%	-1,4%		*-1,9%*	

The potential trajectories for electricity use in data centres in EU27

In this report three forward-looking scenarios for EU27 data centre electricity consumption towards 2050 have been developed – a base case, a low growth scenario and a high growth scenario – each evaluated under alternative PUE trajectories. These EU-level trajectories are subsequently disaggregated to country-level potentials to ensure consistency. Two structural tendencies emerge from the recent evidence on the EU level:

1) Electricity demand growth at EU27 level appears to have been more moderate than earlier high-growth projections suggested, particularly when compared to some market-based "Europe-wide" forecasts that assumed rapid and unconstrained expansion.

2) Improvements in the PUE appear to be progressing faster than previously anticipated, thereby partially offsetting the impact of IT load growth on total facility electricity consumption.

The core drivers and uncertainties of the scenario framework are:

a) Baseline definition: In long-term projections to 2050, the selection of the baseline year and consumption level is critical. Differences in the starting point can compound substantially over multi-decade horizons. A level of 70 TWh for 2024 was chosen as is represents a level the EU Commission refers to and also seems to have been reported for Europe, i.e. it is not an underestimation of the demand in EU27.
b) Assumed annual growth rate of facility electricity demand: Future electricity consumption depends primarily on assumptions regarding the evolution of digital workloads in Europe and globally. Growth in individual countries and in EU27 may be driven by several structural factors, including:
    - Growth of cloud services and very large data centres (hyperscale sites): More companies and public institutions are moving their data, software and storage to the cloud instead of running their own servers.
    - AI computing needs: Training AI models and running AI systems (for example chatbots, image tools, recommendation systems and automation software) requires powerful and energy-intensive computer chips. As AI use expands, electricity demand in data centres increases.

- More data-heavy digital services: Activities such as video streaming, online gaming, cloud storage, real-time communication, Internet of Things (IoT) devices, and digital control systems in industry and households all generate and process large volumes of data. This steadily increases the need for computational power.
- Replacement of older IT systems with centralised digital infrastructure: Many older local servers and on-site IT systems are being replaced by centralised cloud services. While this can improve efficiency overall, it also concentrates electricity demand in large data centres. It may decrease the total electricity demand but would increase the electricity demands in data centres.
- Changes in where data centres are built: Data centres are not evenly distributed. They tend to be located where electricity is affordable, renewable energy is available, land is accessible, and grid connections are possible. Shifts in investment patterns within Europe and competition with the US and Asia influence total EU27 electricity demand, but also the internal distribution in EU27 between member states.

On the other hand, electricity demand from data centres does not automatically have to grow unchecked. Several developments could slow or moderate future growth – some driven by economic interested of being more efficient, some by s-curve effects and up-scaling benefits and some by regulation:

- More energy-efficient servers: New generations of processors and hardware can perform far more calculations using the same or less electricity than older equipment.
- Better cooling systems and lower PUE values: Modern data centres are designed to waste less energy on cooling and auxiliary systems. As cooling technology improves, a larger share of electricity goes directly to computing rather than being lost as overhead.
- Stricter sustainability rules and reporting requirements: New regulations, efficiency standards, and environmental requirements may push operators to optimise performance and limit excessive expansion.

Ultimately, the balance between these efficiency gains and the drivers of digital growth will determine whether total data centre electricity consumption accelerates rapidly, stabilises, or grows more moderately towards 2050.

Table 15 presents the assumed average annual growth rates in electricity consumption for data centres in the EU27 from 2024 to 2050 across three scenarios (low, base, and high growth). It is important to emphasise that these growth rates do not represent the growth in computational demand (e.g. workloads, AI tasks, or data volumes). Instead, they represent facility electricity growth under a simplifying assumption of constant (frozen) PUE. This distinction is critical, because the relationship between computational demand and electricity use is highly non-linear and afected by evolving factors including::

- improvements in chip efficiency (performance per watt),
- changes in software efficiency and workload optimisation,
- shifts between training and inference workloads,
- and increasing use of specialised hardware.

-

Fact Box VI. Data centers waste heat in Ireland

Case: Datacenters waste heat

Location: Tallaght, Ireland (approx. 81,022 people)
The Tallaght District Heating Scheme is Ireland's first large-scale district heating system of its kind, operating under Heat Works, a not-for-profit energy utility wholly owned by South Dublin County Council. The system uses waste heat from a nearby Amazon Web Services datacenter as its primary heat source, demonstrating how datacenter waste heat can be harnessed to deliver low-carbon heat in an urban setting. The network supplies low-carbon heat to public and institutional buildings, including the South Dublin County Council headquarters and TU Dublin's Tallaght campus, with ongoing expansion to include affordable housing and other community buildings. Even though district heating represents less than 1% of the heat market currently, according to some studies it has potential to be the most economically viable low carbon heating option for 64% of the Irish population (IrDEA & Gemserv, 2024). District heating has the potential to meet up to 87% of Dublin's heat demand by 2050 completely transforming how the capital heats its buildings (Codema, 2021). There are many benefits for Dublin's citizens, as in any other city. However, Ireland, has the particularity that it can use the heat from the data centers that are nearby.

Key features:

- First of its kind in Ireland: Operational under Heat Works, Ireland's first not-for-profit energy utility.
- Primary heat source: Waste heat from a nearby Amazon datacenter.
- Heat delivered (first year): ~3.770 MWh distributed.
- CO_2 emissions saved (first year): ~1.100 tCO_2.
- Expansion potential: Plans to connect additional residential and community buildings.

As a result, a direct translation from "data demand growth" to electricity demand is not robust over long time horizons. The growth factors in Table 15 should therefore be interpreted as scenario inputs calibrated to observed historical electricity trends and forward-looking expectations, rather than as a bottom-up modelling of digital activity. The table defines annual growth rates across three-time intervals (2024–2030, 2030–2040, and 2040–2050), reflecting different phases of market and technology development:

- Early period (to 2030): acceleration phase. Growth rates increase across all scenarios, particularly in the base (7%) and high (9%) cases, reflecting rapid expansion of AI-related workloads, continued hyperscale deployment, and pipeline/backlog effects.

- Mid period (2030–2040): constraint- and uncertainty-dominated phase. Growth may begin to moderate (4–7%) as build-out becomes more constrained by grid access and siting, efficiency gains begin to offset part of demand growth, and expansion becomes less exponential.
- Late period (2040–2050): maturation phase. Growth declines further (3–5%), reflecting saturation effects in core digital services, stronger efficiency improvements, and increasing regulatory and physical constraints.

Across all scenarios, declining growth rates over time represent a transition from expansion-driven growth to a more mature, constraint- and efficiency-influenced trajectory.

Table 15, Assumed EU27 average annual growth factors for electricity demands assuming a frozen PUE as well as combining these with the base PUE assumptions towards 2050.

Scenario	**Unit**	**2024-2030**	**2030-2040**	**2040-2050**
Low growth (Frozen PUE)	%/year	5,0%	4,0%	3,0%
Base case (Frozen PUE)	%/year	7,0%	5,5%	4,0%
High growth (Frozen PUE)	%/year	9,0%	7,0%	5,0%
Low growth (Base PUE)	%/year	3,1%	3,0%	2,5%
Base case (Base PUE)	%/year	5,0%	4,4%	3,4%
High growth (Base PUE)	%/year	7,1%	6,0%	4,5%

In Figure 43 the data centre PUEs used in this study are visualised towards 2050. All scenarios start from 1,45 in 2024. The base case reaches 1,29 in 2030, 1,16 in 2040 and 1,10 in 2050. The low-PUE scenario assumes stronger efficiency gains, declining to 1,21 in 2030 and 1,08 by 2050, while the high-PUE scenario reflects more moderate progress, remaining at 1,30 in 2030 and 1,17 in 2050. The average levels of PUE going assumed here are based on the possible-state-of-the-art hyperscale data centres we can see now as well as values in the "Energy and AI" IEA report (IEA, 2025). The implied annual improvements are smaller than the fastest historical gains but remain consistent with continued technological development in cooling systems, improved server efficiency and better operational practices. A gradually slowing PUE improvement rate is assumed towards 2050, rather than either rapid step changes or complete stagnation. The PUEs assumed in the different years are EU27 averages across the two dimensions: the type of data centre and the geographical location. Thus, the PUEs do not represent a lower threshold for the PUE. Having said this, exactly district heating can extend the efficiency frontier beyond what is captured in PUE measure alone.

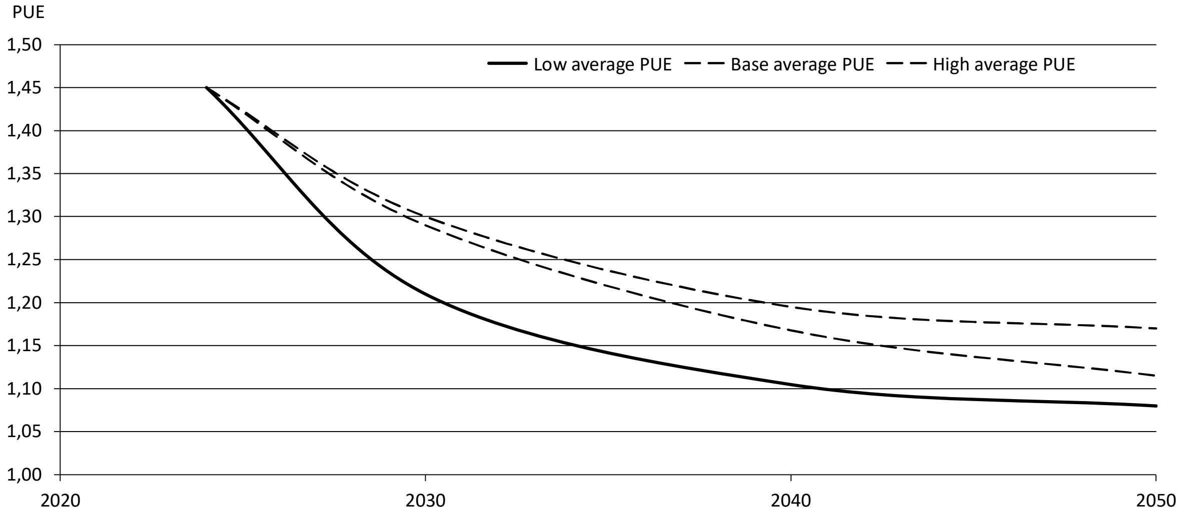


Figure 43, The average PUEs used in this study for EU27 for the low growth, base case and high growth data centre scenarios.

Combining the demand growth rates (Table 15) with the PUE trajectories (Figure 43) yields three EU27 electricity-consumption trajectories towards 2050. Under the low-growth trajectory (Base PUE), facility electricity demand reaches approximately 120% of the 2024 level by 2030, 160% by 2040, and 204% by 2050, corresponding to roughly a doubling of demand by mid-century. Under the base-case trajectory (Base PUE), demand increases to around 134% (2030), 206% (2040), and 288% (2050) compared to the 2024 level, corresponding to approximately a tripling by 2050. Under the high-growth trajectory (Base PUE), demand rises to approximately 151% (2030), 268% (2040), and 415% (2050) of the 2024 level, corresponding to roughly more than a quadrupling by 2050. See the three trajectories and the effects of PUE developed in the project in Figure 44.

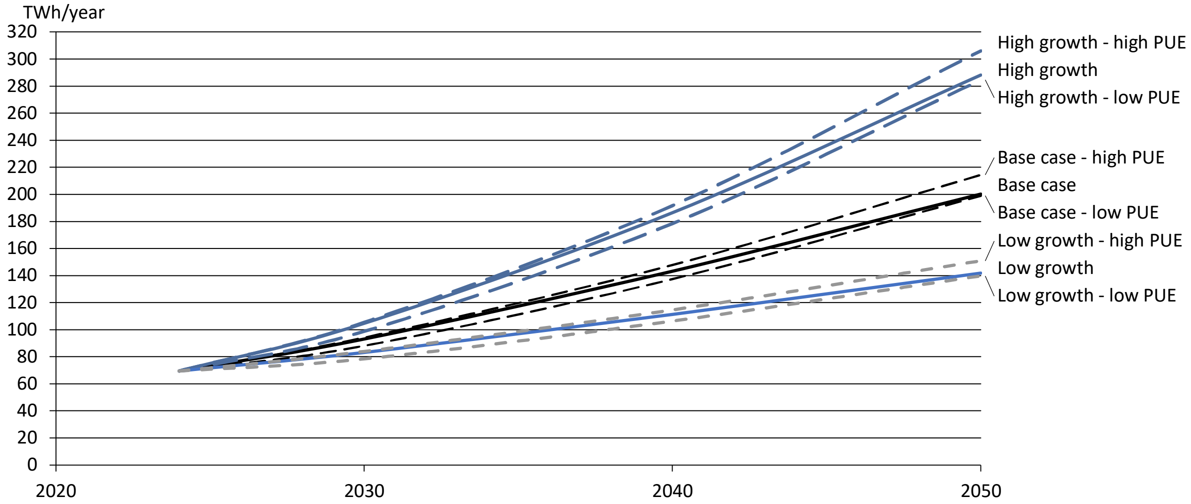


Figure 44, Trajectories towards 2050 considering the three potential electricity growth rates and the three potential average PUE developments. Values are in TWh/year electricity consumption for EU27.

In this framework, the baseline level in 2024 is pivotal, as compounding effects significantly amplify differences over time. Especially beyond 2030, the dominant source of uncertainty is the pace and geographical distribution of workload growth (including AI-driven demand), while improvements in PUE primarily act as a moderating factor rather than the main driver of long-term electricity consumption. The base case outlined in Figure 44 includes the assumption of a consumption of approximately 77 TWh in 2026 and 2030 93 TWh, i.e. 10% and 32% higher than the 70 TWh assumed in EU27 in 2024. The IEA report “Energy and AI” reported a development towards 113 TWh in 2030 in Europe (not EU27) from 68 TWh in 2024. This would require a growth rate of 8-9% pr. year including improved PUE or 10-11% assuming the same PUE as today, which would be unprecedented. In this report we assumed a rather high growth from 2024, at an average annual PUE improvement of 5%, resulting in a demand 77 TWh for 2026 and 93 TWh in 2030 in EU27 including PUE improvements.

Beyond 2030, uncertainty increases. In the base case, electricity consumption reaches around 200 TWh in 2050, which also represents the maximum theoretical technical potential for heat recovery, as nearly all consumed electricity is ultimately converted into heat. In a high-growth scenario, electricity demand increases further to approximately 288 TWh in 2050, while in a low-growth scenario, reflecting potential stagnation combined with strong efficiency improvements, demand reaches around 142 TWh.

Overall, it is evident that the development in total electricity demand for data services is the dominant driver, whereas PUE improvements play a secondary role. However, PUE still has a measurable impact: across scenarios, differences in PUE trajectories can lead to approximately –1% to +6% variation in total electricity consumption by 2050.

The country-level disaggregation of the three trajectories towards 2050 highlights a structurally uneven development of data centre electricity demand across the EU27, with a strong concentration in a limited number of countries. In all scenarios, Germany and France emerge as the dominant contributors, followed by a second level including the Netherlands, Ireland, Italy, Spain, Sweden and Denmark. These countries together account for the majority of total electricity consumption in data centres, reflecting existing clustering of hyperscale infrastructure, favourable market conditions, strong grid connectivity, and access to renewable electricity.

This estimation was conducted with inputs about the reported electricity demands in data centres in each country from 2022 (Kamiya & Bertoldi, 2024). First, each EU27 country’s share of total electricity demand was calculated, forming the primary component of the growth factor. This share was then combined with a growth profile for data centres pr. country going forward derived from the shares of total demand in 2022 (Kamiya & Bertoldi, 2024). Based on their share of existing data centre capacity in 2022, the EU27 countries were categorised into three groups:

1. High growth countries consisting of Belgium, Denmark, Finland, France, Germany, Ireland, The Netherlands and Sweden, representing 77% of current capacities.
2. Medium growth countries including Austria, Italy, Luxembourg, Poland and Spain, responsible for 19% of current capacities.
3. Low growth countries representing the remaining 14 EU27 countries of Bulgaria, Croatia, Cyprus, Czechia, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Portugal, Romania, Slovakia and Slovenia, with the remaining capacity corresponding to 4% approximately.

The shares assume that countries which have already been successful in attracting and hosting data centres are likely to continue to do so, whereas countries with currently limited data centre capacity are expected to remain less competitive. Key determinants of attractiveness include access to electricity based on renewable sources and grid connection and governance structure, amongst others. By default, the growth factor corresponds to each country’s 2022 share of total data centre electricity demand. Here this share is adjusted based on the countries access to expand the renewable electricity production. This adjustment reflects the expectation that data centres will increasingly require access to large amounts of renewable electricity. Consequently, countries with strong prospects for renewable expansion are assumed to attract a larger share of future data centre activity, resulting in a redistribution of growth within the high growth group. Our slightly adjusted shares are based on the access to renewable electricity (wind power and PV). Ireland already has a very high share and also has other sectors to electrify. Also, Germany has many other sectors needing electricity. For Austria, Belgium, Germany, Ireland, Luxembourg and the Netherlands we have assessed a slightly limiting factor due to the access to renewable electricity. For countries with smaller shares today we also assess that the share is small in the future and thus the access to renewable electricity will not have a large effect. For Denmark, Spain, Finland, France, Italy, Poland and Sweden we have assessed that the access to renewable electricity can increase the share of data centres slightly. In Table 16 these slight adjustments are listed.

Table 16, The redistribution of the share of electricity demand due to the availability of renewable electricity in selected countries.

Country	Share of demand 2022	Share of future demand	Difference
Austria	7,1%	6,6%	-0,5%
Belgium	3,7%	3,0%	-0,7%
Denmark	3,3%	6,7%	3,4%
Finland	1,4%	2,2%	0,7%
France	23,3%	24,5%	1,2%
Germany	35,1%	32,0%	-3,2%
Ireland	12,9%	12,2%	-0,7%
Italy	41,1%	41,6%	0,5%
Luxembourg	2,5%	2,0%	-0,5%
Netherlands	13,4%	11,0%	-2,4%
Poland	19,5%	20,7%	1,2%
Spain	27,8%	29,1%	1,2%
Sweden	7,2%	8,4%	1,2%

Using the share of demand in 2022 and the redistributed share of demand, a factor is calculated by multiplying the new national shares of demand by the share of total demand (77% for high growth group, 19% for medium growth group and 4% for low growth group). The factors can be seen from Table 17.

Table 17, The national growth factors used to determine the future national electricity demand for data centres in the three trajectories for electricity consumption in EU27.

Austria	Belgium	Bulgaria	Cyprus	Czechia	Denmark	Estonia	Greece	Spain
0,0125	0,0231	0,0026	0,0009	0,0111	0,0516	0,0026	0,0060	0,0552
Finland	France	Germany	Croatia	Hungary	Ireland	Italy	Lithuania	Luxembourg
0,0167	0,1884	0,2464	0,0026	0,0026	0,0939	0,0791	0,0009	0,0038
Latvia	Malta	Netherlands	Poland	Portugal	Romania	Sweden	Slovakia	Slovenia
0,0009	0,0009	0,0848	0,0394	0,0034	0,0026	0,0651	0,0026	0,0009

These factors are subsequently applied to estimate national electricity demand for data centres by multiplying each country's factor by the projected total electricity consumption for data centres in the EU27. This method is applied to the base-case scenario as well as to the two scenarios representing the lowest and highest projected electricity demands in combination with low and high PUEs respectively (Low Growth–Low PUE and High Growth–High PUE). The resulting demand estimates are summarised in Figure 45.

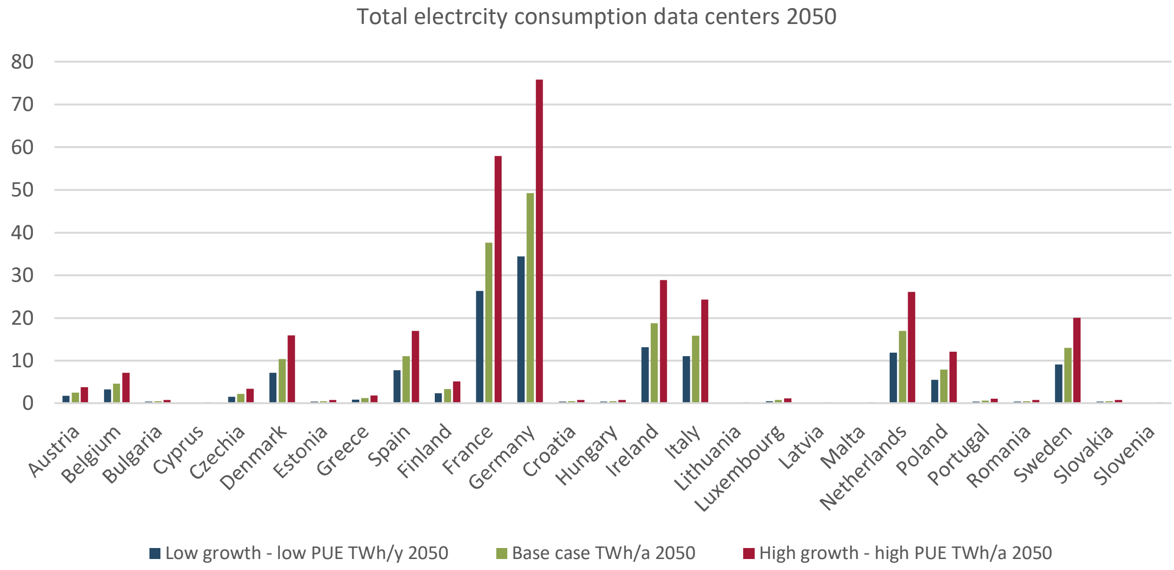


Figure 45, Trajectories towards 2050 considering the three potential electricity growth rates with the base PUE assumption divided into the different countries. Values are in TWh/year electricity consumption all EU27 member states. Note that the shares between the member states may change, depending on the conditions in each member states, hence the level of electricity production in each country is subject to large uncertainties.

A large group of countries remain relatively marginal in absolute terms, even under high-growth assumptions. While relative growth rates may be significant in these countries, the absolute electricity demand remains low, typically below 1-2 TWh by 2050. Overall, the projected data centre landscape remains geographically concentrated rather than evenly distributed, implying that both electricity system impacts and waste heat opportunities will be spatially clustered. Because technical waste heat potential scales directly with electricity consumption, the largest waste heat opportunities occur in the same locations where demand growth is concentrated. This strengthens the case for co-location of data centres with district heating demand, while also highlighting that such co-location is not guaranteed.

To emphasise the increasing uncertainty beyond 2030, it is essential to recognise that both the development of data-centre electricity demand and the utilisation of associated waste heat are subject to a range of structural uncertainties and system constraints:

- At the global level, the overall demand for data centres remains highly uncertain. This is particularly driven by the rapid and still evolving development of AI workloads, cloud computing, and digital services, where both the scale and the efficiency of future computational needs are difficult to project.
- In addition, the geographical distribution of data centres globally is uncertain, as it depends on evolving economic conditions, geopolitical developments, industrial strategies, regulatory frameworks, and considerations related to strategic autonomy.
- Within Europe and the EU27, the spatial distribution of data centres is likewise uncertain. Future deployment will depend on access to reliable and affordable electricity, availability of skilled labour, proximity to digital infrastructure, and national regulatory conditions. In particular, grid connection availability and access to renewable energy are emerging as key constraints. In countries that already host a high concentration of data centres, such as Germany, further expansion may be limited by grid capacity, connection queues, and the need to integrate increasing shares of renewable electricity alongside other electrifying sectors. In practice, such constraints are more likely to redistribute future data-centre capacity geographically rather than reduce overall demand.

At this stage, however, such active policy- or constraint-driven redistribution effects are not explicitly modelled in the present analysis. The allocation of data centre growth across EU Member States should therefore be interpreted as indicative rather than predictive.

The potential trajectories for wate heat from data centres in EU27

In this report, approximately 200 TWh/year of waste heat is assessed as the central technical potential that could be available by 2050, consistent with the base-case electricity demand trajectory and within the interval spanned by the base and high-growth cases (≈200–288 TWh/year electricity consumption in 2050). The lower electricity demand scenario assumed unlikely here due to a rather low growth level going forward.

In this project we have distributed the potential electricity consumption by country and electricity consumption scenario but not assessed precisely how much waste heat can be recovered. In theory 100% of the electricity demand can be used. In practise at most 80-90% in idealised heat recovery ready data centre cases can be recovered. The technical waste heat potential of ~200 TWh/year in 2050 should not be interpreted as directly utilisable heat in district heating systems. In practice, only a fraction of this potential can be realised due to several interacting constraints:

- Spatial mismatch: Many data centres are not co-located with existing or planned district heating networks, and long-distance heat transport is often not economically viable. In this project, this is partially reflected by limiting utilisation to levels compatible with district heating demand; however, location future data centres relative to district heating areas is not guaranteed.
- Temperature compatibility: A large share of waste heat, particularly from air-cooled systems (25 - 35°C), requires upgrading via heat pumps, increasing both costs and electricity demand. Liquid-cooled systems (50 - 60°C) improve usability in low temperature fourth generation district heating but are not yet dominant. This is taken into account by combining these with large-scale heat pumps and thermal storages in the energy system analyses. In reality e.g. an air-cooled system may limit the level of recoverable heat that can be used together with heat pumps. So the up-front data centre design is crucial.
- Temporal mismatch: Data centre waste heat is relatively constant throughout the year, whereas district heating demand is highly seasonal, requiring storage or alternative uses to achieve high utilisation rates. This is taken into account here in our energy system analyses by only utilising to a level of heat demand, where the waste heat can be used over the entire year.

Previous studies, such as in the Reuseheat project (ReUseHeat, 2022), suggest that up to 65% of data centre waste heat could be utilised under favourable conditions. While even higher levels are technically possible, when considering the combined impact of spatial, technical, operational, and institutional constraints outlined above, such utilisation levels represent best-case conditions rather than system-wide outcomes. To ensure a robust and system-consistent assessment, we assume a conservative utilisation assumption of 20% of the total available waste-heat potential in the base case. Applied to the EU27 potential of approximately 200 TWh/year in 2050, this corresponds to around 40 TWh/year of utilisable waste heat, covering roughly 3% of total district heating demand in the recommended scenarios. Other waste heat utilisation levels are assessed in Table 18.

Table 18, Potential waste heat availability depending on utilisation levels for the base case and the high growth electricity consumption scenarios based on the base PUE assumptions. These quantified waste heat potentials in TWh are in some cases 25 - 35 °C and in others 50 - 60°C. We assume however that in most cases the waste heat is in the lower range, requiring an up-grade to use in 3rd or 4th generation district heating networks.

		Technical potential (TWh)	**Examples of heat utilisation levels pr. scenario (%/TWh)**				
2030	Trajectory (base PUE)	100%	90%	65%	50%	40%	20%
	Base case	93	84	61	47	37	19
	High growth	105	94	68	52	42	21
2050	2050						
	Base case	200	180	130	100	80	40
	High growth	288	259	187	144	115	58

By connecting data centres to low-temperature district heating networks by upgrading the recovered heat through large-scale heat pumps, the thermal output can displace fossil, biomass or electric heat production elsewhere in the energy system. Traditional PUE metric describe how efficiently electricity is used within the data centre boundary, but they do not capture how energy is utilised in the wider energy system. In the future we should adjust the PUE or add another criterium to assess data centres on, in order to include a societal perspective. E.g. extended metrics such as a Heat Recovery Readiness level (potential HRR), Energy Reuse Effectiveness (ERE), a System PUE (SPUE) or if taken even further a Heat Recovery Ratio (actual HRR) measure could be implemented, which reflects technical and spatial constraints such as temperature levels, network proximity and temporal matching with district heating demand. From a system perspective, this implies that future efficiency improvements in data centres will increasingly be driven not by reductions in internal losses alone, but by the degree to which waste heat can be integrated into district heating and other sector-coupled energy systems. Further research is required in this regard, but a place to start would be to ensure design standards for data centres to be district heating compliant.

3.3.4 Waste heat from wastewater treatment plants, supermarkets and metros

The quantification in this section is primarily based on the Reuseheat project (ReUseHeat, 2022), which provides a harmonised EU-wide dataset and methodology for estimating urban excess-heat potentials. The project combines geospatial inventories sources wastewater treatment plants (WWT), supermarkets and metro stations with the present Heat Roadmap Europe heat demand areas. The full potentials are identical with the input from the Reuseheat project, while the technical potentials in this project is defined as the amount of the three sources we can utilise up to heat demand areas with district heating covers 63,74% of the market share – which is our upper level analysed for use of district heating in EU27. Our full and technical potentials are before up-grading with large-scale heat pumps if needed. The share is assessed for EU27+UK and for each EU member state.

Waste heat from wastewater treatment plants (WWT)

Wastewater treatment plants are widespread across Europe and represent one of the most ubiquitous and spatially distributed urban heat sources. Approximately 84% of the EU population is connected to sewage systems, with particularly high coverage in urban areas (ReUseHeat, 2022). Wastewater streams contain relatively stable thermal energy originating from households, services and industry.

The technical potential from wastewater treatment is estimated at 183 TWh/year at the EU27 level. This makes wastewater the largest low temperature distributed urban waste heat source. The potential is derived from plant level data including wastewater flow rates, effluent temperatures, and spatial proximity to heat demand. Practical constraints and temperature levels:

- Typical temperature levels: 8–15°C, relatively stable throughout the year
- Upgrading requirement: Heat pumps are required in nearly all cases
- Spatial constraints: Not all WWTs are located close to existing or planned district heating networks
- Hydraulic and operational limits: Extraction must not interfere with treatment processes
- Electricity dependency: Heat recovery depends on electricity availability and price for heat pumps

Despite these constraints, wastewater stands out due to its baseload character, low seasonal variation, and predictable operation. In the Heat Roadmap Europe recommended supply scenario, wastewater heat plays a structural baseload role in low-temperature district heating systems, particularly in urban areas. While the full technical potential is not fully utilisable, wastewater contributes a significant at 99 TWh in EU27.

Waste heat from supermarkets and food retail

Supermarkets and other food retail facilities generate excess heat as a by-product of refrigeration systems. Cooling demand is continuous and driven by food preservation requirements, making these facilities consistent heat emitters embedded directly within urban demand centres.

The Reuseheat based assessment indicates a technical potential of ~31 TWh/year across EU27. This is derived from datasets on supermarket floor area, refrigeration capacity, and operating hours. Practical constraints and temperature levels:

- Typical temperature levels: 25–35°C (higher than wastewater, but still requiring upgrading)
- Scale: Small, highly distributed sources, but always in urban areas
- Integration complexity: Requires aggregation across multiple sites
- Ownership fragmentation: Commercial actors with varying incentives
- Operational variability: Dependent on store operation and refrigeration cycles
- Electricity dependency: Heat recovery depends on electricity availability and price for heat pumps

Supermarkets have a key advantage as they spatially match with heat demand, as they are located within dense urban areas. In the recommended scenario 17 TWh/year is used under the “other sources”.

Fact Box VII. Fact Box VII. Waste heat from Hospital in Spain

Case: Urban waste heat recovery from healthcare facilities

Location: Leganés, Spain (approx. 188,687 people)
The Leganés case demonstrates the technical and economic feasibility of recovering low-temperature waste heat in dense urban environments, specifically from healthcare facilities. Implemented under the Reuseheat project, the system captures surplus heat from hospital processes and reuses it for space heating and domestic hot water, reducing reliance on fossil fuels.

Unlike traditional industrial waste-heat applications, this project addresses the specific operational, regulatory, and reliability requirements of healthcare buildings, illustrating that waste-heat recovery can be successfully extended beyond industrial settings. The Leganés demonstration complements other Reuseheat pilots, including waste heat recovery from metro systems in Berlin, data centres in Brunswick, and wastewater treatment plants in Nice, highlighting the broad applicability of urban waste-heat sources.

Key features:

- Net heat recovered: ~1.883 MWh/year
- Reduction in gas consumption: ~36%
- CO_2 emissions avoided: ~350 tCO_2/year

Waste heat from metro and underground systems

Metro systems generate heat through train operation, braking, passenger density, and underground infrastructure. Heat accumulates in tunnels and stations and is typically removed via ventilation systems. estimated full potential is 9 TWh/year for EU27. The potential is concentrated in cities with extensive metro networks.

Practical constraints and temperature levels:

- Temperature levels: Typically 25–35°C, sometimes higher locally
- Spatial limitation: Only relevant in cities with metro infrastructure
- Intermittency: Linked to transport operation patterns
- Integration challenges: Requires capture from ventilation shafts or station systems
- Institutional barriers: Coordination with transport authorities

- Electricity dependency: Heat recovery depends on electricity availability and price for heat pumps

Compared to other sources, metro heat is more niche and location specific but can be highly valuable in dense urban cores. Metro heat plays a supplementary role, particularly in large metropolitan district heating systems. It is most relevant where existing infrastructure and demand coincide, contributing to local heat supply and improving overall system efficiency.

Urban sources in district heating and system integration

Taken together, these three urban excess-heat sources represent a combined technical potential of ~224 TWh/year. While individually smaller than large industrial or power-sector sources, their key strategic value lies in their urban location, stability, and compatibility with low-temperature district heating systems. In Figure 46 the sources are listed pr. country for EU27+United Kingdom.

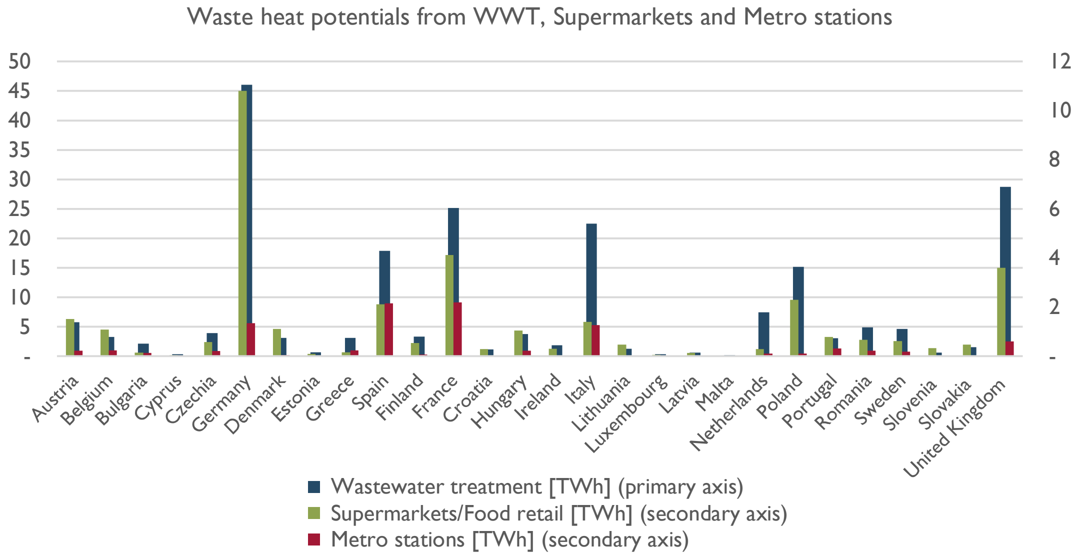


Figure 46, Waste heat potentials pr. country in TWh/year for wastewater treatment plants (WWT), supermarkets and metros. Please note that there are two y-axes as the WWT potentials are substantially larger than the other two sources.

In the present analysis, only a fraction of this technical potential is assumed to be utilized, reflecting real-world constraints related to spatial matching, temperature upgrading, infrastructure investment, and institutional barriers as well as competition with other sources. Nevertheless, these sources contribute to the recommended use of ~124 TWh/year with 55% district heating market share.

From a system perspective, these sources illustrate a broader shift. Future heat systems are not only supplied by large, centralised plants, but increasingly by distributed, low-temperature, and sector-coupled heat sources embedded in the urban areas. Their effective utilisation therefore depends not only on technical potential, but on coordinated planning of district heating expansion, temperature reduction strategies, and integration of large-scale heat pumps and thermal storage.

3.3.5 Waste heat from hydrogen production in electrolysis

Electrolysis is expected to become a key technology in a decarbonised European energy system, primarily driven by demand for hydrogen in synthetic fuels for heavy transport (shipping and aviation), industry, and ammonia for agriculture. As electrolysis capacity expands, it also introduces a new and significant source of excess heat that can potentially be integrated into district heating systems. While this heat source is not fully utilised in the recommended scenario in this analysis, it represents an important additional system resource with long-term strategic relevance. Using the waste heat stream from hydrogen production may also prove to be a key income stream for producers, thereby reducing the cost of hydrogen and synthetic fuels.

Electrolysis converts electricity into hydrogen through processes such as alkaline electrolysis (AEC) and solid oxide electrolysis (SOEC). Polymer electrolyte membrane electrolysis may also contribute but is currently associated with higher costs. In these processes, a share of the input electricity is not converted into chemical energy but instead released as heat. In this study, a technology mix of 70% AEC and 30% SOEC is applied, based on the Danish Energy Agency technology catalogue (DEA, 2024a), with an assumed recoverable heat share of ~12% of electricity input. This is consistent with a broader range of 10 - 15% depending on technology choice and operating conditions (Sorknæs et al., 2024). The assumed average electricity-to-hydrogen conversion efficiency is ~70%. The total hydrogen demand is estimated at 1,3 PWh in 2050 for a decarbonised EU energy system, consistent with assumptions applied in the *sEEnergies* project (Mathiesen, Brian Vad et al., 2022), where hydrogen demand is primarily linked to hard-to-electrify sectors and limited in end-use heating applications. It is assumed that the full potential and the technical potential are identical, as realisation is primarily constrained by plant siting and system integration rather than resource availability. The recoverable heat fraction nevertheless depends on system design, temperature levels, and operational strategies.

Energy system analyses indicate that electrolysis could generate a technical waste heat potential of up to ~164 TWh/year in 2050 at EU27 level. This places electrolysis among some of the largest future waste heat sources, comparable in magnitude to data centres and wastewater treatment. However, this potential is highly dependent on the scale, spatial distribution, and operating patterns of hydrogen production facilities. The scenario for a decarbonised EU27 in 2050 applied in this project assumes a high degree of end-use efficiency, prioritisation of direct electrification in transport and industry, and limited reliance on hydrogen outside sectors where alternatives are not feasible. In addition, hydrogen is not assumed to be used for individual heating or in power generation during periods of low renewable electricity availability, which reduces overall hydrogen demand compared to more hydrogen-intensive scenarios (Abid et al., 2025).

From a technical perspective, AEC systems typically deliver waste heat at temperatures in the range of ~60 - 80°C, which can be directly compatible with low-temperature district heating systems in some cases. SOEC systems can provide higher-temperature heat, improve integration potential and reducing the need for additional upgrading. Nevertheless, several constraints affect real-world utilisation. Access to low-cost electricity is a key determinant for electrolysis siting, which may not coincide with areas of high heat demand. Furthermore, electrolysers are likely to operate flexibly in response to electricity market conditions, introducing temporal mismatches between heat supply and district heating demand. In many cases, integration will require large-scale heat pumps and thermal storage to ensure stable utilisation.

In the recommended Heat Roadmap Europe scenario with a 55% district heating share, approximately 33 TWh/year of electrolysis waste heat is utilised, corresponding to ~20% of the available technical potential. This represents around ~3% of total district heating supply in 2050. The gap between technical potential and utilisation reflects spatial, temporal, and system-integration constraints rather than a lack of resource availability. Consequently, electrolysis should be understood as a strategic supplementary heat source, where utilisation depends on coordinated infrastructure planning between hydrogen production, electricity systems, and district heating networks. Please note that the potential EU27 waste heat level has not been quantified at the member state level in this project, as uncertainties about how this will be distributed it still vast.

3.3.6 Waste heat from power production (CHP) is expected to decrease

Waste heat from CHP plants is expected to decline markedly in future renewables-dominated electricity systems. This is not because thermal capacity is no longer needed, but because CHP and other dispatchable power plants operate far fewer hours. With Energy Efficiency 2.0 - combining end-use savings (Energy Efficiency 1.0) and an energy-system design that maximises low-cost renewable electricity - the role of thermal generation shifts from frequent operation to strategic backup. Today, many CHP units are effectively heat-led: heat demand drives operation, and electricity is produced as a by-product, which can blur electricity price formation. In future systems, operation becomes electricity-led, determined by the availability of lower-cost wind and solar generation; CHP and power plants are primarily reserved for periods with low wind and PV output, including dunkelflaute events. Energy-system modelling indicates utilisation levels of only 5 - 15% in 2050, as plants are dispatched mainly for security of supply (with nuclear continuing to provide baseload where available). While the thermal fleet could in principle provide ~230 - 235 TWh of recoverable heat, only ~30 TWh is assessed as usable once temporal constraints and system integration are considered. As a result, CHP waste heat becomes an increasingly intermittent and constrained resource, reinforcing the need to replace "traditional" CHP-based heat with flexible electrified heat (large heat pumps and electric boilers) combined with thermal storage and other waste/renewable heat sources. This also reflects fuel constraints: baseload CHP operation would require unsustainably large biomass inputs, whereas a more flexible role can be supplied using limited resources such as biogas and residual biomass.

3.3.7 Waste heat potential from nuclear power plants

Nuclear power plants represent a large, but currently underutilised, source of waste heat in the European energy system. Thermodynamically, conventional nuclear plants convert only around one-third of the input energy into electricity, while approximately two-thirds is rejected as low- to medium-temperature heat. This makes nuclear one of the largest concentrated sources of continuous thermal energy available in the system (NEA, 2022).

The technical feasibility of utilising nuclear heat is well established. Around 15% (~67 plants) of the global reactor fleet has been used for non-electric applications such as district heating, desalination, and industrial heat supply, 43 for district heating, 17 for desalination and 7 for industrial purposes (NEA, 2022). Existing examples include dedicated district heating reactors (e.g. AST-500 in former Soviet designs), combined heat and power applications in Russia and China, and heat delivery mostly from conventional light water reactors (LWRs) in Switzerland and elsewhere (IAEA, 2019; World Nuclear Association, 2024).

Most cases of district heating from nuclear power plants are more than 40 years old in Europe and have only provided rather the cases are very small, compared to other sources. One of the earliest examples is Sweden's first nuclear power plant, Ågesta, which operated as a CHP plant from 1964 to 1974 and supplied approximately 65 MWth of heat to a district heating system (Vattenfall, 2025). Another early case is the Greifswald Nuclear Power Plant in former East Germany, which began operation in 1974 and was later expanded in 1983 to deliver waste heat to a district heating network until its decommissioning in 1990 (Wikipedia, 2025). The Beznau Nuclear Power Plant in Switzerland supplies heat for nearby villages (Handl, 1998) and there is another case with heat for about 2.500 apartments in Hungary, in both cases since since the 80'ties (MEKH & MaTáSzSz, 2023). There are other smaller examples of facilities in Bulgaria, Czechia, and Slovakia. These cases demonstrate that nuclear heat can be integrated into district heating systems and reduce thermal discharges to the environment by up to ~30%. There are also investigations of dedicated heat only producing nuclear facilities, however it should be noted that heat these facilities will have to come with other low cost low temperature hat sources. The cases up until now only provides examples of rather small villages and cites with heat from nuclear plants.

From a technical perspective, current reactor designs can typically provide heat below ~300°C, which is suitable for district heating and a range of industrial processes. Future reactor concepts, including high-temperature gas reactors and advanced small modular reactors (SMRs), may expand this range significantly, enabling higher-value industrial heat applications (IAEA, 2017).

This relationship between reactor technologies and feasible heat applications is illustrated in Figure 47. Existing light water reactors (LWR) and heavy water reactors (HWR) are primarily suited for low- to medium-temperature applications, including district heating and desalination. In contrast, emerging reactor concepts offer higher output temperatures, potentially enabling direct integration into industrial processes such as hydrogen production, refining, and high-temperature manufacturing.

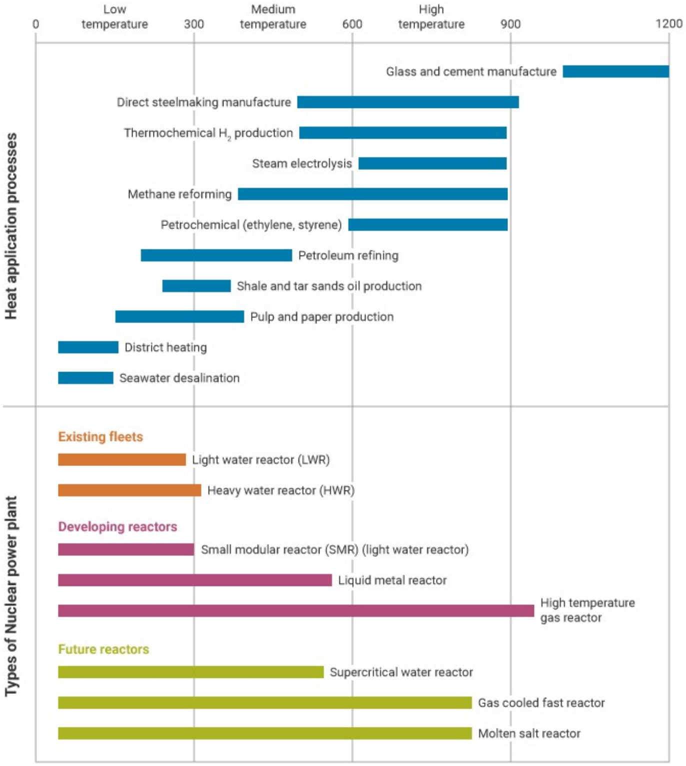


Figure 47. Temperature ranges of heat application processes and types of nuclear power plant (IAEA, 2017).

At EU27 level, the full waste heat potential from nuclear power is estimated at approximately 123 TWh/year by 2050, based on projected electricity production from nuclear reactors and thermal efficiencies. However, only a fraction of this potential is realistically utilisable. In this analysis, a conservative technical potential of ~10% is assumed, corresponding to approximately 12 TWh/year of recoverable heat in 2050. The reason for this is that the majority of the assumed reactors in 2050 are lifetime extensions of the existing plants and only a few already commissioned new plants. The newly commissioned plant in Poland is not included in the analyses or investigated but may also provide heat locally. While more plants may be planned going forward, the heat potential is still limited by the fact current reactors are not connected to district heating and the gap between technical potential and utilisation due to several structural constraints:

- Geographical mismatch: Nuclear plants are often located far from major heat demand centres, while economically viable heat transport is typically limited to ~15–50 km.
- Scale mismatch: Nuclear plants produce very large and continuous heat flows, which often exceed local district heating demand in the closest vicinity, particularly outside peak winter periods.
- Temporal mismatch: Electricity production is typically prioritised and operated baseload, while heat demand is highly seasonal, and may also be covered partly by other waste heat or renewable heat

sources, i.e. the usable heat may be a baseload and exploit the full potential or may be limited to the wintertime i.e. about 40-50% of the potential depending on the context.

- System design priorities: Nuclear plants are optimised for electricity generation, and cogeneration may reduce operational flexibility or economic performance. This can be changed and is not a technical challenge.

The spatial distribution of the full potential is highly concentrated in a few countries. The majority of EU27 nuclear waste heat potential in 2050 is located in a few countries: France (~83 TWh/y), France 83 TWh/y, Czech Republic 12 TWh/y, Finland 9 TWh/y, Romania 7,5 TWh/y, Bulgaria 6 TWh/y and Slovakia 5,5 TWh/y. Together, these account for the 123 TWh/y of potential nuclear waste heat in EU27.

Despite its magnitude, nuclear waste heat is not included in the recommended district heating supply scenario, primarily because it is currently not utilised at scale in EU27 and remains constrained by location and system design. However, it remains a strategic potential that could become relevant under future conditions with stronger co-location of heat demand, deployment of SMRs, or dedicated nuclear cogeneration systems, particularly where system integration conditions improve.

4 Techno-economic modelling assumptions,

This chapter presents the core techno-economic assumptions underpinning the energy system analyses conducted in this study. These assumptions constitute the foundation of the matrix-based modelling framework and are implemented within the advanced energy system analysis tool EnergyPLAN.

The matrix formalises the relationships between the heat demand levels (three), district heating market shares in increments of 5% starting from 5% district heating and 95% individual heating solutions (18 different) and on the other side balancing heat supply and electricity supply. Seven different district heating supply mixes based on bottom-up spatial analyses, are combined with this set-up. All of these analyses are also performed with two performance and cost assumptions for technologies used to provide heat in 3rd and 4th generation district heating. Specifically, the changes are focused on the heat sectors, so the heat supply options are combined with large-scale heat pumps, thermal storages and more, to have a balanced heat supply in the energy systems modelling. In all scenarios the resulting cost changes, primary energy supply changes and system dynamics in the heat supply is generated. The framework integrates both technical and economic dimensions, ensuring that the analysed pathways reflect not only physical feasibility but also cost-effective system configurations. In total, the final scenario set comprises over 15.000 simulations, including intermediate runs used for calibration and sensitivity testing.

Building on the previously defined heat demands and refurbishment costs, waste heat and renewable heat potentials, this chapter introduces the additional inputs required to construct internally consistent scenarios. Four main additional elements are addressed in this chapter:

- the technical structure of the matrix approach, including the relationships between technologies, system design parameters, and operational assumptions across different district heating shares, energy savings levels, and sector coupling configurations.
- outline the development of district heating supply portfolios derived from the spatial analyses of waste heat and renewable heat resources in combination with local heat demand thresholds. These supply options define the feasible integration of diverse heat sources and form a central component of the subsequent energy system simulations.
- the boundary conditions for renewable and climate-neutral energy supply, including the availability, deployment potentials, and system integration of renewable electricity technologies, as well as sustainability-constrained biomass resources. These constraints ensure consistency with physical resource potentials and long-term environmental limits.
- the cost assumptions applied across the entire modelling framework. This includes technology investment costs, operation and maintenance costs, district heating grid expansion costs, electricity system costs, and building refurbishment costs. These cost inputs enable the evaluation of total system costs and the comparison of alternative system configurations, reflecting the transition from fuel-based to capital-intensive energy systems.

Note that all analyses are carried out within the context of a future decarbonised energy system in 2050. The modelling framework therefore focuses on this end-state perspective, where intermediate scenarios are aligned with pathways consistent with achieving this long-term system configuration.

4.1 Technical parameterisation and implementation of the matrix in EnergyPLAN

The matrix framework developed in this study is implemented through a structured and iterative procedure in EnergyPLAN, where techno-economic assumptions, demand levels, and technology interactions are translated into consistent model inputs.

4.1.1 Representation of individual heating systems

The heat supply technologies are dimensioned based on annual heat demands and peak demand conditions derived from EnergyPLAN outputs. Within the matrix framework, total heat demand is first divided into individual heating and district heating components based on the assumed district heating share – and depending on the refurbishment scenario in the concrete analysis. The individual heating segment is then allocated across a set of technologies with predefined roles and constraints to ensure realistic system behaviour.

In the individual heating sector, individual heat pumps is the element varied as the district heating share is altered. The individual heat demands are supplied through a combination of these with shares of electric boilers, biomass boilers, solar thermal systems. Electric boilers are constrained to cover no more than ~5% of whole heat market (including any share of district heating), thereby avoiding over-reliance on direct electric heating. Direct electric heating will still be a part of the future, but it has a negative effect on the need for electric generation capacity in the winter period, and hence limiting this element helps the entire system. Biomass boilers are also limited to about ~5% whole heat market (including any share of district heating). This is due to the biomass resource being scarce and local air pollution. Solar thermal systems are designed to supply approximately 10% of individual heat demand – i.e. in the combination electric heating, biomass boilers and the changing shares of individual heat pumps. This allocation reflects both technical and system-level considerations as well as a recognition that not all citizens would convert to either individual heat pumps or district heating. Heat pumps are always the primary source of heat in induvial solutions, i.e. any configuration of district heating compete with individual heat pumps when changing the shares.

These individual options are coupled with building level storage averaging half a day of the annual heat demand. Their flexibility is inherently limited by building level demand profiles and storage capacities, which distinguishes them from e.g. large-scale heat pumps with thermal storage and other sources in district heating systems.

4.1.2 Representation of 3rd and 4th generation district heating systems and supply mixes

In parallel, the district heating system is modelled as a multi-source system integrating waste heat, renewable heat, and dispatchable technologies. Waste heat sources, such as industrial waste heat, data centres, wastewater treatment, and other sources described in preceding sections, are prioritised in the heat supply hierarchy for ten scenarios where seven are used in the energy system analyses, including one assuming no heat inputs.

The sizing of district heating technologies, on top of the waste heat and renewable heat inputs, follows a set of internally consistent rules. The remaining demand not covered by waste heat is supplied by large-scale heat pumps and biomass boilers. In this structure, heat pumps play a central role in converting electricity into useful heat, while biomass boilers provide additional dispatchable capacity under resource constraints. Biomass boilers are sized up to 100% of peak district heating demand, ensuring sufficient backup, i.e. a robust supply system and peak-load capacity.

Electric boilers are included as a supplementary technology and are dimensioned at approximately 10% of the biomass boiler capacity. This ensures that they remain a marginal but relevant flexibility option, particularly in periods of low electricity prices or excess generation. Changes in this respect do not effect the overall result as the electric boilers are low in CAPEX but high in OPEX. Also – when electricity prices are low – large-scale heat pumps are competing and priorities over large electric boilers thus also limiting he role in this respect.

Large-scale heat pumps constitute a central component of the district heating system. After accounting for waste heat and renewable heat contributions, heat pumps are assumed to cover approximately 60% of the remaining heat demand. This means that the heat pump level changes with changing inputs of our other typically baseload heat sources. Their operating time of around but is 30-40% typically, reflecting their role as flexible units responding to variations in electricity prices and system conditions in combination with other sources and thermal storages.

Thermal storage is included as an integral component of the system and is dimensioned as approximately 1% of total annual district heating production, providing short- to medium-term (depending on the season) flexibility in system operation. The assumed level of thermal storage is robust as the level has been tested in several different systems revealing that substantially larger storage does not improve the system design.

An important dimension of the matrix approach is the explicit differentiation between 3rd and 4th generation district heating systems. These two system configurations differ in terms of temperature levels, efficiencies, costs, and their ability to integrate renewable and low-temperature heat sources.

4th generation district heating systems operate at lower supply temperatures, enabling improved integration of waste heat and higher efficiencies for heat pumps. This is reflected in the assumed coefficient of performance (COP) for large-scale heat pumps, which increases from 4,2 in 3rd generation systems to 5,5 in 4th generation systems. Literature suggests that even higher COP values may be achievable under optimal conditions, indicating additional improvement potential beyond the assumptions used here. However our assumption include and recognised that heat pumps in some cases need use air or seawater as the sources. Thus our COP assumption reflect and average that in many cases can be higher under local conditions.

Similarly, the efficiency of biomass boilers increases from 95% to 105%, reflecting improved system integration and the use of flue gas condensation in low-temperature networks. CHP efficiency also improves modestly, while solar thermal costs are reduced due to better system integration and higher utilisation rates.

At the same time, 4th generation systems exhibit slightly higher investment costs, particularly for thermal storage, but benefit from reduced grid losses due to lower operating temperatures. These differences are systematically incorporated into the matrix, allowing a direct comparison of system performance under different technological configurations.

Overall, the district heating system is constructed to maximise the utilisation of low-cost and low-carbon heat sources, while maintaining operational flexibility through storage and dispatchable technologies.

In the district heating supply analysis contributions of waste heat for electrolyses and the production of synthetic fuels were not included from a temporal perspective. On one hand this eliminates the option to capture the temporal effects on the waste heat supply structure connected to the operation of e.g. electrolysers. On the other hand, this enables transparency in the modelling process regarding the effects of the seven different heat supply mixes. This approach does not eliminate this waste heat source as an option, but ensures the system dynamics are transparent when other, much higher waste and renewable heat streams are included.

4.1.3 Electricity demand, renewable integration, and system coupling

A key step in the implementation is the calibration of renewable electricity capacities. This is performed iteratively by running the model and adjusting installed capacities, primarily onshore wind, until a predefined system balance is achieved.

Across the scenarios analysed the nature of the electricity demands in the heating sectors changes form the induvial heat pumps to the more flexible but also larger large-scale heat pumps. The system is calibrated to operate with a maximum of 15% CEEP, while ensuring a stable electricity supply in all hours. Power plants are designed to cover demands flexibility when wind power, PV and nuclear cannot cover the demands. The installed capacities are found to be 450-500 GW between different scenarios – equivalent to the current installed level in EU27. Though iterations, the share of CHP capacity is found feasible in the scenarios when identifying the average hourly GW demand and defining 25% of that as the CHP capacity, thereby contributing to both heat supply and electricity system flexibility.

For photovoltaic a scaling factor is used to calibrate solar PV capacity relative to the non-flexible electricity demand excluding electricity for heating technologies and electrolytes but including transport electricity consumption. This share of the electricity demand is used to ensure realistic shares of PV. The average hourly demand is multiplied by the scaling factor to identify a suitable capacity. A factor of 3,5 is used while analyses focusing only on northern Europe may benefit from a factor of 2,5. In the modelling this means that large-scale heat pumps, electric boilers in district heating and electrolyses have both access to wind power and PV. Though iterative analyses it was found that such a scaling factor ensures a feasible level of PV, while also considering our CEEP limitations.

4.2 Simulations and assumptions behind the different district heat supply options

In reality there are thousands of combinations of heat supply options in district heating. In this section our included heat supply configurations are described. In some of the district heating supply configurations the focus is to maximise e.g. geothermal, solar thermal or waste heat from WtE. In other scenarios the different heat options are prioritised. This exercise is done for the EU27 level inputs.

Gradually, additional heat sources are incrementally added to the prioritisation in the district heating supply options created. The simulation uses prioritisation strategies for heat supply sources to meet the overall district heat demand in the context of the base load limited assumption for waste heat and the limitations for solar thermal and geothermal as described previously. Each strategy was applied to assess its potential to evaluate heat sources are more suitable and determine how the different waste heat sources can have an impact on the final in the subsequent energy system analyses. Not that it is in the energy system simulation sources such as large-scale heat pumps, thermal storage and CPHs are utilised. In Table 19 the different outputs from GIS defining the district heating heat supply scenarios are listed and in Table 20 the prioritisation of the different sources in those scenarios is listed. The prioritisation assumptions are based on higher value or temperatures of some sources and higher costs of others. As an example, geothermal is prioritised over other sources in some of the included GIS based scenarios. This approach also forms the background to identify the technical potentials for the different sources. In Table 19 the maximum potential considering the maximum district heating supply level is listed for the supply scenarios relevant.

The results reveal that the location of the WtE provides an opportunity to utilise most of the source, thus this waste heat pushes out other sources. This can be attributed to the preexisting infrastructure and the continuous generation of municipal waste suitable for this purpose across urban centres. This is not the case for industrial waste heat where vast amounts are placed outside urban centres while our approach to geolocation low-, and medium-temperature waste heat reveals that this is placed closer to use cases similar to waste heat from WWT and metros e.g. Regarding solar energy, the minimum potential is notably low due to the hierarchy arrangement of the sources. Specifically, the scenario exhibiting the lowest solar potential coincides with that of high industrial waste heat utilization. This inverse relationship between solar and industrial waste heat in certain scenarios are like this because of the demand, of course with other profiles or other demands, more heat sources could be use.

Table 19. Description of the different heat prioritisation scenarios applied in the energy system analyses including maximum potentials up to the maximum investigated market share of the ~64% district heating.

Scenario	Description of waste heat and/or renewable heat source included	Remarks	Max TWh potentials
0.0	No input	Used for calibration and an outset of results in the energy system analysis tool.	0
0.1	No limit to the heat waste sources / compensation pool	An output from GIS to identify the "room" for other waste heat sources not geolocated in the supply scenario.	1.720
0.2	Including the solar potential and free will on the rest of sources	GIS output as the maximum potential for solar thermal and quantification of compensation pool.	-
0.3	Including the solar and WtE potentials and free will on the rest of sources	GIS output as the maximum potential for WtE and quantification of compensation pool.	-
0.4	Including the solar, WtE and geothermal potentials and free will on the rest of sources	GIS output as the maximum potential for solar, WtE, geothermal and quantification of compensation pool.	-
A	Only geothermal heat sources are used	-	250
B	Only solar thermal heat sources are used	-	124
C	Solar thermal, waste heat from WtE and high temperature industry heat sources are used	-	425
D	All heat sources are used	Used in the recommended scenario.	651
E	Solar thermal and waste to energy heat sources are used	-	215

Table 20, Waste heat type of output for the different district heating supply options.

Scenario	Scenario name	Compensation pool	WtE	Solar	Geothermal	Industry and others
0.0	No waste heat					
0.1	Maximum waste heat utilisation	X				
0.2	Solar and maximum utilisation	X		X		
0.3	WtE, solar and maximum utilisation	X	X	X		
0.4	WtE, solar, geo and maximum utilisation	X	X	X	X	
A	Geothermal scenario				X	
B	Solar scenario			X		
C	All high industry		X	X		X
D	All in scenario		X	X	X	X
E	WtE and solar scenario		X	X		
F	All in half of low industry scenario		X	X	X	50% of the source

In the energy system analyses, a structured subset of the defined heat prioritisation scenarios has been applied in order to ensure both comparability across simulations and a clear interpretation of system behaviour under different resource constraints. Specifically, seven scenarios - labelled 0.0, 0.1, A, B, C, D, and E - have been selected as the core input configurations for the EnergyPLAN modelling. This has been chosen to one hand limit the amount of analyses needed to have viable result while on the other hand ensuring a spectrum of heat supply options are included.

The 0.0 scenario serves as a reference case without any contribution from waste heat or renewable heat sources within district heating. It is primarily used for calibration purposes and to establish a baseline against which the impact of integrating different heat sources can be assessed. By excluding all such sources, this scenario provides a clear picture of the system reliance on conventional and flexible technologies such as heat pumps, electric boilers, and biomass.

The remaining scenarios represent progressively more complex and realistic configurations of heat supply, each isolating or combining specific resource categories:

- Scenario A (geothermal only) represents a system where district heating relies exclusively on geothermal energy as the primary renewable heat source. This allows for assessing the role of stable baseload heat supply with relatively high temperatures and limited temporal variability. The maximum technical potential in this configuration is approximately 250 TWh.
- Scenario B (solar thermal only) isolates the contribution of solar district heating. This scenario highlights the implications of a highly seasonal and storage-dependent heat source, with a total potential of around 124 TWh. It is particularly relevant for understanding the interaction between solar thermal production, seasonal storage, and other technologies.
- Scenario C (solar + WtE + high-temperature industry) introduces a combination of key urban and industrial heat sources, including solar thermal, waste-to-energy (WtE), and high-temperature industrial excess heat. This configuration reflects a more integrated system with both renewable and waste heat contributions, reaching a combined potential of approximately 425 TWh.
- Scenario D (all sources included) represents the most comprehensive and system-optimised configuration. All identified waste heat and renewable heat sources are included, including geothermal, solar thermal, industrial excess heat (across temperature levels), WtE, wastewater, and distributed urban sources. This scenario forms the basis of the recommended supply configuration, with a total potential of approximately ~650 TWh, and is used as the central case in the analysis.
- Scenario E (solar + WtE) provides an intermediate configuration focusing on widely available and already mature technologies. By combining solar thermal and waste-to-energy a potential of approximately 215 TWh is possible to utilise.

It should be noted that while additional scenarios (0.1-0.4) were defined in the broader framework - primarily representing unconstrained or GIS-derived maximum potentials - they are not directly used as primary inputs in the energy system simulations. Instead, they serve as analytical boundary conditions to understand the upper limits of resource availability and to quantify the “compensation pool” of non-geolocated or flexible heat sources.

Overall, the selection of scenarios 0.0 and A - E ensures a balanced representation of both constrained and fully integrated heat supply configurations. This enables a systematic evaluation of how different combinations of waste heat and renewable heat sources influence the performance, costs, and flexibility of future district heating systems within a decarbonised EU27 energy system.

4.3 Renewable capacities and critical excess electricity production

A key determinant of the system design is the installed renewable electricity capacity and the associated capacity factors, since these define both total annual production and the temporal structure of generation. For current-year baselines, installed capacities and electricity production were taken from the Energy Charts database (Fraunhofer, 2024), which provides consistent time series and enables the derivation of empirical capacity factors across technologies and countries. These baseline values were cross-checked with IEA country profiles (IEA, 2024a) to ensure that the starting point for national simulations is aligned with other widely used statistical sources. For some technologies and countries where current empirical profiles are not available (e.g., where offshore wind is planned but not yet deployed), proxy profiles were used, such as applying a comparable neighbouring-country offshore profile as an approximation.

To represent 2030 and 2050 conditions, the temporal profiles and capacity factors were adjusted using the JRC ENSPRESO (Ruiz et al., 2019). This is important because a future system cannot be represented simply by scaling today's output: both wind and solar technologies are expected to exhibit performance improvements, and the geographical distribution of deployment shifts over time. ENSPRESO provides a harmonised basis for adjusting future capacity factors and resource availability, enabling a consistent translation from installed capacity to annual production for long-term scenarios.

The long-term renewable capacity "ceiling" applied in the analysis is anchored in the same JRC ENSPRESO potentials. These potentials represent technical feasibility under land and resource constraints rather than an economic optimum. Table 21 therefore serves two purposes: it documents the JRC potential ranges for onshore and offshore wind, provides the JRC solar PV technical potential, and shows the capacities applied in the recommended 2050 scenario. The resulting pattern is not "maximum build-out"; rather, it reflects a system design where renewable capacities are chosen to balance feasibility, integration, and the diminishing system value of additional variable generation at very high penetration levels.

Table 21, EU27 renewable potentials in 2050 from JRC ENSPRESO (Ruiz et al., 2019).

Technology	JRC Low (GW)	JRC Medium (GW)	JRC High (GW)
Offshore wind	37	226	3,149
Onshore wind	2,725	4,512	5,950
Solar PV	–	–	4,517

A central integration concept in the modelling is Critical Excess Electricity Production (CEEP), which captures electricity that cannot be used at the time it is generated and cannot be exported in sufficient volumes, and therefore must be curtailed. In earlier work, a CEEP level around 5-10% has often been treated as a socioeconomic feasible design point. In this study, the target is set higher at ~15%, reflecting the reality that a deeply renewable system is likely to involve non-trivial curtailment unless extreme (and often expensive) flexibility investments are made. The level is based on several iterations of the energy system renewable energy capacities and due to especially solar PV having a rather low price, a higher CEEP level was chosen as a design parameter, to ensure also the lowest possible overall energy system costs. The final choice of ~15% is therefore a pragmatic system-design assumption: it acknowledges that some curtailment is economically rational in a system dominated by variable renewables, as capturing every peak production is not feasible.

Operationally, the model achieves the CEEP target by adjusting onshore wind capacity while holding solar PV and offshore wind fixed across scenario variants. This choice reflects that onshore wind is generally the most scalable technology across the EU27, has broad geographical applicability relative to offshore wind. Also under expected cost reductions, due to the allowed curtailment, represents a flexible lever for matching system-wide curtailment levels. Solar PV cannot be increased uniformly across countries because resource quality and seasonal coincidence differ substantially; offshore wind is not technically available to all countries; and hydro and other dispatchable renewables are constrained by geography. Onshore wind therefore becomes the marginal capacity used to tune the CEEP outcome.

These renewable electricity assumptions should be seen within a broader smart energy systems logic that emphasises flexibility through sector coupling, and here in particularly via heating. The distinction between household-level heat pumps and large-scale heat pumps connected to district heating is important in this regard, as one example of how curtailment can be lowered. Household heat pumps provide limited flexibility because their operation is constrained by short-term heat demand and relatively small thermal storage volumes, and their performance can be reduced during very cold periods when heat needs are highest. By contrast, large-scale heat pumps in district heating systems can be paired with substantial thermal storage and complementary heat sources (including CHP, waste heat, and peak load fuel boilers), enabling load shifting over longer time horizons. This improves the system's ability to absorb variable renewable electricity and reduce the "criticality" of excess generation. The implication is that the renewable capacity levels and the acceptable CEEP level are not purely electricity-sector choices; they are co-determined by heating infrastructure, storage, and the availability of sector-coupled demand such as electrolysis and electric mobility. For the energy system design it has the effect that a better handling of curtailment can mean an allowed higher capacity of renewable electricity, and this enable also a reduction in biomass consumption and providing more low-cost electricity also for other sectors than heating.

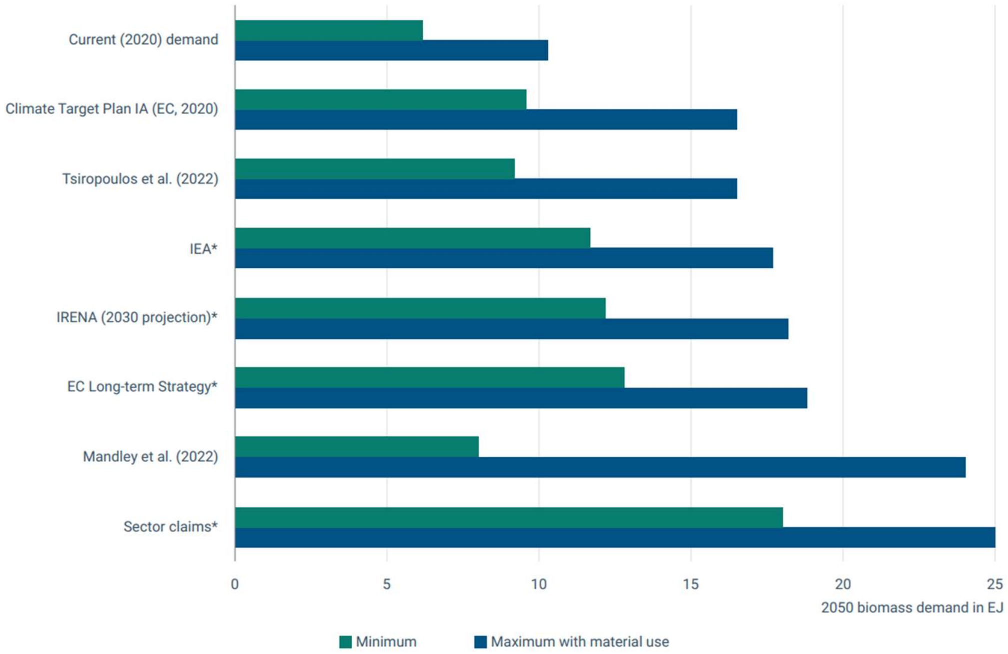
4.4 Assumed development of nuclear power

The nuclear energy is an important asset in the current energy mix, especially in countries like France which has the largest nuclear fleet in Europe with ~57 plants. The main assumption here for nuclear power plants is that those plants we have today, as well as those already contracted, have a lifetime of 60 years i.e. and assumed lifetime extension (Crownhart, 2024). The country-by-country assumptions are outline in the associated "Data and country profiles" report. For the current fleet and data the sources are publicly available from the World Nuclear Association's (WNA, 2024) and the International Atomic Energy Agency's databases (IAEA, 2024).

In the analysed 2050 energy system, nuclear power plays a supporting role in the electricity supply, complementing a highly renewable-based system dominated by wind and solar PV. The total nuclear electricity generation is assumed to be ~130 TWh/year based on an installed capacity of around 21 GW. This is a modest level compared to renewable generation, where onshore wind, offshore wind, and solar PV together account for several PWh of annual electricity production. The overall system is therefore characterised by deep electrification, with renewable energy forming the main expansion of capacities over the next 25-30 years. It should be noted that the results are not determined by this and should there be a higher build out of nuclear power, that would not change the overall energy efficient concept of sectors integration, us of low-temperature district heating and an advantage of expanding district heating.

4.5 Sustainable biomass assessment

Today bio-energy represents the largest share of renewable sources used in district heating, and has been a fuel of choice to decouple the heat market from fossil fuels in some countries e.g. Sweden, Denmark, Latvia, Lithuania, Latvia, France. While the use of biomass at this level does potentially not have a large negative climate effect dues to land-use change, a full replacement of the use of fossil fuel in existing district heating most likely would. In this project the aim is also to investigate the expand the level of district heating. In that light it is important to ensure that we limit the biomass consumption to a sustainable level. This is done in the overall energy system design using a smart energy systems approach; and in district heating, by using waste heat and renewable heat streams as well as large capacities of heat pumps, i.e. flexibility electrifying by combining these sources with thermal storages. Both for the electricity sector and the overall energy system, bioenergy may have a role to play in peak demands, in high temperature industry and in limited hours in the electricity supply. The project foresees a changing role for bioenergy in line with the potential for sustainable bioenergy sources and within the context of the broader decarbonisation of all economic sectors.



Notes: Current (2020) demand is shown for reference (multiple sources).

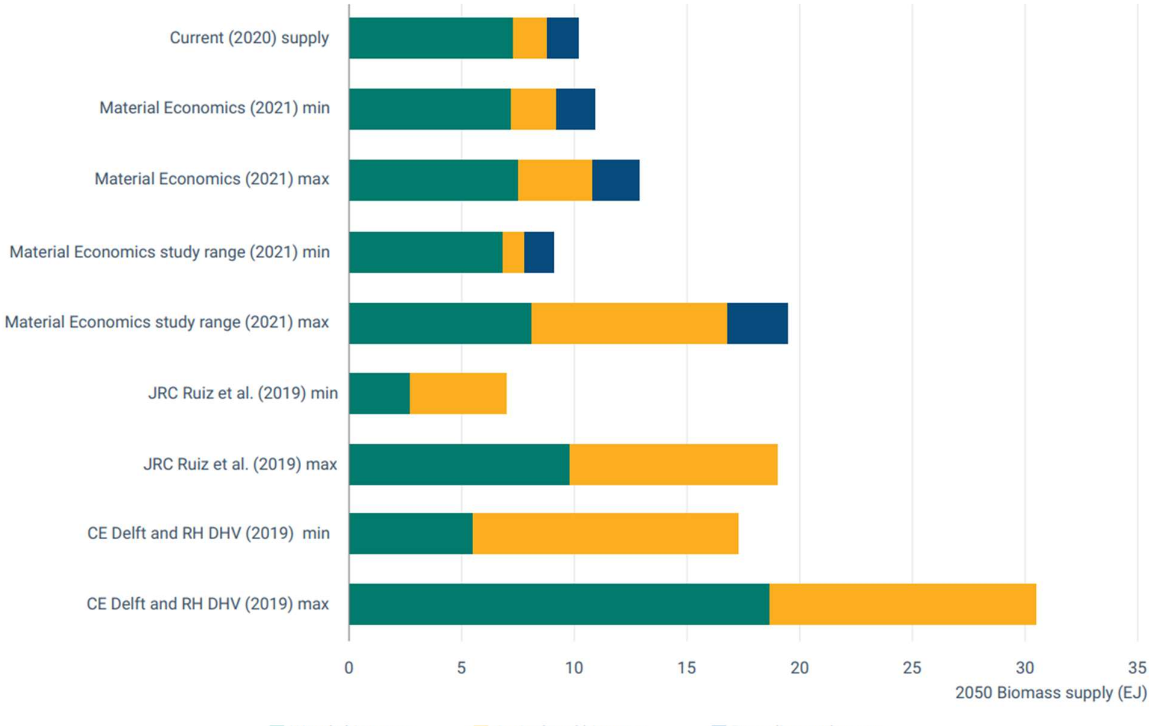
(*) source interpreted by Material Economics (2021). Minimum indicates minimum projected biomass use demand in the studies; maximum indicates maximum projected biomass use demand in the studies.

Source: EEA based on multiple sources.

*Figure 48. Projections of biomass demand for bioenergy and bio-based material use in *Europe 2050.*
(European Environment Agency, 2023).

The aim is to have a lower biomass consumption than the sustainable levels of biomass from residual sources, which requires an understanding of the levels per country and EU levels. As the use in the energy sector is only part of what residual or sustainable biomass may be needed for, the use should be significantly than the threshold due to the potential need for biomass for materials, chemicals and other services that are currently based on petrochemical input. In Figure 48, the European Environmental Agency has gathered different studies for Europe with regards to the demands for biomass, both for long term 2050 and their year 2000 value (European Environment Agency, 2023). The different studies show a minimum and a maximum level potential. The current minimum and maximum demand corresponding to without biomass for material use is around 6.000 – 7.000 PJ (~1.700 - 1.900 TWh) while the future towards 2050 show a range of around 9.000 to 16.000 PJ as a minimum and 11.000 – 25.000 PJ as a maximum (~2.500 – 7.000 TWh). Clearly, the biomass demands range widely across different studies and within studies. However, an increase in biomass demand to 1,5-2 times current level towards 2050 may be the case looking at different demand scenarios (European Environment Agency, 2023).

For biomass land-use climate effect are especially important to consider. For context, in 2018, there were 7,4 million hectares of land used for biofuels production (European Environment Agency, 2023), which is roughly the land area of Ireland and with the projected increase in demand for biomass in 2050 would also negatively impact the land use and other associated factors. This underlines that increasing demand must be considered together with land constraints and other sustainability criteria. In this study no biofuels are used for this reason in the scenarios. Figure 49 compiles projections for biomass supply to 2050 and breaks them down by woody, agricultural, and recycling & waste streams. This provides the counterpart to Figure 48 to provide a better understanding of demand – supply and source dynamics.



Notes: Current supply is shown for reference (multiple sources).
Minimum indicates minimum projected biomass supply; maximum indicates maximum projected biomass supply.

Source: EEA based on multiple sources.

Figure 49. Projections of biomass supply for Europe in 2050. *(European Environment Agency, 2023)*

There are discrepancies between what different entities consider the full potential to be, which range from approximately ~6.000 PJ at the low end to >30.000 PJ at the very high end. Most central results lie in the ~10.000 –20.000 EJ band. The graph also shows that higher totals are usually driven by larger agricultural contributions, whereas more conservative cases rely mainly on woody residues plus a modest waste share. Understood together with Figure 48, this suggests that while demand could rise to 2050, sustainably available supply is likely constrained to below 15.000 PJ unless optimistic assumptions are made. Even though, there is no agreed definition of what constitutes "sustainable biomass", sustainability criteria are key drivers when assessing the final amount of biomass available for energy (Ruiz et al., 2019). Another study reviews across different investigations find lows at ~8.000 PJ, medium levels at 12.000 –15.000 PJ and high levels of up to 21.000 PJ (Soler, 2022). From the different studies there is one clear conclusion: the published estimates of biomass supply available for energy or materials vary widely. This huge range can be the consequence of different approaches and considerations to some key factors, such as the land usage for the biomass production mentioned above and then the application of sustainability criteria, which in some there is none, due to the lack of a consistent definition. A global study and review of studies indicate ~30–50 EJ biomass globally and a European of around 5.000–7.000 PJ/year by 2050 but also includes reviewed studies indicating >100 EJ globally (ETC, 2021). This is typically when assumptions are less stringent on allowing dedicated energy crops, looser land-use constraints, and a broader sustainability interpretation.

For Europe, the sustainable biomass limit with the application of stringent sustainability criteria is set at around 5.000 – 7.000 PJ for 2050 (1.400 – 2.000 TWh). With an EU27 population of ~447 million in 2050 (Eurostat, 2024), this implies roughly 22 GJ/capita for the central 10 EJ case. To frame uncertainty, we also use the low/high restriction cases discussed above: ~15 GJ/capita (≈ 6,7 EJ) and ~40 GJ/capita (≈ 17,9 EJ). This corresponds to about 1.860 TWh, 2.780 TWh, and 4.980 TWh of primary energy, respectively. Table 22 summarises the country potentials and reports the per-capita availability for 2030 and 2050. Biomass availability comes from the ENSPRESO dataset at NUTS-2 level for all EU and neighbouring countries; the dataset applies GIS-based land-restriction scenarios that account for land availability, agricultural development, and re/deforestation (Ruiz et al., 2019).

Table 22. Sustainable biomass per capita for 2030 and 2050 based on (Eurostat, 2024; Ruiz et al., 2019).

Sustainable biomass per capita		**2030**			**2050**		
	Population 2030 (Eurostat)	LOW (GJ)	MEDIUM (GJ)	HIGH (GJ)	LOW (GJ)	MEDIUM (GJ)	HIGH (GJ)
EU27	452.700.101	15	22	38	15	23	40
EU27+UK	521.907.298	14	23	40	13	21	36
Austria	9.214.690	22	31	58	19	31	57
Belgium	12.009.045	9	14	23	8	13	22
Bulgaria	6.574.153	19	30	56	24	36	67
Cyrpus	957.744	4	6	8	4	6	9
Czech Republic	10.851.301	21	29	48	18	29	48
Germany	85.284.256	10	15	26	10	16	27
Denmark	6.059.699	11	17	29	11	18	31
Estonia	1.358.611	54	75	139	48	73	131
Spain	49.266.930	13	18	31	13	19	34
Finland	5.631.487	52	75	150	48	83	165
France	69.386.211	17	24	39	15	23	39
Greece	10.032.545	7	10	18	8	12	23
Croatia	3.693.206	20	22	34	20	25	39
Hungary	9.526.758	27	37	57	28	41	66
Ireland	5.416.927	7	13	23	6	12	23
Italy	58.773.783	8	12	20	8	12	22
Lithuania	2.741.927	52	71	108	57	78	121
Luxembourg	740.420	6	7	14	4	6	11
Latvia	1.756.334	61	90	175	63	111	219
Malta	604.727	0	0	0	0	0	0
Netherlands	18.341.701	4	6	9	4	6	9
Poland	37.420.524	16	24	41	19	29	49
Portugal	10.249.138	9	15	31	9	18	37
Romania	18.218.553	29	41	69	28	45	79
Sweden	11.020.442	45	65	130	34	60	121
Slovenia	2.118.806	26	37	77	20	36	75
Slovakia	5.450.183	18	25	44	14	23	43
UK	69.207.197	6	8	12	4	7	11

4.6 Main cost assumptions

This section provides an overview of the cost assumptions applied in the energy system modelling framework. The total system cost is determined by multiple interacting components, including technology investments, operation and maintenance costs, electricity and district heating grid infrastructure, and associated system integration costs. These cost elements are consistently implemented across all scenarios to ensure comparability and robustness of results. Building energy efficiency improvements constitute a major cost component in the overall system and is investigated in chapter 2. Across the EU27, cumulative additional refurbishment investments required up to 2050 amount to approximately 1,4 trillion € under the Moderate savings scenario, 2,0 trillion € under the Ambitious savings scenario, and 2,6 trillion € under the Very High savings scenario.

4.6.1 Technology cost assumptions

A comprehensive technology cost database has been developed to support the modelling. This database includes both current and projected cost data and is based on established principles of technological learning and cost reductions driven by scale, innovation, and industrialisation. The projections account for investment costs, fixed operation and maintenance (O&M), and technical lifetimes, reflecting detailed cost breakdowns in each technology needed on the demand and supply side.

The cost data have been updated from the *sEEnergies* project using the April 2024 Danish Energy Agency technology catalogue (DEA, 2024b) and supplemented with assumptions from IDA's Climate Response 2045 (Lund, Henrik et al., 2021). To ensure consistency across the EU27 modelling framework, identical technology cost assumptions are applied across all countries. While local variations in labour or financing costs exist, these are not differentiated in the model in order to isolate system design effects rather than regional price differences. A uniform real discount rate of 3% is applied across all technologies. The DEA catalogue provides cost data across multiple categories; in this analysis, the focus is on electricity generation, district heating technologies, storage, and sector coupling technologies. Key cost parameters include nominal investment costs (€/unit), fixed O&M (% of investment), and technical lifetimes. Table 23 summarises some of the key selected cost assumptions applied in the model for technologies in 2050.

Table 23. Some of the updated costs from technology catalogue in 2050 (DEA, 2024b; Lund, Henrik et al., 2021).

Technology [Unit]	Cost [M€/unit]	Lifetime [Years]	O&M [%]
Large CHP [MW]	0,85	25	3,5
Heat storage CHP [GWh]	3,9	40	0,29
Waste CHP [TWh/year]	275,5	25	2,3
District heating HP [MW]	2,56	25	0,3
Boilers [MW]	0,88	25	3,55
Electric boilers [MW]	0,13	25	1,1
Large PP [MW]	0,85	25	3,5
Onshore [MW]	1,03	30	1,67
Offshore [MW]	1,9	30	2,51
PV [MW]	0,6	40	1,5
Hydro [MW]	3,3	50	2
Hydro storage [GWh]	7,5	50	1,5
Geothermal [TWh/year]	175	30	4,06
Solar thermal [TWh/year]	382	30	0
Heat storage solar [GWh]	3,17	25	0,59
Industrial Waste heat [TWh/year]	59	30	1
Biogas plant [TWh/year]	234,1	20	13,4
Electrolyser (70% AEC & 30% SOEC) [MW]	0,36	25	6,4

4.6.2 District heating grid costs

In addition to generation technologies, the expansion and refurbishment of district heating infrastructure represent a major cost component in the system. Grid costs are modelled using a simplified approach based on linear cost functions derived from the sEEnergies methodology. District heating pipe costs are represented by two parameters: 1) a fixed component (c_1) representing base installation costs per metre and 2) a variable component (c_2) scaling with pipe diameter (€/m^2). This formulation captures the relationship between pipe dimensioning and cost, where larger transmission pipes increase costs proportionally. The same cost structure is applied across all countries to ensure consistency with the system-level modelling approach nut may in practice very. These grid costs are a key determinant of district heating feasibility and are directly linked to heat density and spatial distribution of demand. High-density urban areas typically exhibit lower specific grid costs per MWh, while lower-density areas increase costs significantly.

The EU-level grid-cost curve is derived by ranking potential district heating areas and then estimating investment costs as the district heating market share increases in 5% intervals. Each 5% step represents a progressive move from dense, highly heat-dense zones towards lower-density and more spatially dispersed zones. Figure 50 shows the non-accumulated costs, i.e. the incremental grid investment required to increase the market share from one step to the next. The resulting costs required to move from one 5% district heating market share step to the next does not increase monotonically from the outset. The first 5% step is dominated by large, dense urban systems with high heat demands, including city cores and complex retrofit environments where network construction may be costly (e.g. congested underground space, utilities conflicts, traffic management, and higher installation complexity). These areas are prioritised early because they represent the largest concentration of heat demands and also constitutes challenges for decarbonation, should apartment blocks e.g. heat individual heat pumps. The next step, 5% - 10%, includes a larger share of high-density extensions and secondary urban areas where construction conditions may be less complex (more space, more greenfield or semi-greenfield opportunity, fewer inner-city constraints), so the incremental investment can fall - even though the model is still, overall, prioritising heat-dense areas. In other words, the early build-out is driven by system importance and heat density, not by a simplistic "cheapest first" logic.

From this point onwards, the non-accumulated investments generally rise with market share. The step-wise results indicate gradually increasing grid investments as the expansion progresses into areas with lower heat density and less favourable network economics. In the curve, a relatively flat development is visible up to 35%, followed by a clearer increase, and then a gradual rise with more pronounced step increases at around 55% and beyond. These inflection points are consistent with a transition from core urban areas and dense extensions towards more heterogeneous and increasingly marginal district heating areas, where higher pipe lengths per delivered MWh and more dispersed demand increase the specific grid investment.

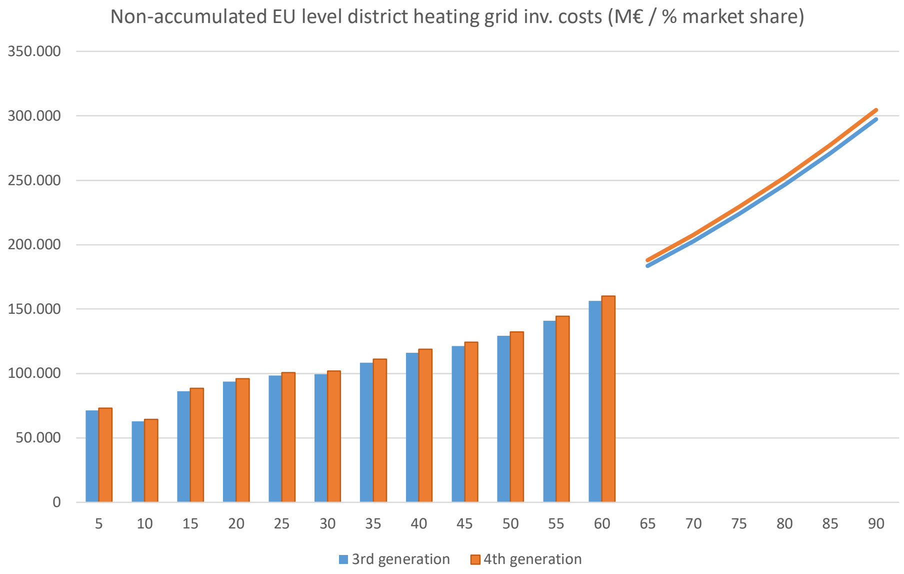


Figure 50, Non-accumulated EU27 level district heating grid costs in 5% intervals for both 3rd and 4th generation district heating. Beyond a ~64% market share the cost uncertainties are vast. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

Finally, it is worth noting that values beyond ~64% are shown as a smooth extension and should be interpreted as indicative rather than as directly comparable to the lower market-share steps. Close to the technical upper bound, the cost ceiling, threshold effects, and the increasing heterogeneity of the remaining high-cost areas imply that results become more sensitive to modelling choices (thresholds, smoothing, and the representation of dispersed demand pockets). The divergence between 3rd and 4th generation costs remains systematic but modest, reflecting the underlying cost-difference assumptions applied in the grid-cost model.

The accumulated cost illustrated in Figure 51 shows a non-linear cost curve: early expansion delivers substantial market-share gains for relatively modest cumulative investments, but the slope steepens as the market share rises. This shape is consistent with the stepwise behaviour seen in the non-accumulated curve. In the early stages, district heating is deployed first in large and dense urban areas that dominate total heat demand. Even where construction conditions can be complex and expensive in absolute €/m terms (city cores, congested underground space, utility conflicts), these areas still deliver large heat volumes per kilometre of network, so the cumulative cost per percentage-point of market share remains comparatively favourable.

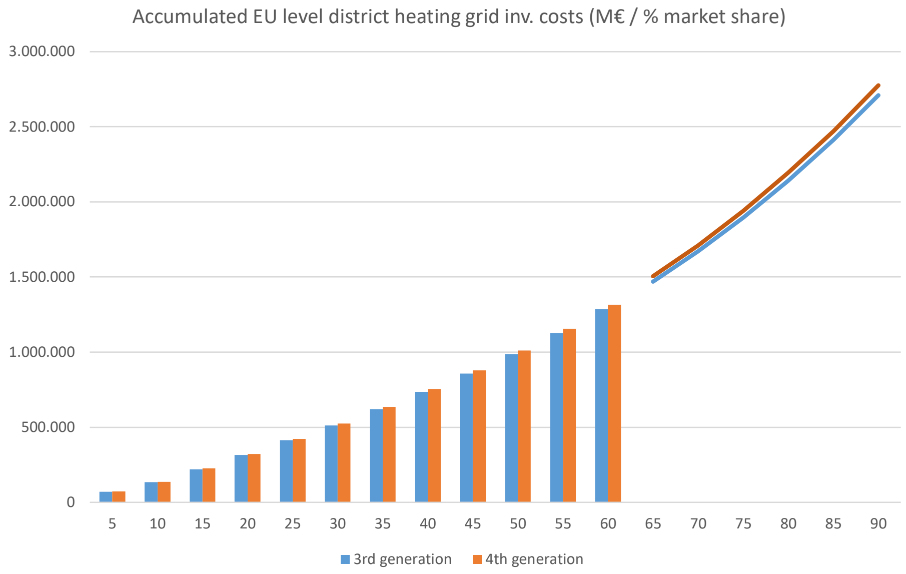


Figure 51, Accumulated EU27 level district heating grid costs in 5% intervals for both 3rd and 4th generation district heating. Beyond a ~64% market share the cost uncertainties are vast. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

As the district heating share increases, expansion progressively reaches lower-density and more spatially dispersed areas where additional network length is required per unit of delivered heat, and where a larger fraction of the remaining heat demand is located in heterogeneous heat demand areas that do not connect as efficiently into continuous network corridors.

Crucially, these discrete district heating market share levels (evaluated in 5% steps) are not only a way of presenting grid cost curves - they are used directly as inputs to the techno-economic modelling. In the matrix approach, each district heating market-share step defines a corresponding heat-demand split between district heating and individual heating, together with the associated grid investments and losses for 3rd and 4th generation district heating grids. These stepwise inputs are used in EnergyPLAN simulations, ensuring that changes in market shares are consistently reflected in both (i) infrastructure costs and (ii) system operation and technology sizing (e.g. large-scale heat pumps, boilers, CHP, storage, and the utilisation of renewable and waste heat sources).

5 The recommended long term heat market design for EU27

This chapter consolidates the main results that underpin a recommended long-term design of the EU27 heat market towards 2050. The purpose is not to describe every simulation output, but to make the decision logic transparent - i.e. which combinations of heat-demand reduction, district heating expansion, grid technology, and heat-supply configuration provide robust outcomes across cost and sustainability criteria.

The analysis varies (i) three heat-saving levels in buildings, (ii) the district heating market share, (iii) district heating generations, (iv) alternative district heating supply configurations that constrain which waste and renewable heat sources can be utilised, and (v) the overall resulting system design, costs structure and subsequent 2040 and 2030 intermediate levels, including the needed build out with new district heating systems. Each combination is evaluated using total annual energy-system costs, heating-sector costs (including the split between individual and collective solutions) and biomass use.

5.1 Primary energy supply and biomass demand across heat supply scenarios

This subsection evaluates how primary energy supply (PES) and biomass demand respond to different heat-supply portfolios and heat-saving levels within the EU27 2050 energy-system simulations. The purpose is not to compare individual technologies in isolation, but to assess the overall system effects of varying these parameters under otherwise consistent boundary conditions.

In Figure 52 the effects of the system designs on PES are illustrated for the 4th generation district heating system analyses in EU27 for 2050. Across the scenario space, two structural patterns dominate. First, PES declines as heat demand savings increase, because lower final heat demand reduces the required conversion and peak capacity buffers across the coupled energy system. This effect is visible with the PES decrease when moving from moderate to ambitious and very high savings. Second, the spread between heat supply portfolios is smaller than the spread between saving levels, indicating that demand side efficiency remains the first order driver of overall resource use even in highly sector-coupled systems.

Within each heat saving level, PES is also affected by how much of the district heating market share demand can be met by direct renewable heat and recoverable waste heat versus technologies that require additional upstream energy conversion. Portfolios with broader access to waste heat and renewable heat generally yield lower PES, because they reduce the need for additional electricity generation (and associated conversion losses) to drive heat production, and they reduce the reliance on fuel based peak supply in heating and balancing. Conversely, portfolios that restrict the available heat sources tend to show higher PES, since the system compensates by leaning more heavily on electricity-driven heat supply and dispatchable capacity, which increases total primary energy requirements at system level.

From the PES results the highest saving level possible have the highest effects and more district in each savings level reduces the PES. Across the district heating portfolios, three qualitative observations are relevant:

- “Maximum waste heat” produces the largest PES reduction among the supply mixes. However, this case represents an upper-bound assumption, since it effectively requires that waste and renewable heat are available in all district heating areas to a degree that is unlikely to be achievable in practice.
- The “no waste heat” and “solar thermal” district heating scenarios experience similar trends: 1) large-scale heat pumps in district heating areas are more efficient and flexible than individual heat pumps, revealed in a declining trend and 2) These appear to have a lower PES than the other scenarios with different mixes of waste heat and renewable heat, however a rather high COP for the large-scale heat pumps is required to achieve such a trend. The would in that can in reality induce a higher PES than illustrated.

- The other heat supply mix scenarios experience first little or no reductions in PES and then a down turned trend. There are indications that the lower the heat savings levels the higher the effect of combining district heating and waste heat and renewable heat is.

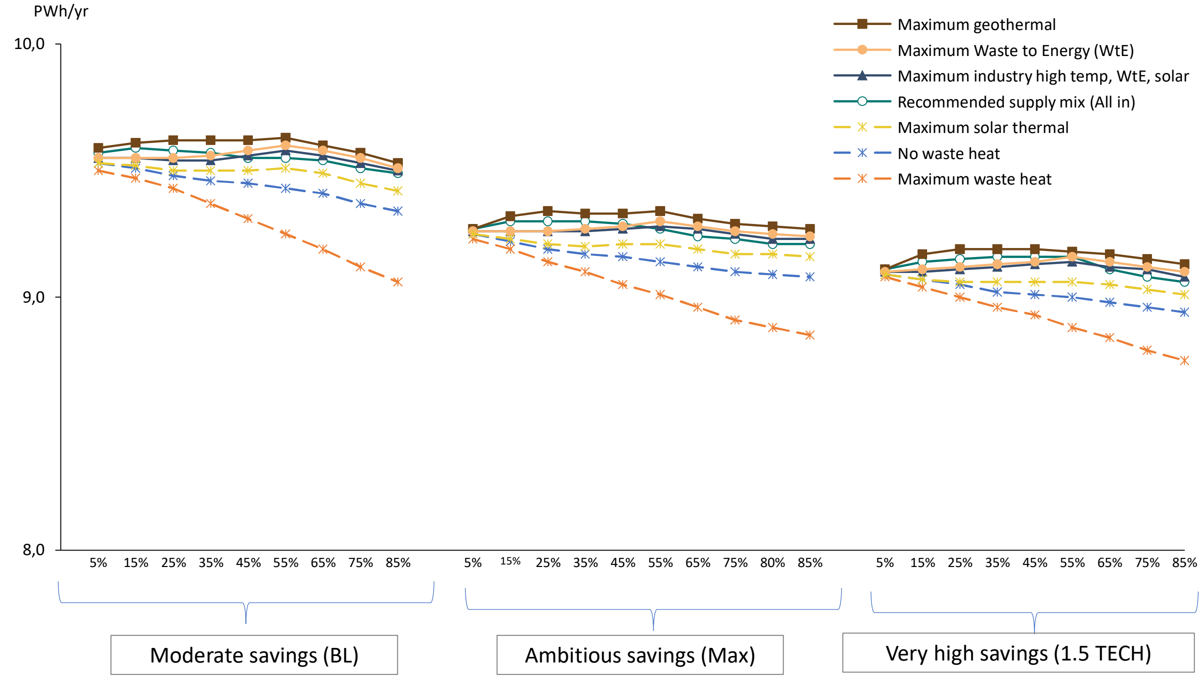


Figure 52, Primary energy supply (PES) across heat supply scenarios and heat saving levels in the EU27 2050 full energy system with 4th generation district heating systems. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

When considering the energy system design, biomass (or in general the fuel consumption) becomes an important metric in combination with the PES. Biomass demand shows a clearer effect of the system changes sensitivity than PES, because biomass plays a distinct system role in the fully decarbonised configurations, as a dispatchable balancing sources in heating and electricity supply. Please not that biomass include biogas here.

In Figure 53 the effects of the system designs on the biomass input needs are illustrated for the 4th generation district heating system analyses in EU27 for 2050. Across the scenario set, the total biomass demand remains well below the conservative EU level sustainability boundary discussed previously in the report. In the analysed range, total biomass use lies around 1.050 - 1.350 TWh across scenarios, compared to a stringent sustainable availability range of roughly 1.400 – 2.000 TWh by 2050. This is a necessary credibility condition for the scenario set, because heavy reliance on biomass would otherwise shift decarbonisation pressures into land-use change, biodiversity impacts, and competition with food and bio-based materials. Again, the maximum waste heat portfolio is unlikely to be possible. And the no waste heat and maximum solar thermal most like overestimate the COP in large-scale heat pumps, meaning that the biomass consumption in these cases would be higher than illustrated.

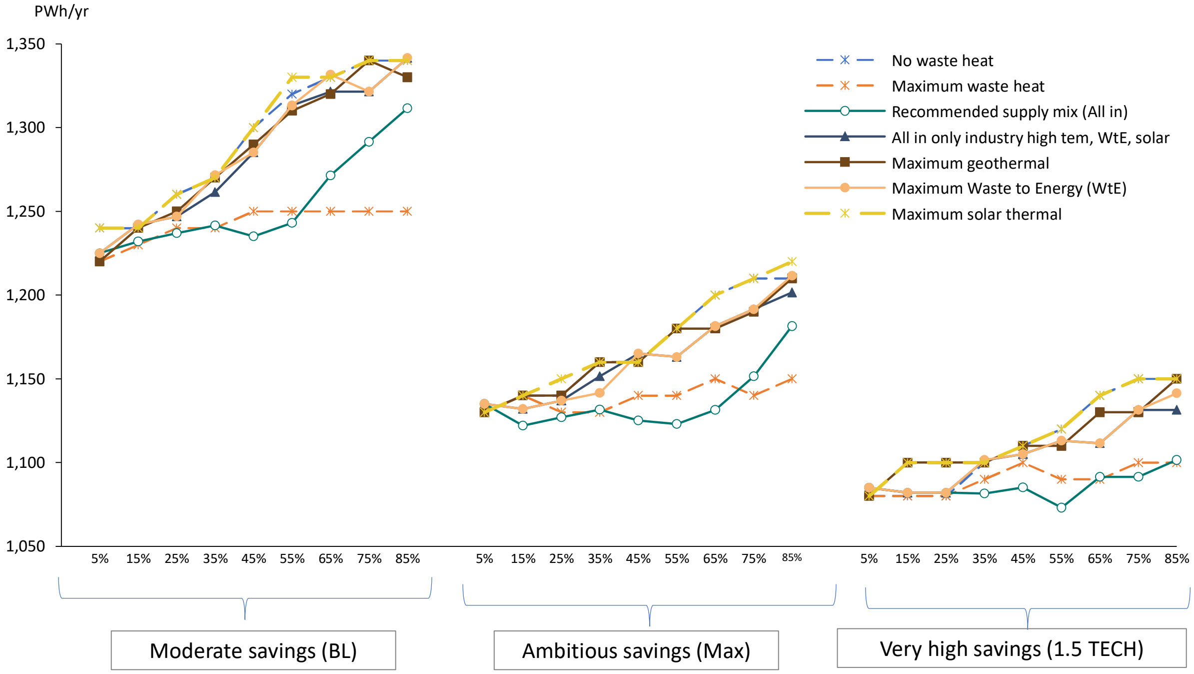


Figure 53, Biomass supply across heat supply scenarios and heat saving levels in the EU27 2050 full energy system with 4th generation district heating systems. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

The biomass results also show that heat demand savings are the strongest structural lever. Moving from moderate to ambitious and very-high savings reduces the level of biomass required for the same overall system service, even when district heating market shares increase, because lower heat demand reduces both annual energy and winter peak requirements.

Within each savings level, the portfolio effect becomes visible: scenarios with larger effective access to waste heat and renewable heat tend to reduce biomass by displacing fuel-based heat supply and by reducing the amount of dispatchable balancing required in the coupled system. Portfolios that constrain heat sources (for instance, single-source or low-waste-heat cases) generally increase biomass dependence because the system must maintain robustness during cold periods and low renewable-output periods. In other words, biomass demand is not merely a function of annual heat demand - it reflects how effectively the system can combine heat source diversity, heat pump electrification, and thermal storage to avoid using scarce fuels for routine heat delivery. The main driver for the increases in biomass consumption is that the replacement of rather efficient individual heat pumps in the system analyse are replaced by a supply not able to provide the same efficiency. From the PES results compared to the results regarding the biomass consumption we see, that a varied input of waste heat sources can decrease both PES and biomass, while other single heat sources replace renewable electricity with a larger biomass consumption, i.e. the recommended all in supply mix.

In the future biomass should serve as a backup supply and the portfolio choice in the district heating supply: the broader waste and renewable heat access we have, the more occasions where biomass is the least cost option for maintaining system adequacy is reduced. Not that in all supply systems analysed large-scale heat pumps play a crucial role in district heating – not biomass. The biomass is used in balancing both the electricity supply and the heat supply. With more usable waste heat and renewable heat both PES (through avoided conversion and lower upstream generation needs) and biomass (through reduced reliance dispatchable fuels) are reduced.

In Figure 54 the difference between 3rd generation district heating and 4th generation district heating is evaluated, focusing on biomass demand and the savings levels. The biomass consumption across the three heat-saving levels (moderate, ambitious, very high) under a 55% district heating configuration, spanning the set of the seven heat-supply portfolios are compared.

Again we see that the recommended supply mix in the 55% district heating supply share has the lowest biomass consumption, although the difference is marginal. The dominant result is that saving level outweighs district heating supply options as a driver of biomass consumption reductions. Moving from moderate to ambitious savings reduces biomass demand by roughly 10%, even though total heat demand does not fall one-to-one with biomass. This reflects the aggregated system effect of demand reduction: it lowers winter peak load, reduces the need for dispatchable capacity, and improves the ability of electrified heat supply (and storage) to cover a larger share of heat provision without fuel back-up. Against that background, the transition from 3rd to 4th generation district heating delivers a smaller but systematic additional reduction in biomass demand. In the ambitious savings case, shifting to low-temperature district heating reduces biomass by around 2%, and a similar order of magnitude reduction is observed in the very high savings case. The moderate savings level in the 4th generation district heating supply option may not be possible due to the higher temperature needs however. If the comparison is made between the moderate savings 3rd generation district heating and the ambitious savings 4th generation the biomass savings are 12%.

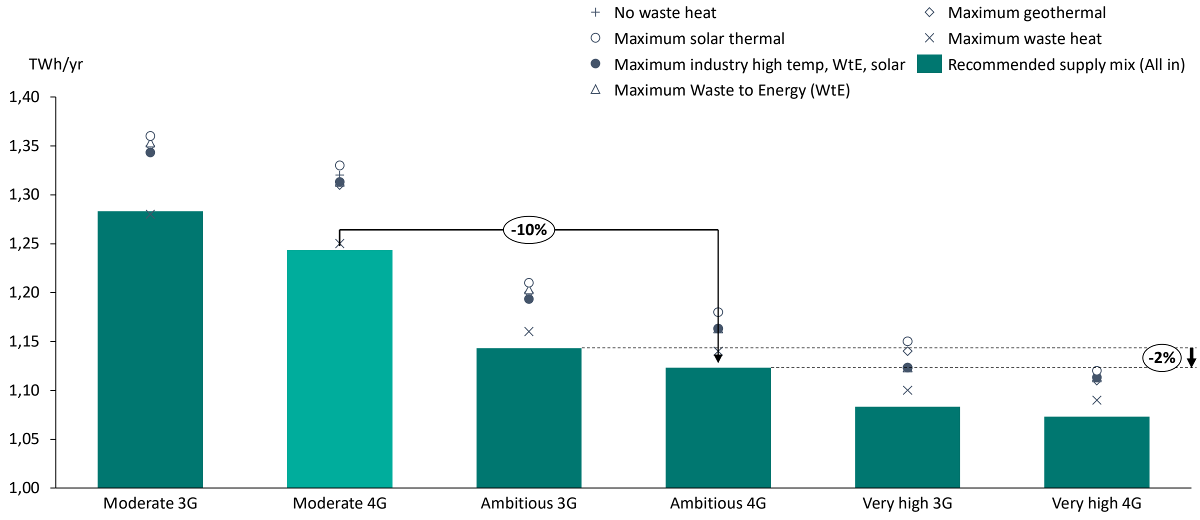


Figure 54, Biomass consumption across saving levels and heat-supply scenarios at 55% district heating for both 3rd and 4th generation district heating (EU27).

Overall, the combined results give the following hierarchy of system change elements: heat demand reduction is the primary determinant of biomass needs; portfolio access to waste and renewable heat is the second-order determinant that reduced biomass need. With ambitious savings 4th generation district heating provides is made possible which can provide further reductions.

5.2 Total energy system costs - across savings levels and district heating market shares

This section evaluates how total energy system costs evolve across district heating market shares and heat saving levels. In contrast to heat only metrics, total system cost captures the combined investment and operating implications across electricity, heating, transport, and industry, including the sector coupling measures required to integrate high shares of variable renewable electricity. The intent is therefore not to identify the consequence of a single solutions in isolation, but to explain the structure of the costs across scenarios and why it changes with 1) the demand savings, 2) the supply side district heating market share, 3) the district heating supply mix and 4) the district heating generation.

Figure 55 shows total EU27 system costs (B€/yr) as a function of district heating market share under the three heat saving levels for the two generations of district heating using the recommended (all in) district heating supply mix. A consistent pattern appears: for each saving level, the cost curve is convex - costs decline as district heating expands from low shares, then flatten and can rise again at higher market shares. The early decline reflects the system economics effects of district heating in heat dense areas: shared infrastructure, higher utilisation of technologies, and access to low-cost waste heat and renewable heat streams that are difficult to exploit with individual heating options. System wide, this also reduces the need for upstream electricity generation and peak backup, because a district heating system can combine large heat pumps with thermal storage and dispatchable units more efficiently than a fully building level electrified scenario.

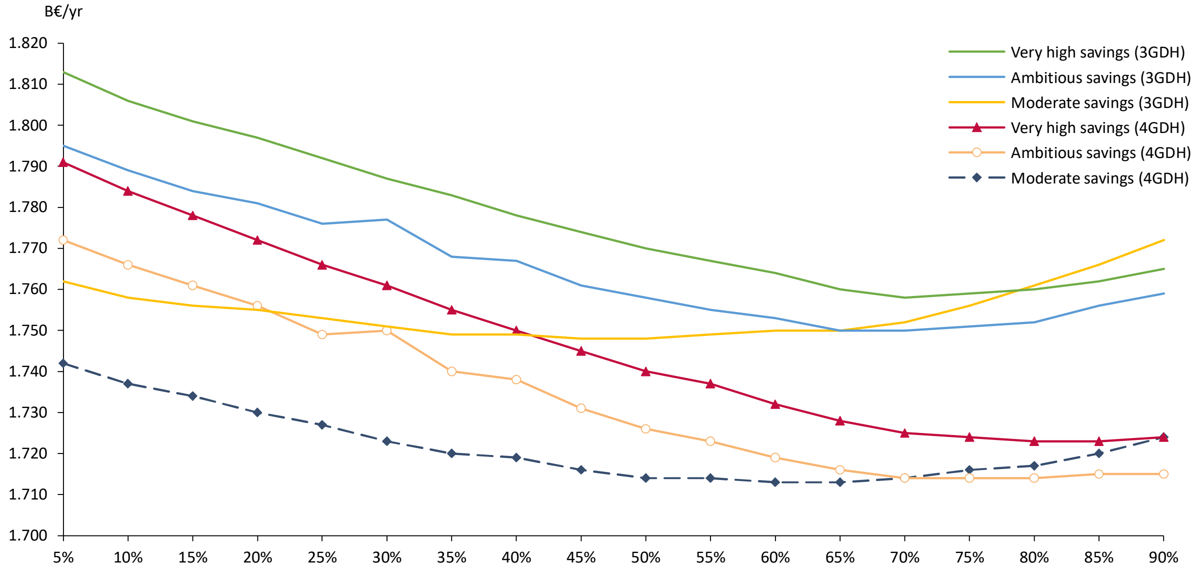


Figure 55, Development of total system costs as a function district heating market shares and across the three heat saving levels for the recommended district heating supply mix combined with both 3rd and 4th generation district heating supply mixes. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

Moderate savings yields the lowest total system when comparing savings levels in 3rd generation and 4th generation supply portfolio separately because the costs of savings are higher than the system level shared cost benefits. As the district heating share increases, the ambitious savings tends be close to the moderate savings trajectory. Very-high savings can be costlier because refurbishment investments become the dominant driver and marginal savings are increasingly expensive.

While moderate savings with ~55-60% district heating mark the point of minimum total system costs in the 4th generation district heating system, the ambitious savings scenario offers substantial system-level and resource benefits at only slightly higher cost. The moderate savings scenario is shown as a dotted line in order to highlight that it is uncertain whether the low temperatures can be achieved with only the moderate savings level. In some local conditions this may be the case. In others it is not. The costs with moderate savings and 3rd generation district heating are shown for comparison. Ambitious savings lead to larger absolute reductions in primary energy use, particularly biomass, which is a limited resource in a decarbonised energy system. If temperature levels cannot be reduced with only moderate savings, the comparison of the ambitions savings with 4th generation district heating should be conducted with the 3rd generation moderate savings, i.e. then the ambitious savings with 4th generation district heating technology is the lowest cost option.

The cost of savings are also important to consider. Under the ambitious 2050 refurbishment level the specific heat consumption declines to between 60 - 80 kWh/m² ·year in 2050, yielding about 43 % end-use savings and a total heat demand near 1,6 PWh per year. The 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) at increasing marginal cost.

Based on the total costs analyses the ambitions savings level is recommended at it enables substantial savings in PES and biomass and considering that it enables the 4th generation district heating option, also may be the lowest cost option.

Considering the ambitious savings level, Figure 56 compares the total system costs of the seven different district heating supply options across the district heating market shares. The cost differences between the options are small in comparison to the effects on costs from the savings levels and the district heating generation analyses and are not decisive at EU27 scale. This indicates that, within the modelling assumptions, several different renewable heat and waste heat integration strategies can deliver similar total system costs once the system is constrained to reach the same end-use demand level and security-of-supply requirements.

In practice, this favors a diversified portfolio that combines multiple waste heat and renewable heat sources to reduce dependence on any single resource or infrastructure bottleneck, create a more resilient and spatially realistic option and to reduce biomass use. In Figure 56 the maximum waste heat is a dashed line as the scenarios requires and unrealistic use of waste heat or renewable heat in all district heating areas, as is the no waste heat scenario, as it may entail too optimistic COP values for large-scale heat pumps, if these are not combined with medium- or low-temperature heat sources.

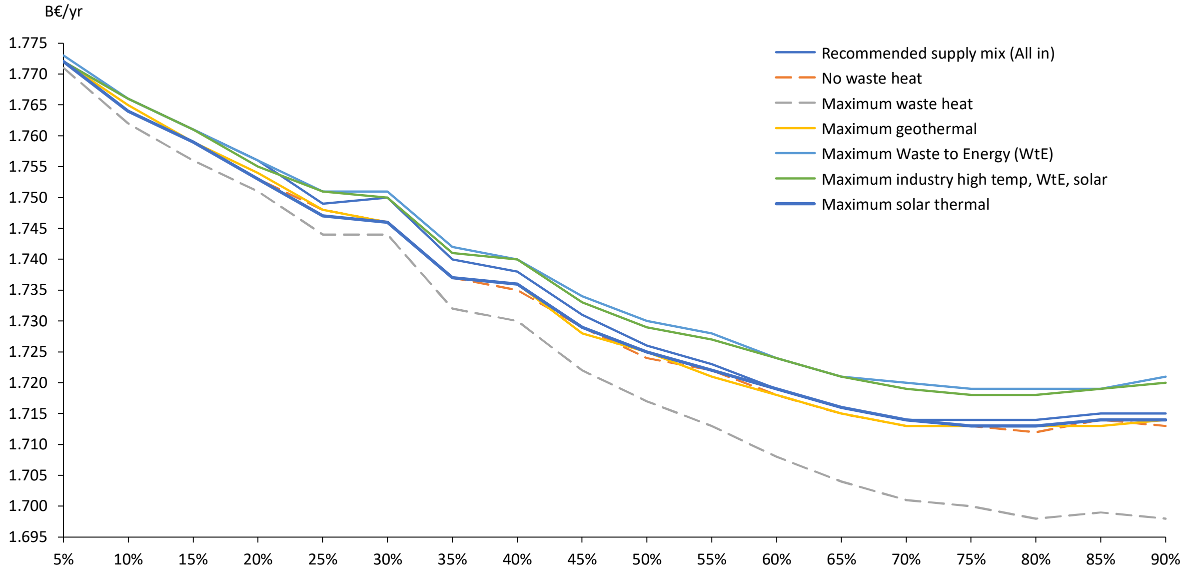


Figure 56, Total system costs for the ambitious savings level in combination the seven district heating supply mixes analysed and over the full scale of the district heating market shares. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

When considering the full energy system, the integration of district heating with renewable and waste heat sources with a 55% district heating market share results in total system costs approximately 2,5-3,1% or 40-50 billion € lower than those of scenarios dominated by individual heating solutions and with less heat savings.

5.3 Heat market costs - across savings levels and district heating market shares

The total cost evaluations revellers lower total systems costs with higher levels of district heating shares, with waste heat and renewable heat sources and going towards 4th generation district heating. In this section we investigate to what extent these cost reductions can yield lower heating costs, and to what extent this benefit is allocated to other sectors in the energy system.

In Figure 57 the unit costs of delivered heat (€/MWh) for district heating and individual heating across the two comparable building-renovation levels – *ambitious* and *very high saving* - and several market-share scenarios are illustrated. The estimated total unit cost for the *moderate savings level* is included for the 3rd generation district heating option which is the one comparable to the two other options illustrated with 4th generation district heating.

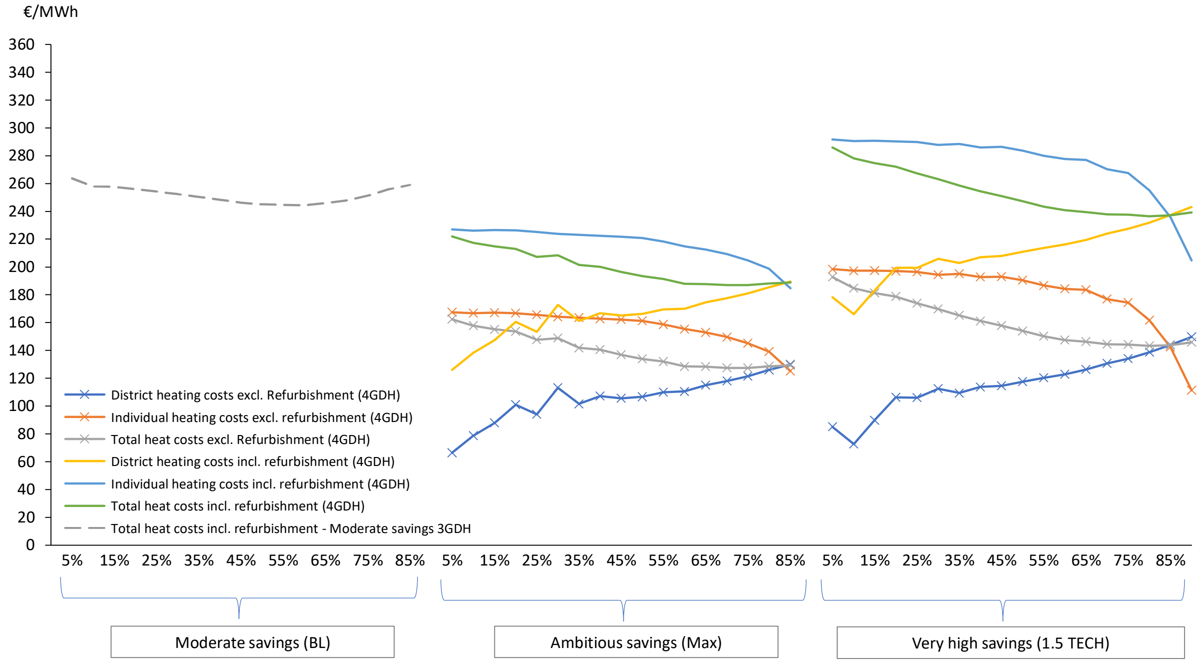


Figure 57, Costs per energy unit divided into total, district heating and individual heating, spread out on different market shares as well as on ambitious and very high savings levels for 4th generation distract heating and for moderate savings with 3rd generation district heating. Please note that beyond ~64% district heating market share the uncertainty of the district heating grid costs increases substantially.

Focusing on the heating sector alone instead of the total energy system cost reductions, the cost reduction in percentages is even greater. The heating costs can be reduced by 10-30 billion or10-20%, depending on the systems you compare. By far most of this benefit will be allocated to those connected to distract heating. Note that the cost points in the illustrate in Figure 57 illustrate the average cost, and this changes from one level of distract heating to the next may mean that all the newly connected customers have significantly higher costs than the first to connect. This also means that the local conditions must be decisive of how far to go. Nevertheless, the analyses indicate that the cost reductions of may be 30-35% for those with district heating connected. The analyses indicate that the solutions with 3rd generation district heating and only moderate savings would higher costs compared to the ambitions savings and similar costs to the very high savings.

5.4 District heating supply energy system effects

The options for supplying heat in the analyses for 2050 combined different elements of waste heat, renewable heat, large-scale heat pumps, thermal storage and conventional production units such as CHPs and fuel boilers. The heat supply options analysed in this project draw on the results of the GIS analyses as well as the temporal energy system analyses. Seven different prioritizations have been modelled which allows to check and compare different configurations regarding system effects, resource efficiencies and costs elaborated in the previous sections. In **Fejl! Henvisningskilde ikke fundet.** the seven different district heating supply options are illustrated in the recommended 55% district heating scenarios with ambitions heat savings and the 4th generation district heating.

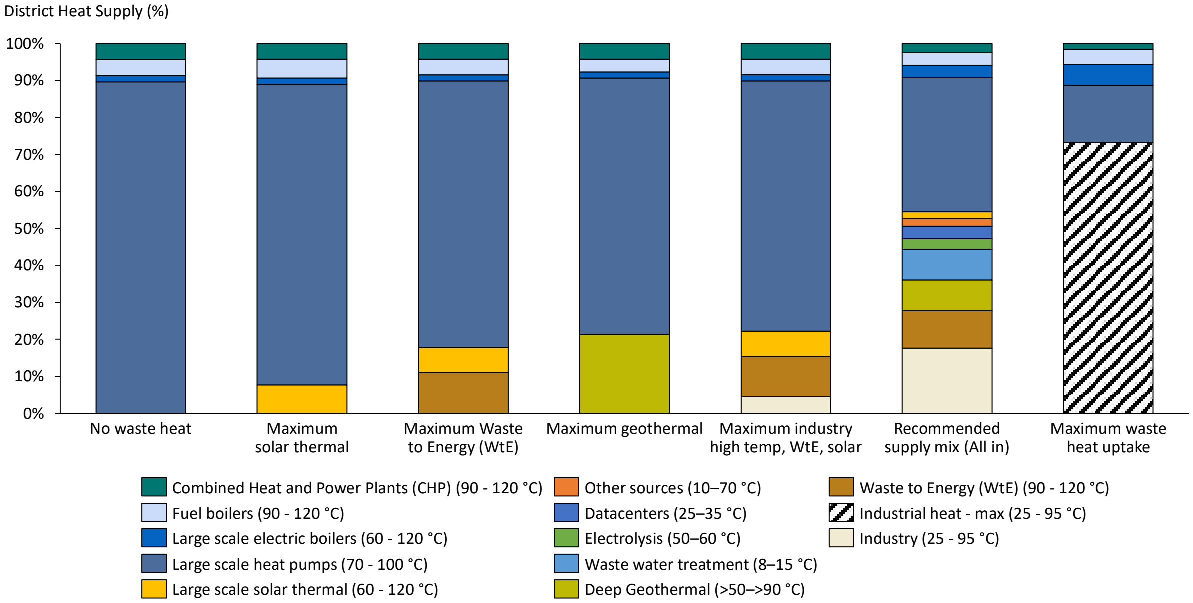


Figure 58. District heating supply options analysed with 55% district heating market share combined with ambitious savings and 4th generation district heating.

In the investigation of the supply options an upper limit has been identified in the maximum waste heat scenario The upper limit in the system to integrate waste heat and renewable heat sources is ~73% of the share 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 that local conditions vary and may not enable an implementation of local heat sources in all district heating systems. 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. This excludes the non-geolocated new sources such as e.g. data centres. 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 sources in the recommended scenario, replace low temperature industrial waste heat we know currently to be located in areas with district heating potentials.

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 all the scenarios CHP plays a minor role compared to today, although there is a tendency that with lower amounts of other waste heat and renewable heat sources, CHPs will have a slightly larger share. Fuel boilers also have a smaller role compared to today, but in some cases a larger role that CHP plants. This is connected to the lower operation hours needed for power production for the CHPs. In the modelling CHPs are activated by the electricity market – not by needs in the district heating market. There is a tendency that electric boilers have a higher operation time with large heat inputs. This is due to the heat pump capacities being reduced and thus not being able to play the same role. The large-scale heat pumps play a mayor role in the scenarios for the district heating supply.

In the recommended supply mix several sources are utilised, however not to the full extent technically possible. In Figure 59 The shares of the potential waste heat and renewable heat sources are illustrated fort the recommended 55% district heating market share combined with the ambitious savings and low-temperature 4th generation distract heating.

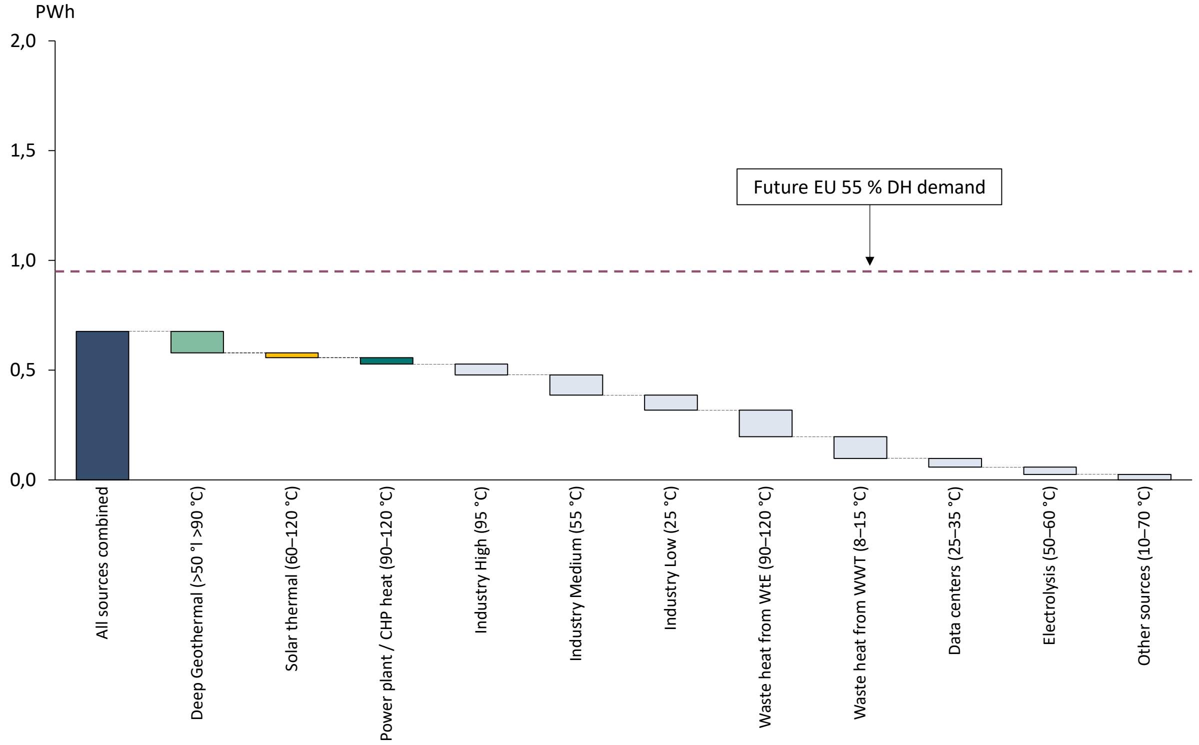


Figure 59, Diagram of the EU27 heat sources using in the recommended scenario with 55% district heating, ambitious heat savings and 4th generation district heating. All heat sources except data centres and electrolysis are assessed from a geographical perspective and in the vicinity of current heat demands. WWT: wastewater treatment. WtE: waste-to-energy, other sources include supermarkets and metro stations.

In Table 8, the percentage of the technical potentials used in the recommended scenarios is listed. Across all renewable and waste heat sources (excluding power plant / CHP heat), the technical potential amounts to 1.322 TWh, while the recommended use is 646 TWh - i.e. 49% of the technical potential is utilised, leaving 676 TWh technically available but unused. When CHP plants heat is included, the technical potential rises to 1,569 TWh, but recommended use only increases to 676 TWh, corresponding to 43% utilisation and 893 TWh unused. This aggregate result is important. It shows that the recommended 55% district heating configuration is *not* constrained by a lack of technical renewable. However, some sources are overlaying or some prioritisaed over others due to temperature levels, spatial match, and temporal integration.

Geothermal has the largest full potential (997 TWh), but only 250 TWh is technical under the district heating -relevant spatial constraints, and 98 TWh is used in the recommended case - 39% of the technical potential. For geothermal the full resource is large, but only a subset intersects with sufficiently large and suitable district heating systems. Geothermal is also limited but other sources, especially high temperature sources, that may be available in the same areas.

Solar thermal follows a similar pattern but with a stronger seasonal constraint. The full potential is 239 TWh, technical potential 124 TWh, but recommended use is only 22 TWh - 18% of technical. This low utilisation is consistent with solar thermal's dependence on seasonal matching and storage availability: once district heating areas can access baseload waste heat or geothermal heat (e.g., WtE, industrial heat, wastewater), solar thermal is often displaced unless there is space and economics for large storages and the local supply stack lacks other low-cost sources. In the analyses solar thermal is prioritised in smaller cities with no other heat sources.

Aggregated, renewable heat sources (geothermal + solar thermal) have 374 TWh technical potential, with 120 TWh used - 32% utilisation - indicating that renewables are valuable but may also be in competition with other urban waste heat sources in a 55% district heating scenario.

In Table 8, several waste heat categories are used almost to their full technical potential. In the recommended supply mix they have been priorities due to their strong spatial match to district heating demands:

- Waste heat from Waste-to-Energy (WtE): 121 TWh used out of 121 TWh technical - 100% utilisation. This reflects that WtE plants are typically close to urban heat loads and provide stable heat output at usable temperature levels. In the recommended case, WtE effectively becomes a "fully harvested" technical resource. In reality this may be hard to achieve, on the other hand the planning of facilities can take the location and waste heat usage into consideration.
- Industry - high temperature: 48/52 TWh - 92% utilisation. High-temperature surplus heat is comparatively easier to integrate (less upgrading required) and is often co-located with urban and industrial district heating demands.
- Industry - medium temperature: 93/100 TWh - 93% utilisation. Similar logic applies as for high temperature industrial waste heat. Medium-temperature waste heat is still attractive and can be upgraded efficiently with high COP values in large-scale heat pumps.
- Wastewater treatment (WWT): 99/107 TWh - 92% utilisation. This indicates strong geographic alignment (ubiquity in urban areas) and stable availability. They require heat pumps due to temperature output levels.
- Other sources (supermarkets + metro): 25/28 TWh - 91% utilisation. This potential is absolute terms, but location very centrally in for district heating areas and systems with many sources and a decentralised district heating production. The source is small and if a high utilisation rate is not possible other sources are available.

By contrast, categories with low utilisation rates have been chosen when temperatures are low or when the technical potential and location of these are uncertain:

- Industry - low temperature: 68/176 TWh - 39% utilisation (with 108 TWh unused technical). Low-temperature industrial waste heat sources are vast and higher than the high-, and medium-temperature industrial waste heat taken together. In some cases there are other higher temperature sources available, which spatially minimises the use-cases. The efficiency of up-grading is also lower compared to e.g. medium temperature industrial waste heat sources.
- Data centres' heat: 40/200 TWh - 20% utilisation (with 160 TWh unused technical). This reflects the combined effect of 1) uncertainty of future spatial distribution and heat recovery readiness depending on the type and design of data centres, 2) generally low - medium temperature levels that often require large-scale heat pumps and local coordinates with several stakeholders, and 3) the fact that other urban sources may already fill much of the baseload potential in district heating areas.

- Electrolysis: 33/164 TWh - 20% utilisation (with 131 TWh unused technical). The technical potential exists at system level, but realisation depends heavily on where electrolysers are built, how many are built, whether they are co-located with district heating demands, and whether heat recovery is a design parameter.

Aggregated, waste heat sources have 948 TWh technical potential with 527 TWh used - 56% utilisation.

Waste heat from power production in CHP plants has a much lower potential compared to the energy system of today. Only 13% is utilised in the recommended scenario (30/235 TWh). This low uptake is driven by the future need for dispatchable plants, increasingly operating for electricity adequacy rather than heat-driven operation. With limited operating hours and limited temporal fit with district heating, the potential is low. It should be noted that the 30 TWh is a modelling output from energy system analyses, indirectly connected also to geolocated sources prioritised in the hour-by-hour energy system design. Nuclear waste heat has a full potential of 123 but a technical potential of 12 TWh due to mainly a geographical mismatch. Most larger heat demand centres are ~15-50 km away from current locations. They are situated close to smaller towns and villages. While the potential of 12 TWh remains, it has not been used in the recommended scenario.

Figure 60 summarises how heat-demand reduction changes the scale of the heat market and, consequently, the size of the district heating task. The left-hand bars show that total EU27 heat demand declines from the moderate to the ambitious and very-high savings levels. The second bar translates these demand levels into the corresponding district heating production requirement at a 55% market share (including grid losses), which declines in parallel with total demand.

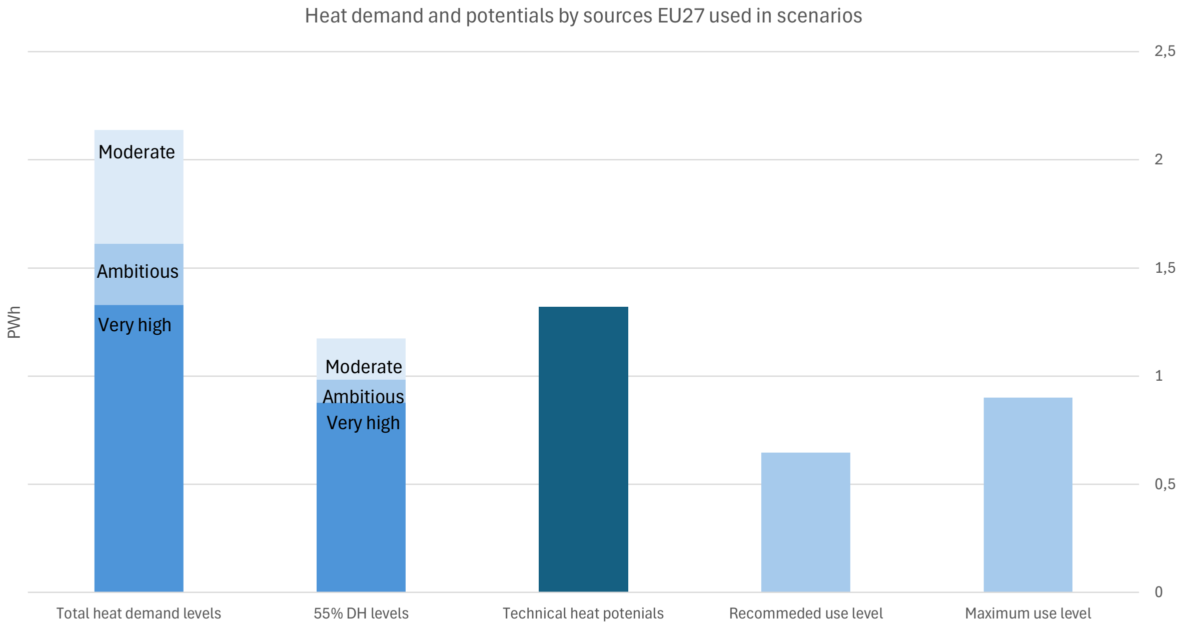


Figure 60, EU27 total heat demand levels and corresponding district heating production needs at 55% market share (including grid losses), compared with the technical potential, the recommended utilisation level, and an illustrative maximum utilisation level for renewable and waste heat sources.

The remaining bars provide system level reference levels for the use of renewable and waste heat: 1) the technical potential, representing the geographically and technically accessible resource base; 2) the recommended utilisation level, representing the amount that can be integrated in a system-consistent way under the assumed heat-market structure; and 3) a maximum utilisation level, illustrating an upper bound if renewable/waste heat were available and connectable across essentially all district heating areas.

A key interpretation is that, although annual heat demand varies substantially across savings levels, the practically utilisable share of renewable and waste heat is constrained by baseload and integration conditions. Many of these sources are most valuable as near-continuous contributors and their annual utilisation is therefore limited by (a) summer, and shoulder-season heat demand, (b) local availability and proximity to networks, and (c) the ability to absorb constant supply in a strongly seasonal heat market without excessive curtailment or costly infrastructure overcapacity. Some sources may in practice deliver higher shares during the winter half-year, but the annual utilisable level depends on local costs, temperature levels, and storage/heat pump integration. The maximum waste heat us bar should therefore be interpreted as an absolute maximum as achieving it would require that nearly all district-heating areas have access to non-production heat sources, which is unlikely in practice.

5.5 Heat and energy system primary energy demands in and towards the 2050 scenario

In the recommended 2050 energy and heat market design, the reduction in primary energy supply (PES) and the concurrent shift in the fuel mix are the result of interacting structural changes in both end-use demand and energy conversion. The analysed pathway combines accelerated electrification with a redesign of heat supply and heat markets, relying on renewable electricity and systematic integration of low-temperature renewable and waste heat sources. As illustrated in Figure 61 in the energy system development, the transition entails a structural redesign of end demands and a shift away from fossil fuels, with PES savings driven by a set of mutually reinforcing drivers acting on both end-use efficiency and system efficiency.

A practical implication is that several "no-regret" technology and implementation priorities in the heating sector deliver benefits both in terms of direct heating costs and in terms of system-wide integration of renewable electricity. Key current focuses should include:

- refurbishment and expansion of district heating grids, requiring the initiation of many new district heating systems now that can be expanded over the coming 2.5 decades;
- deployment of waste heat and renewable heat sources in combination with large-scale heat pumps and thermal storage in existing grids, supported by energy and spatial planning that enables access to both conventional and emerging waste heat sources; and
- early and continuous implementation of building heat savings, recognising that each realised heat saving in existing buildings reduces annual demand and winter peaks, and that achieving the targeted 43% reduction in building heat demand by 2050 requires sustained action whenever buildings are renovated for other purposes.

In 2050 the use of renewable sources is within the boundaries identified. Biomass consumption is approximately ~1,1 PWh, corresponding to roughly 10 GJ/capita per year, which is well below commonly cited ranges for sustainable biomass availability within the EU. The scenario design thus aims to maintain system adequacy while constraining biomass use within a strict sustainability framework and preserving biomass for competing non-energy applications (e.g., materials and chemicals). Within the renewable electricity production onshore wind (4,61 PWh), offshore wind (0,73 PWh), and solar PV (1,79 PWh) forms the main contributions to the primary energy balance. The renewable electricity capacities assumed in the recommended 2050 scenario are relatively conservative compared to published potentials. Installed capacities of ~221 GW offshore wind, ~1.985 GW onshore wind, and ~1.634 GW solar PV remain well below JRC high-case levels (3.149 GW, 5.950 GW and 4.517 GW respectively), and in the case of onshore wind are even below the JRC low-case value (2.725 GW). In the system design methodology extensive CEEP is accepted as this enables lower costs systems. In total in the recommended scenarios about 1.1 PWh is curtailed equivalent to about 12-13%. It should be noted that the energy system model includes extensive use of batteries, Power2X and – large-scale heat pumps. However, a certain level of CEEP should be accepted to reduce the overall system costs. Lower CEEP does not change the recommendation for the heating sector.

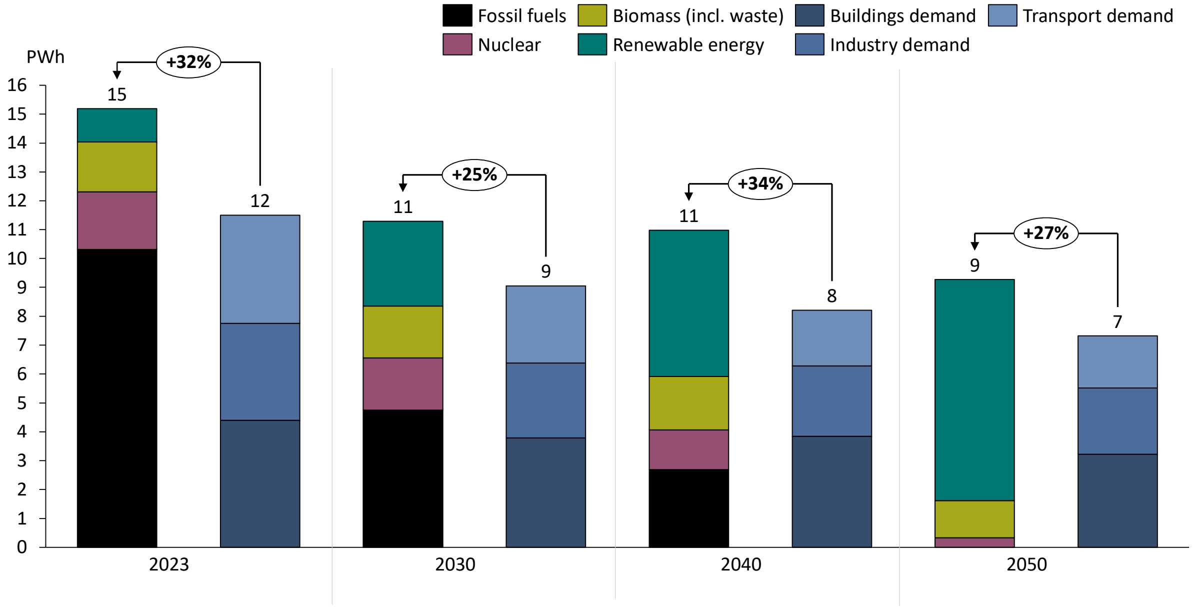


Figure 61, Primary energy supply and end demand development per sector towards 2050.

Overall, the observed PES reduction and fuel-mix changes can be interpreted through five interacting drivers:

1. End-use heat savings in buildings through renovation, improved envelopes, and building codes, reducing both annual heat demand and winter peak loads.
2. Decarbonisation of electricity supply via wind and solar, eliminating thermal conversion losses in power generation and CHP.
3. Electrification of end-uses across buildings, industry, and mobility (e.g., heat pumps, electric drivetrains, electrified process heat), increasing delivered useful energy per unit of final energy input and reducing combustion losses.
4. Increased utilisation of waste heat and renewable heat in district heating networks, reducing the need for heat production from fuels or electricity during constrained periods and structurally enabling heat inputs that would otherwise be lost.
5. Sector coupling and storage expansion, including thermal storage, flexible electric loads, and Power-to-X and hydrogen chains, enabling higher renewable penetration with improved adequacy and reduced reliance on continuous operation of dispatchable plants.

These drivers are cumulative and mutually reinforcing. In particular, the expansion and modernisation of district heating - combined with large-scale heat pumps, thermal storage, and systematic waste heat integration - links the heating sector directly to renewable electricity variability and enables "Energy Efficiency 2.0" system logic, where reduced end-demand, reduced conversion losses, and increased flexibility jointly lower the required scale of primary energy inputs while strengthening security of supply.

For the heat market design the key drivers are intermediate targets for savings on the heating sector as well as for the expansion of district heating. This section specifies the recommended heat market structure and the associated portfolio of key technologies required for a resilient, fully decarbonised EU27 heating and hot water system by 2050, including intermediate milestones for 2030 and 2040. The results are presented as market shares between district heating and individual solutions and the evolving technology mix in Figure 62. By 2050, the district heating share is suggested to be 55% and has risen from ~13% today, to 20% in 2030 and 33% in 2040. At the same time the recommended 43% reduction in building heat demand and hot water in 2050 relative to the 2015 levels enabled by refurbishment. The total heat market (heating and hot water) declines from ~2,8 PWh in 2023 (370 TWh district heating + 2.400 TWh individual) to ~1,6 PWh in 2050 (910 TWh district heating + 720 TWh individual). The heat market changes character and enables low-temperature 4th generation district heating. District heating market share increases, while the TWh district heating production increases at a slower pace. Compared to today the production increases 2,5 times form 366 TWh to 913 TWh while the market share increases fourfold.

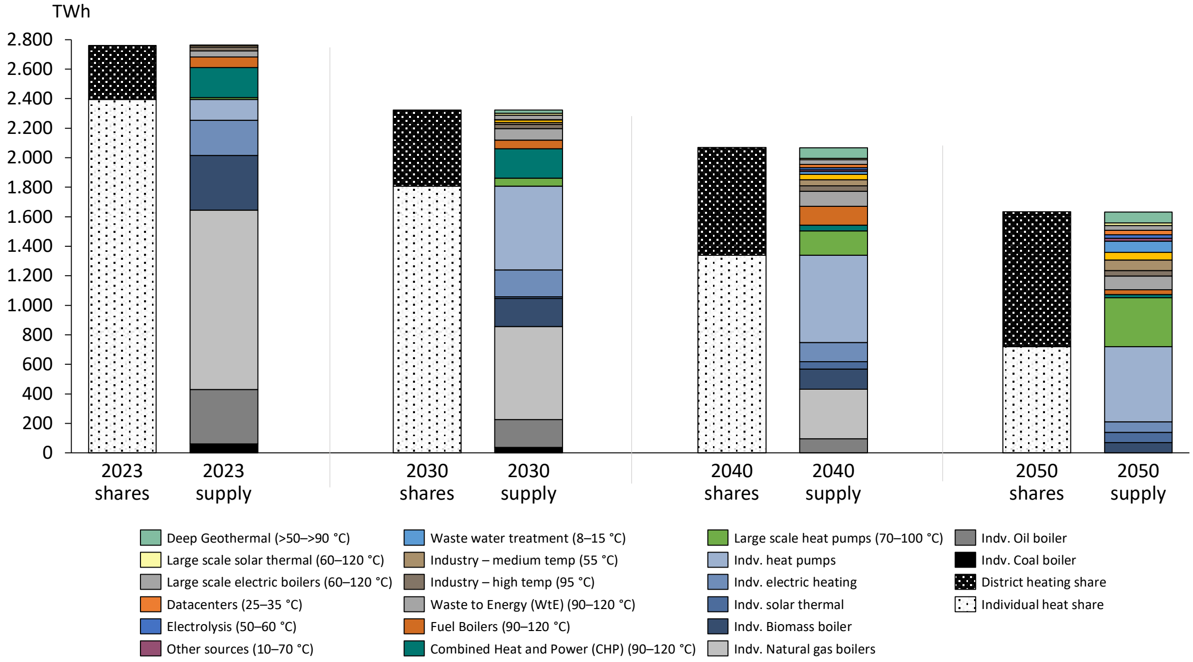


Figure 62, The development of the heat market, i.e. heating and hot water. Supply technologies and division between district heating and individual solutions. Industry sources, wastewater treatment, supermarkets and in some instances geothermal need large scale heat pumps. In this figure these sources 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.

In the 2050 system the heating system is electrified to a large extent – like also other sectors. In the system level more than half of heat demand met by heat pumps in 2050 with large-scale heat pumps in district heating covering 331 TWh (excluding contribution form input low-temperature heat sources) and individual heat pumps with 510 TWh. Together this is accounts for 841 TWh, corresponding to >50% of total 2050 heat demand. Heat pumps therefore constitute the single most important end-use conversion technology class in the 2050 heat market design, and they are also a primary lever for flexibility provision to the power system when combined with thermal storage. ~24 GW large-scale heat pumps are installed. In the recommended scenarios 33 GWs of low-cost flexibility using electric boilers are installed contributing with 31 TWh in the district heating system. Electric boilers provide low CAPEX flexibility for exploiting very low electricity prices (utilisation typically <15%).

Thermal storage is a system enabling technology for both reducing cost and resilience. The recommended thermal storage volume in district heating is ~11 TWh in 2050 (with 4,4 TWh in 2030 and 6,9 TWh in 2040). Storage shifts operation towards periods with low-cost electricity and high waste heat availability, reduces peak capacity requirements, and mitigates short-duration supply disruptions. In practice, storage designs range from large steel tanks (typically 1 - 3 days coverage in cold periods) to seasonal concepts, depending on local conditions.

In 2023, district heating is dominated by CHP plants heat production (~200 TWh) and fuel boilers (~70 TWh), supported by waste heat from WtE (~40 TWh) and smaller contributions from industry heat and early large-scale heat pumps. In 2023 waste heat utilisation is present but very small compared to the potentials. By 2030, district heating expands to ~516 TWh but remains partly reliant on CHP (~200 TWh) and fuel boilers (~60 TWh). To reach the 2050 targets, it is necessary to begins to scale low-carbon sources such as geothermal (24 TWh), solar thermal (12 TWh), waste-to-energy (78 TWh), and industrial excess heat (~57 TWh across temperature levels), alongside increased large-scale heat pump deployment (54 TWh). By 2040, the district heating mix becomes visibly dominated by renewable heat and waste heat inputs (geothermal, industry heat, wastewater treatment, data centres, electrolysis heat, and waste-to-energy), while CHP falls sharply to ~40 TWh. Large-scale heat pumps rise to ~166 TWh, indicating a transition stage where electrified heat conversion and heat recovery begin to replace conventional fuel-based heat generation at scale. In 2050, renewable and waste heat inputs provide ~54% of district heating production, while large-scale heat pumps provide ~36%. Fuel boilers and CHP are reduced to residual roles, consistent with a system design where dispatchable assets are retained primarily for adequacy, maintenance coverage, and peak demand rather than annual energy delivery. The total fuel consumption across power plants, CHP plants and fuel boilers decreases from approximately ~3 PWh in 2023 to about ~0,6 PWh in 2050.

The remaining ~45% of the heat market (~721 TWh) is met by individual solutions. In 2050 the individual segment is dominated by individual heat pumps (510 TWh) supplemented by ~70 TWh of small solar thermal, ~70 TWh of conventional electric heating, and a reduced residual ~70 TWh contribution from biomass boilers for security-of-supply and peak purposes. Fossil individual boilers (natural gas, oil, coal) are phased out by 2050 in the recommended scenario.

5.6 System costs and investment requirements towards 2050

This section summarises the cost structure of the underlying system analysis and quantifies the investment requirements for the recommended pathway towards a decarbonised and resilient EU27 energy system. The focus here is the heating sector, however other major elements are included. The focus is on how the cost structure changes from today's fuel-dominated expenditures towards a system where capital investments in infrastructure, electrification, and efficiency measures constitute the main cost component.

The investment requirements in the entire energy system increase gradually from the 2030 system to the 2050 system, however the savings in fuel consumption more than out way these investments as discussed in earlier sections. Selected inputs are presented in Table 24.

The cost data represent investments, installed capacities, cost development over time, and fixed assumptions for operation and maintenance, developed to support the energy system analysis. Reported annual system costs are annualised values derived from investment costs using technology-specific lifetimes and a 3% discount rate, consistent with the use of energy system analysis for political decision support and long-term market design.

By 2050, the heating related supply components amount to approximately 2,8 trillion € in cumulative investments, corresponding to an annualised cost of around 200 B€/year, including individual heating solutions. Heating supply investments increase markedly over time as fossil-based technologies (e.g. natural gas boilers) are phased out and replaced by electrified and infrastructure-intensive solutions. The other system components correspond to approximately 1,5 trillion €/year in annualised costs, including also building refurbishment.

Table 24, Overview of investments annual system costs for major components in the energy system from 2030 to 2050 in EU27.

	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	1.156	51
Large heat pumps	37	9	63	12	61	4
Individual heat pumps	477	58	407	97	898	87
Combined heat and power plants	316	29	61	6	70	6
Large scale boilers	14	-	179	16	294	27
Individual boilers	477	49	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	1	16	1	18	1
Total	**1.819**	**165**	**1.971**	**209**	**2.786**	**199**
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)	7.808	834	8.265	884	10.317	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
Electrolysis and hydrogen storage	38	5	198	22	140	27
Gasification, pyrolysis and electrofuels	107	11	121	13	124	12
Smart, flexible electricity requirement	-	-	161	6	345	16
Hydro	1.215	64	837	46	911	51
Building renovation	784	38	1365	66	1.997	96
Total	**13.836**	**1.270**	**16.219**	**1.495**	**20.871**	**1.699**

Overall, the investment structure implies two central characteristics of the transition. First, the system becomes increasingly capital intensive, with the largest investment categories tied to electrification and infrastructure. Second, heating supply infrastructure constitutes a smaller share of total system expenditures (~13% when compared to other components) but remains system-critical because heating choices shape peak electricity demand, and consumer-level costs.

Within the heating components, Table 24 shows that the largest investment categories in 2050 are district heating expansion and 4th generation district heating at 1.156 billion € (annualised 51 B€/yr), and individual heat pumps at 898 B€ (annualised 87 B€/yr). In addition, large-scale boilers account for 294 B€ (annualised

27 B€/yr). Smaller components include individual boilers (94 B€, 11 B€/yr), CHP's (70 B€, 6 B€/yr), individual solar thermal (111 B€, 8 B€/yr), large-scale heat pumps (61 B€, 4 B€/yr), and geothermal (18 B€, 1 B€/yr). This composition reflects the recommended heat market structure in which district heating becomes a majority infrastructure in dense areas, enabled by low-temperature operation and the integration of waste and renewable heat, while individual heat pumps remain the dominant solution in the non-networked building stock.

Two investment classes dominate the pathway and function as primary system heat infrastructure. The first is building refurbishment, with cumulative investments of approximately 2,0 trillion € 2050, targeting heat savings corresponding to a 43% reduction in building heat demand in 2050 relative to 2015 (milestones of 8% by 2030 and 25% by 2040). The implied refurbishment rate is ~1,3% - 1,5% per year, with typical lifetimes around 40 years. The second is district heating expansion and modernisation, with cumulative investments of approximately 1,16 trillion € in low-temperature district heating infrastructure, including replacement of ageing grids. Milestones of 20% and 33% district heating market share are recommended for 2030 and 2040, consistent with the trajectory required to reach the 2050 target. These investments enable multiple system benefits simultaneously: reduced heat demand and peak loads through renovation, and large-scale integration of low-grade heat, flexibility, and reduced peak electricity demand through district heating combined with thermal storage and large-scale heat pumps.

The non-heating components dominate total system costs, primarily due to transport electrification, renewable power generation, and enabling electricity infrastructure. In 2050, the largest categories include electric vehicles at annualised 989 B€/yr, offshore and onshore wind at annualised 170 B€/yr, and solar PV at annualised 57 B€/yr. Additional large categories include new gas-fired power stations billion 34 B€/yr, electrolysis and hydrogen storage 27 B€/yr, and gasification, pyrolysis and electrofuels 12 B€/yr. Overall, this portfolio reflects a broad restructuring away from fossil fuels where large upfront investments in renewables, electrification, and grids replace recurring fuel expenditures. Dispatchable capacity remains present for adequacy but shifts towards lower utilisation and more strategic operation.

Table 24 also shows that investment requirements are substantial already by 2030 and increase towards 2050, while the composition evolves. While heating remains a smaller fraction of the system costs, it is a strategic lever because the balance between district heating and individual solutions affects peak loads, electricity network reinforcement, and the feasibility of integrating waste heat and renewable heat.

5.7 District heating grid coverage - investment needs and required EU27 new networks

Achieving the recommended district heating market share in the EU27 requires a substantial scale-up of network infrastructure alongside refurbishment and replacement of existing grids. This section quantifies:

- the number of new DH systems that must be initiated to reach the targeted district market shares
- the associated grid investment requirements, distinguishing between 3rd generation and 4th generation district heating.

These estimates build on geographical modelling of district heating potential areas, combined with technology-specific cost assumptions and an explicit representation of refurbishment and replacement needs in existing networks.

Potential district heating areas are identified in the spatial model using the two criteria, i.e. the average distribution grid costs in a candidate area must be below a country specific cost ceiling, and the annual heat demand must exceed a predefined threshold. The resulting potential areas are then translated into an estimate of how many district heating systems are required to reach higher district heating market shares.

For identifying the number of networks, a heat-demand-based rule of thumb is applied: small district heating areas with final heat demand below 1 PJ/year are assumed to require one system, while larger areas are counted as requiring multiple systems, up to a maximum of five systems for the largest areas. For reference, 1 PJ/year ≈ 18.000 households at 15 MWh/household-year, although household heat demands vary and non-residential loads can significantly change the effective scale. In practice, district heating can be viable at urban scales down to roughly 10.000 inhabitants where commercial and service-sector demands may also increase heat density, and in some cases also in smaller towns or villages (~100 - 200 households) when supported by local waste heat sources, favourable heat density, and heat pumps combined with suitable thermal storage. Such smaller systems are not considered here.

Figure 63 Table 24illustrated the estimated annual commissioning of new district heating systems required to deliver the overall market-share transition. The implementation pattern reflects three characteristic phases:

- Early acceleration phase (mid-2020s to early 2030s): rapid deployment of new systems, including extensions into dense urban areas (where network installation can be costly and complex) combined with smaller systems in smaller urban areas.
- Peak deployment phase (around 2032): the maximum in annual new system start-ups, reflecting the period where high-yield DH areas are rolled out at scale.
- Maturation phase (after the early 2030s): a gradual decline in new installations as market saturation increases and remaining unserved areas become smaller, less dense, more expensive, or more time-consuming to connect.

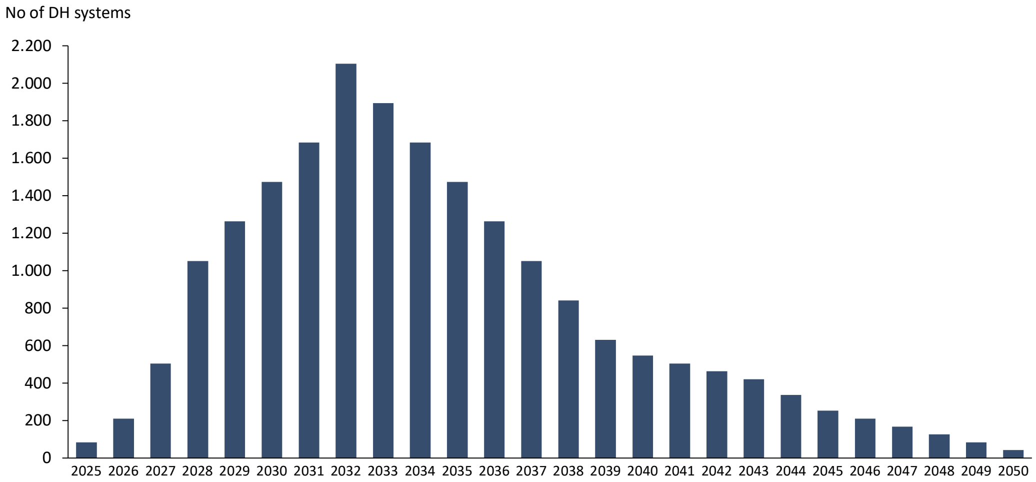


Figure 63. New prospect district heating systems by year towards 2050 in EU27.

By 2050 ~20.370 new DH systems should be started across the EU27, with a strongly frontloaded deployment i.e. about ~23% of the total number of new systems are commissioned by 2030, about ~41% by the 2032 peak, and approximately ~87% by 2040. The commissioning profile is consistent with the required market-share growth rate of approximately ~7% per year until 2030, followed by stabilisation at approximately ~5% per year thereafter, to move from roughly 13% (2023) towards ~55% (2050). In combination deployment of new systems, the existing networks should naturally also be expanded to meet these market shares.

Figure 64 illustrates how cumulative grid investment requirements rise with increasing district heating market share as progressively less favourable areas are included. The EU27 cost curve is consistent with increasing marginal costs: deployment starts in the most heat-dense and cost-effective areas, while higher market shares require connecting areas with lower heat density, longer distribution distances, and more complex and costly grids.

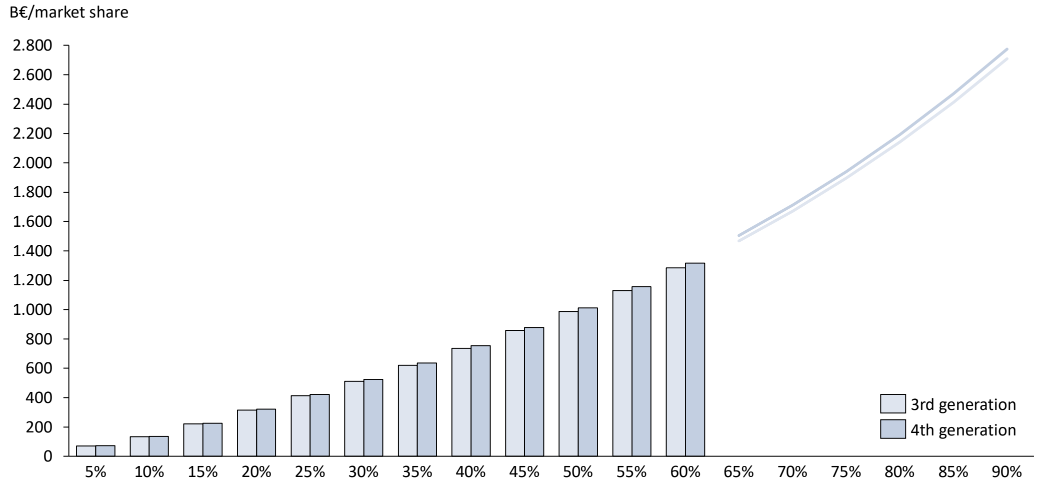


Figure 64, District heating grid costs as a function of market share for EU27 for both 3rd and 4th generation district heating.

A useful way to interpret the curve is via the marginal cost of adding the next 5 % of district heating market share. The increments increase markedly with penetration: moving from 5% to 10% adds about 63 - 65 B€, whereas moving from 55% to 60% adds about 157 - 160 B€. The polynomial extrapolations indicate that above 60% the marginal cost accelerates further: moving from 60% to 65% adds roughly 183 - 188 B€ and as mentioned previously beyond this post, uncertainty increases markedly. This provides a quantitative justification for treating ~55% as a balanced EU-wide target, which is the results of the evaluation of the total costs and energy requirements on the system level.

Regarding the role of 3rd and 4th generation district heating: at the EU27 level, 4GDH grid investments are consistently slightly higher in upfront terms. From a system perspective, the recommended pathway is not a uniform immediate conversion to 4GDH everywhere. Instead, new investments should be designed to be "4GDH-ready" (substations, heat exchangers and network topology compatible with later temperature reductions and diversified source integration), while acknowledging that parts of the building stock (e.g. historic city centres) may continue to require 3G operation due to temperature constraints. Gradually all systems should however move towards low-temperature networks.

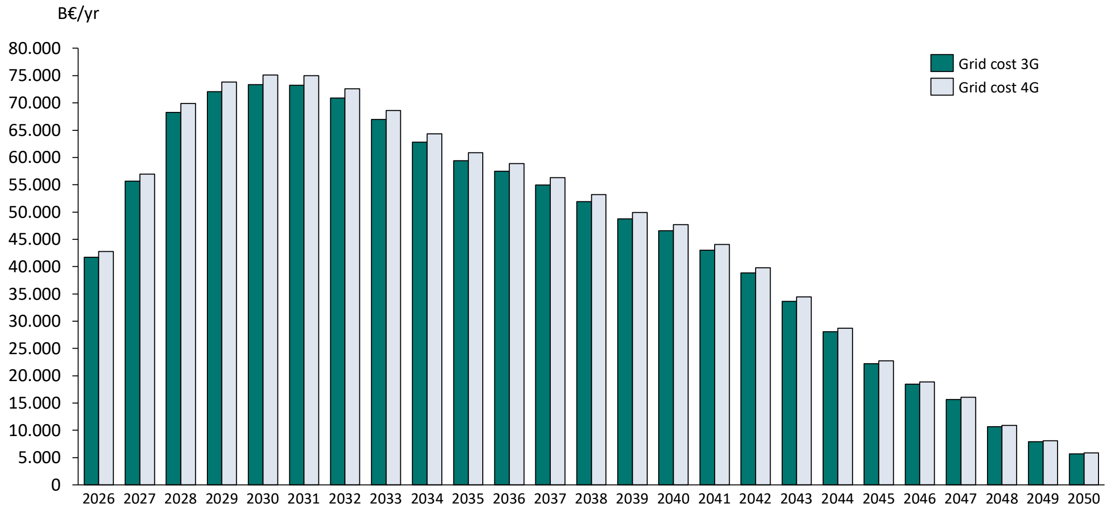


Figure 65. Distribution of grid costs for new district heating systems by year for 3rd and 4rth generation systems in EU27.

Grid investment requirements are front-loaded in the transition in order to achieve the targets. The annual investment series behind Figure 65 is consistent with the cumulative totals in Figure 64.

The annual profile shows that investments ramp rapidly through the late 2020s and peak around 2030 - 2031 at approximately 73 - 75 B€/year in 2030. After the peak, annual investments remain elevated through the mid-2030s (reflecting continued expansion, densification, reinforcement, and refurbishment), before declining steadily towards 2050 (down to ~6 B€/year by 2050). The front-loading is substantial: approximately ~28% of cumulative grid investments occur by 2030, around ~57% by 2035, and around ~80% by 2040. This timing aligns with the staged market share milestones (approximately ~20% by 2030 and ~33% by 2040, on a path to ~55% by 2050), and reflects the practical requirement that network infrastructure must be in place early to enable heat-source integration and system benefits in subsequent decades.

Total grid investment requirements (including both new build-out and refurbishment of existing networks) are estimated at roughly 1,13 - 1,16 trillion € by 2050, with investments of roughly 320 B€ by 2030, 540 - 610 B€ in 2030 - 2040, and 230 - 300 B€ 2040 - 2050. The total includes an estimated ~190 B€ for replacement and refurbishment of existing grids.

The district heating expansion requirement is heterogeneous across member states due to different urban heat densities and costs as illustrated in Figure 66. At the EU27 level, the share increases ~20% in 2030 to ~33% in 2040 and ~54.9% in 2050. The scale of national transitions varies strongly:

- Large scale-up countries (low current shares, high potential): Spain, Netherlands, Germany, Belgium, France, Italy and Poland.
- Already-high DH countries (focus shifts to optimisation and integration): Denmark, Finland and Sweden.

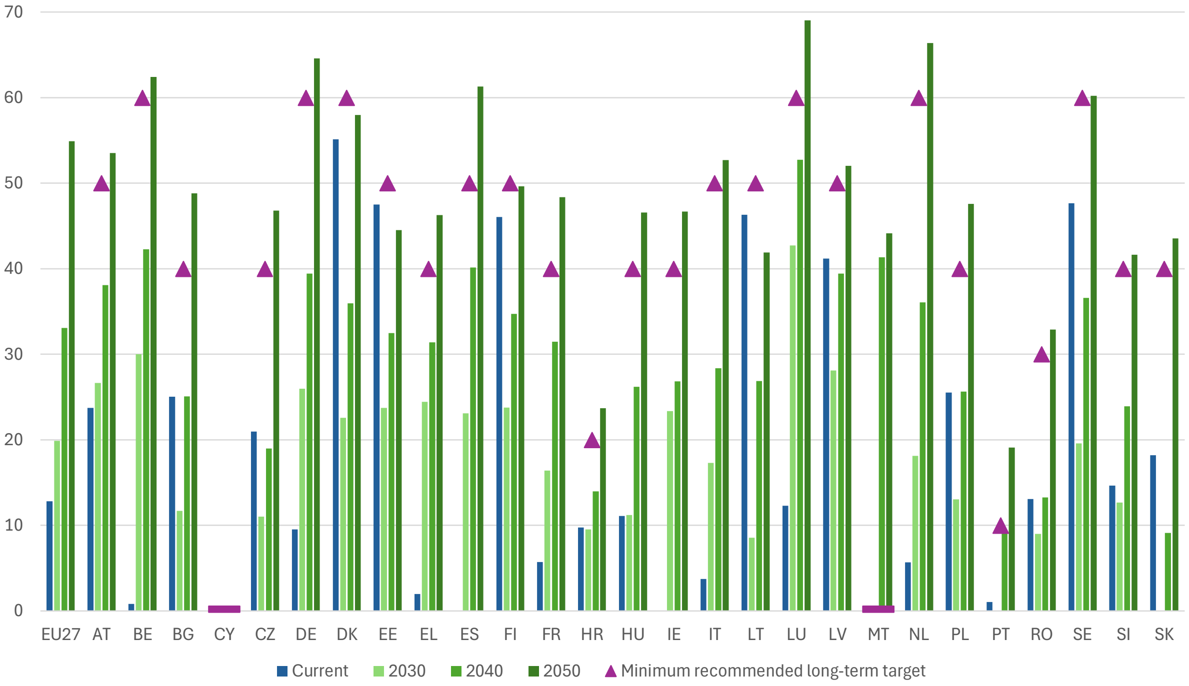


Figure 66, Minimum recommended district heating market shares by country, alongside current (2023) and suggested 2030, 2040 and 2050.

It is important to distinguish between (a) minimum recommended country levels (benchmarks to achieve 55% EU-wide) and (b) the modelled allocation in the pathway. In some cases, modelled values can appear lower than current values. This should not be interpreted as a recommendation to reduce district heating in those countries; rather, it reflects the EU-wide balancing of contributions and the simplified representation of national pathways in the aggregated model output. In practice, countries already above the minimum benchmark would be expected to maintain or strengthen district heating, focusing on low-temperature readiness, system integration, and diversified heat sources.

6 References

Abid, H., Østergaard, P. A., Skov, I. R., & Mathiesen, B. V. (2025). Comparative assessment of future hydrogen demand potentials in a decarbonised European energy system. *International Journal of Hydrogen Energy, 122*, 82–96. 10.1016/j.ijhydene.2025.03.362

Bruegel. (2025, -04-29). *European natural gas imports.* Retrieved May 8, 2025, from https://www.bruegel.org/dataset/european-natural-gas-imports

CEWEP. (2023). *Circular Economy Calculation tool.* https://www.cewep.eu/circular-economy-calculations-2/. https://www.cewep.eu/circular-economy-calculations-2/

Codema. (2021). *Dublin Region Energy Master Plan.* https://www.codema.ie/: Codema.

Connolly, D., Mathiesen, B. V., Østergaard, P. A., Möller, B., Nielsen, S., Lund, H., Trier, D., Persson, U., Nilsson, D., & Werner, S. (2012). *Heat Roadmap Europe: First pre-study for EU27*. Aalborg University, Halmstad University, and Euroheat & Power.

Crownhart, C. (2024, April 4). *Why the lifetime of nuclear plants is getting longer.* https://www.technologyreview.com/2024/04/04/1090630/old-nuclear-plants/. Retrieved Feb 13, 2025, from

Czyzak, P., Theisen, N., & Mindekova, T. (2025). *The final push for EU Russian gas phase-out.* Ember. https://ember-energy.org/app/uploads/2025/03/Ember-Report-The-final-push-for-EU-Russian-gas-phase-out.pdf

DEA. (2024a). *Technology Catalogue for Renewable Fuels.* https://ens.dk/. https://ens.dk/analyser-og-statistik/teknologikatalog-fornybare-braendstoffer

DEA. (2024b, February). *Technology Data for Generation of Electricity and District Heating | The Danish Energy Agency.* https://ens.dk/en/our-services/technology-catalogues/technology-data-generation-electricity-and-district-heating

Dekeyrel, S. (2024). The European energy crisis: Shock therapy for the EU's clean energy transition. https://www.epc.eu/content/PDF/2024/Simon_Energy_policy_Brief.pdf

Dodd, N., Alfieri, F., Maya-Drysdale, L., Viegand, L., Flucler, S., Tozer, R., Whitehead, B., Wu, A., & Brocklehurst, F. (2020). *Development of the EU Green Public Procurement (GPP) Criteria for Data Centres, Server Rooms and Cloud Services. Final Technical Report,.* Luxembourg: Publications Office of the European Union. 10.2760/964841 https://op.europa.eu/en/publication-detail/-/publication/89971797-a9fa-11ea-bb7a-01aa75ed71a1/language-en

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS REPowerEU Plan, (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

EC. (2024). The future of European competitiveness.

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Roadmap towards ending Russian energy imports, (2025a).

EC. (2025b, Nov). *Energy Efficiency Directive: Datacentre Reporting Dashboard.* Retrieved Dec, 2025, from

EEA. (2025a, Sep 29). *Europe's environment 2025 4.6 Benefits of a circular economy.* https://www.eea.europa.eu/. Retrieved 2025, from https://www.eea.europa.eu/en/europe-environment-2025/thematic-briefings/circular-economy-and-other-enablers-of-transformative-change/benefits-of-a-circular-economy

EEA. (2025b, Mar 3). *Waste generation in Europe (Indicator).* https://www.eea.europa.eu/. Retrieved 2025, from https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/waste-generation-in-europe-indicator?utm_source=chatgpt.com

ETC. (2021, July). *Bioresources Within A Net-Zero Emissions Economy - ETC.* https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/

EU. (2024). *Waste hierarchy - EUR-Lex.* Retrieved Dec 3, 2024, from https://eur-lex.europa.eu/EN/legal-content/glossary/waste-hierarchy.html

European Commission. (2018). A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. *Com(2018) 773,*

European Environment Agency. (2023). *The European Biomass Puzzle — European Environment Agency.* https://www.eea.europa.eu/publications/the-european-biomass-puzzle

European Union. (2023, 20/09). *Directive (EU) 2023/1791 on energy efficiency and amending Regulation (EU) 2023/955 (recast) – European Sources Online.* Retrieved Nov 13, 2023, from https://www.europeansources.info/record/proposal-for-a-directive-on-energy-efficiency-recast/

EuroStat. (2023). *EUROPOP2023 - Population projections at national level (2022-2100).* https://ec.europa.eu/eurostat. https://ec.europa.eu/eurostat/web/population-demography/population-projections/database

Eurostat. (2024). Population EU Statistics | Eurostat. https://ec.europa.eu/eurostat/databrowser/view/tps00002/default/table?lang=en&category=t_proj

Eurostat. (2025a, Sep 22). *Generation of waste by waste category, hazardousness and NACE Rev. 2 activity.* https://ec.europa.eu/eurostat. https://ec.europa.eu/eurostat/databrowser/view/env_wasgen/default/table?lang=en

Eurostat. (2025b, Oct 17). *Municipal waste by waste management operations.* https://ec.europa.eu/eurostat. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

Eurostat. (2025c, Sep 23). *Treatment of waste by waste category, hazardousness and waste management operations.* https://ec.europa.eu/eurostat. https://ec.europa.eu/eurostat/databrowser/view/env_wastrt/default/table?lang=en

Fallahnejad, M. (2022). *Data set on district heating potentials in EU-27 countries.*

Fallahnejad, M., Kranzl, L., Haas, R., Hummel, M., Müller, A., Sánchez-García, L., & Persson, U. (2024). District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth. *Applied Energy, 353*10.1016/j.apenergy.2023.122154

Fraunhofer. (2024). *Energy Charts.* https://energy-charts.info/index.html?l=en&c=FR. https://energy-charts.info/index.html?l=en&c=FR

Fremtidens Fjernvarme. (2022). *Anvedte FFH50 forudsøtninger, potentialer of prognoser.* https://varmeplanhovedstaden.dk/publikationer/anvendte-ffh50-forudsaetninger-potentialer-og-prognoser/.

GEODH. (2022). GEODH | Geothermal District Heating. http://geodh.eu/

Google. (2025). *Growing the internet while reducing energy consumption.* https://datacenters.google/efficiency/. Retrieved 2025, from https://datacenters.google/efficiency/

Grama, M. (2025, Nov 05). *Global data center power demand expected to almost double by 2030.* https://www.spglobal.com/. Retrieved 2025

Handl, K. -. (1998). 75 MW Heat Extraction from Beznau Nuclear Power Plant (Switzerland)., 18. https://ETDE/INIS accession: XA9848828. (Available via OSTI ETDEWeb “purl/298145”, 18 pp.)

IAEA. (2017). Opportunities for Cogeneration with Nuclear Energy. https://www-pub.iaea.org/MTCD/Publications/PDF/P1749_web.pdf

IAEA. (2019). Guidance on Nuclear Energy Cogeneration. https://www-pub.iaea.org/MTCD/Publications/PDF/P1862_web.pdf

IAEA. (2024). *PRIS - Home.* https://pris.iaea.org/PRIS/home.aspx

IEA. (2018). *The Future of Cooling*
Opportunities for energy-efficient air conditioning. https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf

IEA. (2024a). *Countries & Regions - IEA.* https://www.iea.org/countries

IEA. (2024b). *Electricity 2024: Analysis and forecast to 2026.* Paris: IEA. https://www.iea.org/reports/electricity-2024

IEA. (2024c). The Future of Geothermal Energy. https://iea.blob.core.windows.net/assets/fe8d11b6-b1a6-43d9-9351-47d86ed1dfbc/TheFutureofGeothermal.pdf?utm_campaign=IEA+newsletters&utm_medium=Email&utm_source=SendGrid

IEA. (2025). *Energy and AI.* IEA. https://www.iea.org/data-and-statistics/data-product/energy-and-ai

IrDEA, & Gemserv. (2024). *District Energy in Ireland: Low-Carbon Heating Options Appraisal.* https://districtenergy.ie/policy: Irish District Energy Association.

Kamiya, G., & Bertoldi, P. (2024). Energy Consumption in Data Centres and
Broadband Communication Networks in
the EU. *Https://Interactdc.Com/Static/Images/Documents/JRC135926_01.Pdf,* 10.2760/706491

Kranzl, L., Forthuber, S., Fallahnejad, M., Büchele, R., Müller, A., & Hummel, M. (2021). *ENER/C1/2018-494 – Renewable Space Heating under the Revised*
Renewable Energy Directive. Brussels: https://op.europa.eu/en/publication-detail/-/publication/16710ac3-eac0-11ec-a534-01aa75ed71a1

Leiserson, L., Thompson, T., Emer, E., Kuszmaul, K., Lampson, L., Sanchez, S., & Schardl, S. (2020). There's plenty of room at the Top: What will drive computer performance after Moore's law? *Science, 368*(6495), eaam9744. 10.1126/science.aam9744

Lund, H., Thellufsen, J., & et. al. (2021). EnergyPLAN e Advanced analysis of smart energy systems. https://vbn.aau.dk/ws/portalfiles/portal/466427770/1_s2.0_S2666955221000071_main.pdf

Lund, H., Mathiesen, B. V., Thellufsen, J. Z., Sorknaes, P., Chang, M., Kany, M. S., & Skov, I. R. (2021). *IDAs Klimasvar 2045 Sådan bliver vi klimaneutrale*. Aalborg University.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy, 68*, 1–11. 10.1016/j.energy.2014.02.089

Mathiesen, B. V., Lund, H., Nielsen, S., Sorknæs, P., Moreno, D., & Thellufsen, J. Z. (2021). *Varmeplan Danmark 2021 - En Klimaneutral Varmeforsyning / Heat Plan Denmark 2021 - A climate neutral heat supply.* https://vbn.aau.dk/ws/portalfiles/portal/449742535/Varmeplan_Danmark_2021_Hovedrapport.pdf

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K., & Hvelplund, F. K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Applied Energy, 145*, 139–154. 10.1016/j.apenergy.2015.01.075

Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., Paardekooper, S., Thellufsen, J. Z., & Djørup, S. R. (2019). Towards a decarbonised heating and cooling sector in Europe. https://vbn.aau.dk/ws/portalfiles/portal/316535596/Towards_a_decarbonised_H_C_sector_in_EU_Final_Report.pdf

Mathiesen, B. V., Ilieva, L. S., Skov, I. R., Maya-Drysdale, D. W., & Korberg, A. D. (2022). *Synergies between the Energy Efficiency First Principle and 2050 Renewable Energy Systems in Europe (sEEnergies).* Copenhagen: Aalborg University. https://vbn.aau.dk/ws/portalfiles/portal/477605970/sEEnergies_D8.3_FINAL.pdf

Mathiesen, B. V., Wild, C., & Nielsen, S. (2023). *Heat Matters: The Missing Link in REPowerEU. 2030 District Heating Deployment for a long-term Fossil-free Future.* Aalborg University. https://vbn.aau.dk/ws/portalfiles/portal/603638943/20231114_REPower_District_Heating_HRE5_Final_V2.pdf

Maya-Drysdale, D. W., Abid, H., Korberg, A. D., Skov, I. R., Mathiesen, B. V., Ilieva, L. S., & Dahl Nielsen, F. (2022). Energy Efficiency 2050 Roadmap for Europe. https://vbn.aau.dk/ws/portalfiles/portal/477603927/sEEnergies_D6.3_FINAL.pdf

MEKH, & MaTáSzSz. (2023). *A magyar távhőszektor 2022. évi adatai / Data of the Hungarian District Heating Sector 2022.* Magyar Energetikai és Közmű-szabályozási Hivatal (MEKH) Magyar Távhőszolgáltatók Szakmai Szövetsége. SSN 2560-1156 https://tavho.org/uploads/statisztika/MEKH_statisztikai_kiadvany_tavho_2023_A4_web.pdf

Monteavecchi, F., Stickler, T., Hintermann, R., & Hinterholzer, S. (2020). *Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market.* Luxembourg: Publications Office of the European Union. 10.2759/3320 https://www.researchgate.net/publication/345687292_Energy-efficient_Cloud_Computing_Technologies_and_Policies_for_an_Eco-friendly_Cloud_Market

Moore, G. E. (1965). Cramming more components
onto integrated circuits. *Electronics, 8*(Volume 38) https://hasler.ece.gatech.edu/Published_papers/Technology_overview/gordon_moore_1965_article.pdf

NEA. (2022). Beyond Electricity: The Economics of Nuclear Cogeneration. https://www.oecd-nea.org/upload/docs/application/pdf/2022-07/7363_cogen.pdf

Odyssee-Mure. (2021). *Energy efficiency trends and policies.* Enerdata. https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/european-union.html

OECD. (2019). *Global Material Resources
Outlook to 2060: Economic drivers and environmental consequences.* Paris: https://doi.org/10.1787/9789264307452-en

Paardekooper, S., Lund, R. S. o., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L., David, A., Dahlb aek, J., Kapetanakis, J., Lund, H., Bertelsen, N., Hansen, K., Drysdale, D., & Persson, U. (2018). *Heat Roadmap Europe 4: Quantifying the Impact of Low-carbon Heating and Cooling Roadmaps.* Copenhagen: Department of Planning, Aalborg Uiversity. https://vbn.aau.dk/ws/portalfiles/portal/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps..pdf

Persson, U., Möller, B., Sánchez-García, L., & Wiechers, E. (2021). *District heating investment costs and allocation of local resources for EU28 in 2030 and 2050.* Copenhagen: Aalborg University. https://doi.org/10.5281/zenodo.4892271

Reiter, U., Palacios, A., & Lienhard, L. (2021). Data set on energy efficiency potentials, describing the cost curves for building envelope refurbishment measures on single building level.10.5281/zenodo.6531783

Renewables.ninja (2024). Rebewables ninja. Retrieved Jan 7, 2025, from https://www.renewables.ninja/

ReUseHeat. (2022). *ReUseHeat.* https://www.reuseheat.eu/facts-figures/. https://www.reuseheat.eu/facts-figures/

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B. S., Brosowski, A., & Thrän, D. (2019). ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews, 26*10.1016/j.esr.2019.100379

Sánchez-García, L., Averfalk, H., & Persson, U. (2022). *sEEnergies special report : Construction costs of new district heating networks in Germany.* sEEnergies. Retrieved from DiVA http://hh.diva-portal.org/smash/get/diva2:1702170/FULLTEXT01.pdf http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-48303

Savills Research. (2022). *European Data Centres: Deep dive in the data sphere.* https://pdf.euro.savills.co.uk/. https://pdf.euro.savills.co.uk/european/european-commercial-markets/spotlight-eu-data-centre---november-2022-.pdf

Soler, A. (2022). *Sustainable biomass availability in the EU towards 2050 (RED II Annex IX, Parts A and B)*

Sorknæs, P., Nielsen, S., Skov, I. R., Lund, H., & Dahl Nielsen, F. (2024). Forundersøgelse af grundlag og muligheder for udnyttelse af overskudsvarme fra
Power-to-X i Region Hovedstaden - Baggrundsrapport.
https://vbn.aau.dk/ws/portalfiles/portal/695994299/Baggrundsrapport.pdf

The European Parliament, & The European Council. (2008). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*. European Union Law.

The European Parliament, & The European Council. (2018). *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance)*. European Union Law.

Vattenfall. (2025). *Ågesta power plant.* https://history.vattenfall.com/. Retrieved 2025, from https://history.vattenfall.com/stories/agesta-power-plant

Wikipedia. (2025, dec). *Greifswald Nuclear Power Plant.* Retrieved dec, 2025, from https://de.wikipedia.org/wiki/Kernkraftwerk_Greifswald#Bau_der_Fernw%C3%A4rme-Trasse

WNA. (2024). *Reactor Database Search - World Nuclear Association.* https://world-nuclear.org/nuclear-reactor-database#_

World Nuclear Association. (2024). Nuclear Process Heat for Industry - World Nuclear Association. https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry