Heat Matters: The Missing Link in REPowerEU

2030 District Heating Deployment for a long-term Fossil-free Future

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2030 District Heating Deployment
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This report employs a Smart Energy System approach to redesign Europe's energy infrastructure, emphasizing the expansion of district heating as a strategic move to eliminate gas-based heating in European buildings. It introduces a novel quantification of waste heat potentials and integrates it with analyses of future potential district heating market shares in Europe. Both in a REPowerEU 2030 and long-term decarbonization temporal perspective. Additionally, it provides a quantification of the investment required in district heating infrastructure to achieve substantial reductions in the EU's natural gas consumption. This report contributes to the ongoing the Heat Roadmap Europe project series.

By Brian Vad Mathiesen, Christopher Wild and Steffen Nielsen

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2050
Heat Roadmap Europe
A low-carbon heating and cooling strategy

Executive summary

REPowerEU marked a change in speed in the European energy transition. While the energy crisis started in the summer of 2021, its impact on citizens and businesses was felt most severely in Europe during 2022 and 2023, after the Russian invasion of Ukraine.

With the REPowerEU package, the European Union (EU) has risen to the challenge by presenting ambitious proposals aimed at making the EU independent of natural gas imports from Russia by 2027. The implementation of the REPowerEU has been effective to reduce the EU natural gas consumption and imports from Russia. However, the European response to the crisis lacks a key strategic element: fundamentally redesigning the energy system to decarbonise heating in buildings and strengthen our energy security. Without additional measures that go beyond the 2027 target of breaking free from Russian natural gas the EU becomes structurally more dependent on e.g., North Africa, Qatar, Azerbaijan and the US as we cannot expect more natural gas from Norway or from within EU. In the first half of 2023 14% of the natural gas import came from Russia.

Heating in the EU: State of Play and Challenges

Space and water heating is responsible for about one third of the final energy demand in the European Union (EU) and over 75% of this heat comes from burning fossil fuels. Natural gas is the single most used primary fuel for heating in the EU. Its use in individual boilers has increased by 50% since 1990 to reach a market share of about 40% now. Developing all clean heat solutions to phase out fossil-fuels in heating is therefore essential to achieve climate targets, and break-free from fossil import dependency in the near term. In particular the role of heating networks has been greatly overlooked. The study shows:

- Countries where district heating is well established not only have lower natural gas dependence in the heating sector, but also have a lower reliance on fossil fuels in individual heating:
- Two thirds (nine out of fourteen) of the countries where district heating has a market share below 20% have a reliance of half or more on fossil fuels in individual heating;
- Individual boilers firing fossil fuels represent over 70% of the heat market in the ten countries where district heating has a market share of about 10% or below e.g. Germany, Italy, Belgium, Ireland and the Netherlands.

To understand the changes and potentials of energy efficiency in the heating sector it is pivotal to shift perspective and develop an analysis that is both holistic - considering the energy system as a whole - and granular – high time and geographic resolution. This is the ambition of this study.

Potentials of District Heating in the REPowerEU Perspective

When doing so, the potential of deploying and decarbonising district heating networks to phase out natural gas use is brought to light. A goal of providing 20% of the European heat demands with district heating by 2030 would:

1) increase the short-term energy efficiency of the European energy system
2) increase the amount of natural gas displaced with energy efficiency
3) provide a cost-effective reduction of natural gas consumption
4) unlock the contribution of vast waste heat and renewable energy sources not accessible without district heating networks.

Such a deployment would occur with the development of new systems, the densification of existing ones and with changes in the fuel mix to integrate a higher share of new renewable and waste heat sources. Based on the sEEnergies project the study shows the additional reduction of gas imports - on top of the REPowerEU initiative - that could be delivered with a system focus.

District heating appears amongst the top solutions to reduce natural gas imports, providing a reduction of 24 bcm by 2030 – while households heat pumps, energy efficiency in buildings, Efficiency/electrification in the industrial sectors deliver respectively 33, 23 and 25 bcm. Out of the 24 bcm, 15 bcm reflects a new district heating production mix, 3 bcm are from utilizing biomethane in efficient CHP plants and 6 bcm stems from an enlargement to 20% of the heat demands met by district heating. Deploying new systems and upgrading existing ones can ensure an efficient heat transition for central and eastern European countries, which can build on the large pre-existing infrastructure to harness renewable and waste heat resources.

The redesigned 2030 energy system in sEEnergies can achieve a total of 328 bcm gas saved in 2030, which is about 15% higher than the level set out by the European Commission's Fit for 55 and REPowerEU measures. In our redesigned system district heating provides about half of this increase or 8% of the additional savings.

The Smart Energy System Approach for the Long-term Climate Neutrality Goal

Accelerating the deployment of heating networks by 2030, additionally to existing REPowerEU measures, puts Europe on track to achieve much greater gas and fossil fuel savings by 2050. Further increasing the market share to 48% in combination with end-savings in buildings enables a cost-effective, resource-efficient heat decarbonisation strategy, tapping into the potential of waste heat, and a broader diversity of renewable energy sources such as geothermal and solar thermal. The deployment of district heating is also a critical enabler to balance the energy system and integrate more renewables such as wind power and solar PV in the electricity grid. It is part of a smart energy system approach that enables the cost-efficient integration of renewable energy.

To thoroughly assess opportunities for enhanced energy efficiency within the heating sector, it is essential to consider heating within the context of the total energy system. This entails an hour-by-hour analysis for the years 2015, 2019, 2030, and 2050, taking both an EU27-wide and an individual country perspective. Advanced energy system analysis tools are used in this study that enable this type of approach. In many cases the traditional tools used for energy-system modelling are not able to identify cross-sector synergies. It can be recommended to carefully consider the temporal and geographical scopes of energy system analysis tools used, as it seems that many energy systems modeling underestimate cross-sector synergies and specifically the potential in the heating sector.

The smart energy system approach applied in this study enables a more sustainable future with a 20-30% lower primary energy input compared to the European Commission scenario meeting the Paris Agreement towards 2050.

The sEE 2050 scenario (sEEnergies) represents a robust system redesign paired with the Energy Efficiency First Principle, which allows for a better integration of variable electricity and builds on cross-sectorial connections to release additional flexibility sources, i.e., electric vehicles, electrofuels, district heating systems as well as several types of storages based on known technologies. When compared to the long-term decarbonisation scenario 1.5 TECH conducted by the European Commission these are the main differences:

- The sEE 2050 scenario has a 40% reduction in the heat demand in the building stock. These are less savings in end-demands in building compared to the 55% in 1.5 TECH. The extra costs to reach 55% energy savings are almost 200%.
- sEE 2050 suggests a 48% market share for district heating with high and low- temperature heat sources representing 49% of the fuel mix.
- The energy system redesign focuses on maximizing synergies across different sectors, combining energy efficiency measures with renewable energy and energy storage.
- sEE 2050 has a higher degree of electrification of industry and transport compared to 1.5 TECH.

In total the sEE 2050 scenario enables a more sustainable energy use with a 20-30% lower primary energy input compared to the European Commission scenario meeting the Paris Agreement 1.5 TECH . Also, the total costs are about 10% lower than the 1.5 TECH scenario. Compared to 2019 the sEEnergies 2030 and 2050 scenarios lead to a reduction in primary and final energy consumption of about 25 and 45% respectively. Steps towards 2030 within district heating are pivotal to achieve this outcome.

District Heating is the next enabling technology for the Integration of Renewable Energy
Space heating and hot water preparation demands fluctuate significantly throughout the year. Baseload heat sources like industrial waste heat, geothermal, and waste-to-energy, alongside emergent ones from datacenters and electrolysis, offer constant availability. Yet, these sources typically cannot be combined due to their continuous output, with the most cost-effective source dominating local supply. Solar thermal may supplement in cases where waste heat is scarce, and any excess waste heat during low-demand periods (summer season) can offset grid losses.

Elevating district heating's market share to 20% by 2030 and 48% by 2050 is transformative, delivering short-term benefits addressing the energy crisis and long-term climate solutions with higher system level renewable energy shares:

- Significant utilisation of geothermal and otherwise wasted heat, constituting 29% of the mix by 2030 and 49% by 2050.
- Integration of fluctuating renewable electricity with:
  - thermal storage combined with flexible operation of CHP plants[1]
  - large-scale heat pumps gradually replacing CHP plants as well as inefficient fuel boilers, enhancing energy efficiency and electricity grid stability

The renovation of the building stock combined with district heating are key enablers for:

- Direct use of low to medium-temperature waste heat sources and deep geothermal sources
- A higher COP[2] for large-scale heat pumps combined with waste heat or geothermal
- A changed structure for heat demands with lower winter peaks leading to a better and greater use of base-load waste heat streams and geothermal

Countries such as Belgium, Cyprus, Greece, Spain, France, Ireland, Italy, Malta, Netherlands, Portugal and the UK currently have extremely low district heating shares, below 6%. They all have a pressing need for a robust district heating development towards 2050 targeting between 35 and 55% and 10 to 15% by 2030. Other countries have a slightly higher outset but should aim for similar district heating shares by 2050. Germany, Croatia, Hungary, Luxembourg, Romania and Slovenia, district heating has currently market shares between 10 to 20% district heating share. District heating is well established in Northern European countries. Finland, Denmark, and Sweden as well as the three Baltic countries currently have high district heating market shares of about 50%. The analyses show that Finland and Lithuania should aim for a market share of 60% in 2050.

Vast amounts of Waste Heat and Deep Geothermal available in all EU countries
The total current and potential future heat sources are above 2,000 TWh pr year in the assessment of waste heat sources conducted here from industry, waste heat from wastewater treatment plants, food retail, metro stations, electrolyses, data centres and deep geothermal, see Figure 1. In the 2050 energy system heat demands are 40% lower compared to today. 48% of the 1,850 TWh heat demand in 2050 can be supplied with district heating. This means that there are untapped heat sources available to cover twice the feasible district heating level in 2050. The current waste heat sources combined with renewable heat sources could

[1] Combined heat and power plants.
[2] The coefficient of performance or COP of a heat pump is a ratio of useful heating pr. electricity input.

theoretically cover half the total current heat demands. There are plenty of opportunities in almost all countries:

- 22 countries can cover 50% or more of the current country level heat demand with resources currently availed, i.e., all untapped sources mentioned except metro stations and electrolysis. The same is the case for those countries considering the reduced 2050 country level heat demands. This includes larger countries like, Germany, Spain, France, Italy, the Netherlands and Poland.
- Some countries may have more than 100% untapped heat potential for 2050. These countries include Cyprus, Spain, Poland, Croatia, Portugal, Slovenia and Slovakia.

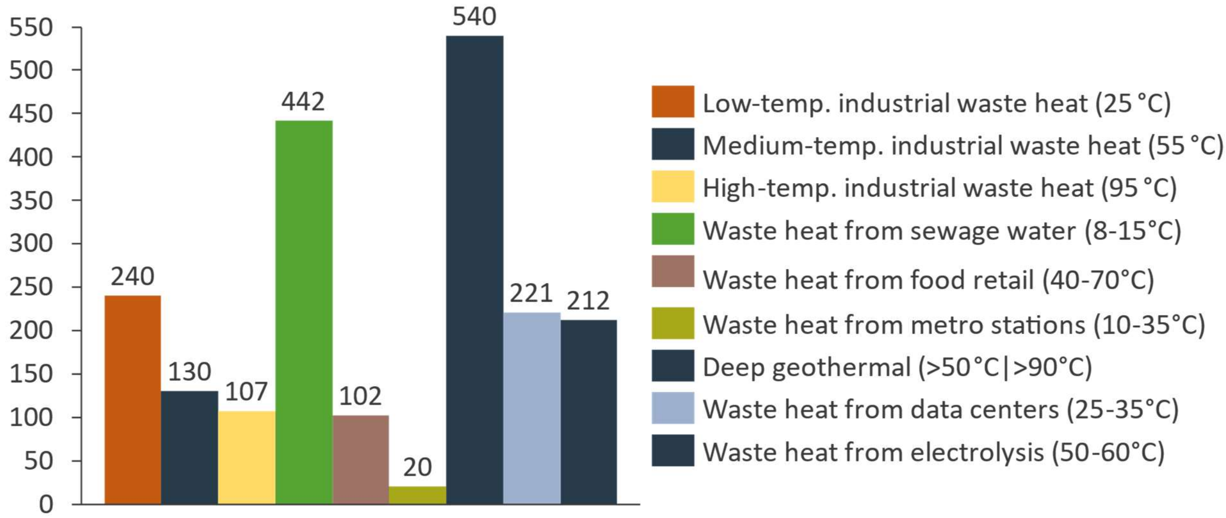

Figure 1, Heat source types and potentials for use in district heating systems towards in 2050 in EU27 in TWh/year. It should be noted that due to the costs and production profiles far from all these resources can be used and many or mutually out ruling each other. The references, assumptions, and methodology are listed below. Some of the sources require large-scale heat pumps for the exploitation. For background and methodology please refer to chapter 4.

Investment in District Heating and number of New Systems

Expanding district heating will require significant investments in heating infrastructure. By 2030 a total of 144 billion EUR is needed to grow from 13% - today's market share - to 20 % and an additional 541 billion EUR to reach 48% by 2050. Belgium, Germany, Spain, France, Italy, the Netherlands and the United Kingdom are the countries where the highest level of investments is needed. Each will need to invest over 20 billion EUR to expand District Heating before 2050. Other countries like Austria, the Czech Republic, Grece, Hungary, Poland, Portugal and Romania need to invest at least 5 billion EUR before 2050.

Typically, new district heating systems in the larger urban areas will merge as they grow and cover most of the urban area. About 3,500 district heating systems need to be developed by 2030 and further 15,000 district heating systems by 2050, see Figure 2. Many new plants need to be started to reach the long-term levels in each country.

To ensure to tap into the vast potential for district heating about 18,500 new district heating systems need to be established. The distribution between countries follows district heating investments with many systems in the larger countries, where Germany, Spain, France, Italy, Poland and the UK need to start more than 1,000 new district heating systems each towards 2050, while Austria, Belgium, Lithuania, Poland and Romania need to establish more than 500 new district heating systems.

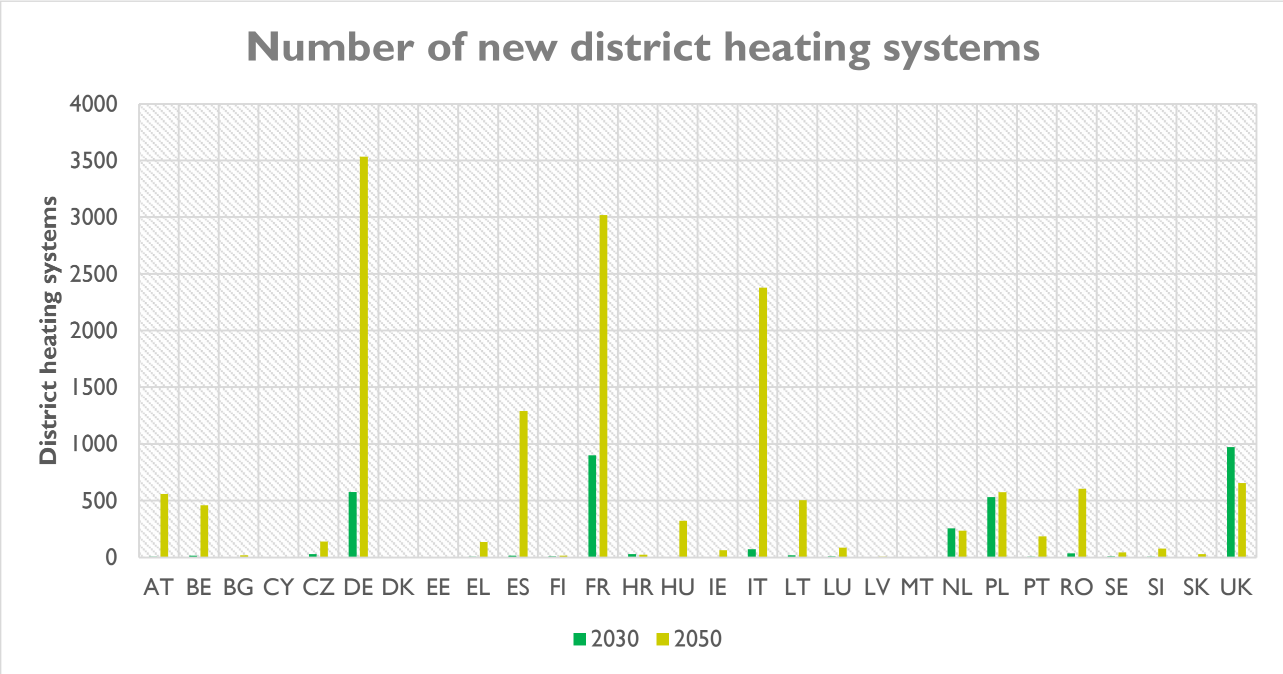

Figure 2, Number of district heating systems per country. For background and methodology please refer to chapter 4.

Content

1 Introduction

The energy crisis began in the summer of 2021, due to a worrying depletion of European gas storage reserves, which impacted severely electricity prices. Yet, the crisis hit most European citizens from February 2022 and during 2023, when heating and electricity prices surged. It has exposed the dependency of the European heating sector on natural gas use.

Space heating and hot water is responsible for about one third of the final energy demand in the European Union and more than 75% of this heat comes from burning fossil fuels (Kranzl, Forthuber et al. 2021). When breaking down the EU's gas demand, the residential sector emerges as the largest consumer, constituting 40% of the demand for natural gas: transitioning away from natural gas use in heating is therefore essential for both energy security and the achievement of the climate goals. So far, Europe's energy transition strategy to decarbonise the EU heating sector has relied on two main pillars: energy savings and the reduction of the heat demand in new and refurbished buildings, and the deployment of renewable electricity sources. The EU energy efficiency policies in the end-user demands pr. service have had mixed results. Buildings are much more efficient pr. square meter compared to in the year 2000, however there are more dwellings, appliances and larger homes, so the resulting energy demand is the same today (Odyssee-Mure 2021). For heating in general compared to electricity, the integration of renewable energy has not been as successful. Overall, the impact of these policies has been beneficial yet uneven across Europe. At the same time, many essential aspects to successfully reduce gas demand in heating and cooling have been overlooked:

- A sole focus on energy efficiency in buildings has not unlocked a more sustainable energy supply for heating;
- A sole focus on electrification of heating overshadows the significant potential of renewable and excess heat sources, and may increase the need for electricity grids and power plants beyond what is economically and technically feasible;
- The necessary integration of renewable electricity sources in the energy system is not limited to developing electricity grid infrastructures and interconnections between countries. It should also consider the benefits of vertical integration within district heating grids, to convert excess electricity production into renewable heat and provide system flexibility.
- An exclusive focus on renewable electricity does not unlock the potential for other renewable energy sources such as geothermal and solar thermal.

A more coordinated and integrated energy system approach is needed. In the light of recent developments, it is also clear that a stronger focus is needed on deploying alternative heat sources to substitute natural gas that still supplies 40% of buildings. In 2016, the European Commission published the European Heating and Cooling Strategy which gave some directions for a smarter and more diversified policy on energy savings and energy supply in the heating sector (European Commission 2016).

The conclusions of the strategy were partially reflected in the recent energy and climate legislation adopted by the EU to accelerate the heat transition, in particular the Clean Energy for all Europeans from November 2016 and the Fit for 55 Package from July 2021. However, this did not spark the same implementation focus seen for other sectors e.g. the potential for renewable and waste heat sources has remained unexploited, while fundings for natural gas grids continued.

The latest Directive on Energy Efficiency EU2023/1791 introduced a mandate to carry out heating and cooling plans for cities larger than 45.000 inhabitants, a new breadth supporting the much-needed diversification of Europe's heat supply, and the deployment of essential energy infrastructures such as district heating and cooling (European Union 2023). Even though this is not yet fully implemented in every member state and while more is needed at EU level to ensure structural changes locally e.g., it is a small but important leap forward.

This report sheds light on the continued risks of a high dependence on natural gas in the heating sector and analyzes the potentials of alternative clean heat technologies such as efficient district heating to handle the short-term energy crisis while enabling a cost-effective decarbonisation towards 2050. This report builds on the results of the sEEnergies project (Mathiesen, Ilieva et al. 2022a, Mathiesen, Ilieva et al. 2022b) .

2 The Energy Crisis is not over

The Energy Union initiated by the previous European commission did not have a gas exit strategy. Instead, it established a gas diversification strategy with the aim of having more suppliers of natural gas which failed. Shortly before the invasion of Ukraine in February 2022, 40% of Europe's gas import were coming from Russia and Nord Stream 2 was supposed to start operation. Combined with Nord Stream 1, Nord Stream 2 could have eliminated the need for gas diversification, increasing the European dependency to Russian gas supply in a highly uncertain geopolitical context. With the largest share of natural gas used for heating households and industrial and tertiary buildings in Europe, the risks are essentially borne by European citizens and industries. As of October 2023, the European dependence on Russian gas imports is still too high to claim victory for real European energy independence. Existing measures must be complemented by additional policies to decarbonise heating.

The buildup of natural gas import dependency and the importance of the heating sector

In the decade from 2011 to 2021, the primary energy extraction of coal and other solid fossil fuels, oil, natural gas, and nuclear energy structurally declined in EU. Natural gas experienced the most pronounced reduction by 63%. While domestic natural gas extraction has decreased in Europe, the use of natural gas remains important, see Figure 3. Solid fossil fuels and oil and petroleum products decreased by 39% and 36% respectively. In contrast, the production of renewable energies increased by 48% during this period.

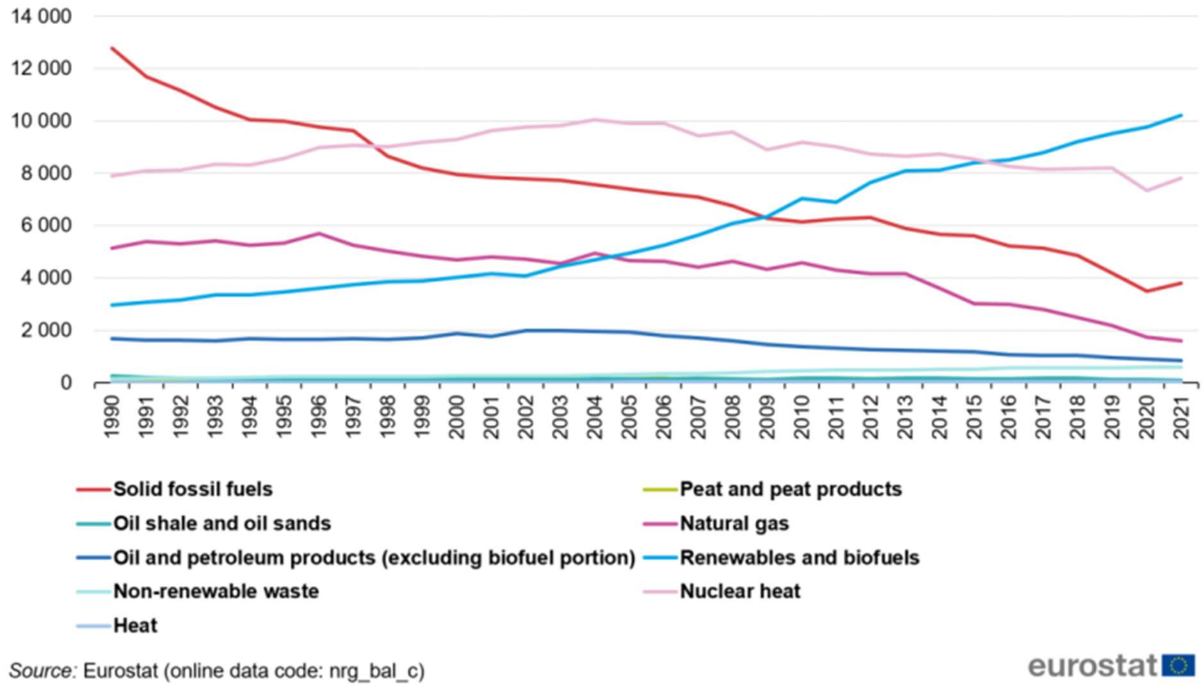

Figure 3, The Primary Energy Production by fuel within EU27, selected years 1-2021 in PJ (Petajoule) (Eurostat 2023).

In the period from 1990 to 2021, the overall energy consumption stagnated at about 60,000 PJ for EU27, while natural gas consumption increased in the same period from about 10,000 PJ to about 14,000 PJ today, see Figure 4.

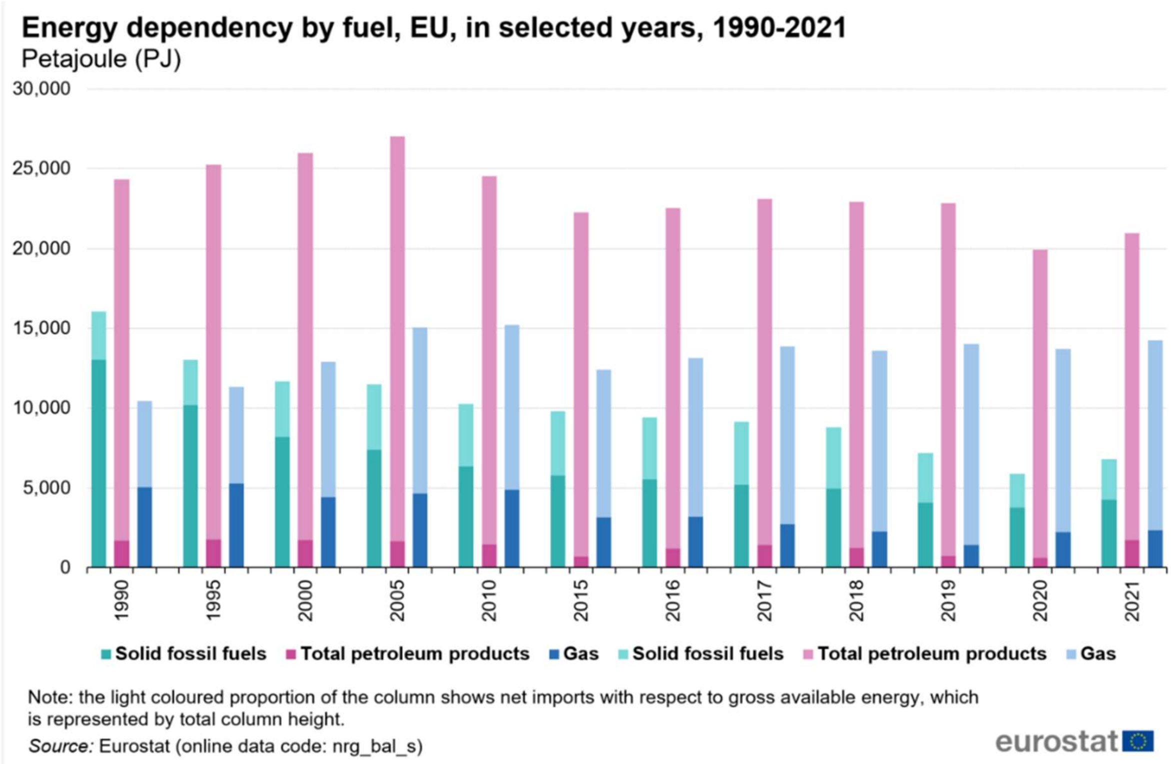

Figure 4, Energy import dependency by fuel, EU27, selected years 1990-2021 in PJ (Petajoule) (Eurostat 2023).

In 2021 93% of oil and petroleum products in the EU was imported. 83% of the natural gas demand was met through imports, with domestic production decreasing by 50% over the past decade. The trend from 1990 onward reveals a growing European reliance on fossil imports, in particular natural gas. While only half of all fuels consumed in 1990 was imported, this rose to 56% in 2021, making Europe vulnerable not only geopolitically but also economically.

When breaking down the EU's gas demand, the residential sector emerges as the largest consumer, constituting 40% of the total demand for natural gas. This is trailed by industry and power generation from gas. Since 2000, industrial direct gas consumption decreased by 20%, whereas the use of gas for power generation has increased by 15%.

The structural dependence on natural gas in the heating sector

Since 1990 until today the dependency of natural gas in individual heating boilers has increased by 50%. As mentioned, the overall demand for heating has remained the same even though the volume of square meters heated has increased. The increase in the use of gas-heating has been on the expense of individual coal and oil-based heating systems (Bertelsen, Mathiesen 2020). Nevertheless, there are great differences across countries when it comes to natural gas consumptions within different sectors.

Space heating and hot water consumption constitutes about one third of the final energy demand in Europe (Fleiter, Elsland et al. 2017). In total, gas accounts for about 22% %of the EU's primary energy intake with 40% of households connected to the gas network. In Figure 5 the division of fuels for heating is illustrated. 55% of heating demands from buildings are met with fossil fuel boilers in households (mainly natural gas and heating oil).

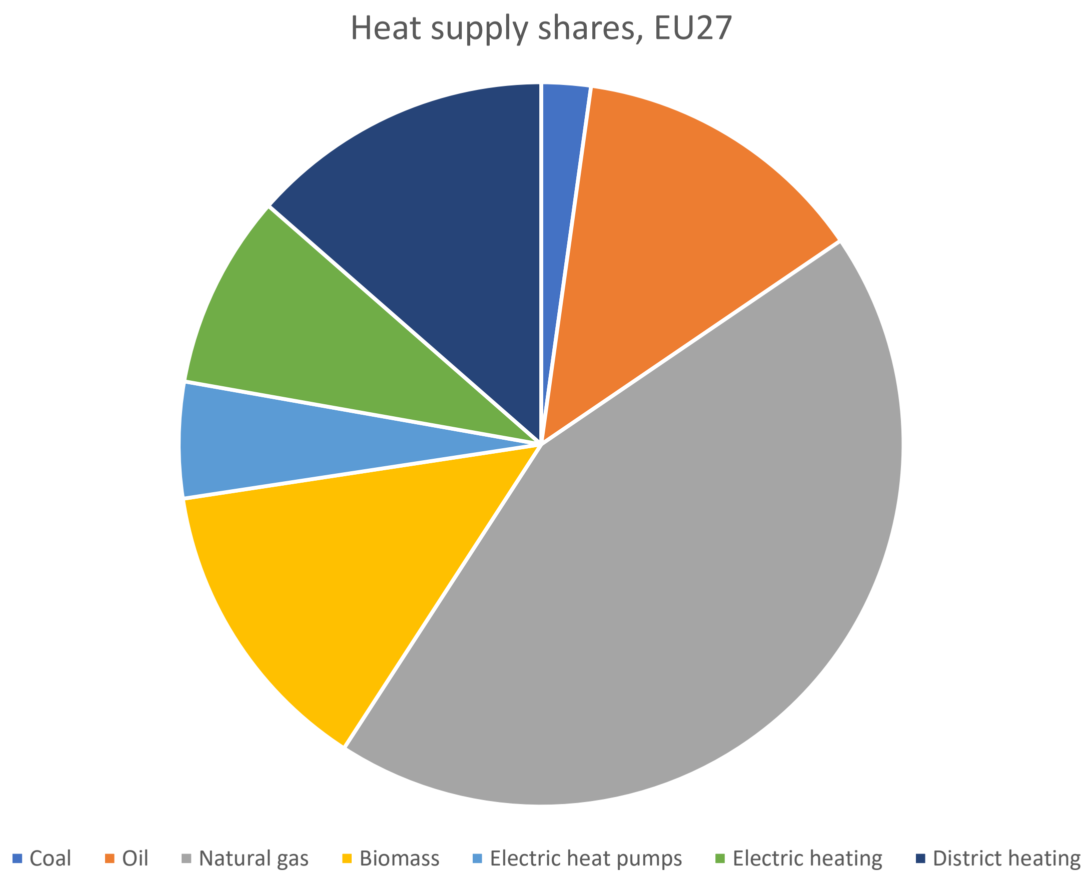

Figure 5, Supply of end heat demand in buildings divided by supply input in the sEEnergies 2019 reference model.

The volume of fossil-fuels needed to heat buildings, as well as the fuel-mix differ greatly among countries, see Figure 6 and Figure 7. Overall, the critical lack of focus on structural change for heating decarbonisation triggered a structural increase in energy imports to meet demand. Still today, large European countries such as Germany, Italy or the UK have a very high dependency rate on natural gas and oil combined. Poland stands out with moderate levels of natural gas and oil in heating but a higher share of coal.

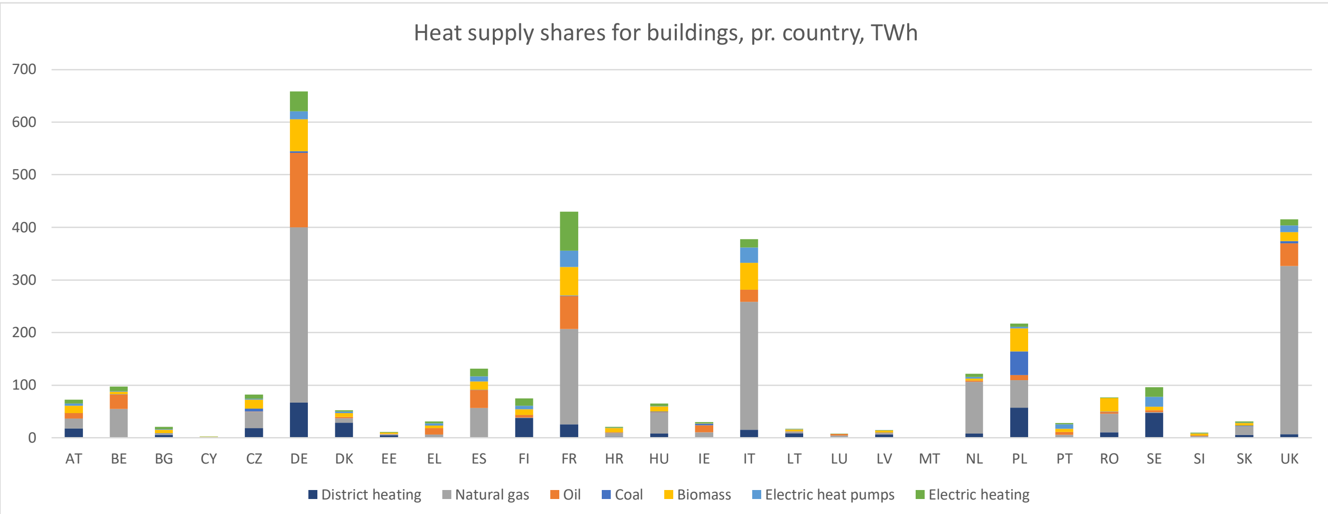

Figure 6, Supply of end heat for buildings in the sEEnergies 2019 reference model divided by input fuel pr. country.

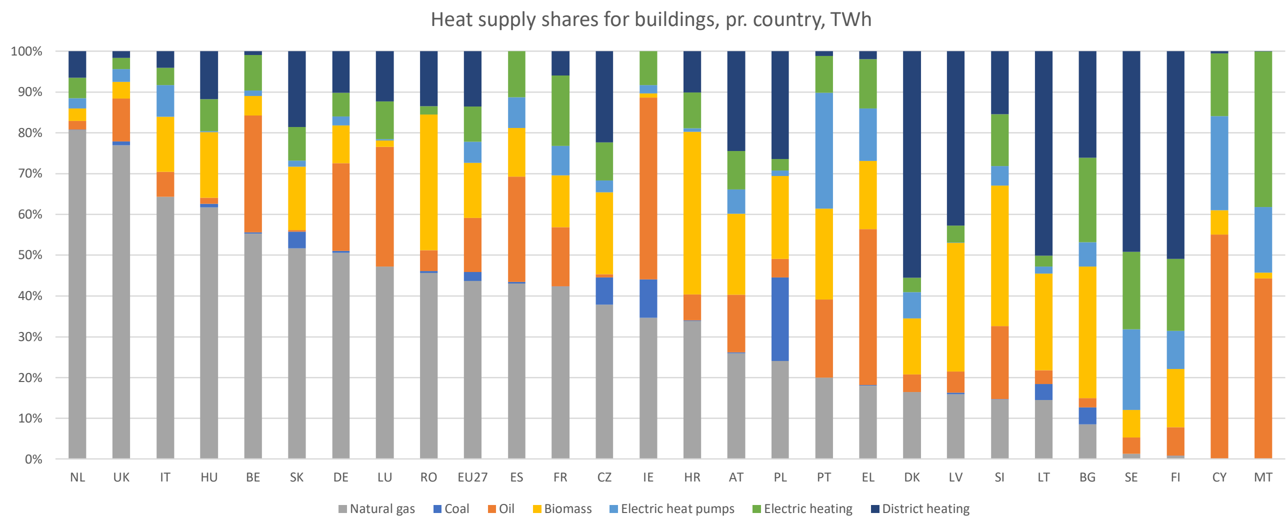

Figure 7, Heat supply shares for buildings in the sEEnergies 2019 reference model divided by fuel share pr. country.

The current situation shows however the value of collective heating solutions such as district heating compared to heating based on individual natural gas boilers, to mitigate and even reduce the fossil-dependency for heating:

- Countries where district heating has a market share over 40% have a share of natural gas boilers lower than 20%, see Figure 8.
- Gas boilers represent over 40% of the heat market in over half of the countries where district heating has a market share below 20%, see Figure 8.

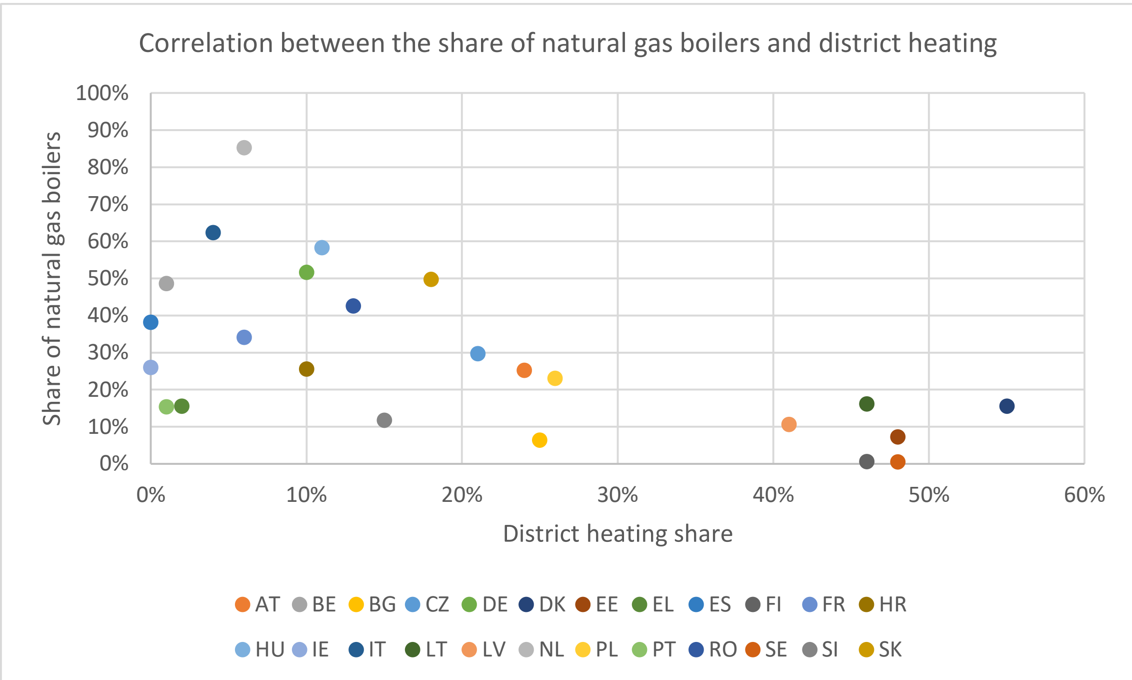

Figure 8, Correlation between the share of natural gas consumption for individual heating systems and district heating share for heating buildings pr. country in 2021. Based on data from (Bertelsen, Mathiesen 2020, Geelen, J., Jossart, J.-M., & Andone, A.-N. 2023).

In Figure 9 the broader structural dependence on fossil fuels is correlated with the levels of district heating. Countries with higher amounts of district heating not only have lower natural gas dependence in the heating sector, but also have a lower reliance on fossil fuels in individual heating:

- Two thirds (nine out of fourteen) of the countries with less than a 20% district heating have a reliance of half or more on fossil fuels in individual heating, see Figure 9.
- The ten countries with 10% district heating shares or less e.g. Germany, Italy, Belgium, Ireland and the Netherland cover heating with more than 70% individual fossil fuel heating systems, see Figure 9.

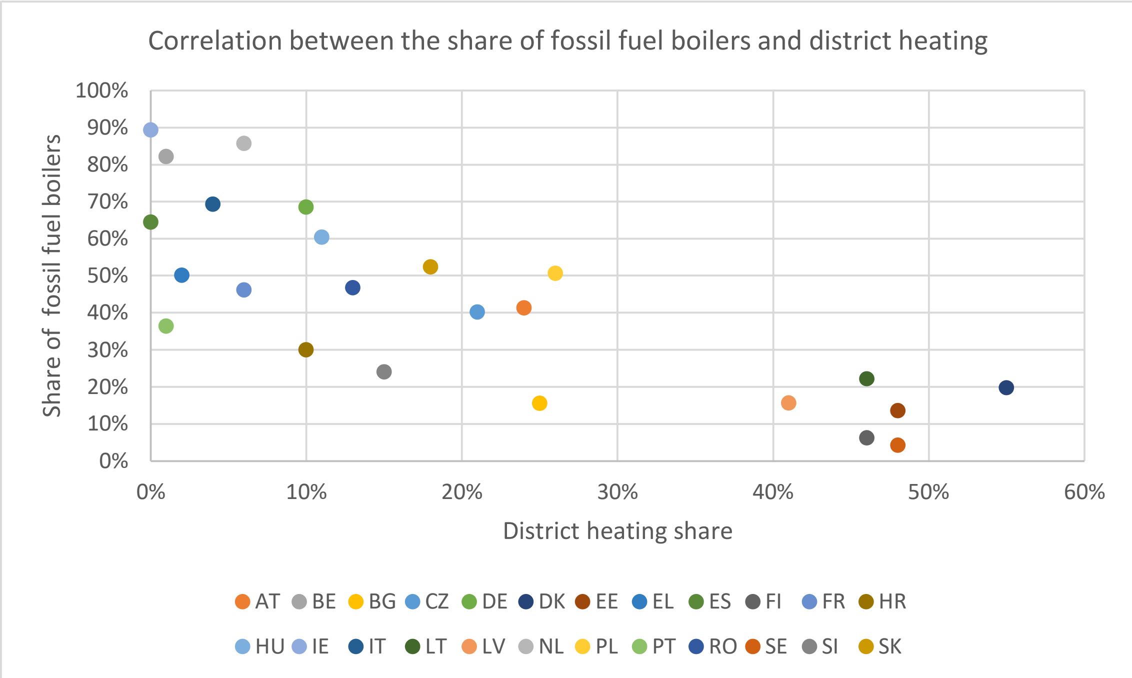

Figure 9, Correlation between the share of fossil fuel consumption for individual heating systems and district heating share for heating buildings pr. country. 2021. Based on data from (Bertelsen, Mathiesen 2020, Geelen, J., Jossart, J.-M., & Andone, A.-N. 2023).

It should be noted that the current district heating infrastructure also uses natural gas. However, the largest share of natural gas is used in high efficiency CHP plants, i.e. this is heat from electricity production otherwise wasted. This situation will change gradually with the introduction of new sources in the coming years, as the gas shares in electricity production will be lower.

REPowerEU initiatives and status

In the aftermath of the COVID-19 crisis EU level decision making entered a new era marked by urgency. As a timely response to the energy crisis the REPowerEU initiative introduced a set of proposals to make the EU independent from Russian natural gas imports, by 2027. These policies have been very effective to reduce the natural gas consumption and import via pipelines from Russia. The initiatives have been divided into three parts: Acceleration of Clean Energy Transition, Save Energy / Energy Efficiency and Diversification of Energy Sources.

According to Bruegel Natural Gas demand tracker the natural gas demand in the EU (excluding storage filling) decreased by 12% compared to the average demand between 2019 and 2021 (McWilliams, B., & Zachmann, G. 2023). The monthly breakdown for the last quarter of 2022 showed that October, November and December experienced decreases of respectively 27%, 24% and 13%. While the summer months showed a significant reduction in industrial demand, October and November marked notable decreases in household consumption. This decrease was, in part, influenced by temperatures being higher than the usual average but also a higher demand for natural gas in the power sector due to lower outputs from nuclear power and hydro power in 2022. The effects of REPowerEU start to become very clear in the first six months of 2023 where the overall EU gas demand for the period is 19% beneath the average. This is more than the overall REPowerEU goal for each EU country to reduce demand by 15%.

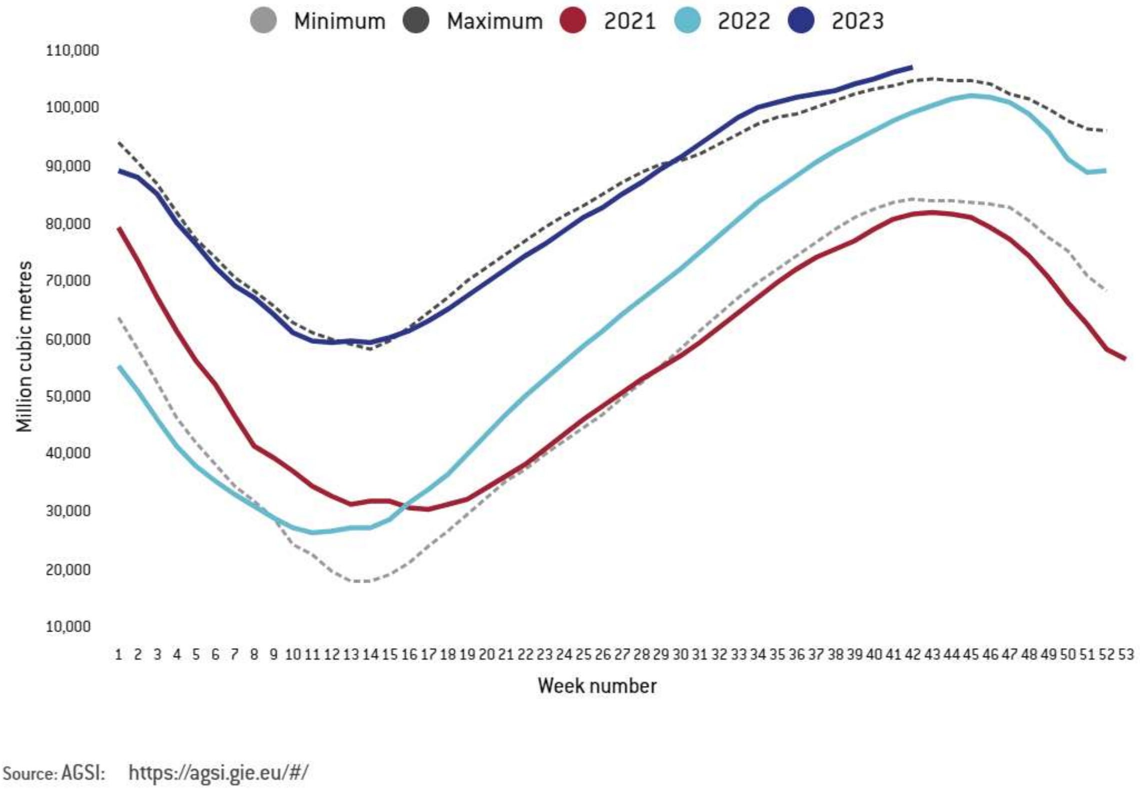

Figure 10, Status of natural gas storages in EU (in million cubic metres). Minimum and maximum values are calculated from the period 2015-2020 (McWilliams, B., & Zachmann, G. 2023).

There are several indicators of the success of the three pillars[3] in the REPowerEU approach. Overall the EU has moved in the right direction to lower demands for natural gas. This has come as an effect of energy savings, an increasing share of renewable energy and in some cases the intermediate use of coal and oil within industries. The diversification of energy sources including new LNG imports have also played a role. The impact of REPowerEU materializes with the current levels of gas storages, at their highest levels since 2015, see, see Figure 10.

While the effects of the initiatives are clear, they have not delivered a situation where the EU can be said to be independent from imports of Russian natural gas. The recent report on the State of the Energy Union (October 2023) by the European Commission shows a clear change in the structure of imports, see Figure 9. The EU has sought to diversify the natural gas suppliers by importing liquified natural gas (LNG) from different parts of the world, including the United States and Qatar. New investments in interconnectors, pipelines, and LNG terminals will allow for a more flexible and diverse energy supply.

[3] The three pillars: Accelerate clean energy transition, Save energy and Diversify energy sources.

Figure 11, Composition of natural gas imports (pipeline and LNG) for the period 2021-2023; Sources: ENER Chief Economist team, based on data from JRC, ENTSO-G (European Commission 2023).

While demands are being reduced, the import dependency is still high, and a share of the Russian natural gas has been replaced with gas consumption from other parts of the world. Most notably there is an increase from the United States. Still natural gas imports from Russia represented 14% of all imports for the first half of the year (European Commission 2023).

With a structural dependence on natural gas imports of 83% before the energy crisis, the end-demand reductions achieved so far are not enough to reduce the dependency on Russian natural gas without increasing the dependency of natural gas from other parts of the world, see Figure 11.

Without additional measures that go beyond the EU 2027 target of independence of Russian natural gas, the EU is set to become structurally more dependent on e.g. North Africa, Qatar, Azerbaijan and the United States as no additional natural gas extraction is expected from Norway or from within EU.

Deploying the right heating solutions is paramount to put an end to the EU's structural dependence on natural gas consumption. As previously mentioned, the countries with the highest shares of individual fossil heating systems have a greater structural dependence on fossil fuels for heating. The REPowerEU focused mainly on the deployment of household heat pumps, which have benefited from a real market boost following the rise in gas prices. However, the benefits of energy system integration and expanding the use of district heating did not get the necessary attention.

In the next parts of this report, we investigate the role of district heating to put an end to the EU's structural dependence on natural gas, from short term gains towards 2030 to longer-term with long term perspectives, by 2050.

3 Methodology

This chapter presents in summary the methodologies and main assumptions in the assessment of the potential effects of district heating infrastructure expansion and decarbonisation, to accelerate gas savings in heating towards 2030. To analyse the changes and potential of energy efficiency in the heating sector it is pivotal to take an energy system perspective. To do so, we analyse changes in 2015, 2019, 2030 and 2050 hour-by-hour from an EU27 and country by country perspective. In some cases, the UK is included in the analyses and when this is the case, it is clearly stated. The analyses are compared to the REPowerEU initiatives as well as to the EU's long term 2050 scenarios aligned with the Paris Agreement, as described in A Clean Planet for All (COM (2018) 773) (European Commission 2018). For a more in-depth understanding of the methodologies in the system redesign and energy system analysis than presented here, we refer to the report in the sEEnergies project (Mathiesen, Ilieva et al. 2022b). The purpose is to assess the effects of the energy efficiency first principle in the project in the current and future energy systems.

Modeling approach for long term 2050 decarbonisation

For the comprehensive energy system analysis of each country within EU27 and for the UK, a tailored modeling platform was employed. This platform integrated energy sector scenarios and grid costs, providing a holistic view of the energy system. From the individual analyses of each country, an aggregated energy system for EU27 plus the UK was established. In the analyses presented here a focus is on EU27 and 2030, however in some cases results for EU28 or EU27 plus the UK are presented which is then clearly stated. The scenarios incorporate various "Energy Efficiency First" strategies across sectors. In addition, the design of these energy system scenarios factors in grid-related costs and spatial analytics. All 28 countries (encompassing the EU27 and the UK) undergo individual assessments, resulting in a consolidated EU scenario, termed sEE 2050. This integrated model provides a blueprint of Europe's potential trajectory, illustrating how, by adhering to the "Energy Efficiency First" principle.

For the advanced energy system analyses, the EnergyPLAN tool was used in combination with GIS (geographical information systems) and tools for a bottom up understanding of the industry, transport and electricity grids. The purpose is to understand the dynamics of the energy system performance of each country in the long term, breaking down their energy usage and requirements hour-by-hour. The energy system analyses tool, EnergyPLAN, is a deterministic simulation model, analysing hourly balances for all energy sectors of the energy system including the heating, power, gas, transportation, and industry sectors (Lund, Thellufsen et al. 2021). The tool is updated regularly to maintain relevance with technological advancements. It does not include spatial allocation of energy demands and supply in the modelled system, but in sEEnergies, several of the data inputs are based on spatial analyses conducted in the individual work packages.

The EnergyPLAN tool is fed by sector scenarios in buildings, transport, industry and for grids, see Figure 12. Also, there is dynamic interaction on selected inputs with GIS for the transport and heating supply systems. The result is a comprehensive bottom-up sector analysis for buildings, transport, industry and grids combined with a top-down energy system analysis.

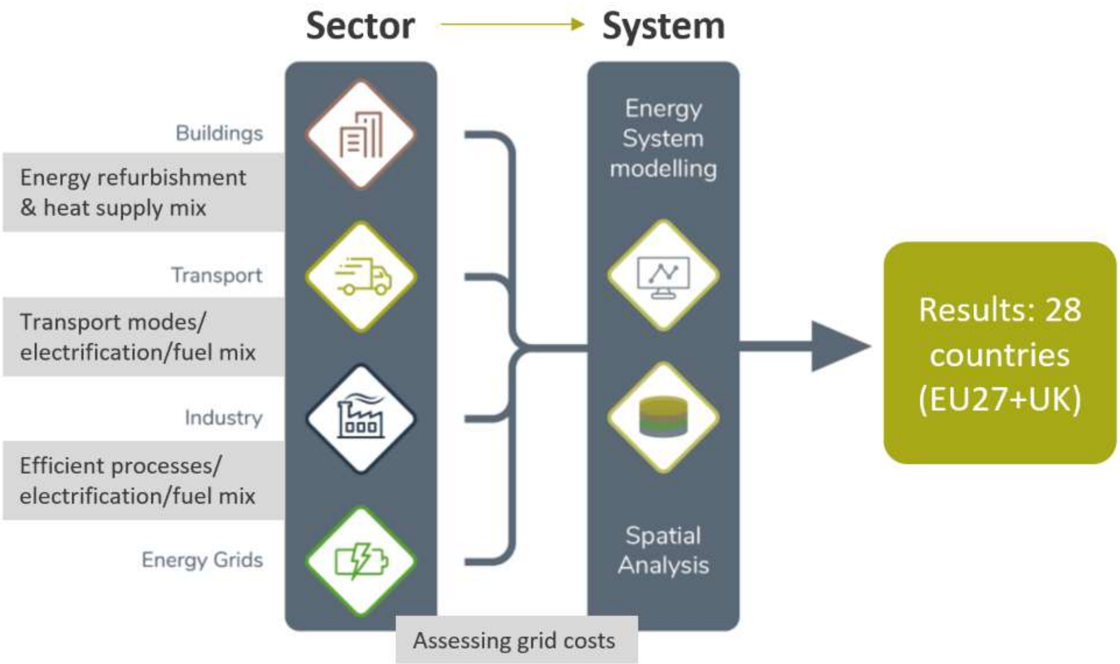

Figure 12, Structure of the modelling performed in sEEnergies for 28 countries, EU27 and the UK (Mathiesen, Ilieva et al. 2022a).

A technology costs database was created to facilitate this aspect of the analysis. This database reflected both current and projected cost levels, ensuring accuracy in the modeling process. The foundation for future costs was established upon the principles of technological progression and a detailed breakdown of costs related to manufacturing and installation, including raw materials, labor and finance.

The results of these analyses for 2050 were decarbonized systems based on 100% renewable energy for each country with a focus on using a smart energy system approach. Various parameters were considered in the energy systems modelling including the socio-economic costs associated with each energy system, the capacity for renewable electricity, the degree of electricity exchange with neighboring nations, the balance between energy efficiency and district heat or household heat pumps as well as the overall consumption of sustainable biomass (Mathiesen, Ilieva et al. 2022a).

The energy scenarios created in sEEnergies for 2050 are compared to the scenarios from the European Commission in "A Clean Planet for All" (European Commission 2018). Two scenarios are included in the modelling: a Baseline for 2050 as well as the 1.5 TECH scenarios, which is one of two long term scenarios in line with the Paris Agreement in the report. In sEEnergies these scenarios were recreated on our modeling platforms in order to create a fair comparison between the different possible future scenarios.

Back-casting to 2030

In sEEnergies a 2030 model was developed based on sEE1.5 2050, using back-casting to assess the effects of the energy system transition on the reduction of natural gas in the light of REPowerEU. Figure 13 visualises the back-casting approach. For numerous energy system components trend curves from 2015 to 2019 were used in combination with an interpolative S-curve transition towards 2050 in order to project the timing for the investment and implementation from 2015 to 2050. Hereby, the prioritisation and timing of the energy efficiency actions based on their impacts, current development level and role within the reconfiguration of the energy system design to 2050 was considered. In addition to that, a focus was set on what can be accelerated in the light of REPowerEU.

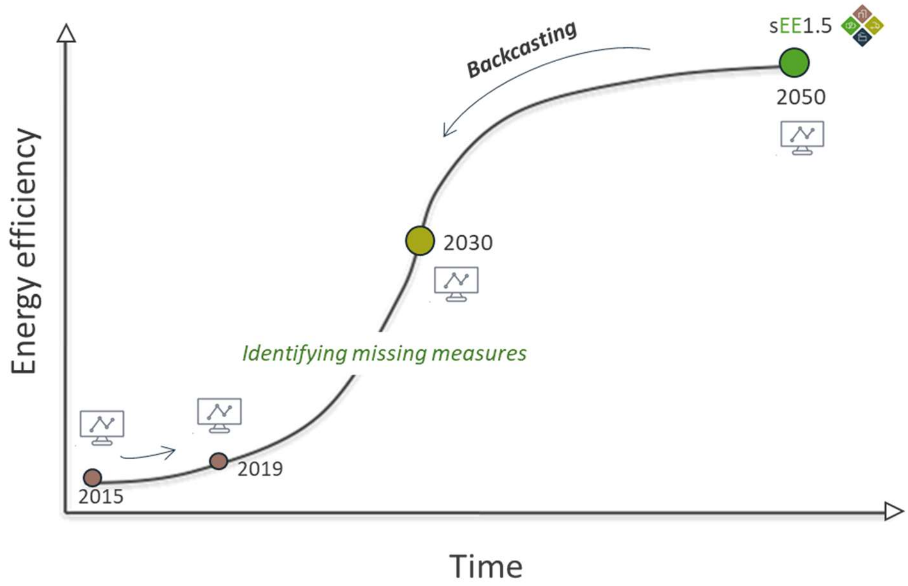

Figure 13, Back-casting principle used in sEEnergies to develop the sEE 2030 scenario (Maya-Drysdale, Abid et al. 2022).

District heating potentials and grid expansion costs

In the analyses in sEEnergies and the previous Heat Roadmap studies a 50% market share for district heating has been assessed based on feasible balances of overall costs as well as resource and energy consumption overall. There are no surveys or inventories of the existing district heating grids in Europe. In this report the district heating grid expansion costs are identified transitioning from the current level of 13% district heating to a 20 and 50% market shares by 2030 and 2050 respectively. The screening of district potentials and expansion costs is based on the research done in sEEnergies, where a comprehensive description of the methodology behind the data is presented (Persson, Möller et al. 2021). The data is used in this report to estimate the potential for 2030 for EU27 countries plus the UK. The specific dataset used is the Urban Area Future District Heating Potential dataset, which includes the aggregated heat demand for around 147,000 urban areas, most of which are the same as city boundaries (Persson, Möller et al. 2022). As there is no high-quality data available on the geographic coverage of existing district systems in Europe, an approximation is made in this report. While the exact location and extent of district heating are not available, the national numbers for district heating coverage and final heat demand are. Thus, the geographic coverage of existing district heating is approximated by sorting cities by high industrial excess heat availability and high heat density areas. Cities are selected in each country until the district heating coverage of each country is reached in the given year. This approach provides a rough estimate of the location of future district heating systems but is by no means predicting precisely where those are located. In reality, the coverage of district heating is a result of historic developments with many factors influencing where district heating was actually developed. As mentioned, no pan-European data is available. We do recommend establishing and build up an actual geographic database of existing district heating systems, similar to what is already existing as part of the in Danish planning system.

In this report, the screening of investment costs in district heating is based on average costs for five different intervals, as the used dataset only includes the potential by urban area where the marginal distribution capital costs are summarized in intervals of 0-2, 2-5, 5-10, 10-20 and >20 EUR/GJ depending on the density of the urban area. In this analysis, costs of 1, 3.5, 7.5, 15 and 20 EUR/GJ are used for the same five categories, as the distribution within each interval is unknown.

Estimation of number of new district heating plants needed

Another aspect of the report is estimating how many district heating systems would need to be built by 2030 and 2050 to achieve the higher share of district heating. A simplified methodology is used for the assessment, assuming larger urban areas will start with more district heating systems and develop gradually into larger unified systems. Therefore, the following is assumed in order to assess a number of new systems needed. It is assumed that urban areas with a final heat demand:

- Less than 1 PJ needs to develop 1 district heating system
- 1-10 PJ:1 district heating system per 1 PJ
- 10-20 PJ: district heating system per 2 PJ
- Above 20 PJ: district heating system per 4 PJ

Applying this methodology means that e.g. a city the size of Vienna would have to develop 9 different district heating systems if district heating was to start there today from nothing. In the results, both the number of cities and the number of district heating systems that need to be developed are presented. Again, this assumption of numbers of district heating system is an approximation, as the actual number will depend a lot on the specific settings in each area.

In addition, the most important district heating cities are estimated for each country.

Assessment of untapped heat sources when expanding district heating

In this report a new assessment of several of the main untapped waste heat sources is conducted. In general, the sources are vast, but the ability to tap into this potential varies depending on geographical and economic characteristics. District heating infrastructure are however always pivotal to use such sources.

The assessments are built on previous analyses of the heat market, combined with existing knowledge of the potential for district heating in 2030 and 2050, and the location of waste and renewable heat sources when possible. The sources included in the analysis are the temperature levels of industrial waste heat, waste water treatment plants, food retail, metro stations, geothermal sources as well as data centres and eletrolyses. The gross levels deemed possible in 2030 and 2050 are assessed at EU level, and at country level when possible:

Geolocated data for waste heat sources with a higher resolution than a country level for 2030 and 2050:

- The potential for industrial waste heat above 55°C is geolocated in sEEnergies and can be assessed for 2030 and 2050 on a country or even smaller urban area level.
- The same is the case for waste heat from wastewater treatment plants using data from the REUSEHEAT project (Persson, Averfalk 2018).

Geolocated data for waste heat sources used ONLY on a country level for 2050:

- For food retail, metro stations, as well as data centres the potential for the use of waste heat is assessed from facilities in REUSEHEAT (Persson, Averfalk 2018). These country level data are used for the assessment of the country level waste heat with slight adjustments.
- Geothermal potentials pr country assessed based on a spatial analysis with the high-density heat demand areas in the Pan-European Thermal Atlas matching with geothermal sources.
- For waste heat from electrolysis only an EU level is assumed, as such facilities are not built yet. It is however anticipated that these facilities will be built close to the low-cost wind power resources in EU both onshore and onshore.

4 Analyses of the role of district heating towards 2030 and 2050

Compared to the situation today, there are many potential options to change the heating system. However, a system redesign including a deployment of district heating grids is needed to facilitate such change. The question is: what is the short-term potential of district heating to reduce the need for natural gas while enabling a long-term decarbonisation?

The main results show the strategic importance of district heating for Europe's 2030 and 2050 energy and climate goals. The untapped heat sources and the potential future market share and production mix for district heating are presented. The modelling of a diversified energy mix for district heating and a need for significant investment in infrastructure is presented as well as the potential for phasing out natural gas with the means of district heating.

Primary and Final Energy Consumption in Europe

In order to understand the potential future heating sector from both a supply and demand side perspectives the modeling in sEEnergies created a bottom-up approach that connects with top-down energy systems analyses. A pivotal factor in understanding and designing future energy systems are the characteristics of technologies and their respective deployment costs. The hourly dynamics and interactions between all components of the energy sector have to be understood. The scenarios include amongst others:

1. The technologies related to energy efficiency, storage as well as renewable energy.
2. The characteristics of energy grids including the effects of savings on electricity, gas and thermal grids (Meunier, Protopapadaki et al. 2021).
3. The dynamics of end-savings in buildings compared to the supply of heat from clean sources.
4. Electrification, efficiency measures and new fuels in the industrial sector, with insights sourced from the IndustryPLAN tool (Mathiesen, Johannsen et al. 2023).
5. Transport infrastructure and electrification, drawing data from the TransportPLAN tool.
6. Integration of Power-2-X technologies and electrofuels.

The "energy efficiency first" principle is behind the focus on the end-use sectors like buildings, transport and industry in sEEnergies, as reducing energy consumption is a key element to achieving the EU 2050 decarbonisation target. The questions are as follows:

1) What is the influence of energy efficiency and energy savings on the broader energy system?
2) How can the nuances of this principle be made clear across end-use sectors?
3) What are the balances between energy efficiency and investments in renewables, energy storage and infrastructures?

The assessment of a feasible pathway for the heating sector builds on the understanding that the energy system is gradually decarbonised. Fully decarbonised renewable energy systems by 2050 were designed to address these questions in sEE 2050, see Figure 14. The sEE scenario is in line with the Paris Agreement target and is compared to the 1.5 TECH and Baseline 2050 scenario from the European Commission. The bottom-up and top-down analyses reveal new balances towards 2050 regarding to the possible changes.

sEE 2050 represents a robust system redesign, which allows for a better integration of variable electricity and builds on cross-sectorial connections to release additional flexibility sources, i.e., electric vehicles, electrofuels and the district heating system. The redesign provides an opportunity to integrate larger amounts of renewable electricity sources such as solar PV and wind in a more cost-effective way compared to the 1.5 TECH scenario, which in turn allows to balance the overall energy system with energy storage, thermal storages, district heating and electrolyses in Power-to-X plants. As a result, primary and final energy demand can be reduced significantly in sEE 2050 compared to today and to the 1.5 TECH scenarios:

- sEE 2050 has a lower primary energy demand compared to the 1.5 TECH PRIMES scenario and is more cost-efficient with similar final energy demands.
- sEE 2050 has a 40% reduction in heat demands from buildings. This is a lower end-demand level of saving compared to the 55% in the 1.5 TECH scenarios. The extra costs to reach 55% energy savings are almost 200%.
- sEE 20050 utilises about 50% district heating and low-temperature heat sources, reducing the necessity for extensive building refurbishments.
- The energy system redesign focuses on maximizing synergies across different sectors, combining energy efficiency measures with renewable energy and energy storage.
- sEE 2050 features a higher degree of electrification of industry and transport compared to 1.5 TECH.

The assessment of a feasible pathway for the heating sector builds on the understanding that the energy system is gradually decarbonised. Fully decarbonised future renewable energy systems for 2050 were modelled to address these questions in sEE 2050. Overall, it is documented in sEEnergies that a more energy efficient system is possible through further system integration, further electrification of industry and transport, as well as with district heating in combination with individual heat pumps and end-savings. This enables a more sustainable use of energy with a 20-30% lower primary energy input compared to the European Commission scenario meeting the Paris Agreement. Also, the total costs are about 10% lower than the 1.5 TECH scenario.

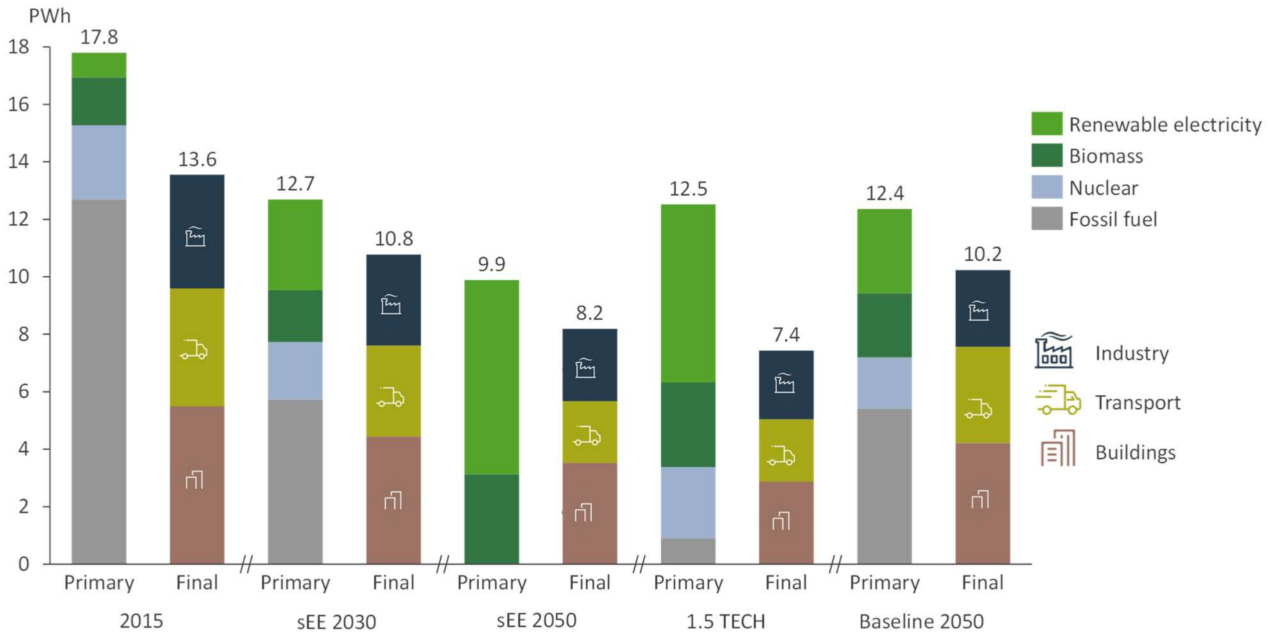

Figure 14, Primary energy supply and final energy demand of the sEEnergies scenarios in 2030 and 2050 for EU28 in comparison with 1.5TECH and the 2015 reference model (Mathiesen, Ilieva et al. 2022b).

The back-casted sEE 2030 scenario enables a comparison with the EU energy efficiency targets to meet energy and climate goals and with the REPowerEU natural gas saving initiatives. The targets are for EU27 and typically measured in million tonnes of oil equivalent (Mtoe). The targets have been set in stages and are as follows:

- 2018 Energy Efficiency Directive (EED) 2030 target: the EU aims to cap its energy consumption to a maximum of 1128 Mtoe for primary energy and 846 Mtoe for final energy by 2030.
- The Commission's Fit for 55 (Ff55) 2030 target: This more ambitious goal seeks to reduce the EU's energy consumption to 1023 Mtoe of primary energy and 787 Mtoe of final energy by 2030. This represents a 9% reduction from the projections made in the 2020 reference scenario for 2030.
- The Commission's REPowerEU 2030 Target: Under this plan, the EU's 2030 targets are even stricter, with a consumption goal of no more than 978 Mtoe for primary energy and 752 Mtoe for final energy consumption.
- 2023 Energy Efficiency Directive (EED) 2030 target: the EU aims to cap its energy consumption to a maximum of 993 Mtoe for primary energy and 763 Mtoe for final energy by 2030.

These targets are compared to sEE 2030 transition energy system, see Figure 15. The sEE 2030 scenario is aligned with the European Commission's REPowerEU Plan and foresees 966 Mtoe in primary energy consumption and 786 Mtoe in final energy consumption by 2030.

The sEE 2030 scenario paves the way for the subsequent transition to the sEEnergies sEE 2050 climate neutral system, targeting further reductions to 720 Mtoe of primary and 570 Mtoe of final energy consumption. The comparison between primary and final energy consumptions emphasizes that the sEEnergies energy system redesign is poised to deliver a more efficient energy system for both 2030 and 2050.

Furthermore, when comparing primary and final energy consumptions, sEEnergies energy system redesign provides a more efficient energy system by 2030 and 2050, building on energy system synergies with balanced end savings in buildings, electrification and the use of untapped heat sources in district heating. Compared to 2019 (baseline), sEE 2030 and 2050 have reductions in primary and final energy consumption of about 25 and 45% respectively.

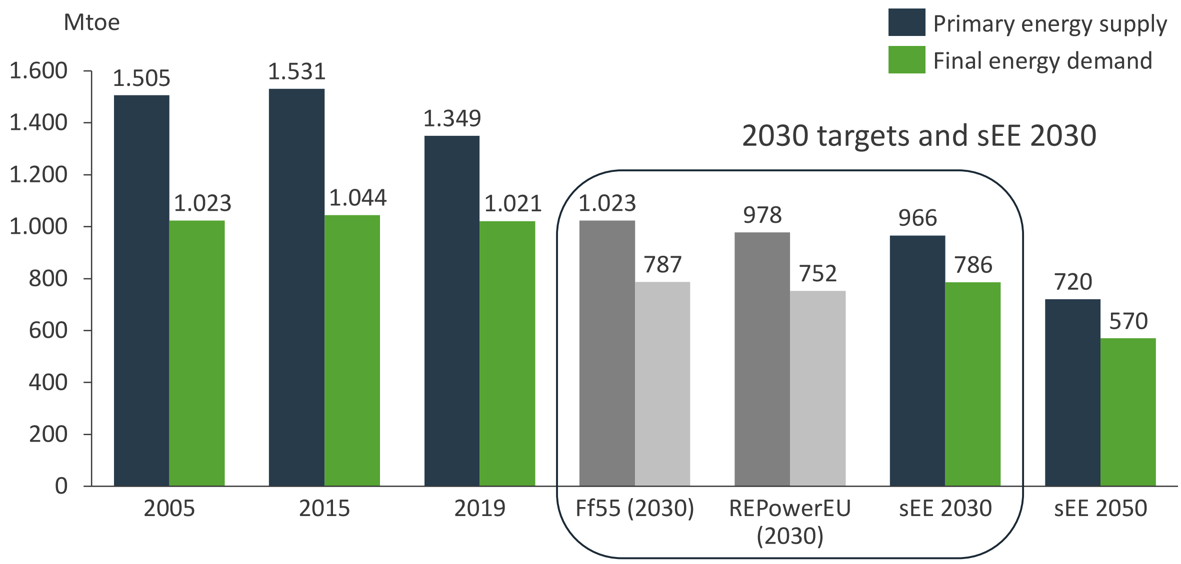

Figure 15, Primary energy supply and final energy demand for EU27 in 2005, 2015, 2019, 2030 and 2050 based on the EU policy targets for 2030 (Fir-for-55 and REPowerEU) and the sEEnergies 2030 and 2050 scenarios (Maya-Drysdale, Abid et al. 2022).

Breakdown of natural gas savings in the sEEnergies 2030 scenario

The role of fossil fuel exports in supporting the Russian aggression has turned the EU's attention on taking decisive action to cut Europe's dependence on Russian gas.

Based on current EU initiatives gas savings from the Fit-for-55 measures amount to a total of 116 bcm, while an additional total 155 bcm is expected from REPowerEU measures (including recent related political decisions, such as the abandoned phase-out of nuclear plants in Belgium and the objective to launch a new plan to construct nuclear reactors in France). In Figure 16 the waterfall chart presents the disaggregated natural gas savings per Ff55 and REPowerEU measure. The unspecified 13 bcm may be accounting for more renewable energy electricity, but this is somewhat unclear. Some of the REPowerEU measures proposed by the Commission are to frontload Fit-for-55 measures (Table 1 in REPowerEU COM(2022) 108), thus these savings have been categorically separated ('frontloaded Ff55') in order to avoid double counting.

Furthermore, the amount of gas displaced by hydrogen was interpreted from the data available in Table 8 in REPowerEU SWD(2022) 230 that shows the hydrogen use by sector in 2030, of which 15 bcm of gas savings are achieved through imported hydrogen, which is also highlighted in the chart. It is unclear whether the 15 bcm from hydrogen import is also accounted the total amounts of 287 bcm.

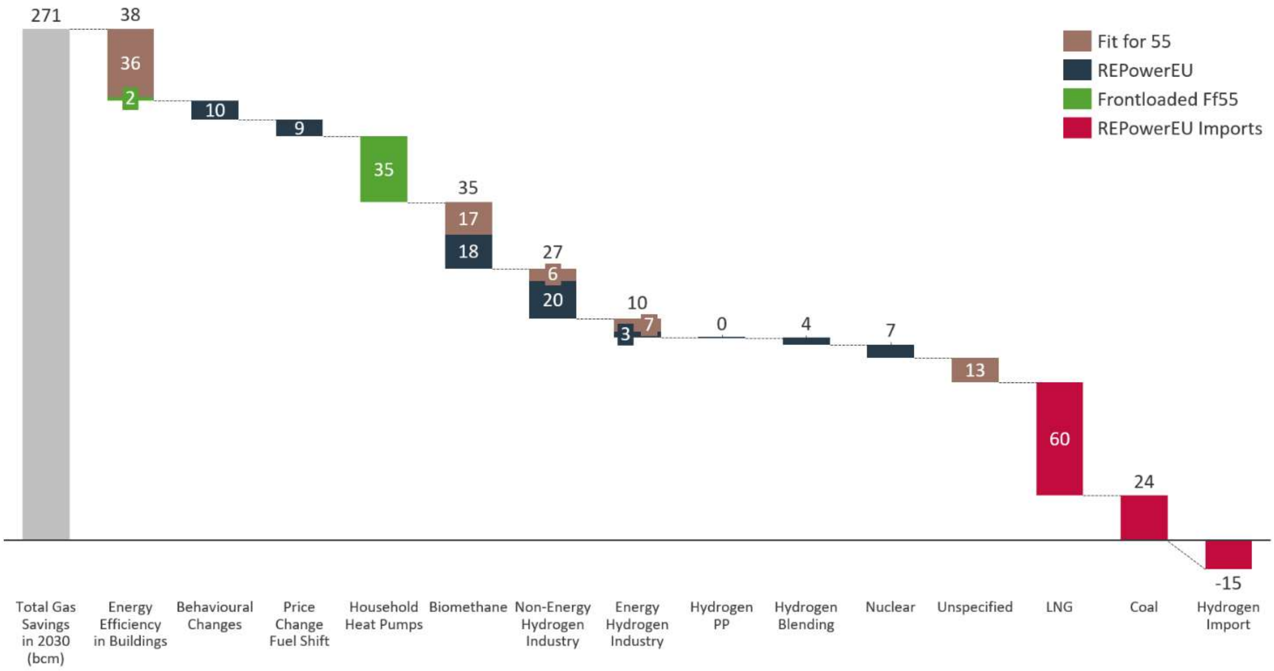

Figure 16, Breakdown of natural gas savings (bcm) in the Fit-for-55 and REPowerEU by 2030 interpreted in sEEnergies (Maya-Drysdale, Abid et al. 2022, Mathiesen, Ilieva et al. 2022a).

The major changes proposed in sEE 2030 are introduced with a system redesign enabling a 58% cut in CO_2 emissions from 1990 levels in line with EU targets as well as a renewable energy share of 47% in the EU's gross final consumption compared to 45% in REPowerEU. The changes are illustrated in Figure 16 and listed below:

- 58 bcm in sEE 2030 are achieved through the deployment of renewable electricity sources.
- This increase is combined with the electrification of industry instead of using hydrogen amounting to 25 bcm. This has a double effect, as it is more efficient to use electricity compared to hydrogen and thus replaces more natural gas in the power sector, and it enables the integration of more renewable energy in the electricity sector.

- 24 bcm stem from district heating making it the fourth largest contributor not counting in LNG and fuel switch to biomethane on its own:
    - New district heating production units such as large-scale heat pumps, electric boilers, geothermal, solar as well as waste heat from industrial/service installations and waste-to-energy plants contribute with 15 bcm.
    - The enlargement of the district heating market share from 13 to 20% with grid expansion can contribute with 6 bcm.
    - A share of the biomethane can be used to displace natural gas in CPH plants accounting for 3 bcm. Changing the district heating production mix has the effect that more renewable electricity can be integrated and that the total renewable energy share on the system level increases.

Other initiatives include higher efficiency on power generation and a slight adjustment in the shares of individual heat pumps. In sEE 2030 a 10% heat demand savings in buildings is included as opposed to 14% in REPowerEU by 2030 compared to 2015. This is more than outweighed by the energy system redesign initiatives. A 10% reduction in energy demands is considered a more realistic and achievable target for Europe in 2030.

In Figure 17 the aggregated natural gas savings proposed in sEE2030 in the heating sector is presented. The production of 33 bcm biomethane by 2030 has been allocated in CHP plants and industry - not in individual boilers. Using a method putting more value on electricity than heat, 3 bcm are estimated to stem from replacing natural gas in CHPs for district heat supply[4]. That gives 11 bcm for electricity production, 16 bcm in industry and 3 in others.

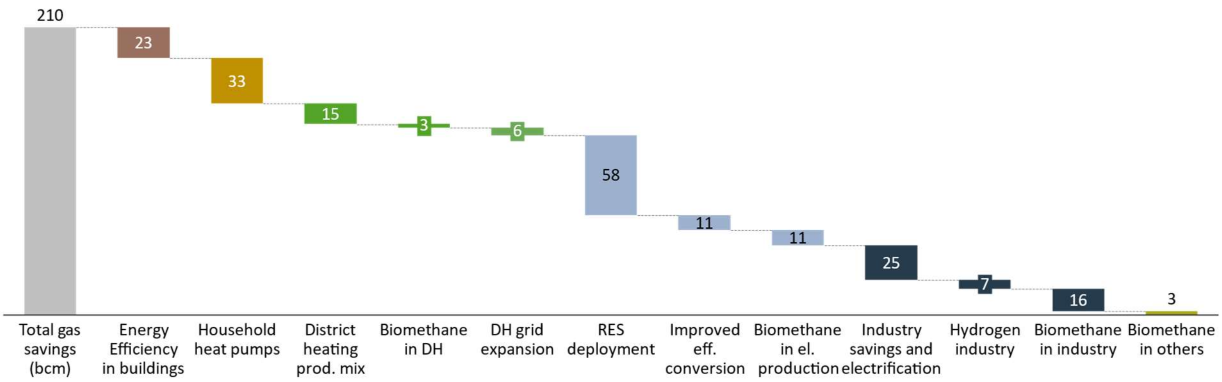

Figure 17, Natural gas savings per category in the sEEnergies 2030 scenario (EU27) compared to the 2019 reference model excluding other measures such as fuel shifts in REPowerEU.

Based on this analysis of REPowerEU initiatives and the sEE 2030 scenario, district heating can contribute with 24 bcm natural gas reduction, of which about 21 bcm areadditional compared to REPowerEU. In other words, if the role of district heatifng is increased it can contribute with 8% additional natural gas savings compared to the 271 bcm in REPowerEU for 2030.

The natural gas savings that can be achieved through fuel shift measures as well as behavioral and price changes can be further added to the sEEnergies 2030 savings to show the full potential for gas savings beyond the energy efficiency and renewable energy measures achieved by sEEnergies 2030. The fuel shift with coal and LNG can be added as well as a hydrogen import. This is shown in Figure 18 where the unchanged

[4] Fuel allocation based on the 200% method introduced by the Danish Energy Agency.

REPowerEU initiatives are included together with the measures added or adjusted in sEE 2030. The combined sEE 2030, behavioral and fuel shift measures in REPowerEU the total is 328 bcm of gas. This is 15% greater than the saving potential of 287 bcm counting in hydrogen as part of EU measures. sEE 2030 achieves about an additional cut of 41 bcm natural gas compared to the EU measures (Mathiesen, Ilieva et al. 2022a).

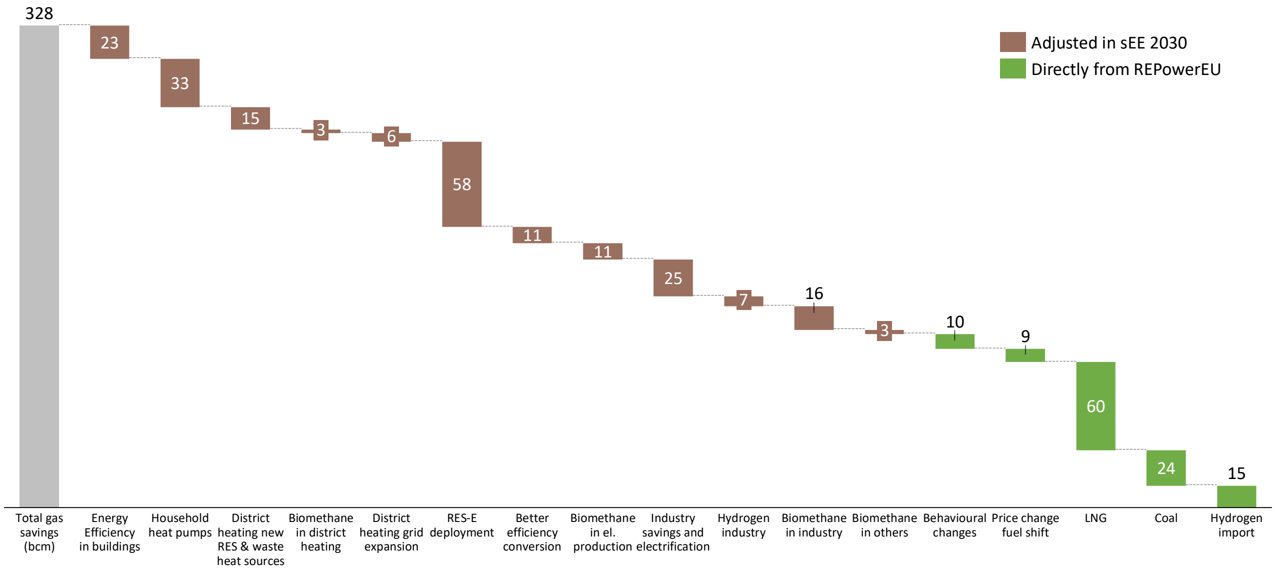

Figure 18, Breakdown of natural gas savings (bcm) achieved by sEEnergies in 2030, including the imported hydrogen, behavioral and fuel price changes, and fuel shift with coal and LNG, as set out by REPowerEU.

In Figure 19 the breakdown of the natural gas savings in the heating sector is shown in more detail. The individual heating in buildings and district heating achieved by the sEEnergies 2030 scenario is compared to the 2019 reference model for EU27. In the next section the district heating production profile is broken down further for 2030 and 2050. Step-wise heat from natural gas boilers and CHPs is replaced by the deployment of large-scale heat pumps, utilisation of waste heat as well as deployment of geothermal and solar thermal.

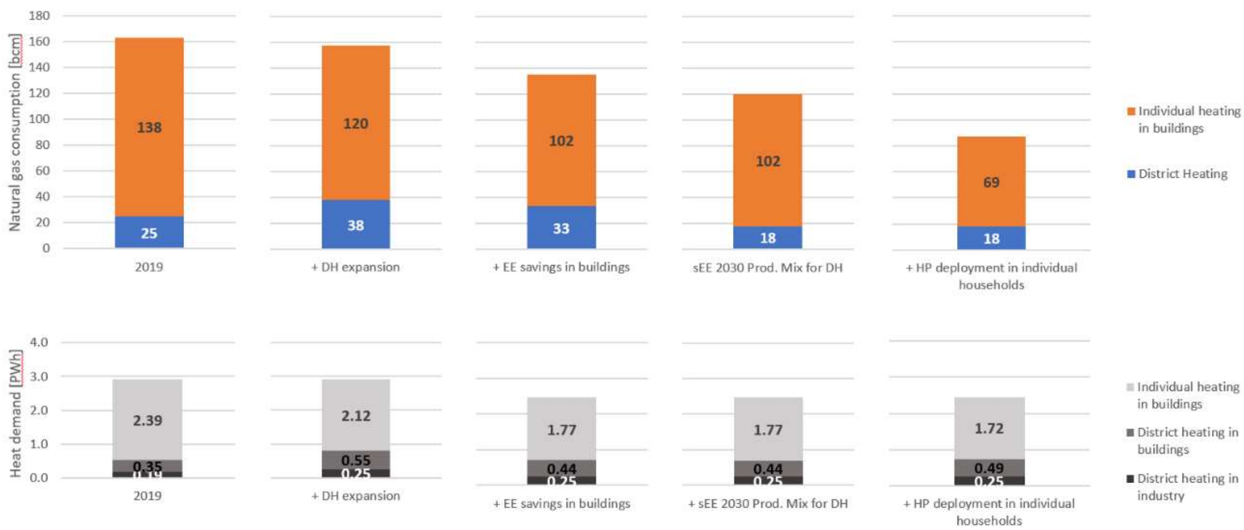

Figure 19, Breakdown of natural gas savings (bcm) in individual heating in buildings and district heating achieved by sEEnergies in 2030 (EU27) compared to the 2019 reference model (upper) and changes in the annual heat demand (PWh) for individual heating in buildings as well as district heating in buildings and the industry (lower). The savings are broken down into 1) the expansion of district heating, 2) energy *efficiency (EE) savings in buildings due to refurbishments, 3) the change in the district heating supply mix with the integration of new renewable and waste heat sources by 2030 and 4) the large-scale deployment of household heat pumps.*

Heat production mix in 2030 and 2050

In sEEnergies there is a stepwise change to lowering energy demands along with gradual changes in the production mix. The total heat demands are reduced by 40% in sEE 2050 compared to about 55% in 1.5 TECH in order to have a technically more achievable level as well as reducing the refurbishment cost to less than a third. In addition, instead of combining boilers with natural gas or oil boilers and carbon capture and storage as well as hydrogen boilers in 2050, sEE increases the level of district heating and individual heat pumps, see Figure 20. In sEE 2030 a realistic way needs be set out that also paves the way for the structural changes in 2050 for each technological change.

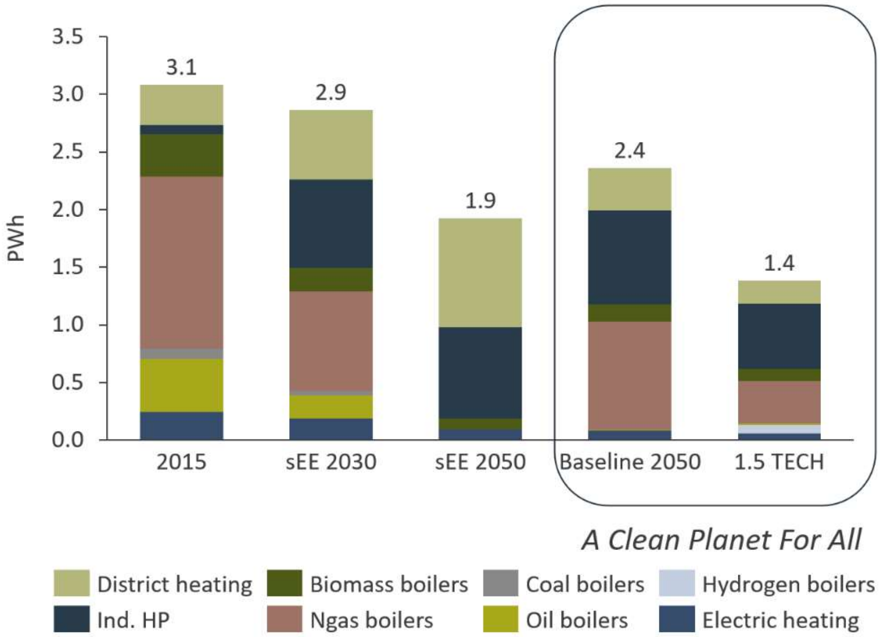

Figure 20, Heat production mix of the sEEnergies scenarios in 2030 and 2050 for EU28 in comparison with 1.5TECH and the 2015 reference model (Mathiesen, Ilieva et al. 2022a).

Figure 21 shows the heat production mix in the sEEnergies scenario for 2030 and 2050 respectively. District heating is a key enabler to phase-out natural gas by 2050 accounting for 20% and 48% of the total heat supply in the sEEnergies scenarios for EU27 in 2030 and 2050 respectively. This excludes industry and losses in the district heating grids.

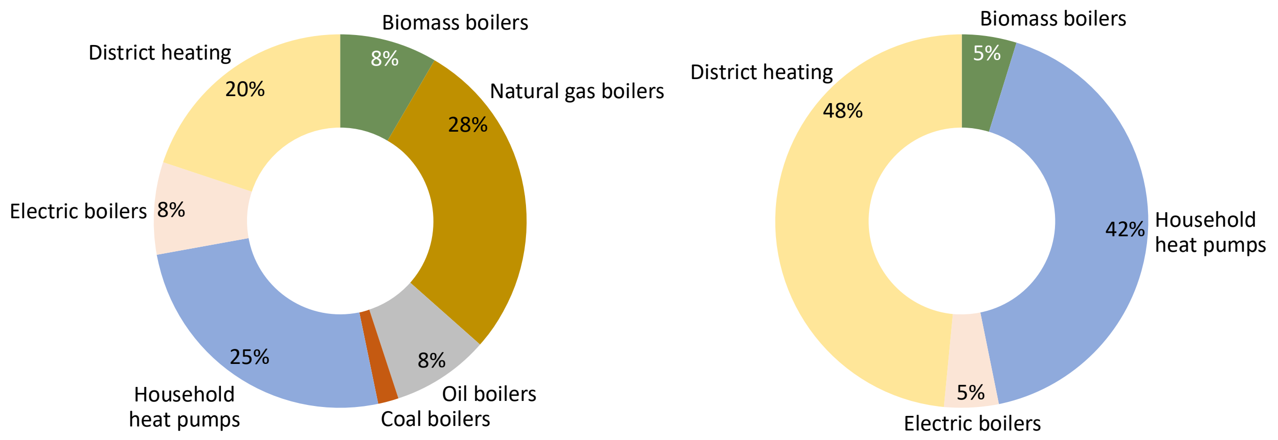

Figure 21, Heat production mix in buildings in the sEEnergies scenarios for 2030 and 2050 (EU27), excluding district heating losses.

District heating production mix in 2030 and 2050

Figure 22 and Figure 23 show the district heating production mix in the sEEnergies scenario for 2030 and 2050 respectively. The change in the fuel mix displays the full potential of district heating in decoupling the heat market from the direct use of fossil fuels. Within this timespan, systems are expected to integrate higher shares of renewable sources like geothermal and solar thermal and sources such as low-temperature heat that will require the use of large heat pumps to provide these sources at a level of temperature fit for purpose.

On the one hand, high-temperature heat sources such as deep geothermal or waste heat e.g. from industry can be directly injected into district heating grids and are suitable for base load supply due to their permanent availability. Together with waste heat from waste-to-energy plants, it accounts for 253 TWh or 29% in 2030 and 490 TWh or 49% in 2050. Without district heating this heat would be wasted. The reference to waste-to-energy plants in this study refers to the valorization of municipal waste that cannot be neither prevented nor recycled. In some member states the deployment of these plants will serve to gradually phase out landfilling, in compliance with the waste hierarchy.

Additional low and medium-temperature industrial waste heat sources together with shallow geothermal, sewage and seawater can be recovered within district heating networks. However, these sources require a temperature lift by heat pumps and thus, additional electricity consumption.

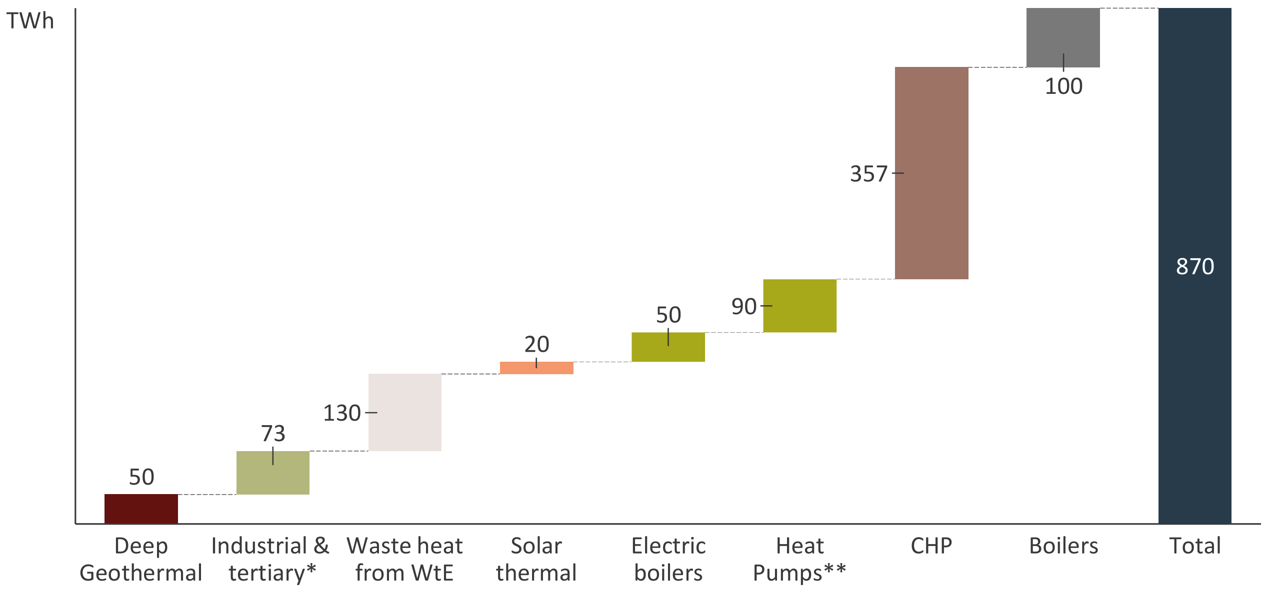

*Figure 22, District heating production mix in the sEEnergies 2030 scenario for EU27; *Industrial & tertiary includes nearly all medium and high-temperature waste heat sources which can be directly fed into district heating grids, including a share of low-temperature input, **Heat pump heat supply based on heat extraction from low and medium temperature heat sources which require electricity for compression and temperature lift.*

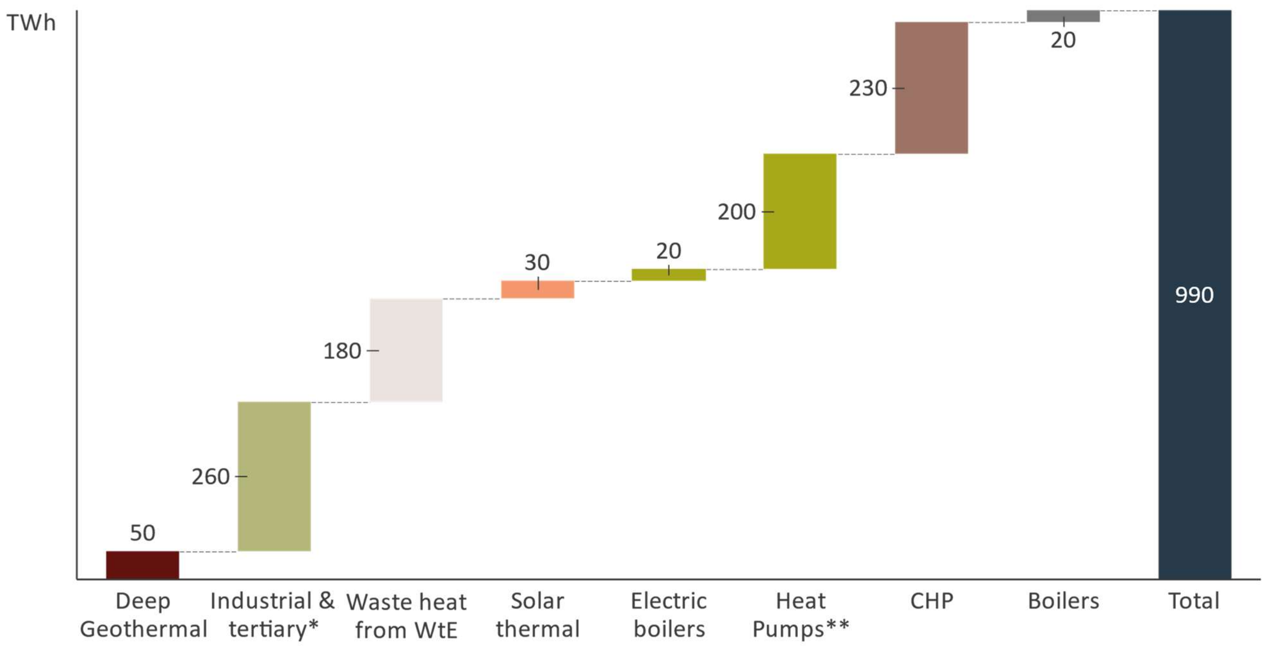

*Figure 23, District heating production mix in the sEEnergies 2050 scenario for EU27; *Industrial & tertiary includes nearly all medium and high-temperature waste heat sources which can be directly injected into district heating grids, **Heat pump heat supply based on heat extraction from low and medium temperature heat sources which require electricity for compression and temperature lift.*

One element is the production for the full year. To understand the heating sector it is pivotal to consider the hour-by-hour dynamics. This is the approach in sEEnergies that underpins the analyses presented for sEE 2030 and sEE 2050.

Demands for space heating and hot water preparation vary very much during the year. Industrial waste heat, geothermal, waste heat from waste-to-energy as well as the new sources such as datacenters and waste heat from electrolyses are all characterized by having a flat baseload type of availability during the year. This dynamic is illustrated for the 2030 and 2050 scenarios in Figure 24 and Figure 25. This creates several challenges:

1) The sources will be mutually exclusive to each other, meaning that a given source will exclude another kind of heat source unless the latter can be used in the summer
2) The heat source providing baseload at the lowest costs in a given area will win, e.g. available directly usable industrial waste heat will be used instead of using geothermal.
3) In some areas solar thermal may have a role to play if no waste heat is available.
4) In some cases there may be a surplus of waste heat available cost-effectively to allow for wasting heat in the summer period.
5) Many of these waste heat streams have low costs and can cover part of the grid losses over the year and especially during the summer period.

An increase in the market share of district heating to 20% in 2030 and 48% in 2050 is a key enabler for:

- Increasing the share of geothermal and waste heat in the district heating mix to 29% in 2030 and 49% by 2050
- Using short-term thermal storages, CHPs and large-scale heat pumps to integrate higher levels of fluctuating renewable energy sources in the electricity grid, while ensuring energy efficiency and grid stability.
- An increase in the overall share of renewable energy at system level due to the inclusion of renewable heat only usable though district heating and due to the integration of more renewable electricity using large-scale heat pumps with district heating.
- From only 2% today, large-scale heat pumps cover 10% of the district heating demand in 2030 and 20% in 2050 using short-term thermal storage in an increasing market.
- Enabling the use of solar thermal with storage in local district heating grids, which are not using waste heat

Large-scale heat pumps are a key enabler for several of the otherwise wasted heat sources. Combining heat pumps with heat sources from e.g. medium or low temperature industrial and tertiary waste heat can provide higher COP values. For this study a value of 4 on average is assumed. The use of the different heat sources in the production mix over the year is illustrated in Figure 24 and Figure 25 The integration of large-scale heat pumps in district heating systems will enable the integration a higher share of fluctuating renewable electricity , reducing the need for CHP plants. Using thermal storage also decreases the need for less efficient fuel boilers and electric boilers. Due to the nature of the district heating system and the profile of heat demands boilers will be needed for security of supply and for peak demands.

Energy savings and energy efficient buildings combined with district heating are key enablers for:

- A more direct use of low to medium-temperature waste heat sources and deep geothermal sources
- Large-scale heat pumps with higher COPs combined with waste heat or geothermal
- A flatter annual demand curve structure with lower peaks during the heating season enabling a better use of baseload waste heat streams and geothermal

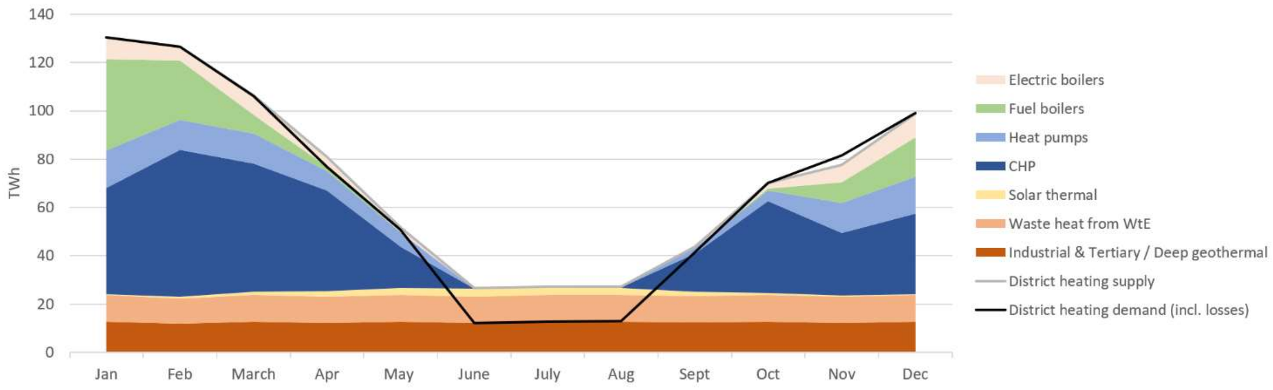

Figure 24, District heating production mix presented in monthly values in the sEEnergies 2030 scenario for EU27. In 2030 the category Industrial & tertiary waste heat refers to medium and high-temperature waste heat sources which can be directly injected into district heating grids. In practice this may be a mix depending on local conditions. Heat pump heat supply is based on heat extraction from low and medium temperature heat sources which require electricity for compression and temperature lift.

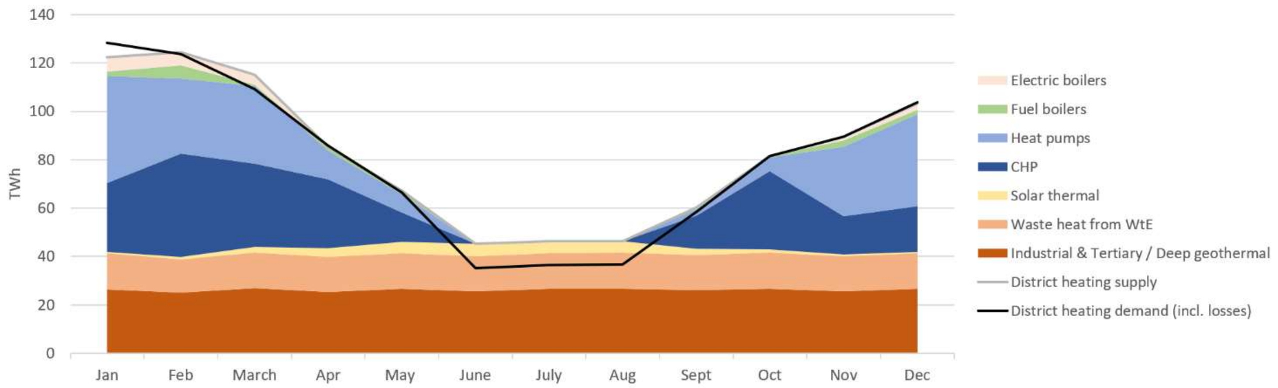

Figure 25, District heating production mix presented in monthly values in the sEEnergies 2050 scenario for EU27; Heat pump heat supply is based on heat extraction from low and medium temperature heat sources which require electricity for compression and temperature lift.

District heating grid investments and number of new systems towards 2030 and 2050

A successful strategy to phase out the imports of natural gas calls for a complete redesign of the energy system including a higher share of district heating. The necessary additional market shares for district heating were assessed for the different countries in the sEEnergies project, including an evaluation of the level of investments necessary to grow heat networks towards 2030.

The assessment of the market share for district heating in 2050 is about 50% for EU27 and the UK. In a system redesign using the synergies between the energy sectors to that level in 2050, investments need to start towards 2030. In sEEnergies a level of 20% district heating is suggested for 2030 from a current market share of 13% (excluding industrial demands), combined with end-demand savings in buildings of 10% in 2030 and 40% in 2050.

For EU27 and each country as well as the UK, the current district heating levels are listed in combination with the levels assessed feasible for 2030 and 2050 in sEEnergies, see Figure 26. This study is based on a complex combination of GIS analyses and energy system analyses pr. country combining grid costs, supply system costs as well as energy savings in buildings. The landscape of district heating within the EU27 presents interesting differences reflecting the different urban fabric in each country. Compared to sEEnergies the updated analyses here entail slight adjustments for Finland, Lithuania and Estonia by 2050. The 2030 country level district heating share is assessed based on the expansion to a 20% pan EU market share by 2030.

Countries such as Belgium, Cyprus, Greece, Spain, France, Ireland, Italy, Malta, Netherlands, Portugal and the UK currently have extremely low district heating shares, below 6%. They all have a pressing need for a robust district heating development towards 2050 targeting between 35 and 55% and 10 to 15% by 2030. Other countries have a slightly higher outset but should aim for similar district heating shares by 2050. Germany, Croatia, Hungary, Luxembourg, Romania, and Slovenia have currently between 10 and 20% district heating share.

District heating is well established in Northern European countries. District heating has market shares of about 50% in Finland, Denmark and Sweden as well as the in three Baltic countries. The analyses show that Finland and Lithuania should aim for a market share of 60% in 2050.

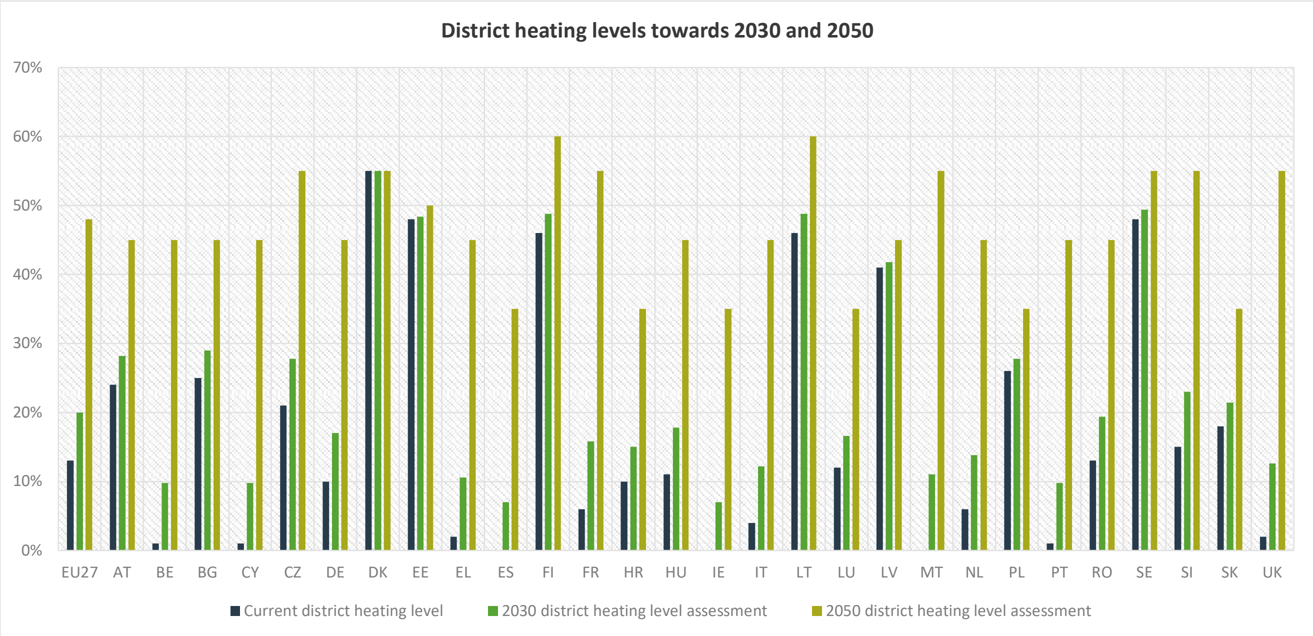

Figure 26, District heating levels towards 2030 and 2050 for heating buildings for EU27, pr. EU country and UK.

Expansion costs 2030 and 2050

Expanding district heating to these will require significant investments in heating infrastructure. For 2030 a total of 144 billion EUR is needed to go from a 13% to 20% market share and in 2050 an additional 541 billion EUR going from 20% to 48 % district heating. Figure 27 shows these costs distributed by country and year. Belgium, Germany, Spain, France, Italy, the Netherlands and the United Kingdom are the countries where the highest level of investments is needed. Each will need to invest over 20 billion EUR to expand District Heating before 2050. Other countries like Austria, the Czech Republic, Greece, Hungary, Poland, Portugal and Romania need to invest at least 5 billion EUR before 2050.

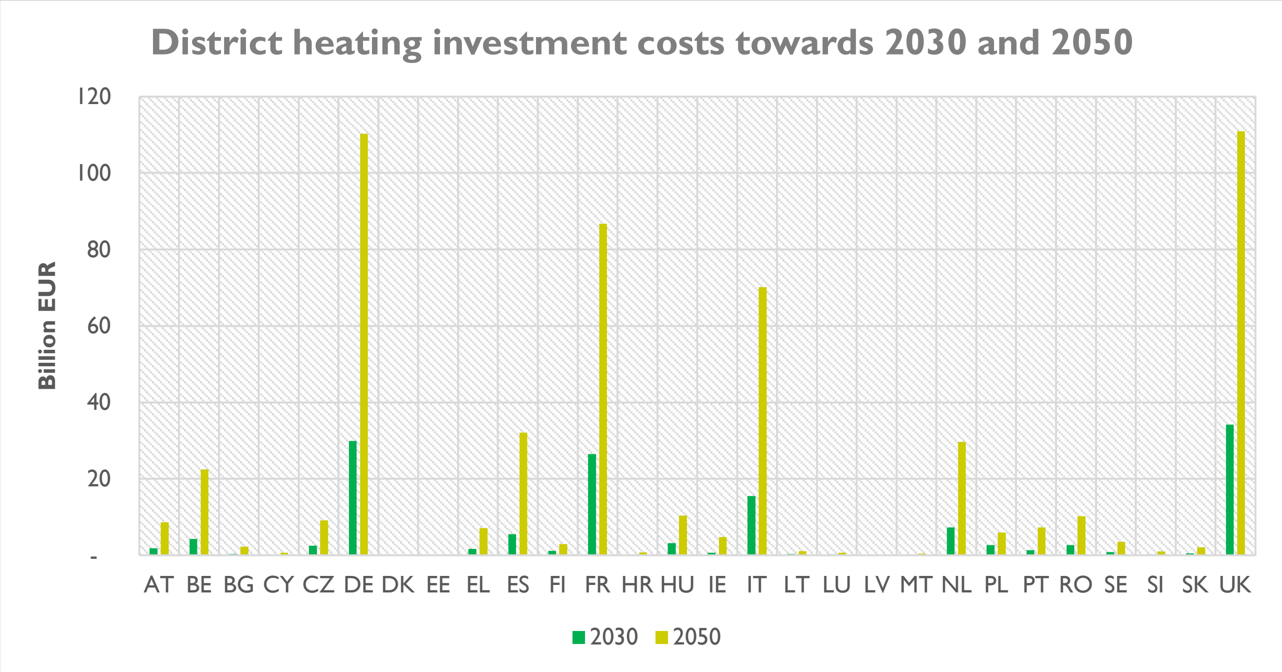

Figure 27, Total investments in district heating networks before 2030 and from 2030 to 2050 per country

Number of district heating systems

The growth of district heating by 2030 and 2050 means that many new systems need to be developed. Estimating exactly how many systems are needed is a challenge for energy modelling, as there is no standard size for a district heating system. The development of new systems will also depend to a great extent on local conditions and strategies. In the methodology, the approach for estimating the number of new systems is described in more detail, but basically it is assumed that smaller urban areas will consist of one district heating system, while larger urban areas will develop multiple district heating systems. Typically, the new district heating systems in the larger urban areas will merge as the district heating systems grow and start to cover most of the urban area. From the methodology applied in this report, around new 3,500 district heating systems (in 3300 urban areas) need to be developed by 2030 to reach a 20% market share and further new 15,000 district heating systems (in 14,000 urban areas) by 2050 to meet the 48% district heating market share.

To tap into the vast potential for district heating about 18,500 new district heating systems need to be established. Figure 28 shows the country distribution of new district heating systems in 2030 and 2050. The distribution is similar to the district heating investments with many systems in the larger countries, where DE, ES, FR, IT, PL, UK need to start more than 1,000 new district heating systems each towards 2050, while Austria, Belgium, Lithuania, Poland and Romania need to establish more than 500 new district heating systems.

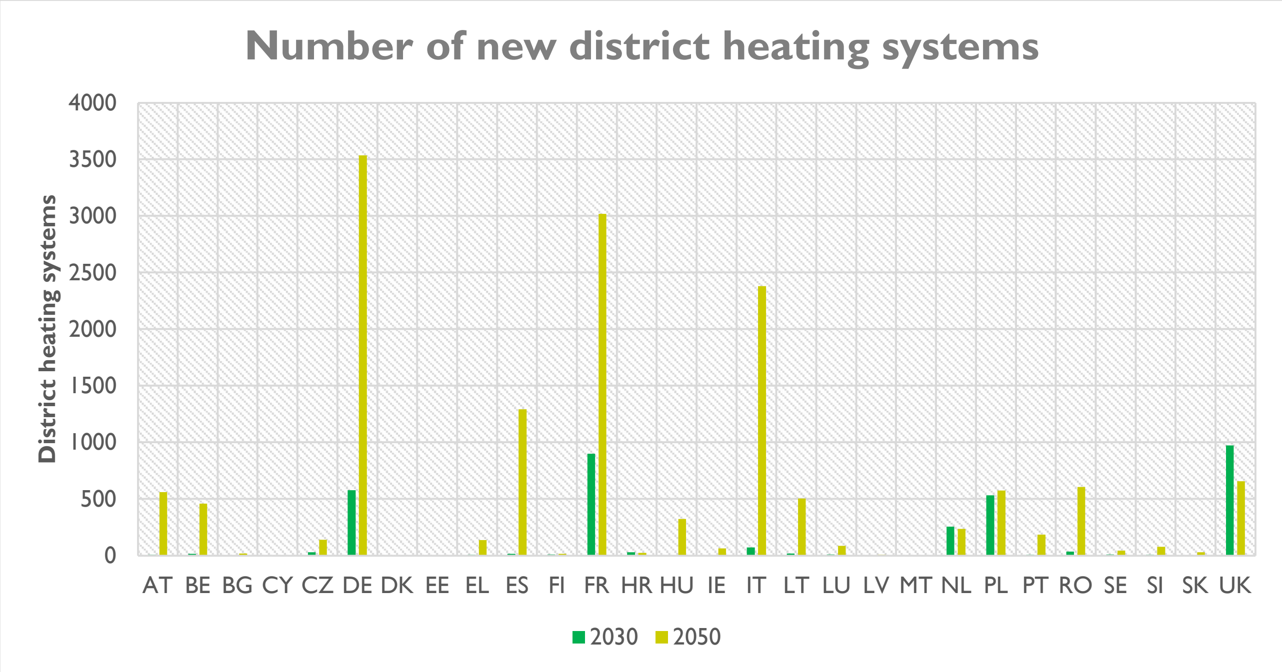

Figure 28, Number of district heating systems per country.

Potential new heat sources in Europe untapped today and long-term

A major focus of the sEEnergies project lies on the investment in district heating and the expansion of the European district heating grids to enhance the replacement of conventional fuel boilers as well as conventional district heating production sources. The overview of the potential new heat sources is listed in Figure 29. The new heat sources can be divided into various categories. Some are already present now but unused. Some are expected to develop further in the future or based on renewable energy.

The challenges are that many of the sources have a constant production profile and provide a base for the heat demands. Or in other words: practicalities and costs can and will mutually rule out some of the potential new heat sources. In addition, the costs of harvesting these sources may be relatively too high, e.g. this is the case for most data centers already constructed. The references and background for the quantification of each source is described in the following.

The total current and potential future heat sources are above 2,000 TWh pr year in the assessment conducted here. sEEnergies assumes a feasible level of heat savings of 40% compared to the baseline (2015) indicating that the potential heat sources are on the same level as the total heat demand in this future 2050 system. The current waste heat sources combined with renewable heat sources could theoretically cover half the total current heat demands.

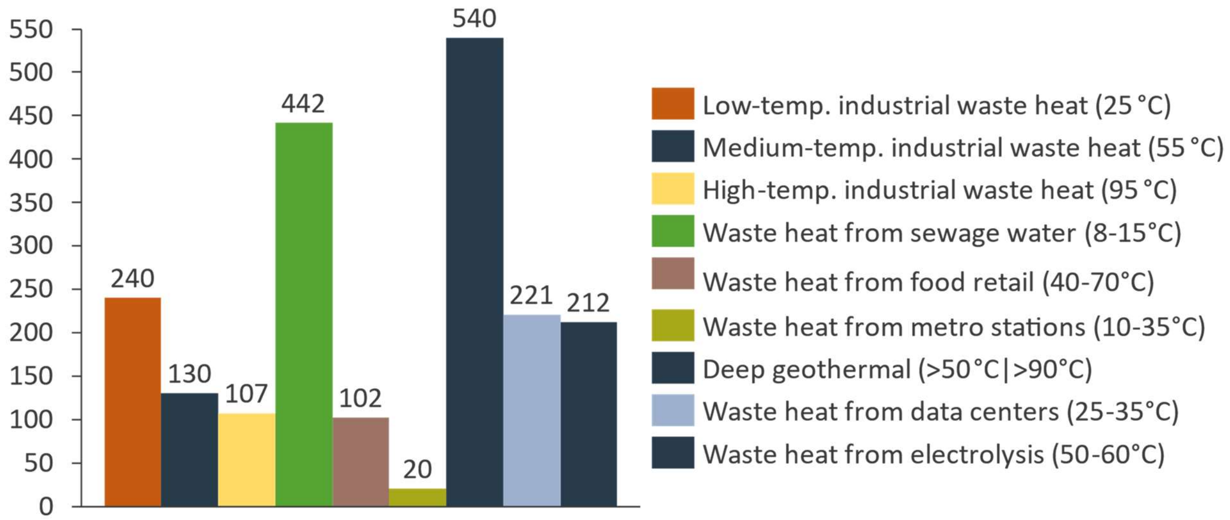

Figure 29, Heat source types and potentials for use in district heating systems towards in 2050 in EU27 in TWh/year. It should be noted that due to the costs and production profiles far from all these resources can be used and many or mutually out ruling each other. The references, assumptions, and methodology are listed below. Some of the sources require large-scale heat pumps for the exploitation.

Current unused heat sources:

- ***Industrial waste heat sources***: sEEnergies provides a comprehensive analysis of industrial waste heat potentials in Europe to emphasize this strategy (Fleiter, Manz et al.). Based on the spatial mapping of potential future district heating networks, the study categorised the industrial waste heat availabilities distinguishing between low (LT: 25°C), medium (MT: 55°C) and high (HT: 95°C) temperature levels within 2050 district heating levels based on the current locations of industries.
- ***Waste water treatment plants waste heat***: The REUSEHEAT project has mapped the potentials for waste heat from several lower temperature sources (Persson, Averfalk 2018). Sewage water has an annual average temperature of 12°C and actual temperatures in the interval of 8°C to 15°C. Sewage water is generated all year round and treatment processes operate continuously, however, post-treatment flows may occasionally (and locally) be warmer during summer season due to higher ambient temperatures. The exploitation requires large-scale heat pumps, and the assessment is conducted with the current locations of the plants combined with potential future district heating grids. In countries with relatively low heat demands and low industrial waste heat levels this source may provide an important contribution, see Figure 30.

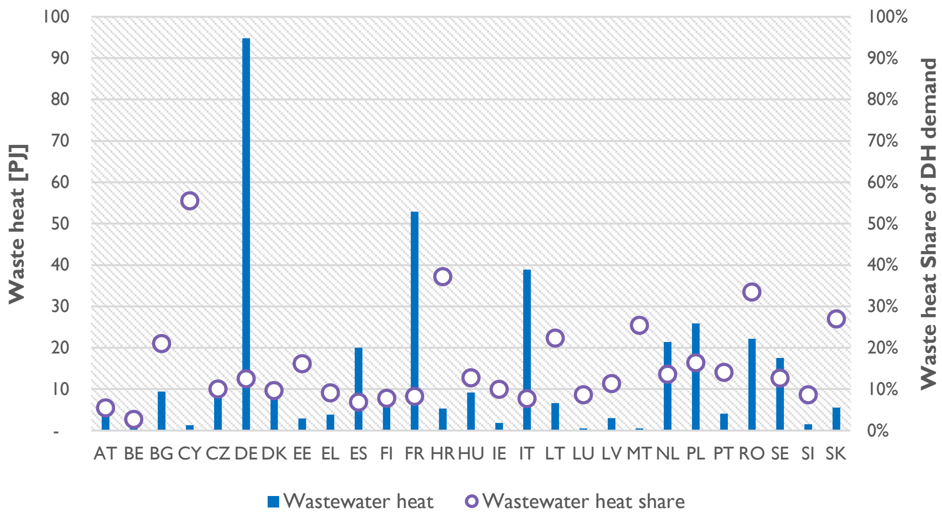

Figure 30, Waste heat from waste water treatment potential in 2050 by country

- ***Food retail waste heat:*** The amount of food retail stores is vast. The cooling demands give way for a potential heat source for district heating. While the point sources are many and are placed in urban areas the study conducted in the REUSEHEAT project indicates the relatively lower waste heat volumes per facility from these sources compared to other sources (Persson, Averfalk 2018). The rejected temperature levels from refrigeration processes are between 40°C and 70°C, which gives way for use with higher efficiencies in large-scale heat pumps than in other sectors. Of the total waste heat assessed available in REUSEHEAT 90% is assumed to be a usable potential within district heating areas in this report.

- ***Metro stations:*** For metro stations the temperature ranges from 10°C to 35°C over the year in platform air ventilation shafts. Such systems would use air to water heat pumps (Persson, Averfalk 2018). The potential is rather limited overall but may be significant in some specific local situations. In this report 100% of the assessed potential in the REUSEHEAT project is assumed to be usable within district heating systems.

- ***Deep Geothermal heat:*** The potentials pr country are assessed based on a spatial analysis of the Pan-European Thermal Atlas (Persson, Möller et al. 2022) matching high-density heat demand areas with a) geothermal temperature levels greater than 90°C at a depth of 2000m, b) areas with a temperature greater than 50°C at a depth of 1000m (Hurter, Haenel 2002) and c) hydrothermal resource areas (Chamorro, García-Cuesta et al. 2013, Dumas, Angelino et al. 2020). The country level potentials matching high-density heat demand areas with geothermal resources in Table 1 were performed by Sánchez-García, Luis from Halmstad University. In most cases these sources will be used via the means of large-scale heat pumps. The COP in the concrete case would depend very much on the actual temperature levels. In Figure 31 the potentials are illustrated in Europe.

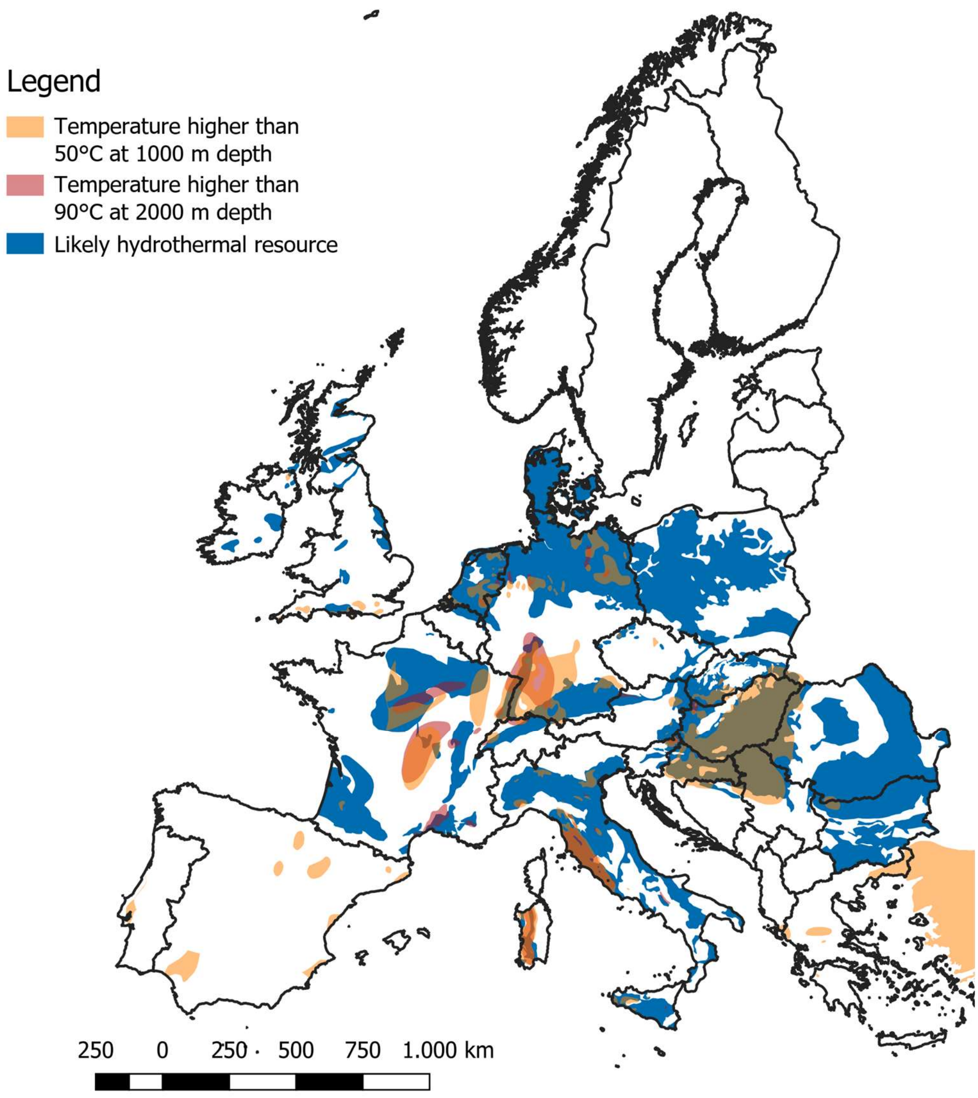

Figure 31, Areas with high temperature heat sources at two different depths and hydrothermal geothermal sources. Illustration by Sánchez-García, Luis from Halmstad University based on the Atlas for Geothermal Resources in Europe and data from the GeoDH project (Hurter, Haenel 2002, Dumas, Angelino et al. 2020).

- ***Solar thermal:*** The potential has been modelled, as the potential for heat from solar thermal is so vast but also concentrated in the summer period that its use to a large degree is limited. With a 20% market share of district heating 20 TWh of solar thermal can be integrated. The challenge is that while smaller urban areas can have land available for seasonal storage for solar thermal, larger and also dominant heat demand areas cannot make use of this, limiting the level of solar thermal. In addition, the potential is limited by other sources of waste heat also available in the summer half year.

Future potential heat sources:

- ***Industrial waste heat sources:*** Many current industrial waste heat sources will persist for a considerable duration. As we transit towards a renewable energy-based industrial sector, there will be a shift towards increased electrification. For processes where electrification is not viable, alternatives such as biogas or hydrogen could supplement the energy mix. The temperature levels required in industrial processes, both now and in the future, vary greatly depending on the specific operations within each industry. For instance, the typically high-temperature waste heat found in industries like food production may decrease. Nonetheless, there will continue to be a demand for food, materials, and chemicals, which means waste heat will remain a by-product, even with increased automation or enhanced product recycling practices. Moreover, there is a trend toward sourcing production back to the EU. While energy efficiency measures may reduce the temperature levels of waste heat, substantial energy demands in industry will remain, even within a decarbonized industrial sector by 2050. Should there be changes in waste heat temperature levels or volumes, the district heating infrastructure is capable of adapting to utilise alternative heat sources. In this report the future of industrial waste heat – depending on the evolution of energy efficiency in these sectors and economic growth - is not assessed.

- ***Data centres:*** The current level of waste heat from data centers is assessed overall in the REUSEHEAT project (Persson, Averfalk 2018). The use of electricity for datacenters has grown globally by 18-64% in the period from 2015 until 2022. Traditional data centers have decreased their energy demand. On the other hand the more energy efficiency hyperscale datacenters now dominate. In the past energy efficiency has increased substantially. Here the waste heat level is assumed to be the same as the current level of existing facilities. Or, in other words, it is assumed that we use twice the electricity for the digitalization towards 2050 or that some of the waste heat from existing datacenters can be utilised. In Table 1 the current levels are listed pr country.
- ***Waste heat from hydrogen production:*** The estimation of the waste heat potential by electrolysis considers a demand for hydrogen of 1.3 PWh planned in the sEE 2050 scenario for EU27 (Mathiesen, Ilieva et al. 2022b). Across Europe the location of such plants will be where cheap electricity is available. Alkaline electrolysis plants are assumed, and a maximum utilisation share of 50% is included in Figure 29. This is due to 1) the vast amounts of electricity needed that will require close placement to renewable energy sources and 2) the uncertainty as to how much of this hydrogen will be produced within the EU.

In Table 1 the resource potentials mentioned above are listed pr. Country, except for solar thermal and electrolysis. It should be noted that many of these resources are in direct competition. The total current heat sources including renewable energy is about 1,600 TWh. Including the future potentials, the total is 2,033 TWh pr. year.

Table 1, The potential heat sources for district heating networks in Europe, excluding electrolysis waste heat and solar thermal in TWh/year. For industry, wastewater treatment and geothermal, GIS has been used to limit the potential within urban areas. Many of the sources listed require large-scale heat pumps. Please refer to the text above for further assumptions and references.

TWh/ year	Industry 25°C	Industry 55°C	Industry 95°C	Wastewater treatment plants	Food Retail	Metro Stations	High temperature OR Hydrothermal geothermal potential	Data Centres	Total
AT	7	4	3	14	5	1	17	6	55
BE	10	5	4	8	3	1	5	7	44
BG	2	1	1	5	0	0	3	3	16
CY	No data	No data	No data	1	0	0	0	0	1
CZ	6	4	3	9	2	0	9	5	39
DE	51	28	23	111	35	3	183	45	478
DK	2	1	1	8	4	0	15	3	33
EE	0	0	0	2	0	0	0	1	3
EL	4	2	2	8	1	1	0	4	22
ES	23	12	10	43	7	5	5	20	125
FI	7	3	3	8	2	0	0	7	30
FR	28	15	13	61	13	5	79	38	251
HR	2	1	1	3	1	0	2	1	11
HU	3	2	1	9	3	1	16	4	39
IE	1	0	0	4	1	0	2	3	11
IT	28	15	13	54	5	3	122	26	265
LT	2	1	1	3	2	0	0	1	9
LU	1	1	1	1	0	0	1	1	5
LV	0	0	0	1	0	0	0	1	3
MT	No data	No data	No data	0	0	0	0	0	0
NL	18	7	5	18	1	0	28	10	88
PL	18	11	10	37	7	0	37	13	133
PT	6	3	3	7	3	1	0	4	26
RO	6	3	3	12	2	1	7	4	38
SE	11	3	4	11	2	0	0	11	44
SI	0	3	0	1	1	0	3	1	10
SK	4	3	2	4	2	0	6	2	22
EU27	240	130	107	442	102	20	540	221	1821
UK	21	10	8	69	12	1	7	28	156
EU27 + UK	261	137	115	511	113	21	547	249	1955

Other heat sources for large-scale heat pumps: There are many resources for large-scale heat pumps for district heating systems. In Table 1 some of the main unconventional are listed. There are some other sources which are not included in this table such as seawater, lakes and shopping centres. Shallow geothermal may also provide a large potential and the temperature levels may be between 8°C and 20°C degrees. These sources are typically used in individual ground source heat pumps. In any case such sources are limited to the heat source being constantly renewed, as otherwise the heat pumps will not be effective. This limitation is especially the case of shallow geothermal. As a last resort air-to-water heat pumps may be used, however these will be less effective. Especially during winter when the ambient air is also colder. On a country bases based on the sources listed in Table 1:

- 22 countries can cover 50% or more of the current country level heat demand with resources currently availed, i.e. all elements mentioned except metro stations and electrolysis. The same is the case for those countries considering the reduced 2050 country level heat demands. This includes larger countries like, Germany, Spain, France, Italy, the Netherlands and Poland.
- Some countries may have more than 100% untapped heat potential for 2050. These countries include Cyprus, Spain, Poland, Croatia, Portugal, Slovenia and Slovakia, see Figure 32.

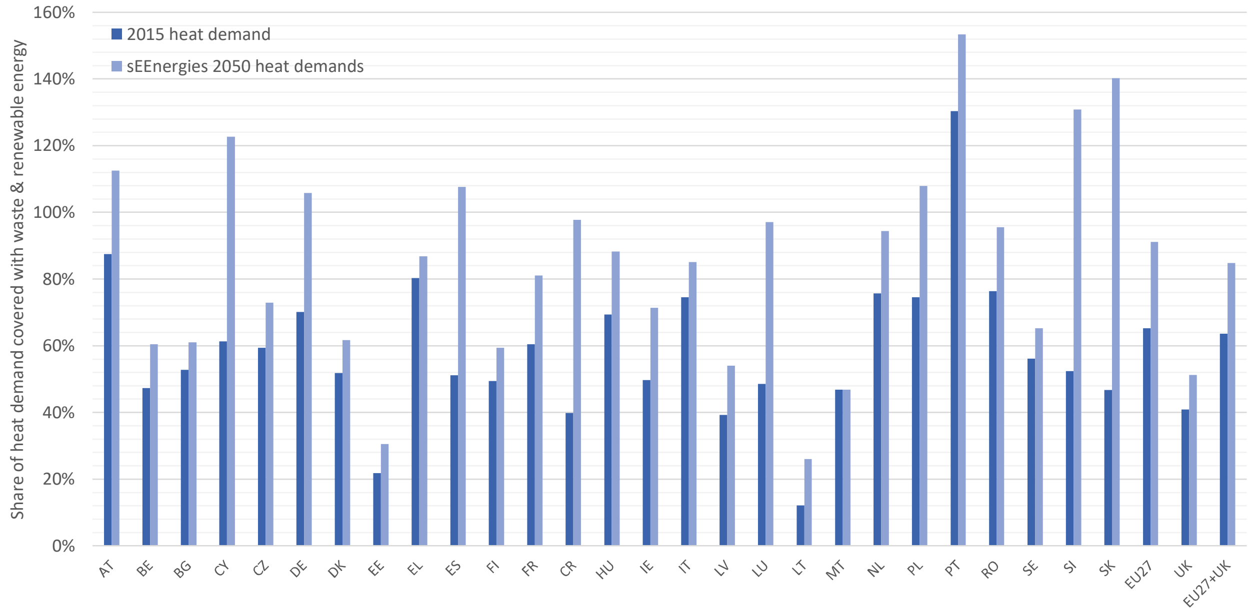

Figure 32, Untapped heat sources based on the sources listed in Table 1 compared to the 2015 heat demand as well as the heat demands suggested in sEEnergies 2050.

5 References

BERTELSEN, N. and MATHIESEN, B.V., 2020. EU-28 Residential Heat Supply and Consumption: Historical Development and Status. *Energies,* **13**(8), pp. 1894.

CHAMORRO, C.R., GARCÍA-CUESTA, J.L., MONDÉJAR, M.E. and PÉREZ-MADRAZO, A., 2013. Enhanced geothermal systems in Europe: An estimation and comparison of the technical and sustainable potentials - ScienceDirect. *Energy,* **65**(1),.

DUMAS, P., ANGELINO, L., LATHAM, A. and PINZUTI, V., 2020. *Developing geothermal district heating in Europe - The GeoDH Project.*

EUROPEAN COMMISSION, 2023. *State of the Energy Union Report 2023 . Brussels, 24.10.2023 COM(2023) 650 final.* Brussels: .

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 COMMISSION, 2016. *An EU strategy on heating and cooling 2016.* COM(2016). European Commission.

EUROPEAN UNION, 20/09/, 2023-last update, Directive (EU) 2023/1791 on energy efficiency and amending Regulation (EU) 2023/955 (recast) – European Sources Online. Available: https://www.europeansources.info/record/proposal-for-a-directive-on-energy-efficiency-recast/ [Nov 13, 2023].

EUROSTAT, 2023-last update, Energy statistics - an overview. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview [Nov 13, 2023].

FLEITER, T., ELSLAND, R., REHFELDT, M., STEINBACH, J., REITER, U., CATENAZZI, G., JAKOB, M., RUTTEN, C., HARMSEN, R., DITTMANN, F., RIVI `ERE, P. and STABAT, P., 2017. *Profile of heating and cooling demand in 2015.* Heat Roadmap Europe Deliverable 3.1.

FLEITER, T., MANZ, P., NEUWIRTH, M., MILDNER, F., PERSSON, U., KERMELI, K., CRIJNS-GRAUS, W. and RUTTEN, C., *Documentation on excess heat potentials of industrial sites including open data file with selected potentials (sEEnergies).* Copenhagen: Aalborg University.

GEELEN, J., JOSSART, J.-M., & ANDONE, A.-N., 2023. *Bioheat. Statistical Report 2023.* Brussels: Bioenergy Europe.

HURTER, S. and HAENEL, R., 2002. *Atlas of geothermal resources in Europe.* Brussels: European Commission, Directorate-General for Research and Innovation.

KRANZL, L., FORTHUBER, S., FALLAHNEJAD, M., BÜCHELE, R., MÜLLER, A. and HUMMEL, M., 2021. *ENER/C1/2018-494 – Renewable Space Heating under the Revised Renewable Energy Directive.* Brussels: .

LUND, H., THELLUFSEN, J.Z., ØSTERGAARD, P.A., SORKNÆS, P., SKOV, I.R. and MATHIESEN, B.V., 2021. EnergyPLAN – Advanced analysis of smart energy systems. *Smart Energy,* **1**, pp. 100007.

MATHIESEN, B.V., ILIEVA, L.S., SKOV, I.R., MAYA-DRYSDALE, D.W. and KORBERG, A.D., 2022a. *REPowerEU and Fitfor55 science-based policy recommendations for achieving the Energy Efficiency First Principle (sEEnergies).* Copenhagen: Aalborg University.

MATHIESEN, B.V., ILIEVA, L.S., SKOV, I.R., MAYA-DRYSDALE, D.W. and KORBERG, A.D., 2022b. *Synergies between the Energy Efficiency First Principle and 2050 Renewable Energy Systems in Europe (sEEnergies).* Copenhagen: Aalborg University.

MATHIESEN, B.V., JOHANNSEN, R.M., KERMELI, K., CRIJNS-GRAUS, W., LUND, H. and SKOV, I.R., 2023. The green transition of industry – An introduction to IndustryPLAN - ScienceDirect. *Smart Energy,* **11**.

MAYA-DRYSDALE, D.W., ABID, H., KORBERG, A.D., SKOV, I.R., MATHIESEN, B.V., ILIEVA, L.S. and DAHL NIELSEN, F., 2022. *Energy Efficiency 2050 Roadmap for Europe (sEEnergies).* Copenhagen: Aalborg University.

MCWILLIAMS, B., & ZACHMANN, G., 2023-last update, Dataset. European natural gas demand tracker (Bruegel). Available: https://www.bruegel.org/dataset/european-natural-gas-demand-tracker.

MEUNIER, S., PROTOPAPADAKI, C., PERSSON, U., SÁNCHEZ-GARCÍA, L., MÖLLER, B., WIECHERS, E., SCHNEIDER, N.C.A. and SAELENS, D., 2021. *Cost and capacity analysis for representative EU energy grids depending on decarbonisation scenarios. (Seenergies).* Copenhagen: Aalborg University.

ODYSSEE-MURE, 2021. *Energy efficiency trends and policies.* Enerdata.

PERSSON, U. and AVERFALK, H., 2018. *Accessible urban waste heat, ReUseHeat Deliverable 1.4.* Halmstad: Halmstad University.

PERSSON, U., MÖLLER, B., SÁNCHEZ-GARCÍA, L. and WIECHERS, E., April, 2022-last update, UA Future DH Potentials [Homepage of Aalborg University], [Online]. Available: https://s-eenergies-open-data-euf.hub.arcgis.com/datasets/21847c1772ee4cef86e1cdbcba39d3c8_0/explore [Nov 13, 2023].

PERSSON, U., MÖLLER, B., SÁNCHEZ-GARCÍA, L. and WIECHERS, E., 2021. *District heating investment costs and allocation of local resources for EU28 in 2030 and 2050.* Copenhagen: Aalborg University.