Renewable Heating and Cooling Pathways –

Towards full decarbonisation by 2050

ENER C1 2019-482

Final report

Sibylle Braungardt, Veit Bürger (OEKO)
Tobias Fleiter, Mahsa Bagheri, Pia Manz, Anna Billerbeck, Khaled Al-Dabbas, Barbara Breitschopf, Jenny Winkler (FRAUNHOFER ISI)
Mostafa Fallahnejad, Daniel Harringer, Jeton Hasani, Ali Kök, Lukas Kranzl, Philipp Mascherbauer (TU WIEN)
Marcus Hummel, Andreas Müller, Jul Habiger (E-THINK)
Urban Persson, Luis Sánchez-García (HALMSTAD UNIVERSITY)

February 2023

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Fraunhofer ISI

TU WIEN

e-think Energy Research

HALMSTAD UNIVERSITY

EUROPEAN COMMISSION

Directorate-General for Energy

Directorate C — Green Transition and Energy System Integration

Unit C1 — Renewables and Energy System Integration Policy

Contact: Matthieu Ballu

E-mail: *matthieu.ballu@ec.europa.eu*

European Commission
B-1049 Brussels

Renewable Heating and Cooling Pathways –

Towards full decarbonisation by 2050

ENER C1 2019-482

Final report

Manuscript completed in March 2023

PDF ISBN 978-92-68-07633-0 doi 10.2833/036342 MJ-04-23-903-EN-N

Luxembourg: Publications Office of the European Union, 2023

Table of Contents

1. Summary

Introduction

With the adoption of the EU Climate Law[1] in 2021, the EU has set itself a binding target to achieve climate neutrality by 2050 and to reduce greenhouse gas emissions by 55 percent compared to 1990 levels by 2030. To support the increased ambition, the EU Commission adopted proposals for revising the key directives and regulations addressing energy efficiency, renewable energies and greenhouse gas emissions in the Fit for 55 package.

The heating and cooling (H&C) sector plays a key role for reaching the EU energy and climate targets. H&C accounts for about 50 percent of the final energy consumption in the EU, and the sector is largely based on fossil fuels. In 2021, the share of renewable energies in H&C reached 23%[2].

The decarbonisation of heating and cooling is addressed across several directives and regulations at EU level as shown in Figure 1.

	Renewable Energy Directive	Energy Efficiency Directive	Energy Performance of Buildings Directive	ETS Directive	Ecodesign Directive
Over-arching	Overall target for renewable share RES-H&C target (Art. 23)	Art. 3: Overall energy efficiency target Art. 7: Energy saving obligations			
Heating in buildings	Target and framework for mainstreaming RES in buildings (Art. 15a)	Role of public buildings Metering and billing (Art. 9-11)	Requirements for energy performance of new and existing buildings	Proposal for ETS 2 for buildings and transport Proposal for Social Climate Fund	Efficiency of heating appliances Proposal to phase-out stand alone fossil heating (RePowerEU)
District heating	Target for renewables in district heating (Art. 24)	Efficient district heating		Carbon pricing in ETS 1	
Process heat	Target for renewables in industry (Art. 22a)	Energy management systems			Efficiency requirements

Figure 1: Overview of EU-level provisions addressing the heating and cooling sector

The aim of this study is to support the analytical basis for the development and implementation of policies to ensure a seamless pathway to the full decarbonisation of the heating and cooling sector by 2050 in buildings and industry.

[1] REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 June 2021 establishing the framework for achieving climate neutrality

[2] Eurostat SHARES data

Renewable heating potentials

The transition of the heating sector in each of the EU Member States depends on the available potentials for renewable heat sources. To support the development of transition pathways, renewable heating potentials have been assessed and summarised for each country.

As a first step, the historical development of renewable energy in H&C is analysed in the EU MS based on Eurostat data. In the second step, existing data on future potentials for renewable energy sources for heating and cooling are identified and prepared. These data are used as a basis for the projections on the decarbonisation of the H&C sector by 2050. Figure 2 shows the potentials per capita for hydropower, biomass and wind.

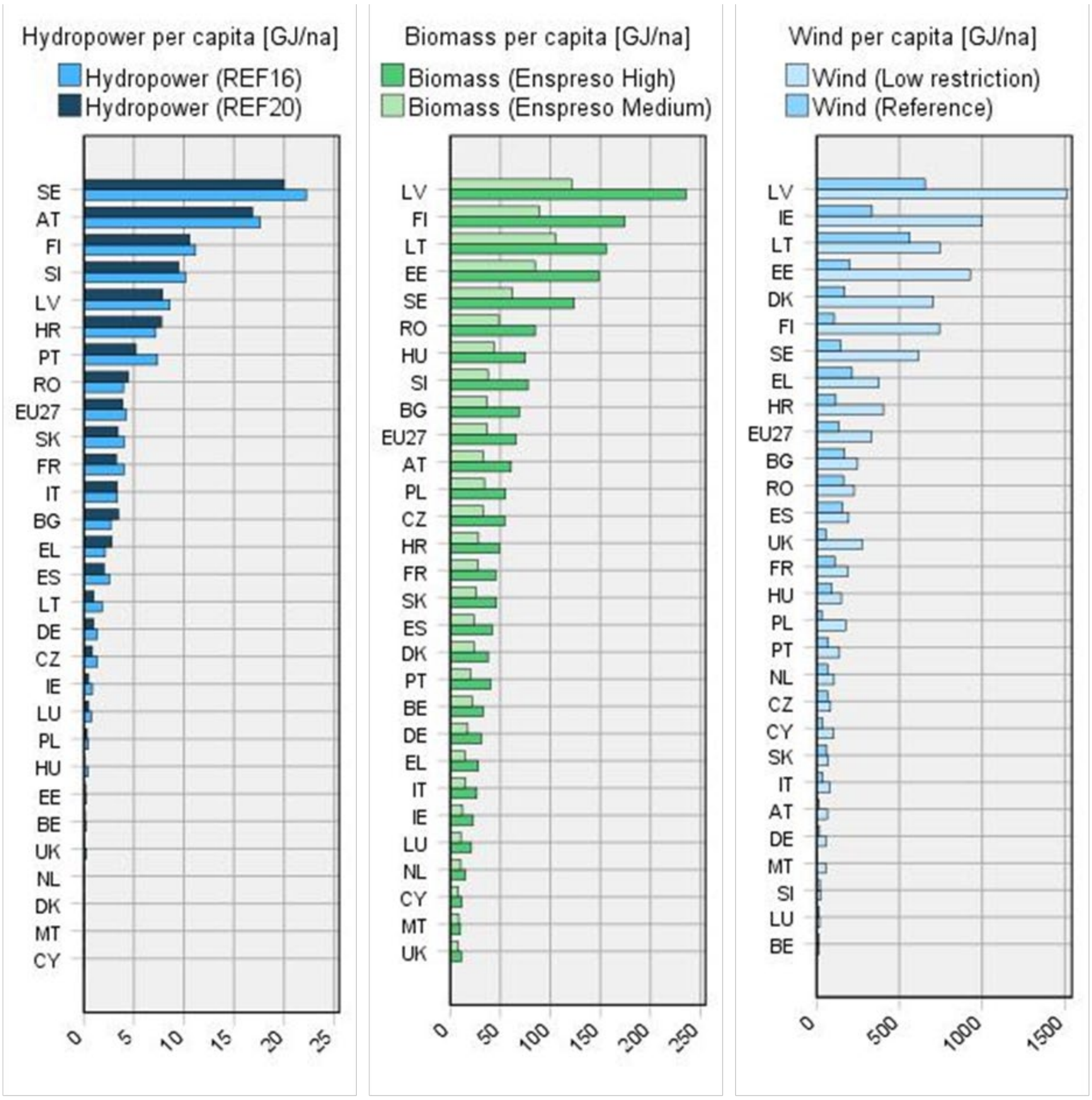


Figure 2: Renewable energy potentials per capita by population projections for 2050: Hydropower (by Primes Reference Scenarios 2016 and 2020) (left), Biomass (by JRC Enspreso High and Medium Availability Scenarios) (centre), and Wind (by JRC Enspreso Low and Reference Restrictions Scenarios). EU27 average values.

For renewable energy sources that are used in district heating, the potentials are mapped spatially and are allocated to district heating areas. Figure 3 depicts the technical potentials for geothermal heat (hydrothermal and petrothermal potentials with the minimum temperature of 65°C or 85°C in the underground), heat from rivers and lakes, wastewater treatment plants and waste heat from industrial sites and waste incineration plants (waste-to-energy, WtE) in Europe (baseline scenario). Solar and roundwood biomass potentials as well as air source heat pumps were not assumed to be limited by spatial availability and therefore not mapped. The technical potentials are visualised based on the amount of energy they could provide per year, which was used for the mapping to the DH areas.

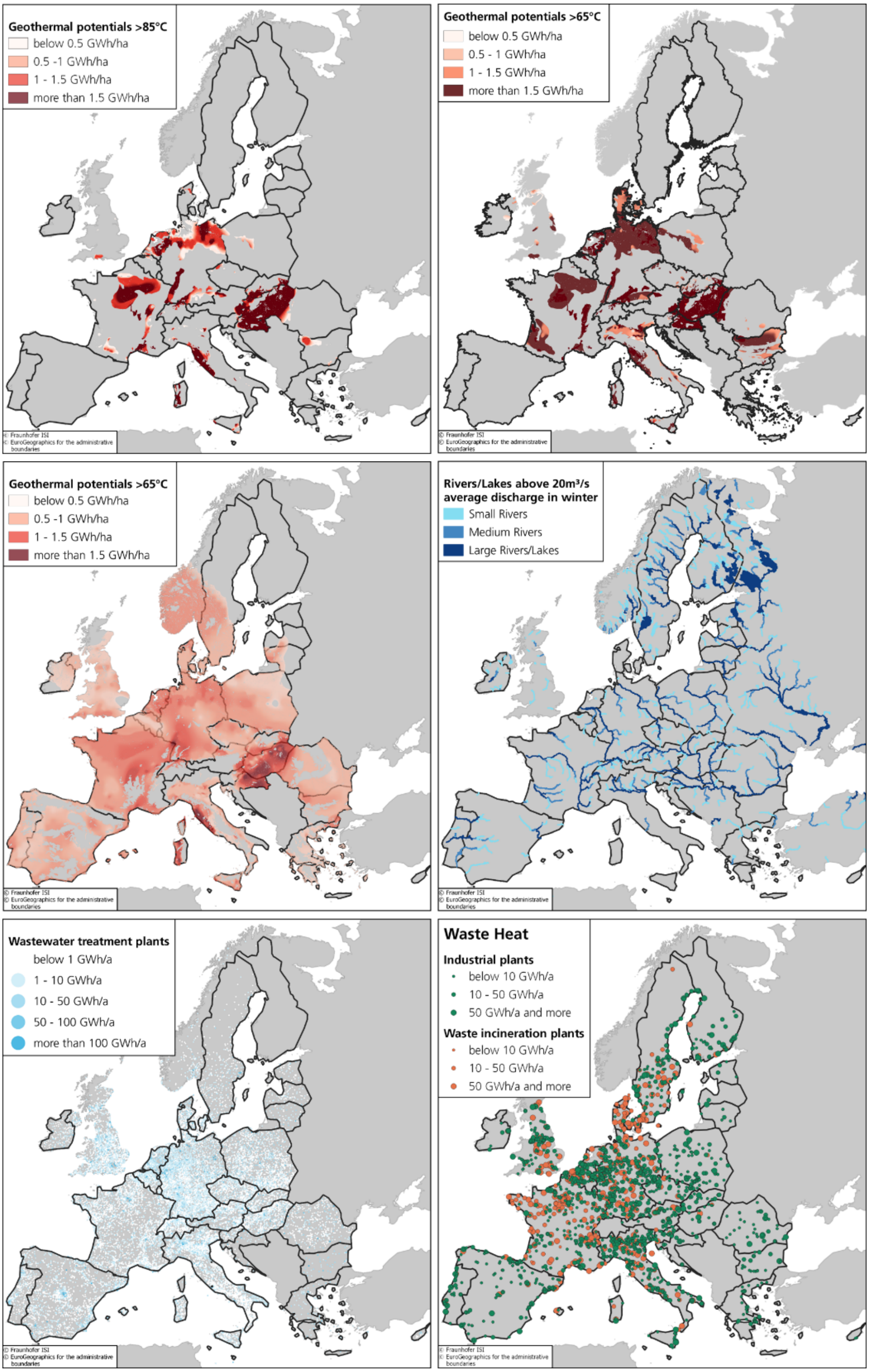


Figure 3: Technical RES and waste heat potentials for DH utilisation in EU in the baseline scenario

Suitability for transition pathways

Across all Member States, the transition of the H&C sector requires different transition strategies to reflect the specific situation in each Member State. This includes the local, regional and national availability of renewable energy sources, the available infrastructure, the energy performance of the building stock, the structure of the industry sector, policies in place as well as climatic conditions. All these factors affect the overall suitability of a country to follow a certain transition strategy.

The suitability of Member States for different transition strategies has been assessed systematically using an indicator-based approach. The transition strategies included are electrification, district heating, individual renewable heating (focus on solar thermal and biomass) as well as e-fuels and hydrogen. For each transition strategy, a specific set of indicators is combined to calculate the overall suitability per country. The indicators cover the economic, market, infrastructure and physical suitability. The countries are then clustered into groups with respect to their similarity in those indicators.

Figure 4 shows an illustration of the suitability analysis for electrification. Accordingly, Sweden and Denmark form cluster 1 and have a very high suitability for electrification and mature heat pump markets. Also the Baltic states have a very high suitability for electrification and form cluster 3, based on good RES potentials. A large group of mostly southern European countries with warm climate, good PV potentials, but less wind potentials is grouped into cluster 2. Remaining western and central European countries have a mixed to moderate suitability for electrification, with cold climate and lower RES-E potentials.

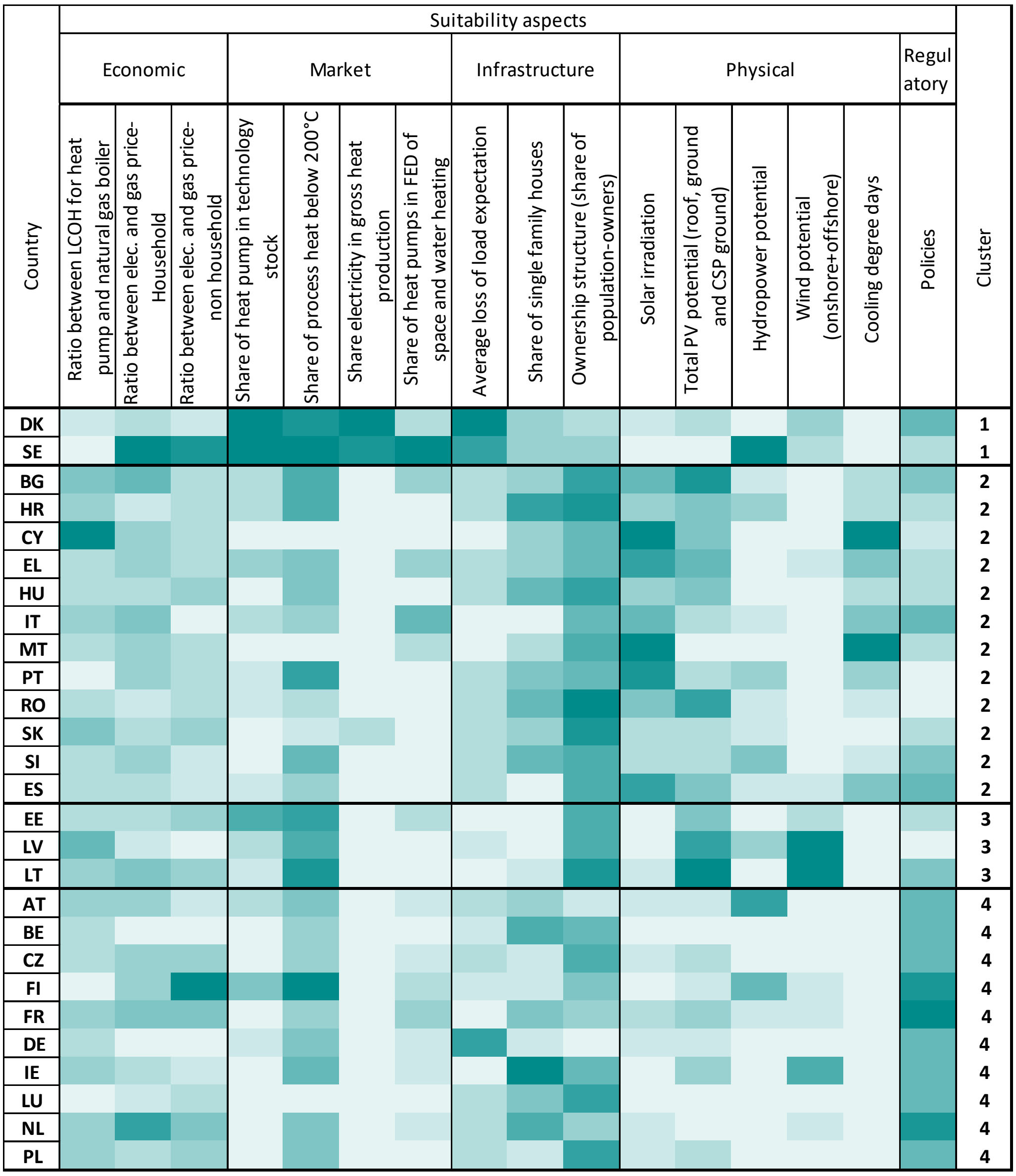


Figure 4: Overview of results for individual suitability indicators by country as used in the hierarchical clustering for the decarbonisation strategy "Electrification"

Overall, results indicate that the suitabilities are very unevenly spread across countries. Some countries have a high suitability for several strategies like Sweden, Denmark or Bulgaria (electrification, district heating, direct RES) or even all strategies like Latvia and Lithuania (driven by high wind and solar energy potentials). Other countries, though, only have less suitable strategies available like Belgium, Luxembourg or Germany (somewhat suitable options in district heating).

Modelling of transition pathways

We use simulation models to calculate pathways for the decarbonisation of heating and cooling until 2050. The modelling in this work builds on a set of well-established and validated sector models, interfaces, and data. The building sector is covered by the model Invert and industrial process heat is modelled in FORECAST. The modelling of the district heating sector considers district heating expansion requirements and decarbonisation of supply based on the Hotmaps methodology. All models have a very high detailed representation of technologies and consider their techno-economic characteristics.

The transition pathways are assessed by comparing the following scenarios: 1) A baseline scenario that considers policies in place before the implementation of the Fit for 55 package and assumes no strong ambitions of MS in the implementation of climate and energy policies. 2) A decarbonisation pathway scenario that achieves full decarbonisation of the H&C sector by 2050. Moreover, the targets described for 2030 in the Fit for 55 package are achieved. 3) A price sensitivity scenario, following the same approach as the decarbonisation pathway scenario, however, with energy prices in the range as they have been observed since late 2021.

The senario results show a significant reduction of total energy use for heating and cooling by about 1/3 from 2019 (5600 TWh) to 2050 (3800 TWh). This is mainly caused by the reduction of final energy demand for space and water heating, mainly driven by renovation of the building envelope, but also by replacement of inefficient, old heating systems. While the final energy demand for space and water heating in buildings decreases by about 40% in this period (in terms of energy delivered even 60%), in the industry sector this reduction amounts to about 22%. For space cooling, the pathway scenario achieves a consolidation of the final energy demand through the very stringent use of passive measures, reducing the cooling demand strongly and increasing efficiency of cooling devices.

Total electricity consumption almost doubles from 2019 until 2050 in the EU-27 in the decarbonisation pathway scenario. While the electricity consumption in the building sector remains more or less constant (or even slightly decreases), the electricity consumption for process heating in the industry increases almost by a factor of 6 to about 700 TWh by 2050. In the buildings sector, the strong increase in heat pumps is the most relevant change in the supply structure. Also in district heating, the role of large-scale heat pumps becomes more important, at least in some countries.

While electricity consumption doubles from 2019 to 2050, the share of electricity and ambient heat in total energy use in the sector increases from 13% in 2019 to more than 46% in 2050.

The role of district heating in the decarbonisation pathway scenario strongly increases: in residential and tertiary buildings the share increases from about 12% in the base year to more than 24% in 2050. The importance of district heating in the decarbonisation pathway significantly differs between countries. This is driven by heat demand densities, policies (in particular zoning policies leading to high connection rates), availability of cheap renewable district heating technologies and the economic comparison to other, decentralised heat supply options. In particular, countries with currently high shares of district heating like the Scandinavian countries and Baltic countries keep and expand these high shares. But also more southern countries like Spain or Italy develop and expand the district heating sector.

Geothermal energy in the decarbonisation scenario turns out to be an important, cost-effective solution for renewable district heating in most countries, possibly providing 30-45% of thermal generation of DH in the long term. However, sensitivities have shown that large-scale heat pumps and (to a lesser extent) biomass can show an equal economic viability, mainly depending on price assumptions (e.g. electricity prices including taxes and fees). Thus, slight differences in policies or cost developments may lead to corresponding changes in the results. Industrial waste heat and the use of heat from municipal solid waste incineration should be increased as much as possible. Solar thermal energy could provide up to 10% of DH generation, depending on cost assumptions.

Long-term, seasonal thermal storage represents a key enabler of renewable district heating. Costs and barriers of different storage systems are still related to considerable uncertainty. Investments in thermal storage will also promote the low-cost integration of renewable heat potentials. The amount of these investments in our modelled scenarios is considered as moderate/conservative. Through higher uptake of low-cost thermal storage, district heating could gain even more relevance in the decarbonisation of space and water heating.

In the decarbonisation pathway scenario, hydrogen plays an important role in industrial process heat in many countries, but not in all. Especially countries with a large steel and chemical industry are likely to need huge quantities of hydrogen to decarbonise. On the other hand, countries with mainly less energy-intensive industries can better electrify. Overall, the hydrogen demand for H&C increases to about 380 TWh in the pathway scenario (plus potential demand for feedstocks in chemicals, which is outside the scope of this study). While the quantity is large, it is still substantially lower than the additional electricity demand in process heating.

For district heating, hydrogen boilers are only relevant for covering peak loads and thus cover only a very minor share of the energy use.

In the building sector, for some countries the full phase-out of gases and liquids presents a considerable challenge. For these countries (e.g. BE, DE, NL) a considerable share of these fuels still remains in the mix of heating systems according to our modelling results. The modelling, however, does not depict in detail the spatial allocation of gas demand and the resulting gas grid decommissioning. Thus, our model results might overestimate the share of gases for space and water heating in the scenario or there might remain some parts of the grid in operation, along which also buildings are supplied.

Solar energy plays a considerable role in particular in some MS for the space and hot water sector, mainly in decentralised heating systems. The share of solar energy for heating in residential and tertiary buildings increases to more than 11% in 2050. However, in some southern countries like CY, EL, IT, PT, ES solar energy covers shares of about 20%. Also in countries like DE, FR or DK significant solar shares are achieved. In order to understand this effect, it is worth noting that we consider both solar thermal collectors as well as on-site PV for space and water heating. Thus, the increasing use of on-site PV will also increase the share of solar energy to the space and water heating sector.

Solid biomass by far holds the largest share in renewable heating and cooling in the base year. The economic viability of biomass in district heating mainly depends on the comparative costs and potentials of geothermal-based district heating and large-scale heat pumps. In industry, the pathway scenario shows a rather constant use of biomass in areas where it is used today: countries with huge potentials and industries where biomass is a production residue like the pulp and paper production. There could be a higher use of biomass in many industrial applications, however, if electrification and hydrogen use are rolled out broadly, there is no need to expand biomass use in industry as it is is always more difficult to handle at an industrial site.

Policies to support the transition

To achieve full decarbonisation of the heating and cooling sector by 2050, ambitious policies are needed. Table 1 summarises key policies needed to decarbonise space and water heating in buildings.

Table 1: Key elements of policy set for individual heating in buildings

Policy set: Renewable heating (individual boilers)			
	Regulations	**Economic instruments**	**Complementary instruments**
EU level	Short term: Fossil-free new buildings (EPBD) Short term: Framework for national fossil fuel phase-out (EPBD/RED) Medium term: End date for selling fossil boilers at EU level (Ecodesign)	Short term: No subsidies for fossil heating technologies in any EU funding schemes From 2027: Carbon pricing ETS 2 (ETS directive) Social Climate Fund: Focus on vulnerable households	Facilitate exchange between Member States Guidelines and framework for national support schemes Technology supply chains and production of technologies
National level	Fast introduction of (gradual) phase-out regulations (use obligations, efficiency requirements, ban) Heat planning and strategy for regulatory framework for decommissioning parts of the gas grid	No subsidies for fossil boilers Subsidies for RES heating Reduce taxes on electricity, add taxes and levies on fossil energy carriers	Facilitate market transformation through information and capacity building Address shortage of workforce in the installer market Expansion of RES-E

The policy set **results in a significant reduction of greenhouse gas emissions** as compared to the baseline scenario: At the EU level, GHG emissions from individual heating systems in buildings decrease by 62 Mt in 2030 as compared to the reference scenario. The impact of the policy set is particularly strong in countries with high shares of individual heating based on fossil fuels: Figure 102 shows that the reduction of greenhouse gas emissions per capita is highest in Ireland, followed by Belgium, France, Germany and the Netherlands, reflecting the fact that these are the countries with the highest shares of fossil-fuel boilers in their energy mix for space heating (see Figure 5). By contrast, the impact is relatively low in countries with low shares of fossil-fuel boilers.

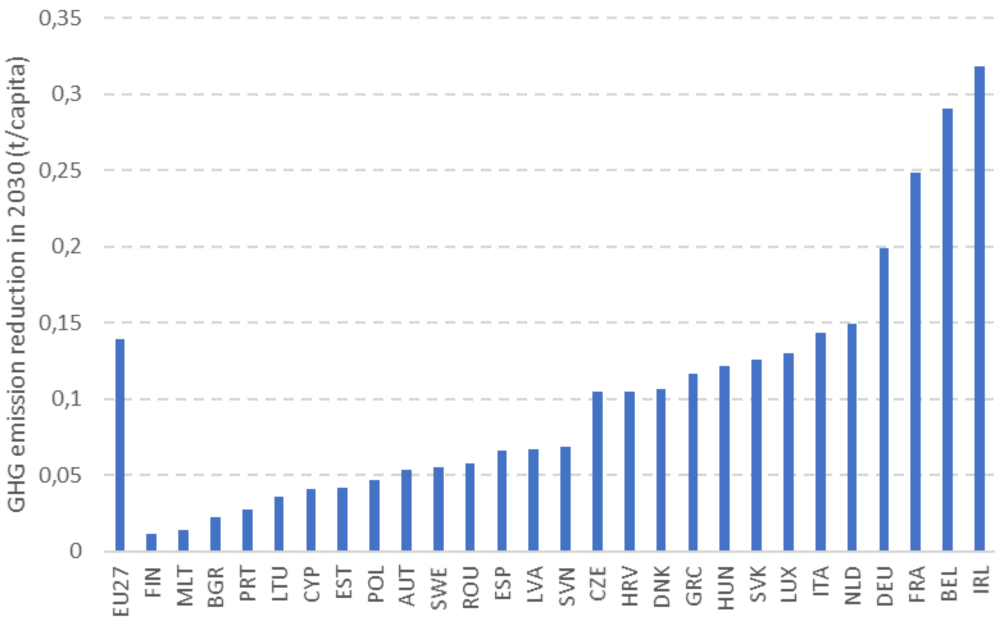


Figure 5: Reductions of greenhouse gas emissions in 2030 in the decarbonisation pathway scenario as compared to the baseline scenario.

As the Member States have largely differing shares of fossil fuel boilers in their current heating energy mixes, it is recommended that Member States **rapidly introduce national phase-out regulations** that support the transition of the market, taking into account country-specific situations. In the medium term, a ban of the sales of fossil fuel boilers at EU level is recommended. This can be introduced within the Ecodesign framework as proposed in the Save Energy Communication. Within this framework, the ban would be introduced as a minimum requirement on energy efficiency, making (hybrid) heat pumps the standard for new heating installations. The introduction of an end date for selling heating equipment that uses fossil fuels should be communicated and legally implemented well in advance to ensure that the market actors adapt their strategies accordingly.

In terms of **economic policies**, a key precondition for the decarbonisation of heating and cooling in buildings is energy pricing. The analysis shows that high prices for fossil fuels strongly support the transition towards renewable heating, whereas electricity prices are key for the deployment of heat pumps. While several countries have implemented carbon pricing schemes to support the transition, a reform of energy pricing can act as a key driver in many countries.

Another important driver for the transition of heating in buildings are **subsidies for heating equipment**. Subsidies for renewable heating systems can support the transition and can reduce the burden of households and companies in the transition. To this end, it is recommended that such policies specifically address low-income households to ensure a fair transition. In addition to ensuring financial support for renewable heating equipment, it is essential that financial support for fossil-fuel boilers is phased out immediately both at EU and national level. At the EU level, this needs to be ensured by providing clear requirements and guidelines in the EU funding schemes. At the national level, for those countries that still include fossil fuel boilers in national schemes, it is recommended to rapidly stop the support and redirect the funding into renewable heating technologies and energy efficiency measures.

Next to the regulatory framework and economic instruments, the market transformation needs to be supported by **complementary policies**. Firstly, on the supply side, this includes measures that address the shortage of skilled labour to ensure that the demand for renewable heating technologies and energy efficiency measures can be met by the market actors. This might encompass European initiatives to ensure the supply chain for equipment like renewable heating systems or control devices, if required also the production of critical products within Europe. Secondly, on the demand side, measures to facilitate retrofit work in buildings and to provide information and advice to building owners are essential, including the establishment of one-stop shops and enhancing the use and quality of Energy Performance Certificates.

Heating and cooling in industry

H&C in industry is dominated by high-temperature process heating in basic materials industries in most countries. The transition to CO_2-neutral process heating requires as key strategies both electrification and increased use of hydrogen. Other options are also relevant for CO_2-neutral process heating but are more of a supporting nature as they can reduce the demand for hydrogen or electricity and lower the pressure on the energy supply system. Examples are solar thermal, geothermal district heating or biomass. Here, we focus on the two main strategies: Electrification and hydrogen use for process heating.

The policy mix needs to assure cost competitiveness of both options compared to fossil-based process heating. In many cases this includes re-investment in new furnace or boiler equipment. In some cases, even a switch to another production process is required (e.g. primary steel production). Main recommended policies are summarised in Table 2. At the centre are policies that target the cost competitiveness of CO_2-neutral process heat supply. These involve on the one hand options that make fossil technologies more expensive by e.g. adding a price on carbon emissions or increasing taxes and on the other hand options that make CO_2-neutral solutions cheaper e.g. by providing dedicated investment or OPEX support or by reducing the price of electricity and hydrogen for industrial consumers.

Table 2: Key elements of the policy mix for CO_2-neutral process heating

Policy set: Process heating			
	Carbon and energy price regime	**Technology support**	**Complementary instruments**
EU level	Strong ETS I with robust price path ETS II also including industry that is not in ETS I Reform of energy taxes and levies to make electrification and hydrogen more attractive compared to fossils	Investment support to accelerate market entry and early diffusion. CAPEX & OPEX support, e.g. via contracts for difference to fill gaps in cost competitiveness of key decarbonisation technologies	Transition of the upstream energy system to ensure sufficient supply of renewable-based electricity and hydrogen for industry Strategies and plans for the roll-out of hydrogen infrastructure incl. regional prioritisation to allow companies to plan investments

Policy set: Process heating			
	Carbon and energy price regime	**Technology support**	**Complementary instruments**
National level	Large part of the reform of energy taxes and levies is Member State activity If the EU ETS II does not materialise or does not include the industry sector, national measures will be needed to introduce a CO_2 price for the industry outside of ETS I	Technology support programmes will need to be implemented by Member States to a large extent	The transition of the upstream system and the development of strategies and plans for the hydrogen roll-out largely falls into Member State responsibilities as well.

The scenario calculation shows that with an ambitious implementation of the policy mix, a transition towards a CO_2-neutral process heat supply in industry can be achieved. Figure 105 shows the development of final energy demand. Key insights from the scenario analysis are:

- **Electricity and hydrogen** from renewables are key to decarbonise industrial process heat supply. Here, a clear policy strategy is needed to reduce uncertainty and make investments plannable.
- **Hydrogen is important in high-temperature processes** like metal or minerals processing.
- However, technologies to use electricity or hydrogen for process heating in **industrial furnaces** are often not yet available at industrial scale. Policies for upscaling and market introduction can facilitate the transition.
- **Electrification** can happen at large scale in the short term to electrify steam generation, if the regulatory frame allows it – technologies are ready. Still, the past has shown that prices for electricity were too high compared to fossils. Main cost drivers are OPEX and less CAPEX. A reform of energy and CO_2 prices and accompanying support policies need to make electrification cost-competitive. Electrification of process heat might be the most efficient way, however, in most cases it also requires a more comprehensive re-investment. Here, policies can provide investment support for electrification solutions.
- Use of direct RES only to supply **low-temperature process heating** below 150 or even 100°C (limited potential). **Industrial heat pumps** allow efficient electrification in this temperature range.
- **Biomass** facilitates a fast phase-out of natural gas, but is not key in the long term.
- **Energy and material efficiency improvements and circularity** overcompensate economic growth and substantially reduce the demand for clean secondary energy carriers.

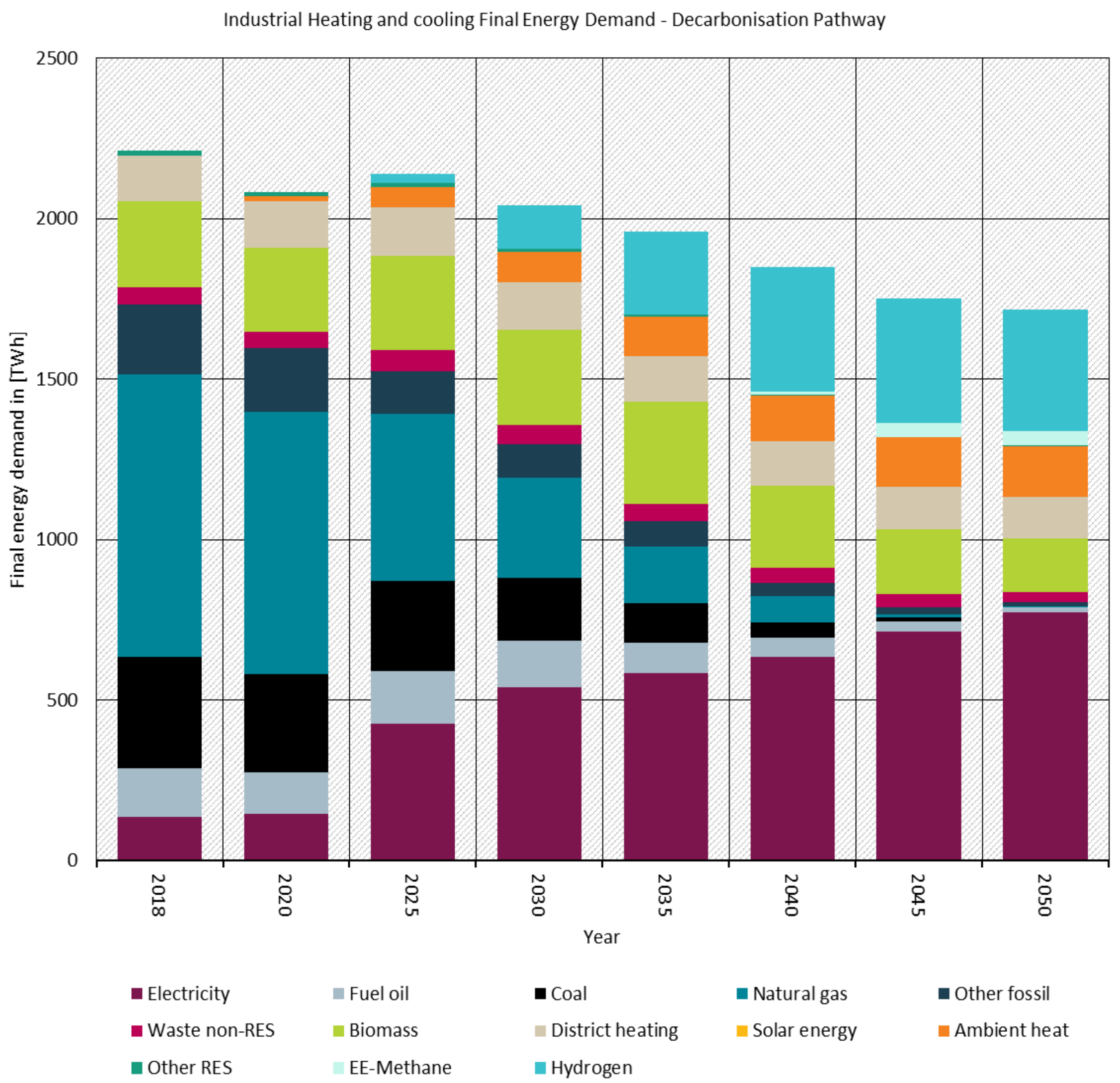


Figure 6: Final energy demand for H&C in industry in 2050 in the pathway scenario (EU27)

District heating

To expand and decarbonise DH, ambitious policies are needed. Table 3 summarises the key elements of the policy set required.

Table 3: Key elements of policy set for district heating

Policy set: District heating			
	Regulations	**Economic instruments**	**Complementary instruments**
EU level	Mandatory grid access for third-party generation from climate-friendly heat generation Obligations to develop transformation	Strong ETS I with robust price path Reform of energy taxes and levies to make electrification and hydrogen more	Support for capacity building and exchange between Member States. Financial support for research and development on

Policy set: District heating			
	Regulations	**Economic instruments**	**Complementary instruments**
	strategies and to expand the use of waste heat.	attractive compared to fossils Specifications for efficiency district heating in EU funding context	innovative district heating and cooling solutions.
National level	Quota/obligations for including renewable energies in DHC Mandatory expansion targets, spatial zoning, mandatory connection to DHC systems.	Subsidy schemes for the expansion and decarbonisation of fossil-free district heating and cooling.	Strategic (local) heat planning approaches, awareness across different market actors, participation

The policy set for DH **results in a significant reduction of greenhouse gas emissions** as compared to the baseline scenario. The impact is particularly strong in countries with high shares of district heating. **In 2050 a fully decarbonised DH mix is reached** in the pathway scenario, mainly due to the high CO_2 price.

Furthermore, the policy set for DH **has a considerable impact on the expansion of district heating**. Figure 7 shows the increase of the DH demand until 2050/2070 in the pathway scenario per capita compared to current levels.[3] Expansion of DH per capita is especially foreseen in Italy, France, the Netherlands, Hungary, Sweden, the Czech Republic and Croatia. Thus, especially in these Member States policy measures for the growth of DH infrastructure are needed.

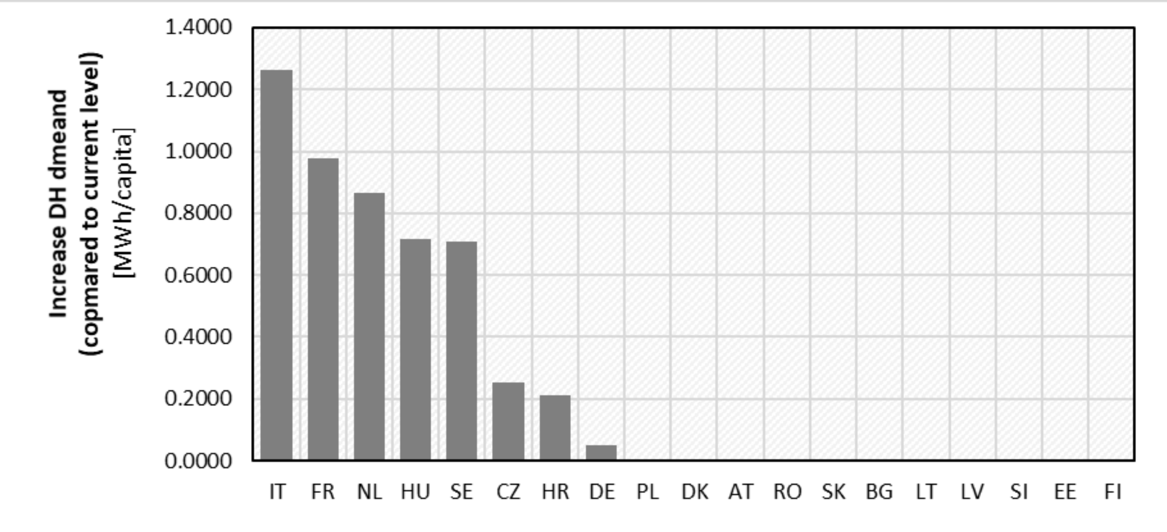


Figure 7: Increase of DH demand until 2050 compared to current level

[3] DH demand in 2050 based on modelling results; current level based on DHC Trend report, https://op.europa.eu/en/publication-detail/-/publication/4e28b0c8-eac1-11ec-a534-01aa75ed71a1/language-en

In addition, the policy set for DH **has a high impact on the generation mix for the DH supply**.

Heat pumps have the highest contribution to the DH supply mix on EU-level and also in several Member States in 2050. Figure 108 shows that in almost all Member States a strong uptake of heat pumps is foreseen (in the pathways scenario). In the modelling, Member State-specific electricity prices are assumed, which are quite high in some Member States. Because of high electricity prices, heat pumps are less cost-competitive in the respective Member States. Lower electricity prices would lead to higher shares of heat pumps with accordingly lower shares of RES, especially geothermal energy. Thus, we recommend policies for the uptake of large-scale heat pumps for all Member States.

An uptake of **geothermal energy** is especially prominent in Denmark (see Figure 109). However, the modelling results foresee a considerable increase of geothermal energy in almost all Member States, except the Netherlands, Estonia and Finland. Thus, policies for the uptake of geothermal energy (i.e. policies to support technical progress and minimise exploration risks to utilise potentials) are highly needed in almost all Member States.

Regarding the use of **biomass** in DH a shift in several countries can be observed (see Figure 110). In line with the modelling results, an increase of biomass is foreseen in Latvia, Croatia and, to a smaller extent, in Austria, Italy, Romania, Germany and Slovakia. In contrast, for several Member States a reduction in the use of biomass until 2050 is foreseen to reach the 2050 results of the pathway scenario. Especially in Denmark, Finland, Estonia, Sweden and Lithuania, a decrease of biomass seems to be cost-optimal in 2050 in the pathway scenario. Policies for the allocation of biomass are needed to trigger this shift.

Furthermore, other waste heat sources should be utilised either directly or together with heat pumps, depending on the temperature level. Waste-to-Energy can have a relevant contribution, so CO_2 price exemptions for waste incineration could be needed.Policies for the integration of industrial waste heat into district heating are needed to exploit the potentials. Policies to decrease the system temperatures down to around 60°C may be needed, together with coordinated actions with building renovation, as renewable and waste heat potentials can be utilised more efficiently. As a result, policy sets are developed and discussed with respect to their suitability and relevance in different Member States. Separate policy sets are developed for space heating, district heating and process heat.

Implications for 2030 targets at EU level

The modelling results show that the targets proposed in the revision of the Renewable Energy Directive are largely overachieved in the scenarios with full decarbonisation by 2050. Table 4 summarises the level of compliance of the three scenarios for EU-27. While the baseline scenario clearly fails to achieve the targets, the decarbonisation pathway clearly overachieves the defined targets. Due to the short-term price elasticity effects on the demand, the price sensitivity scenario leads to slightly higher RES H&C shares and related growth of renewables.

The targets proposed in Art 15a (for buildings) and Art 22a (for industry) refer to overall renewable energy and thus are not limited to heating and cooling. For the purpose and the scope of this project we calculate the contribution of heating and cooling to the total buildings' and industry's sector, according to the RES-H&C shares method according to Art 7 of the Renewable Energy Directive, i.e. not accounting for electricity in the nominator and the denominator of the shares calculation. The calculation of renewable cooling follows the method described in the delegated regulation 2022/759[4].

Table 4: Compliance of scenarios with 2030 targets from the proposed Renewable Energy Directive (RED), EU-27

	Unit	Target according to proposed revision of the RED	Baseline	Decarboni-sation	Price sensitivity
Art 15a - RES in buildings (*)	%	49%	43%	51%	52%
Art 22a - RES increase in industry (*)	ppt	1.1	0.74	2.18	2.64
Art 23 - RES-HC increase	ppt	1.1	1.01	2.03	2.40
Art 23 - RES-HC increase (incl Waste HC)	ppt	1.5	1.05	2.07	2.46
Art 24 - RES-HC increase in DHC	ppt	2.1	0.94	1.6	3.1

(*) calculated only for the heating and cooling related shares

The fact that the targets are exceeded in 2030 in the scenarios reaching full decarbonisation indicates that the proposed increase of ambition presented in the RePowerEU package is better aligned to the target of full decarbonisation than the Fit for 55 proposals, at least for the heating sector.

In addition, the transition pathway developed in the decarbonisation pathway scenario supports the objective of reducing natural gas demand and reducing import dependency. In 2030, natural gas demand in the heating sector is reduced by almost 700 TWh in the decarbonisation pathway scenario as compared to the baseline scenario.

2. Introduction

With the adoption of the EU Climate Law[5] in 2021, the EU has set itself a binding target to achieve climate neutrality by 2050 and to reduce greenhouse gas emissions by 55 percent compared to 1990 levels by 2030. To support the increased ambition, the EU Commission adopted proposals for revising the key directives and regulations addressing energy efficiency, renewable energies and greenhouse gas emissions in the Fit for 55 package.

The heating and cooling (H&C) sector plays a key role for reaching the EU energy and climate targets. H&C accounts for about 50 percent of the final energy consumption in the

[4] European Commission, 2021. Commission delegated regulation (EU) 2022/759 of 14.12.2021 amending Annex VII to Directive (EU) 2018/2001 as regards a methodology for calculating the amount of renewable energy used for cooling and district cooling.

[5] REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

EU, and the sector is largely based on fossil fuels. In 2020, the share of renewable energies in H&C reached 23%[6].

The decarbonisation of heating and cooling is addressed across several directives and regulations at EU level (Figure 8).

	Renewable Energy Directive	Energy Efficiency Directive	Energy Performance of Buildings Directive	ETS Directive	Ecodesign Directive
Over-arching	Overall target for renewable share RES-H&C target (Art. 23)	Art. 3: Overall energy efficiency target Art. 7: Energy saving obligations			
Heating in buildings	Target and framework for mainstreaming RES in buildings (Art. 15a)	Role of public buildings Metering and billing (Art. 9-11)	Requirements for energy performance of new and existing buildings	Proposal for ETS 2 for buildings and transport Proposal for Social Climate Fund	Efficiency of heating appliances Proposal to phase-out stand alone fossil heating (RePowerEU)
District heating	Target for renewables in district heating (Art. 24)	Efficient district heating		Carbon pricing in ETS 1	
Process heat	Target for renewables in industry (Art. 22a)	Energy management systems			Efficiency requirements

Figure 8: Overview of EU-level provisions addressing the heating and cooling sector

The aim of this study is to support the analytical basis for the development and implementation of policies to ensure a seamless pathway to the full decarbonisation of the heating and cooling sector by 2050 in buildings and industry. To this end, the study contains the following elements:

- Chapter 3 provides estimates of the potentials for renewable energy sources for heating and cooling.
- Chapter 4 develops a framework for grouping countries according to their suitability for following different decarbonisation pathways for heating and cooling and presents the results of the suitability analysis.
- Chapter 5 provides an overview of policies and measures to support the decarbonisation of heating and cooling in the EU and its Member States. Based on a set of key indicators, the role of different policy options in the EU Member States is discussed. Furthermore, policy sets to support the decarbonisation of heating and cooling are developed for individual heating in buildings, district heating and cooling as well as process heat.
- Chapter 6 provides a detailed modelling analysis of the decarbonisation of heating and cooling in buildings and industry. The impacts of the policy sets to decarbonise

[6] Eurostat SHARES data

heating and cooling are analysed and discussed in the context of the EU and national policy frameworks.

- In Chapter 7, key results and messages are summarised and conclusions are drawn for the development of the policy framework for the decarbonisation of heating and cooling.

3. Renewable heating and cooling potentials

3.1. Objectives

The objective of this section is to establish potentials of renewable energy assets and resources accessible to the heating and cooling sectors in the EU27 Member States (and the former EU28 where relevant).

The general scope of renewable energy sources to consider for the potential assessment corresponds to that listed in Article 2 (1) of the recast Renewable Energy Directive[7] (RED II), namely: wind, solar (solar thermal and solar photovoltaic), geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.

The share of energy from renewable sources in the European Union energy balance is monitored by the specified calculation methodology defined in Article 7 of the recast Renewable Energy Directive (REDII). Hereby, the total share of energy from renewable sources consists of the sectoral contributions from electricity (RES-E), transport (RES-T), and heating and cooling (RES-H&C), all divided by “Gross Final Consumption of Energy” for each respective sector, to produce sector-specific as well as total shares. The development of these shares from 2004 to 2019 is depicted in Figure 9 where it can be observed that energy from renewable sources – so far – has found largest utilisation in the electricity sector and least so in the transport sector.

[7] Directive 2018/2001/EU

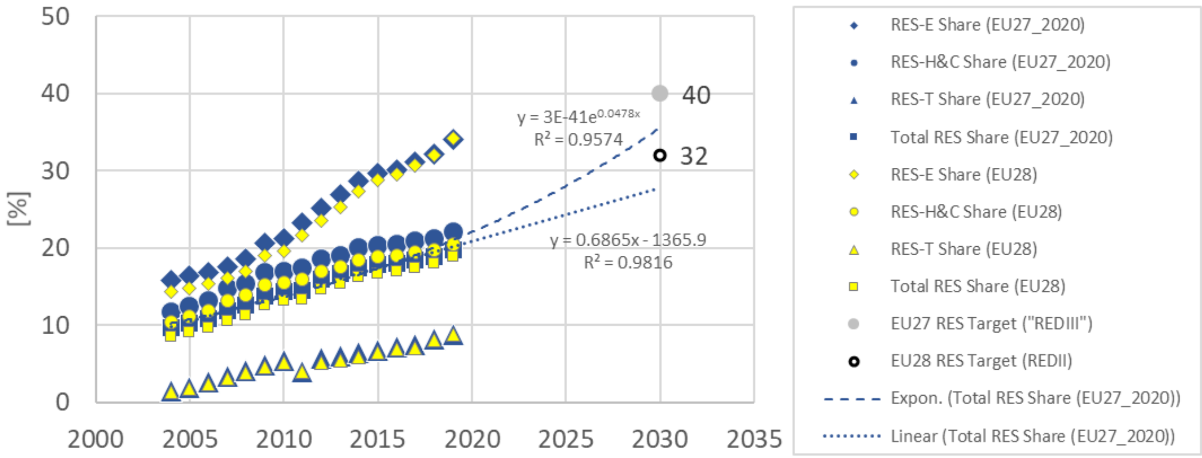


Figure 9: Illustration of renewable shares for EU27 (from 2020) and for EU27 plus United Kingdom (former EU28) between 2004 and 2019 for total share, share in electricity (E), transport (T), and in heating and cooling (H&C), as reported in (NRG_IND_REN, Last update: 2021-04-02).

From Figure 9 it is further noticeable for the total share that the rate of annual increase towards 2030 (for which REDII, Article 3 (1), stipulates a 32% overall target for the former EU28 and for which the "REDIII" proposal[8] stipulates at least 40% for EU27), needs to take place at an annual increment larger than that representing a linear progression of past years' development. For the heating and cooling share especially, given that the EU27 average annual increase during the time period considered has been approximately 0.7%, the stipulated increase rate of 1.1%-1.3% during the ten-year period from 2020 to 2030, as outlined in REDII (Article 23 (1)), seems reasonable indeed. In 2015, the EU27 RES-H&C share climbed up above 20% for the first time (20.3%), but with a large range of Member State variations (lowest between 5% and 7%, highest between 50% and 65%). For the former EU28, the corresponding RES-H&C share reached above 20% not until 2019 (20.5%).

For the establishement of potentials of renewable energy assets and resources accessible for heating and cooling purposes, this report distinguishes between potentials of a different character depending on constraints. The starting point consists of what should be understood as the ultimate maximum, that is, at the theoretically possible or the actual resource base more or less unlimited and unconstrained. This first level, the theoretical potential, which is the main focus in this section, serves to provide the reference from which subsequent levels of potentials can be determined, for example technical, spatial, economic, and systemic potentials.

From what initially can be observed according to the first order nature of the theoretical potentials found, it would seem that a transition from fossil-based to renewable-based energy sources in the EU heating and cooling sector is not principally hampered by a lack of such resources – at an unconstrained resource-base level, these are plentiful to a degree that perhaps needs special emphasis. The sequential treatment of potentials in this report consists firstly of the account in this section regarding the theoretical potentials (and the occasional mixed theoretical/technical potentials where so found, further detailed below), secondly, in further elaborations according to various dimensions and constraints at other locations in the report.

[8] COM(2021) 557 final

3.2. Methodological approach

The work flow consists of three main steps, as outlined in Table 5. The first main step has focused on generating an understanding of the historical development among the countries studied regarding their progress to integrate renewable energy resources in heating and cooling. The second main step has been the identification, gathering, preparation, and sharing, of useful data with regard to future potentials of the renewable resources considered. The third main step has been to provide input to develop future scenarios and the corresponding shares of renewable energy sources available for heating and cooling purposes in the projections (see Chapter 6).

Table 5: Main methodological steps in Task 1

	Main methodological steps in Task 1
1	Establish Member State progress on integrating RES in H&C from 2004 based on SHARES time series data
2	Analysis of available data to determine RES theoretical potentials in H&C
3	RES potentials in H&C for 2030 and 2050

During the first step, national reports under the SHARES reporting tool[9] provided valuable information. During this step, several other sources were used for reference, for example energy statistics from Eurostat and the International Energy Agency. While the SHARES reports (SHARES 2019 detailed results) provide a sufficient level of information detail, the start year for these records is 2004. The main reason for the use of additional energy statistics sources during this step was therefore to be able to establish time series dating back earlier than from 2004 (e.g. from 1990 and onwards). The SHARES detailed results for the EU27 Member States have been extracted and assembled in one comprehensive list which allows extracts by categories, countries, energy sources etc. (see the results section below for some examples).

In the second main step, an elaborate analysis (literature reviews, web searches, project listings etc.) of available data sources by which to determine potentials for energy from renewable sources constitutes the essential content. For some of the renewable energy sources, such as biomass and wind, up-to-date and high-quality potential assessment data is available from exisiting projects, for example through the JRC ENSPRESO initiative[10]. For other sources, such as geothermal, a general lack of easily accessible data suitable for our purposes inspired us to develop new models by which to produce potential assessments.

For the third step, to arrive at renewable energy source potentials for heating and cooling in the future (2030 and 2050), the first level potentials, the theoretical and mixed

[9] SHARES (Renewables): https://ec.europa.eu/eurostat/web/energy/data/shares

[10] ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials: https://www.sciencedirect.com/science/article/pii/S2211467X19300720?via%3Dihub

theoretical/technical potentials established in this section, constitute the main reference. Where applicable, for example in district heating modelling and concerning the sustainable use of biomass, more refined results have been derived by means of further analysis, dialogue and collaboration.

For the application of spatial constraints, for example, the spatial dimension was jointly addressed with respect to network heat distribution by producing new and updated representations of both current and future district heating areas in the EU27 (by means of in-depth mapping of building sector thermal demands among others), together with the application of Local Administrative Units (LAU) for the geographical determination and allocations of locally available renewable energy sources. See in particular Annex 3 (on the modelling of the district heating (DH) sector) for further reading on this topic.

Another example is that for the application of economic and systemic constraints, which relates to how the first level theoretical potentials were further. In this context, fuel and energy carrier costs, emission pricing, temporal availabilities etc. (genuine economic and systemic dimensions), render reduced potentials as an effect of least-cost preferences under market competition conditions (see Section 6.2.5). In themselves, the outputs from this modelling represent final results for what then could be understood as feasible and realistic potentials under the given modelling assumptions. Hereby, the final results are the combined outputs from mapping and modelling with respect partly to the resource potentials themselves, and partly with respect to anticipated levels of future heat supply technologies, infrastructures, and costs.

The main output from this part of the report is, on the one hand, an overview presentation of the historical development of renewables used for heating and cooling in the EU27 (the SHARES reports), on the other hand, data on the established theoretical and mixed theoretical/technical potentials, that is quantified annual energy volumes by each renewable energy source (where applicable) for the two future year settings considered.

For some sources, such as biomass, hydropower and wind power, complementary alternative potentials (not just maximum ones) are included to provide a basis for comparison and reference. In the particular case of biomass, additional attention has been given to anticipate genuinely sustainable future potentials, respecting for example the notion to avoid direct use of roundwood for energy purposes, which is described in a separate section below.

In terms of geographical resolution, the outputs are kept here at the national Member State level. However, noteworthy, these numbers are in most cases aggregates based on more detailed underlying data.

3.3. Overview of data sources for renewable potentials

For the renewable energy source potentials assessed here, information has been gathered partly from already available assessments (such as the JRC ENSPRESO studies (biomass[11] and wind), the PRIMES EU Reference Scenario 2016[12] (hydropower) etc.), where our elaboration has consisted in literature reviews and data management. For others, e.g. geothermal and solar, we have partly developed our own approaches and input datasets. In the particular case of biomass, available assessment data have provided the basis for anticipating a sustainable biomass potential, here labelled "conditioned biomass potential", where this represents a blend of using exisiting data and own approaches. While the available assessment data for biomass is referenced by its original source in this section, the approach for establishing the conditioned biomass potential is described in a separate subsection below.

All the renewable sources considered are presented in Table 6, with brief descriptions relating to the characteristics of the resource potentials, their scope, and the key information sources.

Table 6: Overview table of the renewable energy source potentials assessed with brief descriptions, scope, and source references

Indicator	Description	Scope	Sources
Biomass potential	"High and medium availability scenarios" selected and presented (others are "low") to reflect highest possible potential as well as a likely more realistic potential (theoretical/technical potential for 2050). Resource base implicit for biogas and sewage treatment plant gas. Resource base indicative for landfill gas. Note: a "conditioned biomass potential" was established on the basis of the medium availability scenario	Annual energy volumes by NUTS2 regions for 16 biomass energy commodity categories.	ENSPRESO - Biomass (JRC) JRC-EU-TIMES - JRC TIMES energy system model for the EU | Zenodo
Hydropower potential	From the 2016 reference scenario: Summary energy balances and indicators (A): Production (incl.	Annual energy volumes by Member States.	PRIMES EU Reference scenario 2016 EU Reference Scenario 2016 | Energy (europa.eu) PRIMES EU Reference scenario 2020

[11] The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries.
https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jrc-eu-times-model-bioenergy-potentials-eu-and-neighbouring-countries

[12] EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050
https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

Indicator	Description	Scope	Sources
	recovery of products) – Hydro. From the 2020 reference scenario: Gross Electricity generation by source, Hydro (pumping excluded). (technical potential for 2050)		EU Reference Scenario 2020 | Energy (europa.eu)
Wind potential	"EU-Wide low and reference restrictions scenarios" selected and presented (others are "high restrictions") to reflect highest possible potential as well as a likely more realistic potential (technical potential for 2050).	Annual energy volumes by NUTS2 regions considering a wide set of restricting parameters.	ENSPRESO - Wind (JRC) JRC-EU-TIMES - JRC TIMES energy system model for the EU | Zenodo
Solar irradiation potential	Model developed at HU. Incoming solar irradiation in the horizontal plane on land limited to a selection of Corine land use classes (agriculture) and with slope below 6% (theoretical/technical potential for 2030/2050). Note: data coverage incomplete for FI and SE.	Annual energy volumes by hectares	PVGIS (JRC), Digital Photovoltaic Geographical Information System (PVGIS) | EU Science Hub (europa.eu) Elevation Model (DEM) EU-DEM v1.1 — Copernicus Land Monitoring Service Corine Land Cover (CLC) CORINE Land Cover — Copernicus Land Monitoring Service
Solar photovoltaic potential	Model developed at HU. Incoming solar irradiation at optimal angle times total efficiency of solar panels on land limited to a selection of Corine land use classes (agriculture) and with slope below 6% (theoretical/technical potential for 2030/2050). Note: exclusive of solar thermal potential	Same as solar irradiation potential	Same as solar irradiation potential
Solar thermal potential	Model developed at HU. Incoming solar irradiation at optimal angle times total efficiency of solar collectors on land limited to a selection of Corine land use	Same as solar irradiation potential	Same as solar irradiation potential

Indicator	Description	Scope	Sources
	classes (agriculture) and with slope below 6% (theoretical/technical potential for 2030/2050). Note: exclusive of solar photovoltaic potential		
Geothermal potential	Model developed at HU. Full resource of all land areas in ground from surface to 2 km depth (some areas with missing data for ES, FI, FR, PT, and SE). (theoretical potential for 2030/2050) Note: Geo-DH data on hydropower aquifers used as complement in DH-modelling (see Section 6.2.5) Technical potentials established in association with DH modelling (Section 6.5 and Annex C3: Modelling of the DH sector (DH1 – DH6))	Energy volumes by land area unit	EC Geothermal Atlas (2002), Atlas of geothermal resources in Europe - Publications Office of the EU (europa.eu) WorldClim 2: https://www.worldclim.org/data/worldclim21.html GeoDH: http://geodh.eu/2014.
Geothermal potential (3GDH)	Model developed at HU. Resource of all land areas in ground from surface to 2 km depth limited to threshold temperatures of 80˚C and cooling temperatures of 40˚C (conditions for direct use in 3rd generation district heating systems)	Same as for geothermal potential	Same as for geothermal potential
Geothermal potential (4GDH)	Model developed at HU. Resource of all land areas in ground from surface to 2 km depth limited to threshold temperatures of 55˚C and cooling temperatures of 25˚C (conditions for direct use in 4th generation	Same as for geothermal potential	Same as for geothermal potential

Indicator	Description	Scope	Sources
	district heating systems)		
Tide, wave and other ocean energy	Established in association with DH modelling (Section 6.5 and Annex C3: Modelling of the DH sector (DH1 – DH6))	-	Numerical and spatial data for water ways
Ambient heat potential	Established in association with DH modelling (Section 6.5 and Annex C3: Modelling of the DH sector (DH1 – DH6))	-	Numerical and spatial data on ambient temperatures for air, water, and ground

It should also be noted that several additional data sources not included in Table 6 have been part of the research, for example the comprehensive S2BIOM biomass potentials[13], which covers no less than 55 unique biomass categories by NUTS3 regions while the JRC ENSPRESO datasets used distinguish between 16 categories and NUTS2 regions. In terms of volumes, however, both sources stipulate quite similar EU27 “high” scenario potentials for 2030 (S2BIOM: 18.0 EJ, JRC ENSPRESO: 19.0 EJ). Other sources not elaborated further in this context, but worth mentioning, are for example the additional biomass project BioBoost (which also presents potentials at the NUTS3 region level)[14], the solar potential resource of the Global Solar Atlas[15], and the recent potential assessments of the European Biogas Association[16], just to mention a few.

For the two source categories for which we have developed own models, geothermal and solar thermal, the following two subsections (3.3.1 and 3.3.2, respectively), provide further details. For the one source category for which we have combined the use of available data with own assumptions related to sustainability aspects, biomass, a third subsection (3.3.3) ends this section with a descriptive account.

3.3.1. Description of geothermal potential assessment

Geothermal energy is the heat contained in the ground, whichis released when the ground is cooled down to a certain temperature. The amount of heat may be calculated using the definition of specific heat (c_p), as shown in equation (1).

$$c_p = \frac{1}{m} \cdot \frac{dQ}{dT} \qquad (1)$$

[13] S2BIOM: https://www.s2biom.eu/

[14] BioBoost: https://bioboost.eu/

[15] Global Solar Atlas: https://globalsolaratlas.info/download/europe-and-central-asia

[16] European Biogas Association, EBA Statistical Report 2020: https://www.europeanbiogas.eu/eba-statistical-report-2020/

Assuming a constant specific heat capacity regardless of the temperature, the previous equation may be reformulated into equations (2) and (3):

$$\Delta Q = c_p \cdot \int m \cdot dT \tag{2}$$

$$\Delta Q = c_p \cdot \int \rho \cdot V \cdot dT \tag{3}$$

Where:

ΔQ is the heat released by the ground when cooled down by a certain temperature difference.

V is the volume of rock to be cooled down.

c_p is the specific heat capacity.

ρ is the rock density.

In this context, simplifications have been made with regard to practical considerations such as the geology of the area and the presence of an aquifer and its permeability. Furthermore, we assume in this assessment that the rock has a constant density regardless of the pressure. Additionally, it may be assumed that the temperature varies linearly between two known temperatures at different depths, i.e. there exists a constant temperature gradient. Finally, for a given area under study, temperature variations only occur in the vertical axis and the lateral temperature gradients are disregarded. Applying all these simplifications, it would be possible to obtain equation (4).

$$\Delta Q = c_p \cdot \rho \cdot (A \cdot h) \cdot \left[\left(\frac{T_1 + T_2}{2}\right) - T_{cooling}\right] \tag{4}$$

Where:

A is the horizontal surface of the area under study.

h is the height of the column of rock under study.

T_1 and T_2 are the temperatures at the extremes of the column of rock under study.

$T_{cooling}$ is the temperature to which the rock under study is cooled down.

As an example, a column of rock of 1000 meters height with a density of 2500 Kg/m^3 and a specific heat capacity of 800 J/KgK, which has temperatures of 50°C and 100°C, would release 110 GJ/m^2 when cooled down to 20°C.

The previous equation (4) may be developed into equation (5), which is similar to the equation proposed by J. Lavigne & Ph. Maget in 1978[17], in order to estimate the geothermal resource in an entire region. In this equation only the heat above a certain threshold temperature is considered. In general, most of the parameters in the equation will vary depending on the location and will not be constant throughout the region.

---

[17] *Les ressources géothermiques françaises possibilités de mise en valeur* (Lavigne et al): https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/084/49084009.pdf

However, for the sake of simplicity and due to the lack of more detailed data, the specific heat and the rock density will be considered constant.

$$Q_i = c_p \cdot \rho \cdot \sum_{i=1}^{N} A_i \cdot (h_i) \cdot \left[\left(\frac{T_{max_i} + T_{threshold_i}}{2}\right) - T_{cooling_i}\right] \tag{5}$$

Where:

A_i is the area, with associated certain ground temperatures.

h_i is the depth of the rock above the threshold temperature.

T_{max_i} is the maximum temperature of the ground in the layer studied. Generally, it will be the temperature at the deepest point, although in certain areas with negative temperature gradients, it can the shallowest.

$T_{threshold_i}$ is the temperature above which heat is considered. If the ground has a lower temperature, the heat is disregarded.

$T_{cooling_i}$ is the temperature to which the ground is cooled down.

Three different scenarios have been explored with different values for the various parameters:

Base resource	$T_{threshold_i}$ is the ambient temperature. $T_{cooling_i}$ is the ambient temperature. h_i has a constant value of 1000 m since the ground is always warmer than the atmosphere.
3rd Generation DH Resource	$T_{threshold_i}$ is 80°C. $T_{cooling_i}$ is 40°C. h_i has a variable value depending on the ground temperatures.
4th Generation DH Resource	$T_{threshold_i}$ is 55°C. $T_{cooling_i}$ is 25°C. h_i has a variable value depending on the ground temperatures.

The Base resource accounts for the total amount of energy that could be extracted were the ground to be cooled down to the ambient temperature in each location. The 3rd Generation and 4th Generation resource account for the energy that could be extracted by district heating systems of different generations without the need for heat pumps for a temperature uplift.

The data utilised for this geothermal assessment stems from two sources, partly from the Atlas of Geothermal Resources in Europe and WorldClim 2, a database of 1 km spatial resolution elaborated by Stephen Fick and Robert Hijmans[18], both also outlined and referenced in Table 6. On the one hand, the Atlas has provided the ground temperatures at 1000 meter and 2000-meter depth throughout the European continent. On the other hand, WorldClim 2 provided the average monthly temperatures, which have been used to estimate the annual mean. Whilst the latter has been retrieved in digital format and the changes have been limited, the former was only found in physical format, which has entailed an arduous process of digitalisation. The digitalisation of the Atlas of Geothermal Resources has been performed following these steps:

- Scanning the two maps at a high resolution.
- Georeferencing the two maps in QGIS . Although the Atlas does not indicate the Coordinate Reference System, it was assessed that the Lambert Conformal Conic Coordinate Reference System with EPSG: 3034 was likely employed. A thin plate algorithm was also used for georeferencing.
- Digitalisation of the temperature contour lines for the two maps under study. QGIS trace raster plugin was of invaluable help for completing this task. An example of this result is shown in Figure 10, which depicts the ground temperatures at 2000 m depth.
- Sampling of the contour lines and application of a thin plate spline with tension interpolation so as to obtain a raster file with the temperatures between the contour lines. In order to avoid undershooting or overshooting in areas with a high lateral temperature gradient, a high tension of 5000 had to be applied in ArcGIS' raster interpolation with spline algorithm.

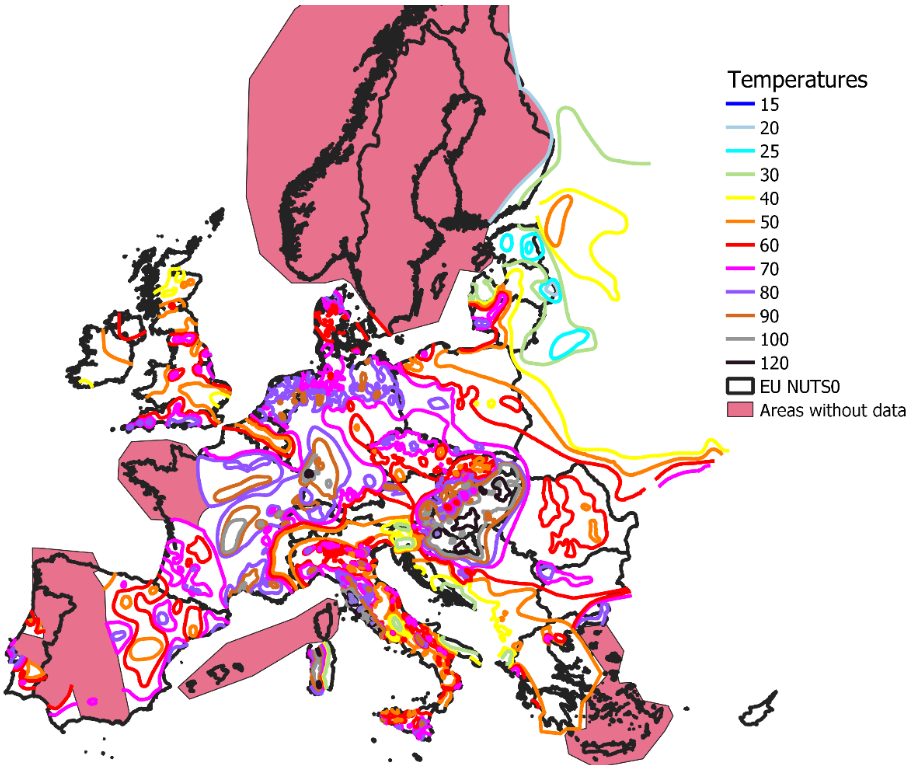


Figure 10: Ground temperatures in Europe at 2000 m depth. Source: Atlas of Geothermal Resource in Europe

[18] WorldClim 2: https://www.worldclim.org/data/worldclim21.html

In both cases, the final rasters were resampled and transformed to the Lambert Azimuthal Equal Area Coordinate Reference System (ETRS-LAEA) with EPSG: 3035 and a resolution of 1000mx1000m.

A constant rock density of 2500 Kg/m^3 and a specific heat capacity of 800 J/KgK was taken from the previously referenced French report *Les ressources géothermiques françaises possibilités de mise en valeur* by J. Lavigne and Ph. Maget. The geothermal resource was calculated separately for two layers of 1000 m depth, whose bound temperatures are the ambient temperature, the temperature at 1000 m depth and the temperature at 2000 m depth.

In the final step, we have aggregated the data to the former EU28 Member States (EU27 from 2020 plus United Kingdom), but the calculated resource maps could be used to provide the resource by other administrative units or in a certain buffer of human settlements. It must further be noted that large areas of Spain, France and Scandinavia were uncharted and therefore it was not possible to estimate the temperature and, hence, the resource in those areas, as also illustrated in Figure 10.

3.3.2. Description of solar potential assessment

The base for the calculation of the solar resource has been the annual solar irradiation at the optimum angle or the horizontal plane, the mean efficiencies for converting the solar irradiation into useful thermal or electrical energy and the suitability of the area. For the sake of simplicity, the thermal and electrical efficiencies have been assumed constant throughout Europe even though they vary depending on the ambient temperature, the district heating system temperature, the technology and so forth.

The three desired values may be calculated by means of equations (6), (7) and (8), which express, for a given area, the total solar irradiation, the solar thermal potential and the solar PV potential respectively:

$$Total\ solar\ irradiation\ area = \sum I_{h_i} \cdot \tau \qquad (6)$$

$$Solar\ thermal\ resource\ in\ an\ area = \sum I_{\alpha_i} \cdot \tau \cdot A_i \cdot \eta_{q_i} \cdot \xi_i \qquad (7)$$

$$Solar\ photovoltaic\ resource\ in\ an\ area = \sum I_{\alpha_i} \cdot \tau \cdot A_i \cdot \eta_{e_i} \cdot \xi_i \qquad (8)$$

Where:

I_{h_i} is the mean annual solar irradiation at the horizontal plane.

τ is the duration of the year.

I_{α_i} is the mean annual solar irradiation at the optimum plane per unit of area of the optimum plane.

A_i is the ground area.

η_{q_i} is the thermal efficiency, this is, the ratio of the useful thermal output and the total irradiation.

η_{e_i} is the electrical efficiency, this is, the ratio of the useful electrical output and the total irradiation.

ξ_i is a binary variable (0 or 1), which indicates whether the area is suitable for the extraction of solar energy.

On the one hand, note that, whereas the irradiation in the horizontal plane has been employed in the determination of the total irradiation in a country, the irradiation at the optimum plane has been used to evaluate the thermal and electrical resource. On the other hand, the suitability of the land area for the development of solar energy has been categorised following these two principles:

Land cover based on the Corine database (see Table 6 for references). Only agricultural areas (2.1.1. - 2.4.4.), sparsely vegetated areas (3.3.3.) and burnt areas (3.3.4.) have been considered.

Slope. Only areas with a maximum slope below 6% have been considered.

The thermal and electrical efficiencies are developed in equations (9) and (10):

$$\eta_q = \eta_c \cdot \frac{1}{\Omega_q} \tag{9}$$

$$\eta_e = \eta_p \cdot pr \cdot \frac{1}{\Omega_{pv}} \tag{10}$$

Where:

η_c is the efficiency of the solar collectors, which, in turn, depends on the collector itself, the inlet and outlet water temperatures and the ambient temperature. It has been assumed to be 40% according to the Danish Energy Agency's Technology Catalogues[19].

Ω_q is the ground area required per unit of collector area. According to the Technology Catalogue, it may be assumed to be 3 m^2 per 1 m^2 of collector.

η_p is the efficiency of the solar panel measured by the manufacturer at standard conditions. It has been assumed to be 15%, which is somewhat lower than the average of 19% reported by the 2019 International Technology Roadmap for Photovoltaic[20].

pr is the performance ratio, which considers the performance degradation of the photovoltaic panels over their lifespan, assumed to be 75% according to JRC's ENSPRESO (solar).

Ω_{pv} is the ground area required per unit of panel area. It is assumed to be the same as Ω_q.

The application of the previous parameters would result into a total thermal efficiency of 13.3% and a total electrical efficiency of 3.75%. Note that in the case of photovoltaic panels, despite the conservative assumptions for the different values, the total efficiency is still

[19] Danish technology catalogues: https://ens.dk/en/our-services/projections-and-models/technology-data

[20] Renewable Power Generation Costs in 2019 (IRENA): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf

higher than the actual values, which can be retrieved from recent large PV parks[21] in the sunniest locations in Europe.

The solar irradiation data at the horizontal and optimal planes have been retrieved from JRC's PVGIS portal (see Table 6 for further references). This portal provides three datasets, thereof the CM SAF Solar Radiation Database has been chosen due to its higher coverage of the continent. The raster file, which had a grid size of 1'30" in the geographic coordinate system WGS84 (EPSG: 4326) has been resampled to the LAEA coordinate reference system (EPSG: 3035) with a resolution of 100mx100m and the same origin as the Corine database. This resample has been executed with R's raster package resample function. It must be noted that this database has an upper bound of 65°01'30" N, and therefore, the northern parts of Sweden and Finland are not chartered, as is visible in the map presented in Figure 11.

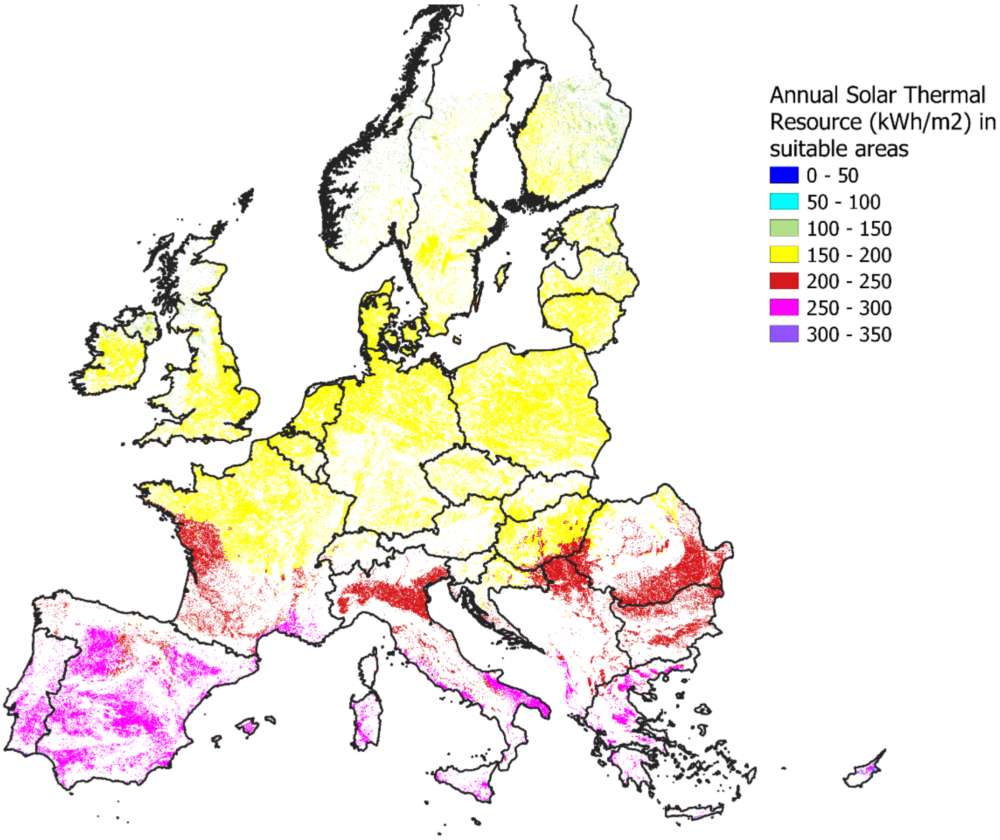


Figure 11: Solar thermal resource in suitable areas

The CORINE Land Cover has been retrieved from the Copernicus Land Monitoring Service's website. This database had a resolution of 100mx100m in the LAEA coordinate system and therefore no changes were applied to it.

The European Digital Elevation Model (EU-DEM), version 1.1 has been retrieved from the Copernicus Land Monitoring Service's website. This dataset provides the ground elevation in a grid of 25mx25m with the LAEA coordinate system and was used to determine the slope of the terrain. For this purpose, the Terrain function with eight neighbours from R's Raster

[21] The 500 MW_p Nuñez de Balboa plant, located in Southern Spain, will produce 832 GWh_e in 1000 ha with an annual radiation of 2100 kWh/m^2 at optimum angle, which renders a total electrical efficiency of 3.6%.

package has been utilised. Later, the resultant slope dataset was aggregated to a resolution of 100mx100m taking the maximum value of the 16 subcells by means of R's Raster package Aggregate function.

The utilisation of these layers along with the previous equations has enabled determining the solar irradiation, the solar thermal and the PV resources in a 100mx100m grid in the entire continent, which later have been aggregated at a national level. Similarly to the geothermal resource, the results may be provided at other aggregation levels. Figure 11 shows one of the resultant datasets, the solar thermal resource in suitable areas. Note that ample areas of southern Europe do not have a useful resource due to their geomorphology and despite their higher solar irradiation. Furthermore, northern Finland and Sweden are excluded.

3.3.3. Description of conditioned biomass potential

The base for the calculation of a conditoned biomass potential is, in terms of available potential assessment data, the JRC ENSPRESO Medium (or “Reference”) scenario dataset, which, as outlined in Table 6 above, consists of annual energy volumes by NUTS2 regions for 16 biomass energy commodity categories. In terms of context, the underlying considerations for developing a conditioned biomass potential originate in recognising the critical role that biomass is expected to play in the future European energy system. Being one of few combustible renewable energy sources, thus with capacity for high-temperature applications in power and heat production, biomass is an important source for renewable-based peak supply, in particular with reference to heating demands, while, in parallel, constituting a viable feedstock for several other uses, such as within alternative fuel production and paper production.

The identification of boundary conditions and constraints for determining the conditioned biomass potential has followed two main principles: (1) no ”quality roundwood” used for energy purposes, which is in line with the proposal for the revised REDII directive[22], and (2) exclusion of all biomass feedstock by which transport fuels can possibly be made, which translates into for example oil crops, starchy crops, sugar beet etc. By these two main principles, including partly also the exclusion of manure and sludge for distribution of regional potentials (biogas production instead directed to transport sector uses), a "sustainable" biomass potential, consisting essentially only of forest and agricultural residues, ”energy grasses”, and consumption waste flows (municipal, industrial etc.), is what constitutes this conditioned biomass potential.

To illustrate and to provide an opportunity for quantitative comparison, Table 7 presents an overview of the biomass potentials elaborated and the corresponding conditioned biomass potential as anticipated by the sustainability constraints applied.

[22] “Quality roundwood” is defined in the REDIII proposal (COM(2021) 557 final) as “roundwood felled or otherwise harvested and removed, whose characteristics… make it suitable for industrial use”. On the topic of a sustainable use of biomass, the REDIII proposal recognises “the need for alignment of bioenergy policies with the cascading principle of biomass use, with a view to ensuring fair access to the biomass raw material market for the development of innovative, high value-added bio-based solutions and a sustainable circular bioeconomy” (Introductory paragraph 4). The cascading principle, in turn, is described as a concept that “aims to achieve resource efficiency of biomass use through prioritising biomass material use to energy use wherever possible, increasing thus the amount of biomass available within the system. In line with the cascading principle, woody biomass should be used according to its highest economic and environmental added value in the following order of priorities: 1) wood-based products, 2) extending their service life, 3) re-use, 4) recycling, 5) bio-energy and 6) disposal” (footnote 11, page 16). The emphasis is also made clear in Article 1 (2b), where Article 3(3) of REDII is proposed to be amended under formulations such as “Member States shall take measures to ensure that energy from biomass is produced in a way that minimises undue distortive effects on the biomass raw material market and harmful impacts on biodiversity”, for which end “(a) Member States shall grant no support for: (i) the use of saw logs, veneer logs, stumps and roots to produce energy”.

Table 7. Renewable energy potentials: Biomass potentials in the EU27 as expressed in the JRC ENSPRESO High and Medium Availability Scenarios for 2050, broken down by main biomass energy commodity categories, and with detail of a conditioned biomass potential by selected energy commodities according to various criteria representing a sustainable use of biomass resources

Biomass Energy Commodity Name	Main sector origin (Anticipated)	Biomass potentials for EU27 in 2050 [PJ/a]			
		High availability	Medium availability	*Medium availability (Conditioned)*	*Medium availability (Conditioned) Comment*
Grassy crops	Agriculture	2,483	1,493	*1,493*	*Available*
Manure	Agriculture	1,609	1,080	-	*Priority methane/ transport*
Oil crops for biodiesels (rape seed, sunflower, soya)	Agriculture	1,062	965	-	*Priority transport*
Poplar	Agriculture	155	78	*78*	*Available*
Primary agricultural residues	Agriculture	2,027	952	*952*	*Available*
Starchy crops	Agriculture	289	263	-	*Priority transport*
Sugar beet for bioethanol	Agriculture	1,020	927	-	*Priority transport*
Willow	Agriculture	401	254	*254*	*Available*
Forestry energy residue	Forest	5,726	1,851	*1,851*	*Available*
Forestry residues from landscape care	Forest	604	242	*242*	*Available*
Roundwood Chips & Pellets	Forest	2,677	2,225	-	*Not for energy purposes*
Roundwood fuelwood	Forest	317	264	-	*Not for energy purposes*
Secondary forestry residues – sawdust	Forest	269	108	*108*	*Available*
Secondary forestry residues – woodchips	Forest	779	312	*312*	*Available*
Municipal waste	Waste	812	646	*646*	*Available*
Sludge	Waste	65	49	-	*Priority methane/ transport*
Grand Total		**20,296**	**11,708**	***5,935***	

From Table 7 it can be seen that the resulting and available, conditioned, biomass potential, conditioned on the basis of the 2050 medium (or "Reference") JRC Enspreso scenario, thus excluding energy commodities associated with the three constraint categories "Not for energy purposes", "Priority transport", and "Priority methane/transport", amounts to 5,935 PJ (equivalent to ~1650 TWh). This total volume is rather similar to current day levels of biomass use in the EU27, but noticeably, with regard to heating and cooling, this volume implicitly resembles a structural transition basically from the use of primary to the use of secondary biomass sources.

Given that the original JRC biomass potential data is given both at national (NUTS0) and regional (NUTS2) levels, the conditioned biomass potential dataset was prepared as various spatial datasets at the NUTS2 level, as illustrated in Figure 12 regarding the total sum of these potentials by NUTS2 regions. Additional spatial datasets were preprared also with sector summations, energy commodity summations etc.The main purpose for the preparation of these spatial datasets was to provide input data for the designation and allocation of the conditioned biomass potential for district heating in general, and for district heating areas (DH Areas) in particular.

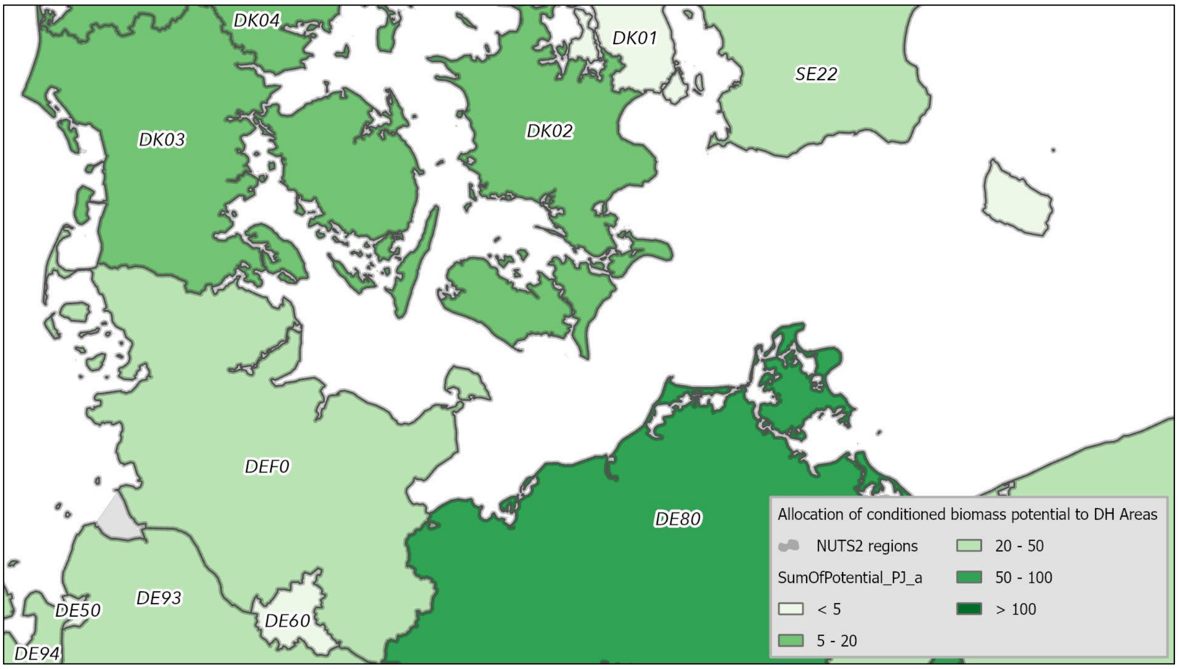


Figure 12: Map illustrating the conditioned biomass potential as total sum by NUTS2 regions for an area in northern Germany and Denmark.

As briefly mentioned above, and further described in Annex C3 (subsection on modelling the district heating (DH) sector), the geographical locations and the corresponding geographical extent of future district heating areas, see further also Figure 13, were assessed by means of spatial modelling and mapping and later associated with the administrative entities of Local Administrative Units (LAU).

In terms of quantities, the share of the conditioned biomass potential that eventually should be available explicitly for district heating was assumed as 50%, as a result of internal discussions and external expert consultation on the matter (the remaining 50% available for individual heating and industry). By this, the conditioned biomass potential for district heating is conceived to represent a reasonable share of the available potential, given that, under a decarbonisation scenario, the European community is willing and able to accept a structural change regarding biomass use for heating and cooling purposes also in terms of a transition from a tradition with individual use to a future more centralised use.

By this assumption, a conditioned biomass potential for district heating has been anticipated at approximately 2970 PJ (824 TWh) per year, as outlined also in Table 10 in subsection 3.4.3 below. By spatial allocation, finally, and as exemplified in Figure 13, after all modelled district heating areas in the decarbonisation scenario (see Section 6.2.5 (on main input data and design of the scenarios) for further references on scenarios) had been linked to corresponding LAU´s by their respective GISCO ID number, a total of 8,217 DH Areas among current EU27 Member States (areas with a modelled district heat demand other than zero in 2050), were matched to a total of 5,815 LAUs (which together represents a total 2050 DH demand of ~2,500 PJ (~695 TWh)).

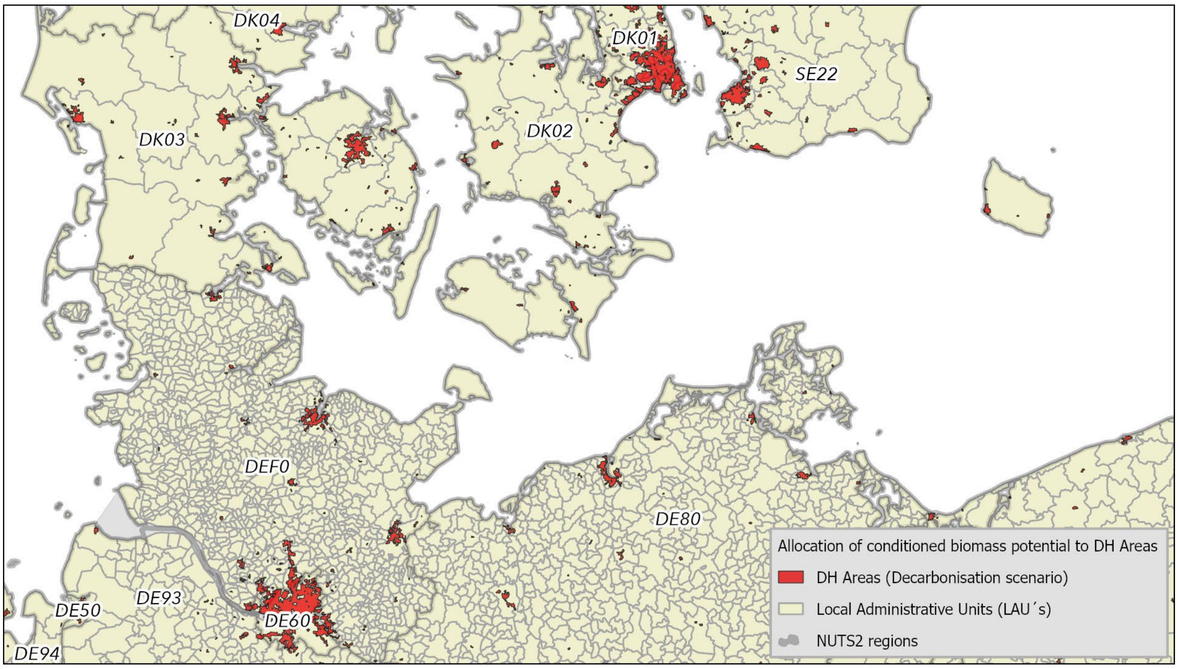


Figure 13: Map illustrating the spatial allocation of a conditioned biomass potential to modelled district heating areas in corresponding Local Administrative Units (LAUs) and NUTS2 regions for an area in northern Germany and Denmark.

The final procedure for allocating the conditioned biomass potential for district heating to district heating areas consisted in calculating a factor which for each LAU represents the share of its DH demand relative to the total NUTS2 region level DH demand, which in turn was established as the sum of all LAU DH demands within each corresponding NUTS2 region. By multiplying this LAU-specific factor with the total anticipated NUTS2 level conditioned biomass potential for district heating, a LAU-specific fraction could be found. The allocation was thus done within each NUTS2 region according to the proportion of modelled DH demand within the LAUs included.

Given that the total count of LAUs considered amounts to 95,606 for EU27 (96,006 LAUs for the former EU28), and that 5.815 were spatially matched in the allocation process, it may be concluded that only 6% of current LAUs are anticipated to host future DH Areas. However, as further presented in Table 10 below, the high relative share that the spatially allocated potential constitutes (2,620 PJ, or 728 TWh) out of the total designated potential (2,967 PJ, or 824 TWh), indicates that ~88% of the NUTS2 regions, for which the conditioned biomass potential was established, host at least one LAU with modelled district heating areas.

3.4. Results

In this section the results from the work of this first part of the report are presented in three subsections: Section 3.4.1 focuses on the shares of renewable energy sources used in heating and cooling according to the SHARES reporting, Section 3.4.2 highlights the particular energy sources which have been used by Member States since 2004 to increase renewable shares in these sectors, and, finally, Section 3.4.3 presents the theoretical and mixed theoretical/technical potentials assessed for energy from renewable energy sources towards 2030 and 2050. The third subsection further includes a series of graphs where the potentials are expressed as per capita values in order to provide a more elaborate understanding of their distribution among Member States. For this purpose, population projections data from Eurostat was used[23].

3.4.1. The Eurostat SHARES reporting of renewable energy sources in heating and cooling

The detailed 2019 results from the SHARES data report on Member State "Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling" for the years 2004 to 2019, and produce a ratio (the "RES-H&C Share", as outlined in Figure 9 above) by dividing this quantity (the numerator) with the "Gross Final Consumption of Energy for Heating and Cooling", i.e. the denominator (here also labelled "Denominator: GFC in H&C"). The numerator, i.e. the total gross annual final consumption volume of renewable energy sources in heating and cooling, consists itself of three main categories:

- Final consumption (excl. Derived Heat and Heat Pumps) – final consumption of renewable energy sources for heating and cooling purposes in all categories other than the two below (also referred to as "Final consumption - industry and other sectors - energy use", code: "FC_IND_OTH_E" in Eurostat NRG_BAL). Labelled here "Numerator: Final Consumption"
- Derived Heat - a proxy for district heating (also "Gross heat production – Renewable Energy Directive", code: "GHP_RED"). Labelled here "Numerator: Derived Heat"
- Heat Pumps – Useful heat from Heat Pumps based on underlying electricity consumption (also "Primary production - Renewable Energy Directive, code: "PPRD_RED"). Labelled here "Numerator: Heat Pumps".

For EU27, the overall RES-H&C share climbed above 20% for the first time ever in 2015 (20.4%) after continuous annual growth since the first recorded value of 11.7% in 2004, as outlined in Table 8. In 2019, the corresponding EU27 RES-H&C share reached 22.1%.

[23] Eurostat population forecast data for 2050: Population on 1st January by age, sex and type of projection [PROJ_19NP, last update: 2020-07-20] (for UK, Eurostat population forecast data for 2050 from 2012-10-02, code: tps00002). Total anticipated population for the corresponding EU27 in 2050: 441.2 million.

Table 8: The share of renewables in heating and cooling in the EU27 for some selected years as reported by Eurostat: Use of renewables for heating and cooling (NRG_IND_URHCD, Last update: 2021-04-02).

	EU27					
[EJ/a]	2004	2005	2010	2015	2018	2019
Numerator	2.6	2.8	3.6	3.9	4.2	4.3
Denominator	22.1	22.2	21.4	19.2	19.6	19.3
RES_H&C	11.7%	12.4%	16.9%	20.3%	21.2%	22.1%

The increasing RES-H&C ratio indicates that the share of renewables for heating and cooling purposes is increasing, which of course is promising, but the growing development of the ratio is only partially due to actual increases in the use of renewable resources (which translates into an increasing numerator). Simultaneously, it can be observed both in Table 8 and in Figure 14, that the overall gross final consumption of energy for heating and cooling purposes in the member states is decreasing. However, the relative growth rate of the numerator has outmatched the relative decline rate of the denominator during the entire reporting period. By 2019, the numerator reflecting the RES-H&C share had increased by approximately 64% relative to the start year 2004 (at average annual growth rates of 4.3%), while the denominator had decreased by a total of approximately -13% (at annual average decline rates of -0.86%). While the numerator annual growth intensity with reference to the 2004 base year reached its highest levels during 2010 and 2012 (with relative annual growth rates compared to the previous year in the order of 11% during both these years), the pace seems to have relaxed somewhat during the last five years (2015 to 2019), during which an average annual increase rate of 4.0% relative to the 2004 base year is observable. In parallel, the denominator decline was interrupted during 2015 and 2016 to, in fact, generate average relative increases of 0.5% for the same five-year period.

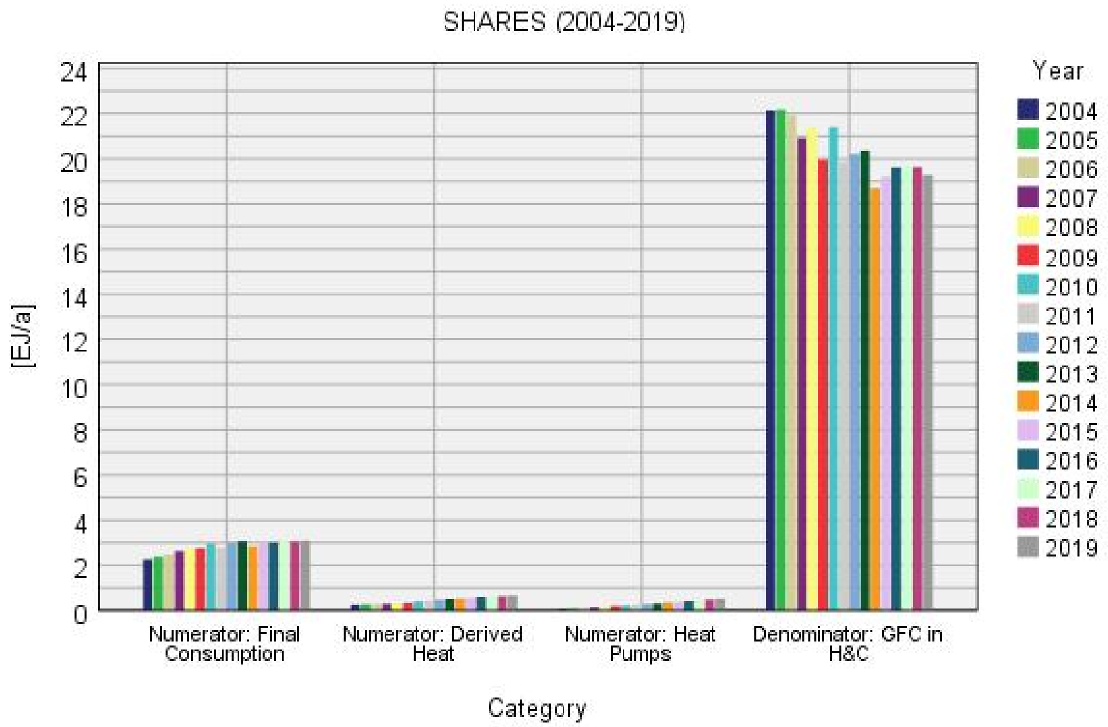


Figure 14: Sum of numerator (by categories Final Consumption, Derived Heat, and Heat Pumps) and denominator (Gross Final Consumption in H&C) annual volumes as reported by all sectors for EU27 on average in SHARES between the years 2004 and 2019.

In terms of main categories, it is quite clear from the SHARES questionnaire responses that the main category of Final Consumption (excl. Derived Heat and Heat Pumps), that is "Numerator: Final Consumption", channels the largest annual volumes of renewable energy sources for heating and cooling purposes, which is visible in Figure 14 and in Figure 15. In 2019, the total energy volume in this category amounted to 3.09 EJ (857 TWh), which, compared to the 2.26 EJ reported for the year 2004 (629 TWh), represents an overall increase of 36% over the entire time period.

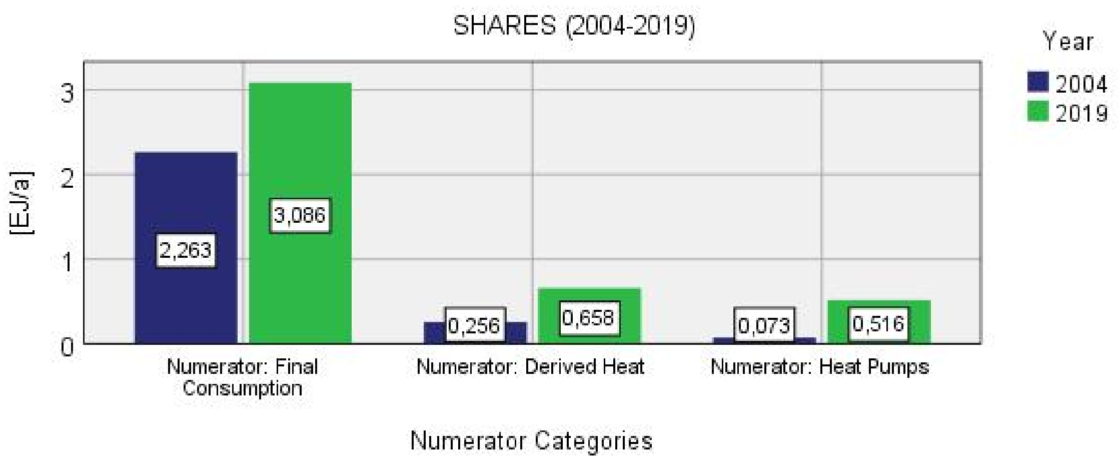


Figure 15: Change in Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 on average for EU27 by the three main numerator categories.

Although significantly smaller in terms of annual total volumes, the other two main categories have increased much more rapidly over these years, as also outlined in Figure

15. For the EU27 context, Derived Heat has grown from 256 PJ in 2004 (71 TWh) to 658 PJ in 2019 (183 TWh), representing an overall increase of 157%, while the main category Heat Pumps has grown principally by a factor 7 from 73 PJ in 2004 (20 TWh) to 516 PJ in 2019 (143 TWh), or by some incredible 604%. For further reference, Figure 16 presents total numerator values reflecting the absolute change in annual volumes between the years 2004 and 2019 by EU27 Member State.

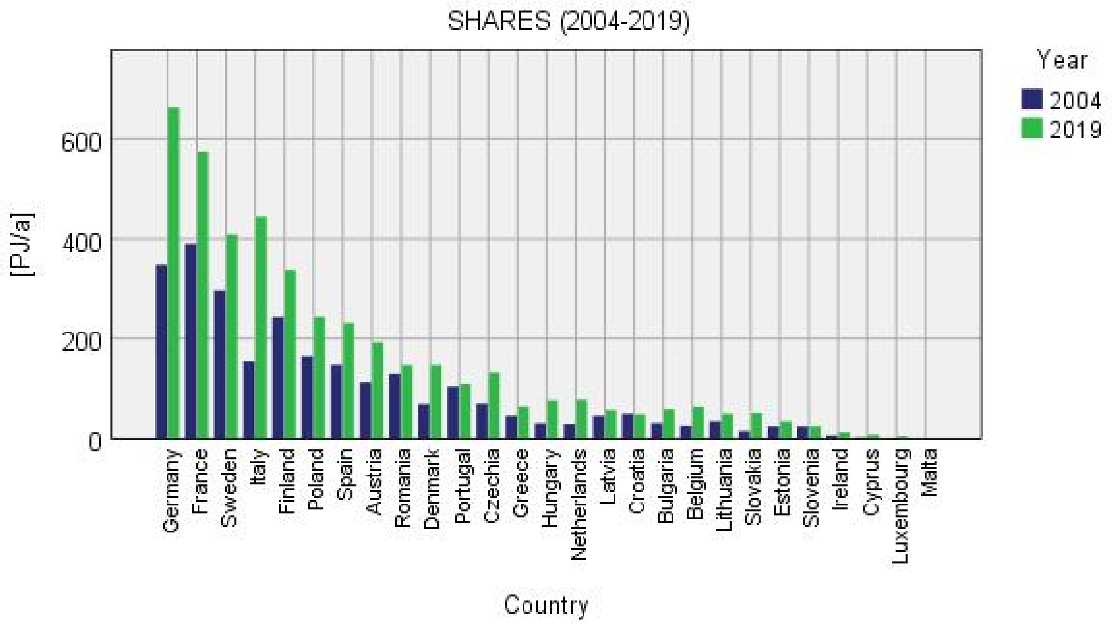


Figure 16: Change in Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for the EU27 Member States, by total volumes.

3.4.2. Renewable energy sources used for heating and cooling

A closer look at the specific energy sources used among the EU27 Member States to achieve the progress of integrating renewable energy sources in heating and cooling reveals, perhaps not so very surprisingly, that biomass (named by two different labels in the sector questionnaires of the SHARES reporting tool: "Solid Biofuels" and "Other Solid Biofuels") dominates the uptake of renewables for heating and cooling purposes on average so far. From Figure 17, it is evident that "Biofuels" (sum of both "Solid Biofuels" and "Other Solid Biofuels"), at approximately 2.35 EJ in 2004 and at 3.25 EJ in 2019, not only has increased (by an average overall growth rate of 38% over the entire period) but, "Biofuels" is the main renewable energy source that is, and has been, utilised throughout the European Union currently and so far.

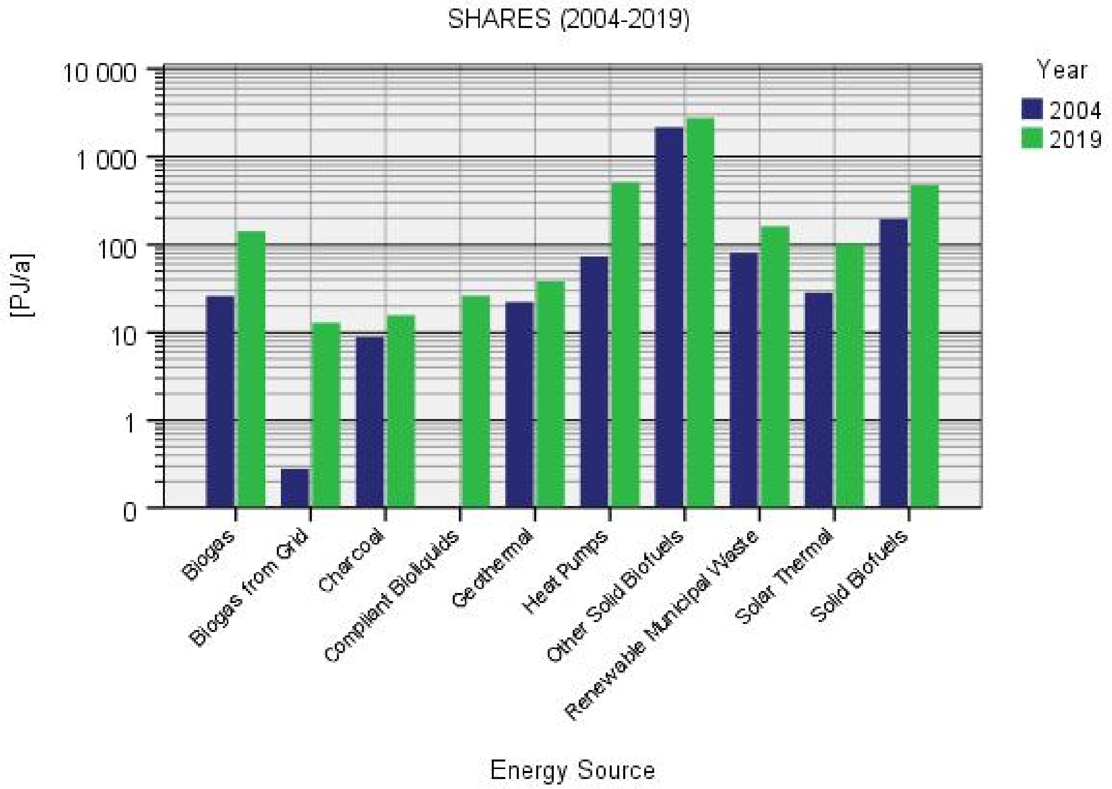


Figure 17: Change in Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for EU27, by energy source.

However, the relative share which “Biofuels” represent among all the renewable energy sources is in fact declining. In 2004 this share consisted for EU27 in 90.8% (the 2.35 EJ of “Biofuels” mentioned above out of a total RES-H&C volume in that year of ~2.59 EJ) while the 3.25 EJ of “Biofuels” recorded in 2019 constituted only 76.2% (the total EU27 RES-H&C volume during 2019 at 4.26 EJ).

As can be seen in Figure 17, but also in the category-specific detailed graphs presented in Figure 18 and Figure 19, the main energy sources – other than “Biofuels” – which drive this relative reduction of the share of “Biofuels” is primarily Heat Pumps (as already mentioned above), Renewable Municipal Waste (up from 80.7 PJ in 2004 to 162 PJ in 2019), Biogas (up from 25.9 PJ in 2004 to 141 PJ in 2019), and Solar Thermal (up from 28.3 PJ in 2004 to 102 PJ in 2019). It might be worth noticing that “Biogas from Grid”, although at relatively small total annual volumes, has undergone a considerable increase by a factor of 46 during the SHARES reporting period so far: from 0.28 PJ in 2004 to 12.9 PJ in 2019. A closer look at how the specific use of renewable energy sources for heating and cooling is distributed among the EU27 Member States, and how this use has changed from 2004 to 2019, may be seen in annex figures (Figure 112 and Figure 113). These distributions are also illustrated in full time series graphs in the same appendix (see further Figure 114 and Figure 115).

The yearly evolutions of different energy sources that constitute the gross final consumption of energy from renewable sources for heating and cooling purposes, are outlined with reference to EU27 in Figure 18 for total numerator volumes. The main trends described in the previous paragraphs are observable in these graphs, where in particular it should be noted that large national variations are present.

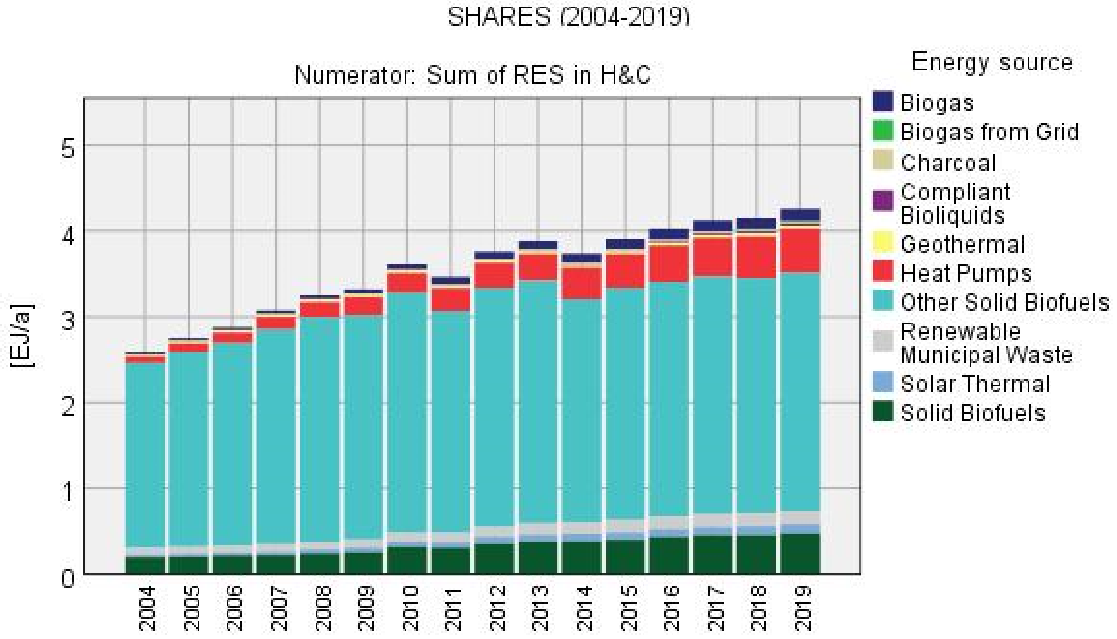


Figure 18: Evolution of Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for EU27, by energy source and the sum of all three numerator categories.

Figure 19 presents the yearly evolution of different energy sources used for heating and cooling purposes among the three main numerator categories Final Consumption (on the left), Derived Heat (centre) and Heat Pumps (on the right).

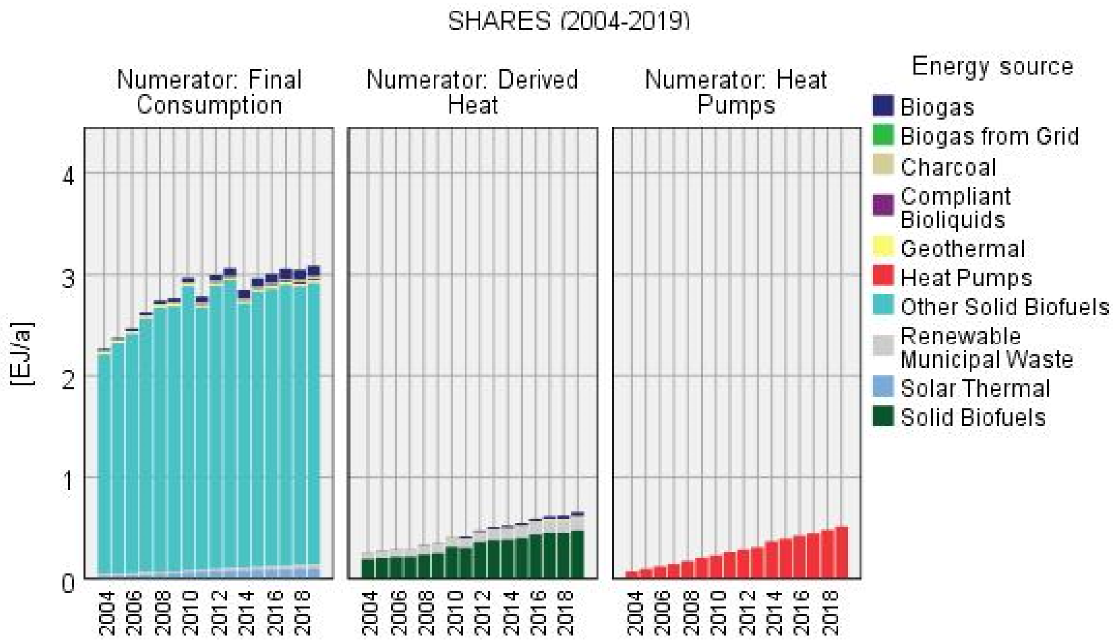


Figure 19: Evolution of Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for EU27, by main numerator categories Final Consumption (left), Derived Heat (centre) and Heat Pumps (right).

3.4.3. Renewable energy potentials for heating and cooling in 2030 and 2050

As indicated above, the main results for the established renewable energy potentials to be presented here refer first of all to the theoretical and mixed theoretical/technical potentials which represent the actual resource base more or less unlimited and unconstrained. Results referring to potentials further constrained by spatial, economic, and systemic dimensions are presented in other sections in the report. One exception relates to conditioned biomass potentials, for which the findings from performing a spatial allocation are presented here (procedure outlined above).

In addition, reference potentials representing less than the default maximum theoretical potentials have been included in some instances. This involves a complementary scenario for the wind potential (labelled “Reference”), indicative of a more cautious anticipation regarding the influence from various restriction parameters. Similarly, the “Medium availability” biomass scenario, upon which furthermore the conditioned biomass potential is based, has been added in complement to the default “High availabililty” scenario. A third complementary scenario consists of the 2050 hydropower potential for EU27, as conceived in the 2020 PRIMES EU Reference Scenario (complement to the 2016 PRIMES EU Reference Scenario).

The quantified (where possible) annual (where applicable) renewable energy potentials by renewable energy source and by Member State are presented in Table 9. These potentials are available for overall energy use in all end-use sectors, not limited to heating and cooling purposes, and together they represent a mixture of purely theoretical and technical potentials (as indicated by “Character” in the table).

Table 9: Renewable energy potentials: Quantified energy volumes by RES source per Member State, for EU27 and for EU28 in aggregates

MS	Biomass (Enspreso High)	Biomass (Enspreso Medium)	Geothermal (Ambient)	Geothermal (3GDH)	Geothermal (4GDH)	Hydropower (REF16)	Hydropower (REF20)	Solar Irradiation (Constrained)	Solar Photovoltaic (Constrained)	Solar Thermal (Constrained)	Wind (Low restriction)	Wind (Reference)
Char.	**Theo./Tech.**	**Theo./Tech.**	**Theo.**	**Theo.**	**Theo.**	**Tech.**	**Tech.**	**Theo./Tech.**	**Theo./Tech.**	**Theo./Tech.**	**Tech.**	**Tech.**
Unit	**[EJ/a]**	**[EJ/a]**	**[EJ]**	**[EJ]**	**[EJ]**	**[EJ/a]**	**[EJ/a]**	**[EJ/a]**	**[EJ/a]**	**[EJ/a]**	**[EJ/a]**	**[EJ/a]**
Year	**2050**	**2050**	**-**	**-**	**-**	**2050**	**2050**	**2030/2050**	**2030/2050**	**2030/2050**	**2050**	**2050**
EU27	20.30	11.71	339650	13600.7	94829	1.496	1.325	5911	221.7	788.2	81.5	37.8
EU28	21.13	12.28	363459	13601.3	97291	1.516	-	6251	234.4	833.5	102.5	42.1
AT	0.57	0.31	9862	178.9	1831	0.165	0.157	46	1.7	6.1	0.6	0.1
BE	0.39	0.26	3010	0.002	435	0.002	0.002	56	2.1	7.4	0.2	0.1
BG	0.39	0.21	11874	0.02	2565	0.015	0.019	176	6.6	23.4	1.4	1.0
HR	0.17	0.10	6999	1417.8	3161	0.024	0.026	75	2.8	10.0	1.4	0.4
CY	0.01	0.01	0	0	0	0	0	18	0.7	2.4	0.1	0.04

MS	Biomass (Enspreso High)	Biomass (Enspreso Medium)	Geothermal (Ambient)	Geothermal (3GDH)	Geothermal (4GDH)	Hydropower (REF16)	Hydropower (REF20)	Solar Irradiation (Constrained)	Solar Photovoltaic (Constrained)	Solar Thermal (Constrained)	Wind (Low restriction)	Wind (Reference)
Char.	Theo./Tech.	Theo./Tech.	Theo.	Theo.	Theo.	Tech.	Tech.	Theo./Tech.	Theo./Tech.	Theo./Tech.	Tech.	Tech.
Unit	[EJ/a]	[EJ/a]	[EJ]	[EJ]	[EJ]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]
Year	2050	2050	-	-	-	2050	2050	2030/2050	2030/2050	2030/2050	2050	2050
CZ	0.57	0.35	9053	0.6	1955	0.014	0.009	88	3.3	11.8	0.9	0.7
DK	0.23	0.14	4445	0.4	813	0.000	0.000	136	5.1	18.1	4.3	1.0
EE	0.19	0.11	2225	0	0	0.000	0.000	52	1.9	6.9	1.2	0.3
FI	0.92	0.47	5521	0	0	0.059	0.056	85	3.2	11.4	3.9	0.6
FR	3.17	1.95	56088	2791.5	23143	0.280	0.227	937	35.1	124.9	13.1	7.7
DE	2.56	1.44	49863	1742.2	19337	0.110	0.080	585	21.9	78.0	4.7	1.4
EL	0.27	0.14	11622	5.7	1323	0.020	0.027	139	5.2	18.6	3.6	2.0

MS	Biomass (Enspreso High)	Biomass (Enspreso Medium)	Geothermal (Ambient)	Geothermal (3GDH)	Geothermal (4GDH)	Hydropower (REF16)	Hydropower (REF20)	Solar Irradiation (Constrained)	Solar Photovoltaic (Constrained)	Solar Thermal (Constrained)	Wind (Low restriction)	Wind (Reference)
Char.	Theo./Tech.	Theo./Tech.	Theo.	Theo.	Theo.	Tech.	Tech.	Theo./Tech.	Theo./Tech.	Theo./Tech.	Tech.	Tech.
Unit	[EJ/a]	[EJ/a]	[EJ]	[EJ]	[EJ]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]
Year	2050	2050	-	-	-	2050	2050	2030/2050	2030/2050	2030/2050	2050	2050
HU	0.70	0.41	17365	4833.9	10568	0.004	0.001	268	10.1	35.8	1.4	0.8
IE	0.14	0.08	5610	0	118	0.005	0.003	123	4.6	16.4	6.2	2.1
IT	1.53	0.90	31150	1788.5	7454	0.194	0.194	457	17.1	60.9	4.7	2.1
LV	0.33	0.17	4314	0	48	0.012	0.011	91	3.4	12.2	2.1	0.9
LT	0.33	0.23	5199	0.1	404	0.004	0.002	149	5.6	19.9	1.6	1.2
LU	0.02	0.01	298	0	54	0.001	0.000	1	0.1	0.2	0.01	0.01
MT	0.01	0.01	0	0	0	0	0	0.4	0.02	0.1	0.04	0.00

MS	Biomass (Enspreso High)	Biomass (Enspreso Medium)	Geothermal (Ambient)	Geothermal (3GDH)	Geothermal (4GDH)	Hydropower (REF16)	Hydropower (REF20)	Solar Irradiation (Constrained)	Solar Photovoltaic (Constrained)	Solar Thermal (Constrained)	Wind (Low restriction)	Wind (Reference)
Char.	Theo./Tech.	Theo./Tech.	Theo.	Theo.	Theo.	Tech.	Tech.	Theo./Tech.	Theo./Tech.	Theo./Tech.	Tech.	Tech.
Unit	[EJ/a]	[EJ/a]	[EJ]	[EJ]	[EJ]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]
Year	2050	2050	-	-	-	2050	2050	2030/2050	2030/2050	2030/2050	2050	2050
NL	0.27	0.19	5560	152.0	2547	0.000	0.000	105	3.9	14.0	1.9	1.2
PL	1.87	1.16	32471	0.1	5838	0.016	0.011	703	26.4	93.7	6.0	1.1
PT	0.38	0.19	2525	0.03	517	0.069	0.049	121	4.6	16.2	1.3	0.6
RO	1.31	0.75	25807	237.5	5190	0.061	0.069	459	17.2	61.1	3.5	2.5
SK	0.24	0.13	6418	385.6	2098	0.021	0.018	56	2.1	7.5	0.4	0.3
SI	0.16	0.08	1899	65.1	350	0.021	0.019	10	0.4	1.3	0.05	0.04
ES	2.06	1.17	22696	0.6	5027	0.125	0.099	856	32.1	114.1	9.5	7.7

MS	Biomass (Enspreso High)	Biomass (Enspreso Medium)	Geothermal (Ambient)	Geothermal (3GDH)	Geothermal (4GDH)	Hydropower (REF16)	Hydropower (REF20)	Solar Irradiation (Constrained)	Solar Photovoltaic (Constrained)	Solar Thermal (Constrained)	Wind (Low restriction)	Wind (Reference)
Char.	Theo./Tech.	Theo./Tech.	Theo.	Theo.	Theo.	Tech.	Tech.	Theo./Tech.	Theo./Tech.	Theo./Tech.	Tech.	Tech.
Unit	[EJ/a]	[EJ/a]	[EJ]	[EJ]	[EJ]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]	[EJ/a]
Year	2050	2050	-	-	-	2050	2050	2030/2050	2030/2050	2030/2050	2050	2050
SE	1.52	0.77	7774	0	51	0.273	0.245	118	4.4	15.8	7.5	1.8
UK	0.83	0.58	23809	0.6	2462	0.020	-	340	12.8	45.4	20.9	4.3

The main characteristic which defines these potentials as either theoretical or technical is to what extent contextual conditions and real-world boundary conditions for their exploitation have been taken into consideration as part of their respective properties. Likewise, the "Solar irradiation potential" presented reflects constrained conditions. As for geothermal, the potentials reflect the complete resource magnitude as such, not an annually available volume. It may be understood by allegory to a mountain mine.

Regarding the biomass potentials in particular, as indicated above, the total EU27 "High" and "Medium" availability potentials, at 20.30 EJ and 11.71 EJ respectively, as outlined in Table 9, were complemented with a conditioned biomass potential based on the "Medium" availability potential as presented in more detail in Table 10 below. By taking into consideration a set of sustainability criteria, this conditioned biomass potential amounts to 5.94 EJ per year for the EU27 (equivalent to 1,648 TWh), and, by explicitly designating 50% to centralised use, to 2.97 EJ per year (824 TWh) for district heating. By allocating this designated fraction moreover to modelled future DH Areas (as detailed further in Annex C3), the EU 27 potential is estimated to some 2.62 EJ per year, or 728 TWh in 2050 under a decarbonised scenario.

Table 10: Renewable energy potentials: Conditioned biomass potential in the EU27 based on the JRC ENSPRESO Medium Availability Scenario and by designation to district heating (DH) and by allocation to modelled district heating areas (DH areas) and corresponding Local Administrative Units (LAUs) and NUTS2 regions

	Conditioned biomass potential		Designated for DH (50%)		Allocated to DH areas (LAU)	
MS	**[PJ/a]**	**[TWh/a]**	**[PJ/a]**	**[TWh/a]**	**[PJ/a]**	**[TWh/a]**
AT	150	42	75	21	70	19
BE	103	29	51	14	19	5
BG	131	36	65	18	63	18
CY	4	1	2	1	0	0
CZ	155	43	77	22	76	21
DE	874	243	437	121	369	103
DK	73	20	37	10	22	6
EE	43	12	21	6	20	5
EL	60	17	30	8	28	8
ES	586	163	293	81	273	76
FI	255	71	128	35	119	33
FR	810	225	405	113	349	97

	Conditioned biomass potential		Designated for DH (50%)		Allocated to DH areas (LAU)	
MS	**[PJ/a]**	**[TWh/a]**	**[PJ/a]**	**[TWh/a]**	**[PJ/a]**	**[TWh/a]**
HR	26	7	13	4	8	2
HU	234	65	117	33	111	31
IE	34	9	17	5	15	4
IT	386	107	193	54	170	47
LT	78	22	39	11	38	11
LU	3	1	2	0	1	0
LV	83	23	42	12	41	11
MT	5	1	3	1	0	0
NL	103	29	52	14	18	5
PL	578	161	289	80	273	76
PT	116	32	58	16	48	13
RO	554	154	277	77	272	75
SE	387	107	193	54	176	49
SI	41	11	20	6	12	3
SK	65	18	32	9	30	8
EU27	**5,935**	**1,648**	**2,967**	**824**	**2,620**	**728**

From Table 9, it can be seen that, for EU27 on average, hydropower represents the energy source with the lowest future potential in absolute magnitude terms. At some 1.5 EJ per year, the expansion scope from current levels (1.15 EJ of Total Energy Supply during 2019 in Eurostat´s NRG_BAL_C, dated 2021-01-24) is in the range of 30%. If expressed as specific potentials, i.e. by per-capita values based on Member State averages as in

Figure 20 on the left, the corresponding average hydropower potential in EU27 would be 4.2 GJ per capita according to the 2016 PRIMES EU Reference Scenario, and approximately 3.9 GJ per capita according to the 2020 PRIMES EU Reference Scenario. A few countries, SE, AT, FI, SI, LV, HR, PT and RO, all display above-EU27-average values, which may be interpreted in such a way that only a few Member States will be able to fully exploit this potential in the future.

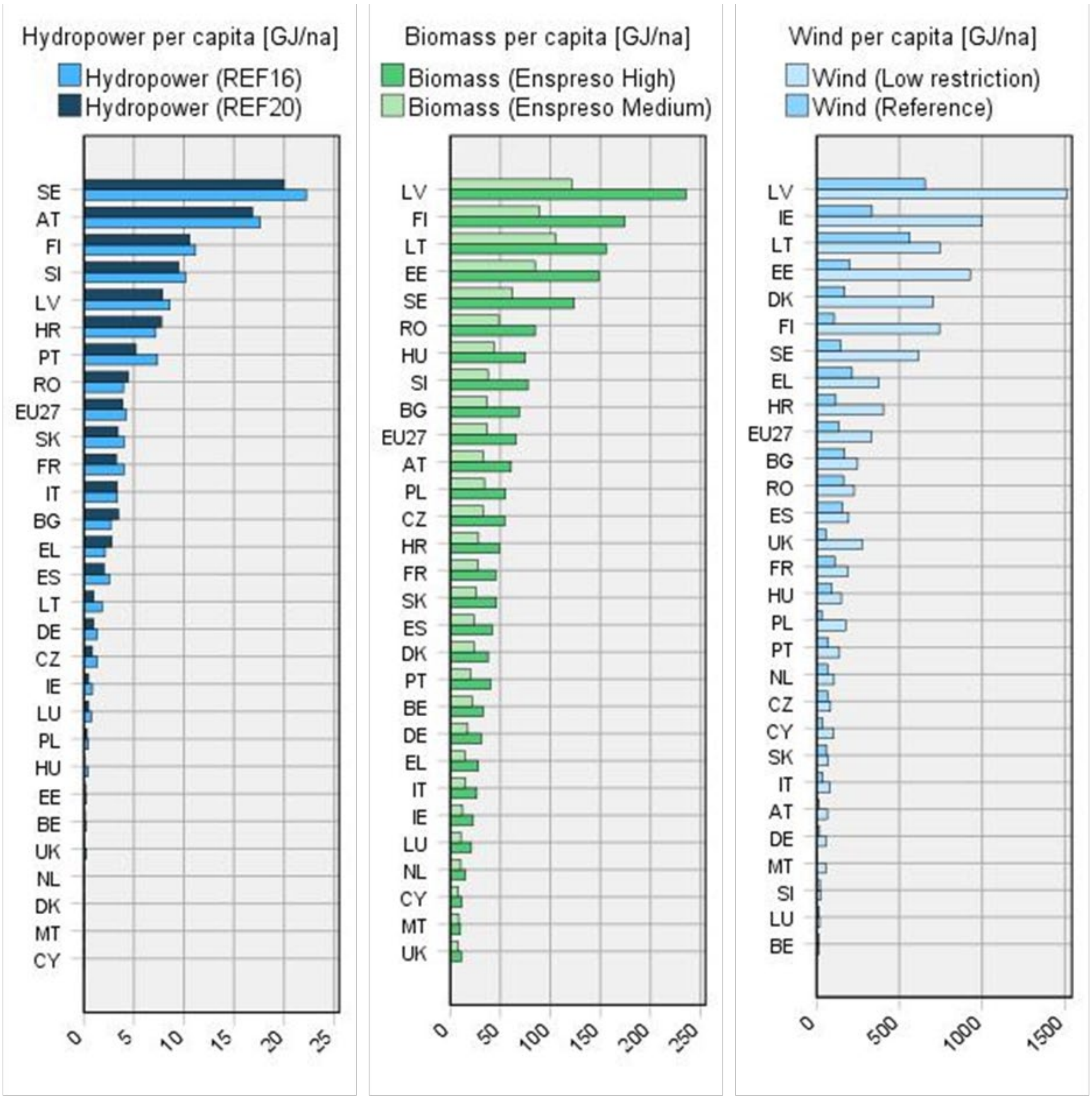


Figure 20: Renewable energy potentials per capita by population projections for 2050: Hydropower (by Primes Reference Scenarios 2016 and 2020) (left), Biomass (by JRC Enspreso High and Medium Availability Scenarios) (centre), and Wind (by JRC Enspreso Low and Reference Restrictions Scenarios). EU27 average values.

The next energy source, if sorted by reference potential magnitude, is biomass, with a potential in the order of 20 EJ per year by 2050 – however, noteworthy, under a “High” availability scenario, meaning at lowest levels of constraints. For reference, the same study presents corresponding 2050 biomass potentials at 8.2 EJ under a “Low” availability scenario and, as we have seen, at 11.7 EJ under “Medium” availability conditions. The specific biomass potentials are presented in Figure 20 in the centre: 65.6 GJ per capita represents the EU27 average maximum, or high availability, value. The medium availability average value is found at 37.0 GJ per capita. For orientation, the conditioned biomass potentials expressed in Member State average per capita values for EU27 would translate into 23.5 GJ per capita (conditioned) and 11.8 GJ per capita (conditioned for DH).

As also mentioned above, there are diverging views in Europe at present regarding the fate of biomass, however, the differences associated with the JRC ENSPRESO potential scenarios referred to above (which align fairly well with other estimates, as for example with the S2BIOM studies referenced above) do not reflect diverging views directly, but rather implicitly by using different application levels of given boundary constraints, such as e.g. available land, expected production, and alternative uses. Once again, if relating to the Eurostat energy balances for 2019, a Total Energy Supply of "Bioenergy" for EU27 at some 5.7 EJ, indicates that these potentials could allow for expanded use of biomass in the future.

The EU27 wind energy potential, as anticipated by the JRC ENSPRESO study (low restrictions and reference restrictions scenarios), opens up the grander scale at which the remaining renewable energy source potentials are found (wind energy potentials at 81.5 EJ per year and 37.8 EJ per year respectively, as outlined in Table 9 above). For comparison, when considering these numbers, it may suffice to emphasise that the complete Total Energy Supply to the EU27 overall energy system has hovered in the average range from approximately 60 EJ to 65 EJ per year since 1990. At the high restrictions' scenario (i.e. lowest potential, not further elaborated here), JRC estimates some 21.2 EJ per year (which is still far from the 1.32 EJ reported for wind in EU27 by Eurostat in 2019). Once again, Figure 20, on the right, presents the specific wind potentials expressed as per-capita values, where we realise that this translates into 334 GJ per year and person on average under low restrictions conditions and into 135 GJ per year and person on average under reference restrictions conditions.

As for both the solar and the geothermal full resource potentials, as presented in Table 9, the numbers found are somehow beyond real grasp: the full geothermal resource from the surface to two kilometres depth, for all land areas and principally unlimited by any other constraint, is anticipated at 340 ZJ (1044 TJ per-capita as an EU27 average, see Figure 22 below), and similarly for solar irradiation on the horizontal plane constrained to available land and a slope threshold at not above 6%, anticipated at 5.9 ZJ (specific value of 18.9 TJ per-capita and year, as presented in Figure 21).

The solar thermal potential, according to the method and assumptions described above, amounts to some 788 EJ for EU27 (834 EJ for EU28) as detailed in Table 9. The corresponding EU27 Member State average specific value was anticipated at some 2.51 TJ per capita and year (Figure 21). Similarly, the solar photovoltaic potential was assessed at 222 EJ per year with a corresponding per-capita value of 0.71 TJ per year.

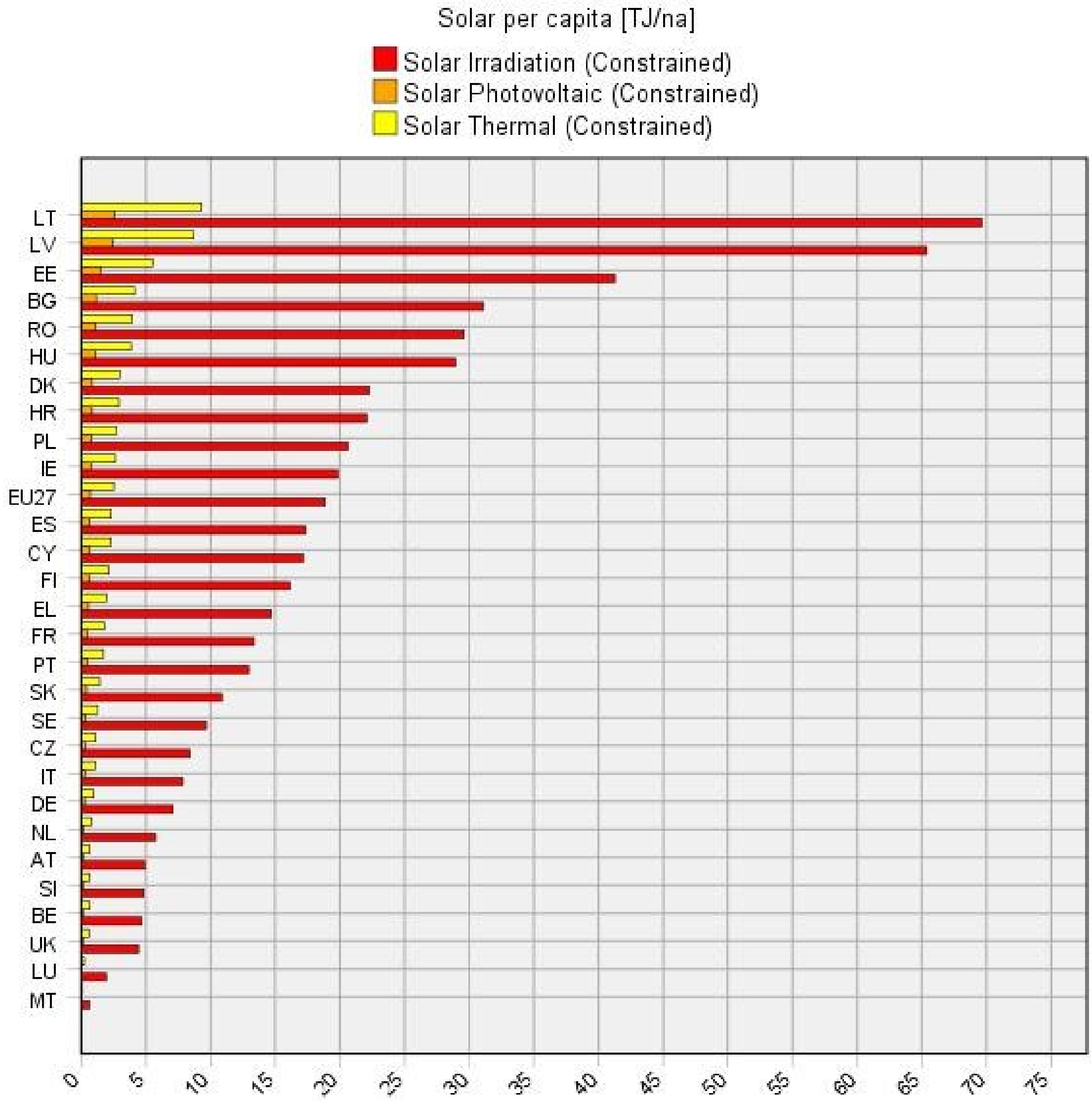


Figure 21: Renewable energy potentials per capita by population projections for 2050: Solar irradiation, Solar photovoltaic, and Solar thermal, all constrained by anticipated land availability and ground slope threshold. EU27 average values.

For the geothermal resource subjected to what may be considered as conditions for 4th generation district heating (4GDH), the total resource is reduced by some 72% to 94.8 thousand EJ (Table 9), which is reflected in an EU27 average specific potential of 208 TJ per-capita, notably in Hungary and Croatia, which is presented in Figure 22. Similarly, the estimated potential for the geothermal resource under conditions for 3rd generation district heating (3GDH) was found at some 13.6 thousand EJ (Table 9), which equates to a 43.8 TJ per-capita specific EU27 average value (see further Figure 22).

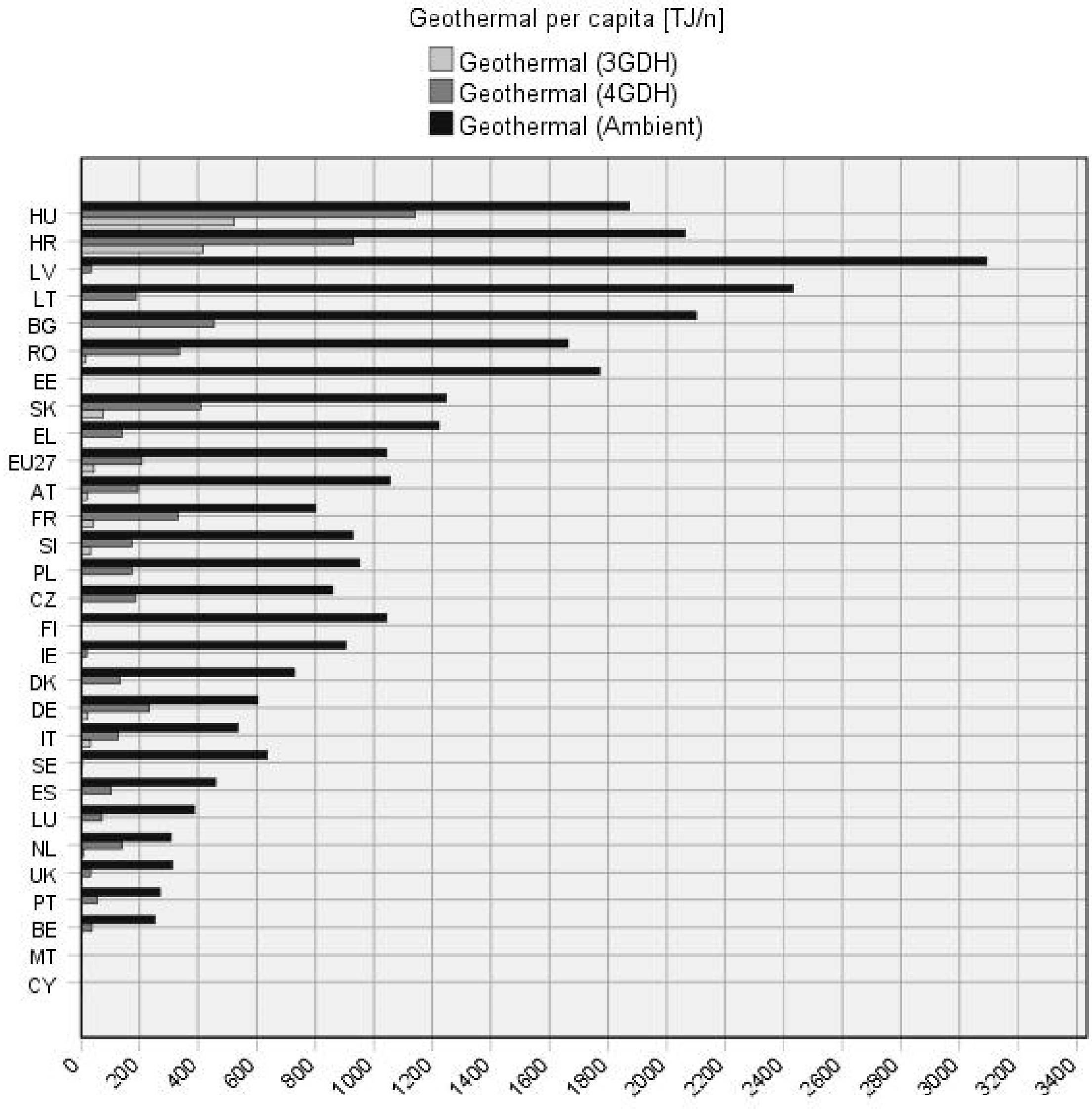


Figure 22: Renewable energy potentials per capita by population projections for 2050: Geothermal resource potential from earth surface to two kilometres depth and cooling to ambient temperatures, cooling to temperature levels reflecting conditions for 4th generation district heating, and cooling to temperature levels reflecting conditions for 3rd generation district heating. EU27 average values.

Now, to conclude this section, the potentials for energy from renewable sources hereby assessed are thought to represent “upper bounds” and are therefore recognised not as final potentials for renewable energy sources in heating and cooling, but as necessary boundary conditions upon which spatial allocation and energy system modelling realistically can be made. Final potentials would essentially be those which result from spatial mapping and energy system modelling where such applications have been possible to establish. For our work on applying spatial constraints, the descriptions in Annex C3 on the modelling of the DH sector provide further detail. For the application of various economic and systemic constraints, see further the approaches and findings elaborated in Chapter 6.

4. Heating and cooling decarbonisation pathway archetypes

This chapter develops archetypes for decarbonisation towards 2050 for the H&C sector for the EU Member States. The archetypes aim to group Member States with similar potentials, challenges and characteristics, as countries will decarbonise following different pathways according to their individual starting points and challenges. Section 4.1 presents the methodology that has been developed for the analysis. The results are shown in Section 4.2.

4.1. Methodological approach: Suitability analysis to derive pathway archetypes

To develop pathway archetypes, we develop a framework of suitability analysis as similar to the framework used by Persson et al. in a 2019 paper[24]. The approach aims to rank countries according to their individual suitability to follow a specific decarbonisation strategy.

Task 2 follows six major steps:

Step 1: Defining the analytical frame

Step 2: Building an integrated data basis of suitability indicators by merging multiple data sources

Step 3: Defining suitability indicators for each decarbonisation strategy

Step 4: Calculation of suitability per country

Step 5: Cluster analysis to group countries according to their suitability

Step 6: Derive recommendations across individual decarbonisation strategies and propose pathway archetypes

4.1.1. Step 1: Defining the analytical frame

Suitability concept and definition of suitability criteria

To identify archetype pathways for the transition in heating and cooling in the EU Member States, this work introduces the following suitability criteria:

Economic suitability: reflecting economic drivers and barriers to the deployment of the technologies such as high fuel prices and/or high investment costs for the technologies

Market suitability: reflecting the maturity and potential size of the market; also barriers and drivers related to the market development and expansion of the technologies

Infrastructural suitability: reflecting technological and infrastructural barriers and drivers such as the quality and the size of the heat, electricity and gas grids; also including settlement patterns

[24] Persson U, Wiechers E, Möller B, Werner S. Heat Roadmap Europe: Heat distribution costs. Energy. 2019; 176:604-22.

Physical suitability: reflecting the availability of energy resources as well as very structurally determined demand aspects like the heat demand density

Regulatory suitability: reflecting the maturity of the respective policy mix

These concepts together are used to assess the suitability of countries to implement specific decarbonisation strategies.

Decarbonisation strategies

The study covers the major decarbonisation strategies that Member States can follow to transform heating and cooling towards renewable energies, covering the main decarbonisation technologies:

- **Electrification:** mainly based on heat pumps for space heating supply as the key technology in supplying CO_2-neutral heat to buildings. Industrial process heat also requires other forms of electrification as heat pumps are mostly not applicable.
- **District heating and cooling, DHC:** The expansion of DHC and the decarbonisation of energy supply in DHC are expected to play an important role for the transition of heating and cooling in many EU Member States.
- **Direct use of renewable energy sources (RES):** solar thermal installations and biomass boilers support the decarbonisation of individual heating and can contribute substantially towards the transition. This strategy explores the role of both, solar thermal and biomass.
- **E-fuels and hydrogen:** This strategy focuses on using e-fuels and hydrogen for heat supply. The role of e-fuels and hydrogen for the decarbonisation of heating and cooling is discussed controversially. While it is generally agreed that hydrogen will be an important element of the decarbonisation of process heat, its role for space heating is uncertain.

For each decarbonisation strategy, individual indicators are defined for the above-mentioned suitability aspects.

4.1.2. Step 2: Building an integrated data basis

Step 2 develops the needed data basis which considers among others social, economic, geographical aspects in the Member States. Data for the indicators are collected using diverse sources, including official statistics, literature review, national energy and climate plans, energy system model databases, and own GIS-based analysis. Table 11 gives an overview of the sources used for the data collection.

As data comparability is a key factor, to ensure data availability for all Member States and consequently provide a complete dataset, for each indicator the data collection year is chosen independently. Whenever possible, quantitative data sources are used and data for EU-27 are included.

Table 11: Overview of data sources used for the table of indicators

Description	Quality Score	Sources
Official statistics	A	Eurostat[25], Building Stock Observatory[26]
Previous/parallel studies	B	RES-H[27], DHC Trend[28], Heat Roadmap Europe[29], Output from Task 1[30], Output from Task 3
Model databases	C	Invert/EE-Lab, FORECAST
Literature review	D	CEER Report on Power Losses[31], Mid-term Adequacy Forecast 2020[32], Heat Roadmap Europe: Heat distribution costs[33]

Sources used for data collection are categorised based on their qualities as shown in Table 11. In selecting the indicators, data completeness was a decisive factor, however, some data gaps were not avoidable in those cases where the indicator had an important role in the suitability aspect and no better quality data was available. In such cases, the mean value of the indicator across the countries was used as the value for the missing countries, otherwise the clustering could not be carried out.

The database developed includes more than 100 indicators covering the following areas:

- Climate
- RES potentials
- Current H&C structure
- Infrastructure
- Industry structure
- Population and settlement structure
- Economic and social organisation
- Structure of the building stock
- Policy approach
- Ambition level
- Energy poverty

---

25 https://ec.europa.eu/eurostat/data/database

26 https://ec.europa.eu/energy/eu-buildings-database_en

27 Renewable space heating under the revised Renewable Energy Directive - Publications Office of the EU (europa.eu)

28 https://op.europa.eu/en/publication-detail/-/publication/4e28b0c8-eac1-11ec-a534-01aa75ed71a1/language-en

29 https://heatroadmap.eu/

30 The sources used in this Task are listed in Table 6.

31 https://www.ceer.eu/documents/104400/-/-/fd4178b4-ed00-6d06-5f4b-8b87d630b060

32 https://eepublicdownloads.entsoe.eu/clean-documents/sdc-documents/MAF/2020/MAF_2020_Appendix_1_Input_Data_Detailed_Results.pdf

33 https://www.sciencedirect.com/science/article/pii/S0360544219306097?via%3Dihub

4.1.3. Step 3: Defining suitability indicators for each decarbonisation strategy

In order to operationalise the analysis, a set of quantitative indicators is selected from the databases to represent the various suitability aspects for each decarbonisation strategy. The definition of the indicators for suitability uses the results of the analysis of barriers for different decarbonisation options developed in TU Wien et.al. 2021[34]. The indicators cover various aspects of suitability, reflecting the extent to which barriers exist to the deployment of the decarbonisation strategies. To allow for a meaningful comparison across the countries some indicators are defined as shares or ratios (e.g. per capita or per m^2) instead of the absolute values.

Table 12 to Table 15 show an overview of the indicators considered to represent the suitability aspects for various decarbonisation strategies as well as a detailed description of the indicators, reasoning for choosing each indicator as well as the sources used.

[34] Report on ENER/C1/2018-494 – Renewable Space Heating under the Revised Renewable Energy Directive, forthcoming

Table 12: Overview of indicators considered for electrification

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
Economic suitability	Ratio between levelised costs of heat for heat pump and natural gas boiler	Proportion of the levelised cost of heat in district heating heat pumps compared to a natural gas boiler	Heat pumps are key technology for the electrification of H&C supply. The difference in costs of producing heat via a heat pump compared to a natural gas boiler shows the economic attractiveness of heat pumps.	Calculated based on RES-H project
	Ratio between electricity and gas price - household	Comparison of the energy prices for household consumption, including all taxes and levies: proportion of electricity price for consumption between 2500 and 5000 kWh to gas price for consumption between 20 and 200 GJ	This indicator strongly affects the economic attractiveness of all kinds of electric H&C solutions. Main competitor is gas in heating. Despite overlaps with LCOH, the indicator is used due to very high relevance and very robust data.	Calculated based on Eurostat [nrg_pc_202] and [nrg_pc_204]
	Ratio between electricity and gas price – non-household	Comparison of the energy prices for non-household consumption, including all taxes and levies: proportion of electricity price for consumption between 500 and 2000 MWh to gas price for consumption between 10000 and 100000 GJ	This indicator strongly affects the economic attractiveness of all kinds of electric H&C solutions. Main competitor is gas in heating. Despite overlaps with LCOH, the indicator is used due to very high relevance and very robust data.	Calculated based on Eurostat [nrg_pc_203] and [nrg_pc_205]
Market suitability	Share of heat pump in space heating technology stock	Number of heat pumps compared to the total number of DH space heating equipment	The share of heat pumps in the overall equipment stock of space heating technologies reflects how mature the heat pump market is. Establishing such a market typically takes time.	RES-H project

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Share of process heat below 200°C	Ratio of total FED in industry sector for the process heat below 200°C to total FED for process heat at all temperature levels	Process heat below 200°C can potentially be supplied by high temperature heat pumps. A country with a high share in this temperature range can potentially electrify process heating with efficient heat pumps.	Heat Roadmap Europe, D3.1.[35]
	Share of electricity in gross heat production	The amount of heat produced using electricity compared to the total heat produced	Reflects how mature the market for electricity-based heat production in district heating is in a country	Eurostat [nrg_bal_peh]
	Share of heat pumps in FED of H&C	Share of heat pumps in total FED in heating and cooling of residential, tertiary and industry sector	Reflects how mature the market for heat pumps is in a country	Heat Roadmap Europe, D3.1.
Suitability of infrastructure	Average loss of load expectation (inverted)	The expected number of hours in a year in which a country's electricity demand cannot be met.	Measures the quality of the electricity grid. Countries with a higher quality grid have a better perspective for electrification, which will strongly challenge the grids.	Mid-term Adequacy Forecast 2020 Appendix 1[36]
	Share of single-family houses	Ratio of number of single-family houses to the number of all buildings in the residential building stock	Single-family houses might have a better opportunity to use heat pumps in combination with PV systems than multi-family houses.	RES-H project

[35] https://heatroadmap.eu/wp-content/uploads/2018/09/3.1-Profile-of-the-heating-and-cooling-demand-in-the-base-year-in-the-14-MSs-in-the-EU28-2.pdf

[36] https://eepublicdownloads.entsoe.eu/clean-documents/sdc-documents/MAF/2020/MAF_2020_Appendix_1_Input_Data_Detailed_Results.pdf

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Ownership structure	Share of owners among the whole population	Owners living in their houses tend to have a higher likelihood to invest in heat pumps and PV as they follow more long-term goals than owners who rent their houses.	Eurostat [ilc_lvps15]
Physical suitability	Solar irradiation per m²	The annual solar irradiation in the horizontal plane on land limited to a selection of Corine land use classes (agriculture) and with slope below 6%	A high solar irradiation is directly correlated with a higher cost-effectiveness of PV-based electricity generation, which is a good basis for heat pumps, especially in small-scale rooftop systems.	Task 1
	Total PV roof + ground and CSP potential	The combined annual potential from ground and rooftop-mounted solar photovoltaics plus concentrated solar panels under a general 85 MW/km^2 capacity and 3% land availability constraint	Countries with a high potential for solar-based electricity generation have a better perspective for electrification of heat supply, which will need high amounts of additional RES-E production	ENSPRESO[37]
	Hydropower potential	The gross electricity generation potential from hydropower as anticipated in the PRIMES EU Reference Scenarios for 2050	Countries with a high potential for hydropower have a better perspective for electrification of heat supply, which will need high amounts of additional RES-E production	Task 1
	Wind potential (onshore and offshore)	The electrical power production per year per technology used and availability of usable land/sea	Countries with a high potential for wind-based electricity generation have a better perspective for electrification of heat supply, which will need high amounts of additional RES-E production	ENSPRESO - Wind (JRC)

[37] https://www.sciencedirect.com/science/article/pii/S2211467X19300720

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Cooling degree days	A technical indicator that describes the annual need for cooling (air-conditioning) in a country. It is calculated based on the difference between outdoor and targeted indoor temperature for every day of the year.	Cooling degree days (CDDs) reflect the cooling needs in a country. High cooling needs might make PV + heat pump systems more attractive as it increases the annual full load hours and usefulness of the system, without increasing investment needs.	Eurostat [nrg_chdd_a]
Regulatory suitability	Ban of fossil fuel heating technologies for new investments	Policy measure that bans the use of fossil fuel heating technologies (encoded with 0 not implemented, 1 planned, 2 implemented)	Strong policy that bans fossil heating and therefore increases need to invest in heat pumps. A longer history and experience of a country in heat pump-support policies allows for more dynamic electrification.	Task 3
	Tax exemptions for electricity for heat pumps	Policy measure that imposes tax exemptions for electricity uses in heat pumps (encoded with 0 not implemented, 1 planned, 2 implemented)	Tax exemptions for electricity used in heat pumps make heat pumps more attractive and incentivise investments in this technology.	Task 3
	Financial support for heat pumps	Policy measure that provides financial support (i.e. grants or subsidies) for heat pumps (encoded with 0 not implemented, 1 planned, 2 implemented)	Financial support for heat pumps makes them more attractive compared to other options.	Task 3
	Financial support for RES and efficient generation in DHC (i.e. including large heat pumps)	Policy measure that provides financial support (i.e. grants or subsidies) for RES and/or efficient generation in DHC (encoded with 0 not implemented, 1 planned, 2 implemented)	Financial support for RES and/or efficient generation plants feeding into DHC networks makes them more attractive compared to other options.	Task 3

Table 13: Overview of indicators considered for district heating

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
Economic suitability	Ratio between DH consumer price and price for gas	Comparison of the energy prices: average district heating prices compared to the gas price including all taxes and levies, for household consumptions between 20 and 200 GJ	The ratio shows the (current) attractiveness of DH compared to natural gas, the main alternative in heat supply.	Calculation based on Eurostat and European district heating price series[38]
	Ratio between DH solar thermal and natural gas	Proportion of the levelised cost of heat in district heating solar thermal compared to annatural gas boiler.	A higher cost-effectiveness of solar thermal DH supply compared to natural gas-based DH supply makes use of solar thermal as supply option more attractive in a country.	Calculated based on RES-H project
	Ratio between DH geothermal and oil boiler	Proportion of the levelised cost of heat in district heating geothermal compared to an oil boiler.	A higher cost-effectiveness of geothermal DH supply compared to oil-based DH supply makes use of geothermal as supply option more attractive in a country.	Calculated based on RES-H project
Market suitability	Share of district heating in H&C FED	Share of district heating in total FED in heating and cooling of residential, tertiary and industry sector	High share of district heating reflects mature market and, thus, a good basis for further expansion of DH	Heat Roadmap Europe, D3.1.
	Share of biomass in DH fuel mix	Share of biomass in the DH generation mix	Countries with a high share of biomass are better positioned to increase the RES share in DH.	Euroheat & Power (2019): Country by County Report[39]
	Share of non-biomass RES in DH fuel mix	Total share of geothermal, solar thermal, heat pumps in the DH generation mix	Non-biomass RES might play a more important role in the future. Countries with currently a high share of non-biomass renewables in the DH fuel mix have very mature markets and are well positioned to increase the share.	Euroheat & Power (2019): Country by County Report

[38] https://energiforskmedia.blob.core.windows.net/media/21926/european-district-heating-price-series-energiforskrapport-2016-316.pdf
[39] https://www.euroheat.org/media-centre/publications/country-by-country.html

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
Suitability of infrastructure	District heating trench length	Length of DH trench per capita	Large existing district heating infrastructure is a good basis for further expansion	DHC-Trend project
	Growth in DH trench length (2013-2019)	Increase in the length of DH trench from 2013 to 2019	Growth in district heating infrastructure in recent years reflects current dynamics. Indicator not included, because it has too many data gaps.	Calculated based on Euroheat and Power (2015) and DHC-Trend project
	Share of dwellings in urban centres	Share of dwellings located in densely populated areas (urban centres) in comparison to all dwellings. The areas are categorised by degree of urbansiation into: densely populated areas (urban centres), intermediate urbanised area (urban clusters), and thinly-populated areas (rural areas).	Dwellings in urban areas are most suitable for DH supply, because heat densities are higher. More urbanised countries are more suitable for DH expansion.	BSO, Eurostat
	Share of multi-family houses in total housing stock	Ratio of number of multi-family houses to the number of all buildings in the residential building stock	Multi-family houses can be more cost-efficiently supplied by district heating than single-family houses. Thus, countries with higher shares of multi-family houses are more suitable for DH expansion.	RES-H project
Physical suitabilit y	Share of areas with heat demand density above 500 GJ/hectare (Classes 3-5)	Ratio of land use areas with a high heat demand density (above 500 GJ/hectare) to total land use areas. In total 5 classes are defined and this threshold corresponds to the lower band of the third class.	Areas with higher heat densities are more suitable for DH supply. Countries with higher shares of such areas are more suitable for DH expansion.	Heat Roadmap Europe: Heat distribution costs[40]

[40] https://www.sciencedirect.com/science/article/pii/S0360544219306097

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Industrial waste heat potential matched with high heat density areas	Heat from industrial plants that can be utilised technically in future DH systems on the temperature level of 95°C close to the heat density classes 3-5. In this potential, future developments in industry (production, efficiency, carbon-neutral processes) are included.	A country with higher RES resource potentials has a higher suitability to use RES in DH.	ISI Industrial Database (see Task 6)
	Wastewater treatment potential matched with high heat density areas	Heat from waste water treatment plants that can be utilised technically in combination with heat pumps. Only plants in high heat density areas (classes 3-5) are included.	A country with higher RES resource potentials has a higher suitability to use RES in DH.	Peta 5, Hotmaps (see Task 6)
	Rivers potential matched with high heat density areas	Heat from water (rivers, lakes, ocean) that can be utilised technically in future DH systems in combination with heat pumps. Only plants in high heat density areas (classes 3-5) are included.	A country with higher RES resource potentials has a higher suitability to use RES in DH.	Copernicus (see Task 6)
	Waste-to-energy potential matched with high heat density areas	Heat from waste-to-energy plants (waste incineration) that can be utilised technically in future DH systems. Only plants in high heat density areas (classes 3-5) are included.	A country with higher RES resource potentials has a higher suitability to use RES in DH.	Peta 5 (see Task 6)
	Geothermal potential matched with high heat density areas	Technical potentials that can be utilised technically in future DH systems based on the temperatures of the rock underground. Assumed is a depth of 2000-3000m, and typical flow rates from petrothermal projects, with a minimum temperature of 65°C. Only plants in high heat density areas (classes 3-5) are included.	A country with higher RES resource potentials has a higher suitability to use RES in DH.	Copernicus (see Task 1 and 6)
Regulatory suitability	Financial support for RES and efficient generation in DHC	Policy measure that provides financial support (i.e. grants or subsidies) for RES and/or efficient generation in DHC (encoded with 0 not implemented, 1 planned, 2 implemented).	Financial support for RES and efficient generation plants feeding into DHC networks makes these technologies more attractive compared to other options (i.e. fossil fuel based technologies).	Task 3

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	RES quota in DHC	Policy measures that impose a RES quota in DHC networks, i.e. an obligation to use a certain amount (i.e. X%) of RES in the generation mix (encoded with 0 not implemented, 1 planned, 2 implemented).	Strong policy that increases the share of RES in DHC. The obligation to use RES in DHC stimulates the integration of existing potential.	Task 3
	Requirements for urban heat planning	Policy measure that impose an obligation for urban/spatial heat planning (encoded with 0 not implemented, 1 planned, 2 implemented).	Urban heat planning is used to develop a strategy for the long-term conversion of the heat supply with the goal of climate neutrality. In particular, district heating can be addressed as one suitable option.	Task 3
	Financial incentives for DHC infrastructure	Policy measure that provides financial support for DHC infrastructure, e.g. for new pipes or substations etc. (encoded with 0 not implemented, 1 planned, 2 implemented).	Financial support for DHC infrastructure incentivises the modernisation and expansion of DHC.	Task 3
	Mandatory connection of end users to DHC under certain conditions (i.e. new buildings or in specific areas)	Policy measure that imposes an obligation for end users to connect and use the local DHC network (in a certain area, i.e. zoning) (encoded with 0 not implemented, 1 planned, 2 implemented).	Many DHC networks face the challenge that not enough users are willing to connect. Mandatory connection addresses this challenge and thus provides (investment) security for the expansion of DHC.	Task 3

Table 14: Overview of indicators considered for direct RES

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
Economic suitability	Ratio between LCOH for solar thermal and natural gas boiler	Proportion of the levelised cost of heat in district heating solar thermal compared to a natural gas boiler	The difference in costs of producing heat via a solar thermal installation compared to a natural gas boiler shows the economic attractiveness of solar thermal.	Calculated based on RES-H project
	Ratio between price for biomass and natural gas	Ratio of fuel price for biomass compared to natural gas	The ratio between the price for biomass and natural gas shows how economically attractive biomass is compared to the main competitor.	Calculated based on RES-H project
Market suitability	Share of solar energy in gross heat production	The amount of heat produced with solar energy compared to the total heat produced	A high share of solar energy in gross heat production shows mature solar thermal markets in district heating.	Eurostat [nrg_bal_peh]
	Share of biomass in gross heat production	The amount of heat produced using biomass compared to the total heat produced	A high share of biomass in gross heat production shows mature biomass markets in district heating.	Eurostat [nrg_bal_peh]
	Share of process heat below 200°C	Ratio of total FED in industry sector for the process heat below 200°C to total FED for process heat at all temperature levels	Process heat below 200°C can be supplied to a large extent by solar thermal energy and biomass, while this is less possible for higher temperature ranges. Countries with a high share of process heat below 200°C can use RES to provide process heat.	Heat Roadmap Europe, D3.1.
	Share of solar thermal in total stock of space heating equipment	Number of solar thermal equipment compared to the total number of DH heating equipment	A high share of solar thermal installations in the heating system stock indicates mature markets in the residential consumer segment.	RES-H project

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Share of biomass in total stock of space heating equipment	Number of biomass equipment compared to the total number of DH heating equipment	A high share of biomass installations in the heating system stock indicates mature markets in the residential consumer segment.	RES-H project
Suitability of infra-structure	Share of multi- family houses	Ratio of number of multi-family houses to the number of all buildings in the residential building stock	Single-family houses might be better suited to integrate solar thermal or biomass energy, while multi-family houses might be better suited to integrate both energy carriers via district heating.	RES-H project
Physical suitability	Biomass potential	The annual energy available from biomass resources under given constraints on land availability, yearly production yields, competing uses etc.	Countries with a high biomass resource potential are better suited to decarbonise by using biomass at large scale.	Task 1
	Solar thermal energy rooftop potential	Solar thermal rooftop potential	Countries with a high solar thermal resource potential are better suited to decarbonise by using solar thermal at large scale.	Invert/EE-Lab[41]
	Solar irradiation per m²	The annual solar irradiation in the horizontal plane on land limited to a selection of Corine land use classes (agriculture) and with slope below 6%	A high solar irradiation indicates very good cost-effectiveness to use solar thermal energy.	Task 1
Regulato ry suitabilit y	CO_2 tax/price	Policy measure that imposes a tax on CO_2 (in the heating sector) in order to encourage polluters to reduce the combustion of coal, oil and gas (encoded with 0 not implemented, 1 planned, 2 implemented).	A CO_2 tax/price makes fossil fuels more expensive and therefore incentivises investments in carbon-free technologies.	Task 3

[41] https://www.invert.at/

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
	Financial support for decentralised RES-H	Policy measure that provides financial support (i.e. grants or subsidies) for decentralised RES-H technologies (encoded with 0 not implemented, 1 planned, 2 implemented).	Financial support for decentralised RES-H technologies makes them more attractive compared to other options.	Task 3
	Ban of fossil fuel heating technologies	Policy measure that bans the use of fossil fuel heating technologies (encoded with 0 not implemented, 1 planned, 2 implemented).	Strong policy that bans fossil heating and therefore increases need to invest in heat pumps. A longer history and experience of a country in heat pump-support policies allows for more dynamic electrification.	Task 3
	RES-H obligation for existing buildings	Policy measure that imposes a RES obligation in existing buildings, i.e. an obligation to use a certain amount (i.e. X%) of RES-H (encoded with 0 not implemented, 1 planned, 2 implemented).	Strong policy that increases the share of RES-H in buildings.	Task 3

Table 15: Overview of indicators considered for e-fuels and hydrogen

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
Market suitability	Share of chemical and petrochemical industries in total industrial FED	Ratio of FED in industry sector for chemical and petrochemical sub-sector to total FED in industry sector	Hydrogen will likely play an important role in the decarbonisation of the chemical industry. Countries with a large chemical industry are thus likely to need more hydrogen.	Eurostat [nrg_bal_s]
	Share of iron and steel industry in total industrial FED	Ratio of FED in industry sector for iron and steel sub-sector to total FED in industry sector	Many steel industry companies aim to decarbonise by switching from coal to hydrogen. A large-scale switch will be a major driver for hydrogen infrastructure and markets.	Eurostat [nrg_bal_s]
Suitability of infrastructure	Natural gas in gross heat production per capita	The total quantity of natural gas in gross heat production per capita	High current share of natural gas in district heating supply indicates established markets (and infrastructure) and thus the respective country is more suitable to decarbonise via e-gases/hydrogen	Calculated based on Eurostat [nrg_bal_peh] and Eurostat [tps00001]
	Share of natural gas in residential sector final energy demand	Proportion of natural gas in the FED of space and water heating in residential sector to the total FED	Countries with a high share of natural gas in the supply of residential buildings also have a very dense gas distribution infrastructure.	RES-H project
Physical suitability	Solar irradiation per m²	The annual solar irradiation in the horizontal plane on land limited to a selection of Corine land use classes (agriculture) and with slope below 6%	High solar irradiation allows more cost-effective domestic production of e-fuels/hydrogen	Task 1
	Hydropower potential	The gross electricity generation potential from hydropower as anticipated in the PRIMES EU Reference Scenarios for 2050	High RES-E potentials allow more likely domestic production of large amounts of e-fuels and hydrogen. Such countries are less dependent on	

Suitability aspect	Indicator	Description of the indicator	Reason for choosing the indicator	Source
			imports and have domestic value creation. Thus, they are more suitable to use e-fuels/hydrogen	
	Total PV potential (roof, ground and CSP ground)	Potentials include photovoltaics roof, ground and concentrated solar power as provided by the JRC ENSPRESO database. We used the least optimistic potential: 85 W/m² and 3% of land available.	High RES-E potentials allow more likely domestic production of large amounts of e-fuels and hydrogen. Such countries are less dependent on imports and have domestic value creation. Thus, they are more suitable to use e-fuels/hydrogen	
	Wind potential (onshore and offshore)	The electrical power production per year by technology used and availability of usable land/sea	High RES-E potentials allow more likely domestic production of large amounts of e-fuels and hydrogen. Such countries are less dependent on imports and have domestic value creation. Thus, they are more suitable to use e-fuels/hydrogen	
Regulatory suitability[42]	CO_2 tax/price	Policy measure that imposes a tax on CO_2 (in the heating sector) in order to encourage polluters to reduce the combustion of coal, oil and gas (encoded with 0 not implemented, 1 planned, 2 implemented).	A CO_2 tax/price makes fossil fuels more expensive and therefore incentivises investments in carbon-free technologies.	
	Financial support for e-fuels/hydrogen (e.g. fuel cells and/or infrastructure)	Policy measure that provides financial support for generation and/or transport of e-fuels/hydrogen, e.g. fuel cells and/or infrastructure (encoded with 0 not implemented, 1 planned, 2 implemented).	Financial support for generation and/or transport of e-fuels/hydrogen makes them more attractive.	

[42] Indicators in this category are not considered in the analysis and clustering of Section 4.2.4. To see the results including the policies see Annex

It is to be noted that the indicator sets shown in the tables above are the results of an iterative process where alternative indicator combinations for each decarbonisation strategy were tested and draft results were assessed. The aim was to include only relevant indicators, minimise overlaps between indicators and reach a balanced number of indicators.

4.1.4. Step 4: Calculation of countries' suitability

After defining the indicators for each suitability aspect, the data for the allocated indicators is collected from the dataset developed. Using this data, each indicator and Member State is given a value between 0 and 1, with 0 reflecting the lowest and 1 the highest suitability. For each indicator these values are calculated based on the difference to the minimum and maximum figures for that specific indicator across the countries.[43]

In the next step a single value for each suitability aspect is calculated as the mean value of all indicators in that suitability aspect. The sum of these mean values is then considered as the total suitability, used for ranking the Member States and determining the most and least suitable countries in each strategy.

4.1.5. Step 5: Country clustering

A hierarchical clustering algorithm is used in order to group the Member States and finally indicate their suitability to a pathway. Thereby, the algorithm calculates the dissimilarity between all elements and gradually combines two elements with the least dissimilarity into a cluster. This cluster is then used again in the next iteration. As schemes for the dissimilarity calculation and linkage types, we use Ward's minimum variance method and the Euclidean distance. Key input figures for the clustering analysis are the relevant suitability indicators. For a detailed explanation of the methodology used see Murtagh and Contreras 2012[44] and Nielsen 2016[45].

4.2. Results of the suitability analysis

In this section, results of the suitability analysis are provided. They are reported by decarbonisation strategy and present the most and least suitable countries and the ranking of each suitability aspect, where the darker colours indicate higher suitability. In addition, countries are grouped according to their similarity using hierarchical clustering and an overview of individual indicators is provided for each decarbonisation strategy.

4.2.1. Decarbonisation strategy “Electrification”

Figure 23 shows the ranking of countries according to their overall suitability to implement the H&C decarbonisation strategy "Electrification". The totals simply represent sums of the

[43] In this analysis, a higher figure for an indicator means a higher suitability of one country with respect to the decarbonisation strategy discussed. Thus, when a higher value for an indicatior initially indicates the lower suitability for the strategy, the data series for that indicator is inverted. As an example for the indicator “Ratio between levelised costs for heating of heat pumps compared to natural gas boilers”, a higher value indicates higher costs of heat pumps and thus less suitability of the country for electrification. Therefore the data series for this indicator is inverted to consider this inverse proportion.

[44] Murtagh, F.; Contreras, P. (2012): Algorithms for hierarchical clustering: an overview. In: WIREs Data Mining Knowl Discov 2 (1), S. 86–97. DOI: 10.1002/widm.53.

[45] Nielsen, F. (2016): Hierarchical Clustering. In: Frank Nielsen (Hg.): Introduction to HPC with MPI for Data Science. Cham: Springer International Publishing (Undergraduate Topics in Computer Science), S. 195–211.

individual suitability criteria (economic, market, infrastructure, physical, regulatory). According to these totals, differences are observed between countries. Countries including Sweden, France, Finland, Latvia, Denmark, Ireland and the Netherlands are more suitable than other countries. There is, however, also a large number of countries without a clear tendency. In general, the difference across countries is moderate and all countries are relatively close to the EU average. Figure 24 shows aggregated values for each individual suitability aspect and explains differences in the totals between countries. E.g. Sweden and Denmark have a very strong market suitability, reflecting a very mature heat pump market.

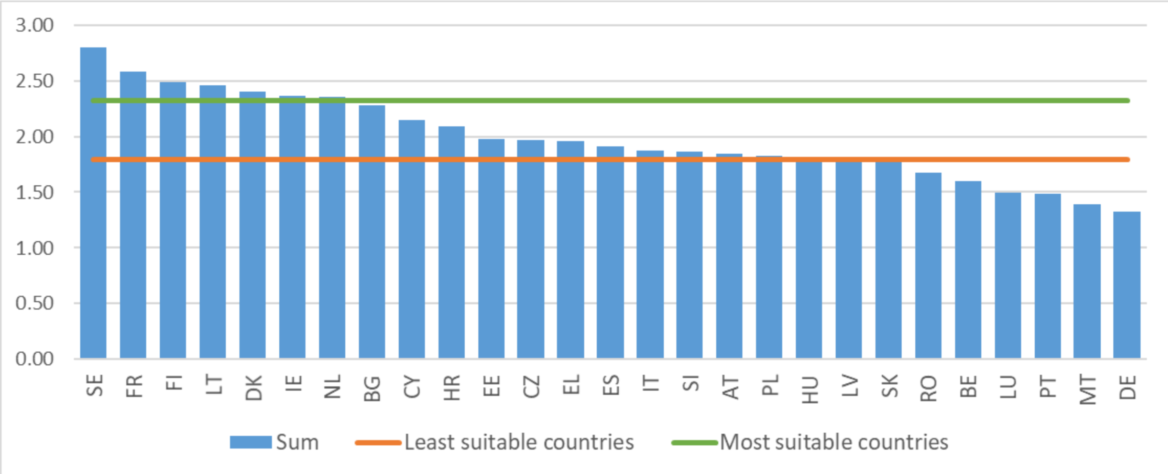


Figure 23: Total suitability ranking of countries for Electrification

Figure 24: Ranking of different suitability aspects for Electrification (only most and least suitable countries)

Figure 25 and Figure 26 show the results of the suitability analysis for individual indicators and the hierarchical clustering. It allows a deeper understanding of the main reasons for the clustering results and is the basis for interpreting the resulting country clusters. The following observations are made.

Cluster 1 (DK and SE): Very high suitability for electrification and mature heat pump markets. Cluster 1 has the highest suitability for electrification and has a major similarity with the mature market for heat pumps. Both are the only countries with a substantial share of electricity used for heat production in district heating. Still, there are also major differences among the two countries like the higher electricity price and the lower hydropower potential in Denmark.

Cluster 2 (BG, HR, CY, EL, HU, IT, MT, PT, RO, SK, SI, ES): Countries with warm climate, good PV potentials, but less wind potentials. Cluster 2 consists of mostly Southern European countries, which all have a substantial need for cooling. The potential for wind power is low (except Greece and Spain) while the potential for PV is high in this cluster (except Malta, where low land availability limits the potential for ground-mounted PV drastically). Solar irradiation per m² is, however, very high in Malta and most other countries in this cluster. The ownership structure of buildings is dominated by a large share of house owners and less renting. The size of the heat pump market gives a mixed picture with some countries reflecting high heat pump shares (e.g. Italy, Greece) and many others with less developed heat pump markets. Also the number of heat pump support policies in force is different across the countries but generally, the number of policies is lower in this cluster. Overall, this cluster has a very good suitability to decarbonise via electrification using decentralised systems like heat pumps for heating and cooling combined with a PV system. Also the high importance of single-family houses and the low share of rented dwellings support this strategy. On the other hand, the low wind potentials might limit large-scale electrification at some point.

Cluster 3 (EE, LV, LT): Very good physical suitability (RES potentials) for electrification, but not yet mature markets. Cluster 3 has very good physical suitability for electrification, meaning high solar and wind potentials (as a result of low population density). At the same time, their markets for heat pumps are not yet developed.

Cluster 4 (AT, BE, CZ, FI, FR, DE, IE, LU, NL, PL): Western and Central European countries with cold climate and less RES-E potentials show diverse suitability for electrification. Cluster 4 is described by low cooling degree days (colder climate), low solar potentials and mixed wind potentials (Ireland with high wind potential and Finland, France and the Netherlands with good wind potentials, others with low potentials), mostly heat pump markets emerging and all with several heat pump support policies in force. Other indicators are more diverse across countries. All countries are from North-Western Europe. Some countries have a very good suitability for large-scale electrification like Finland, France and Ireland, while others are at the lower end like Belgium, Germany and Luxembourg.

Overall, it can be observed that for the decarbonisation strategy "Electrification" countries are clustered very much according to their geographical location.

Country	Cluster	Sum	Average in each cluster
DK	1	6.5	7.7
SE	1	8.8	
BG	2	6.0	4.8
HR	2	5.3	
CY	2	5.3	
EL	2	5.6	
HU	2	4.2	
IT	2	4.5	
MT	2	4.3	
PT	2	4.5	
RO	2	4.4	
SK	2	4.1	
SI	2	4.3	
ES	2	4.8	
EE	3	4.4	5.0
LV	3	4.8	
LT	3	5.7	
AT	4	4.4	4.0
BE	4	2.8	
CZ	4	3.7	
FI	4	5.6	
FR	4	4.9	
DE	4	2.8	
IE	4	4.8	
LU	4	2.8	
NL	4	4.4	
PL	4	3.8	

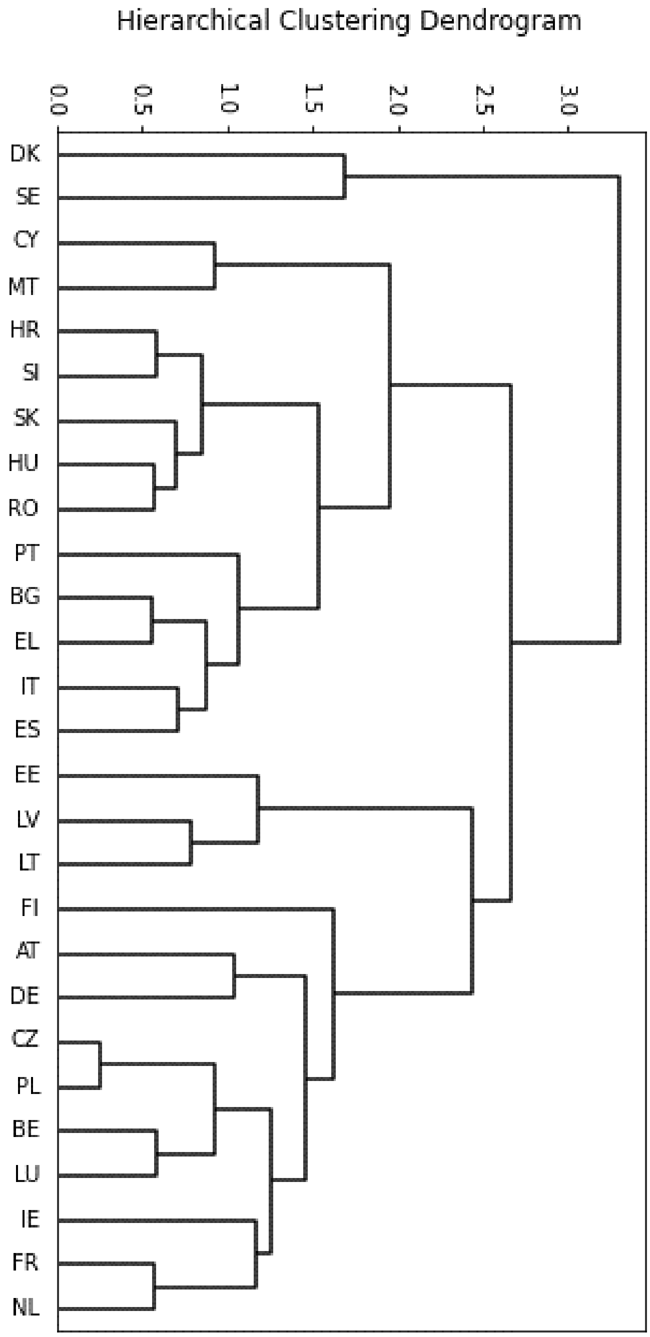


Figure 25: Results of hierarchical clustering for decarbonisation strategy "Electrification"

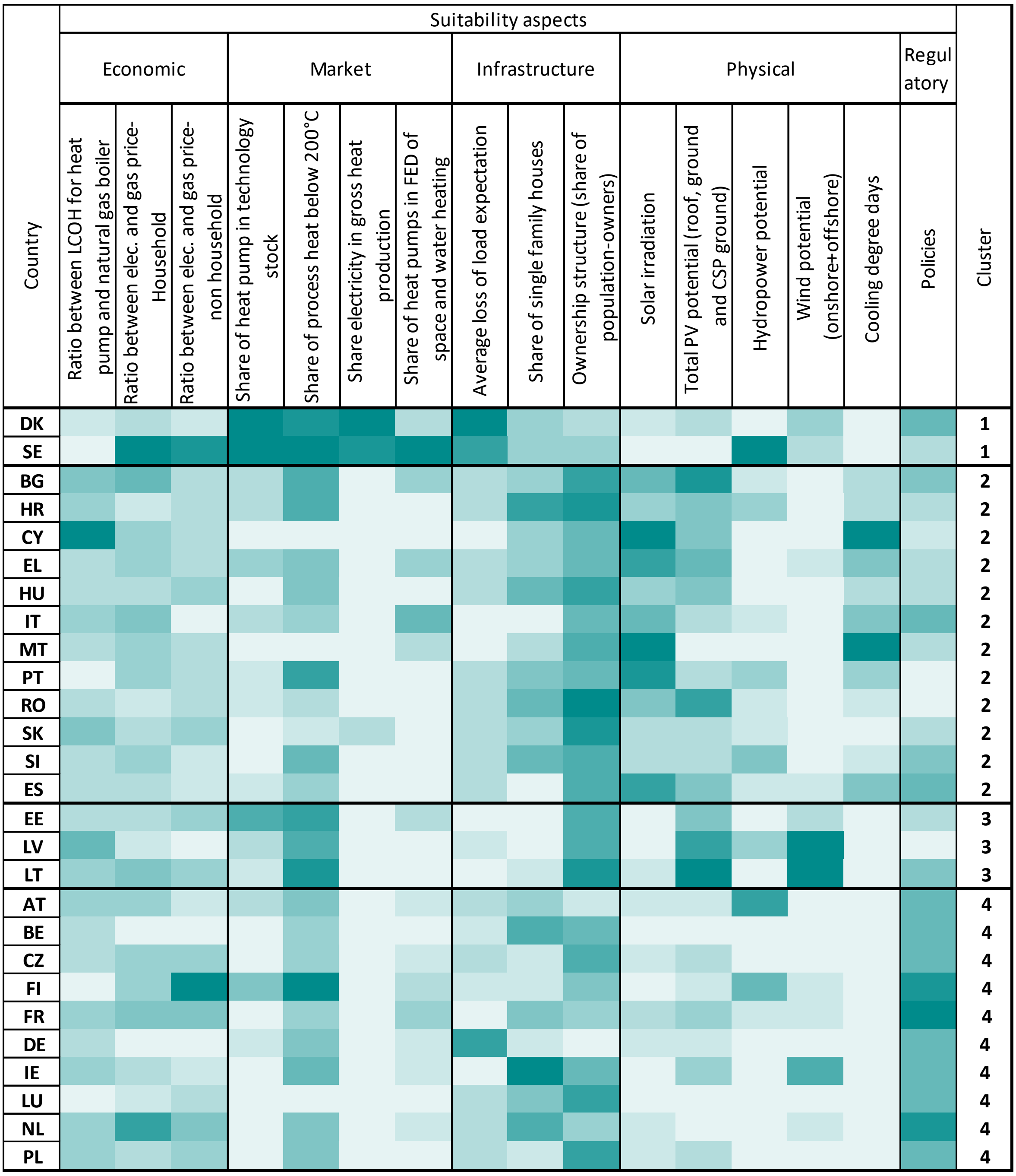


Figure 26: Overview of results for individual suitability indicators by country as used in the hierarchical clustering for the decarbonisation strategy "Electrification"

4.2.2. Decarbonisation strategy "District heating"

The following figures show the ranking of countries according to their overall suitability to implement the H&C decarbonisation strategy "District heating" as well as the results by suitability aspect. The overall results show a wide spread between countries. Most suitable countries are Sweden, Denmark, France, Italy, Germany, Austria, Lithuania and Estonia. Particularly Sweden and Denmark show a suitability that is substantially above other countries. This is mainly related to an already mature market for district heating, existing infrastructure, but also good RES potentials. For the least suitable countries, a major reason is the opposite, the less developed market for district heating.

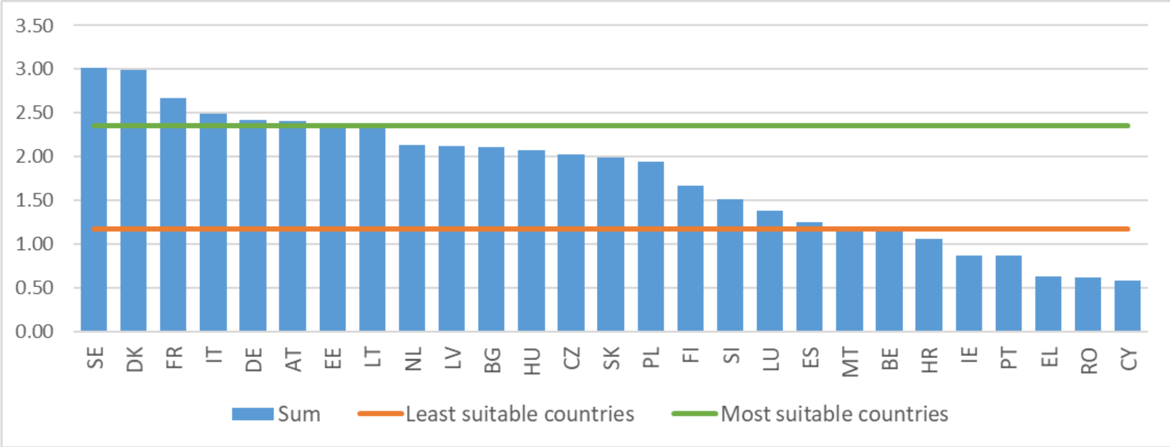


Figure 27: Total suitability ranking of countries for District heating

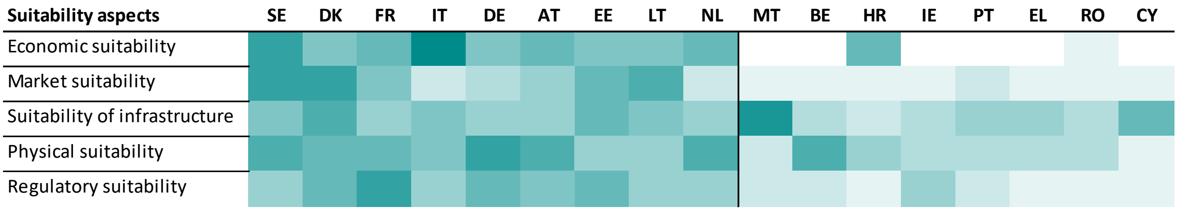


Figure 28: Ranking of different suitability aspects for District heating

Figure 27 and Figure 28 provide results of the clustering analysis. Based on these results, the clusters can be summarised as follows.

Cluster 1 (DK, EE, FI, LV, LT): Northern countries with excellent suitability for large-scale role of DH. Cluster 1 countries have a very high suitability to decarbonise via district heating. The cluster is characterised by a high share of DH in FED, reflecting very mature DH markets combined with a high share of biomass in the DH fuel mix. The settlement structure with high share of multi-family houses and urbanisation is very suitable for DH expansion. Cluster 1 countries have good RES potentials for DH supply, but not the highest. Geographically, cluster 1 consists of the Nordic and Baltic countries.

Cluster 2 (SE): Sweden defines a separate cluster by itself. While it is close to cluster 1, it differs in terms of very high economic suitability for district heating and a comparably high share of non-biomass in DH supply. Sweden has the highest suitability for DH.

Cluster 3 (HR, CY, EL, MT, PT, RO): Southern countries with less potentials for large-scale use of DH. This cluster shows a relatively low suitability for a large-scale use of district heating. Many of the countries currently have a low share of district heating in the FED for heating, reflecting less developed markets. Expansion of district heating might be less attractive in many cases, because heat demand densities are lower than for example in cluster 1. The potentials for future use of RES in district heating systems are limited. The countries have only few or no policies in place to support RES in DH or the expansion of district heating. However, while these countries certainly are less well positioned for a large-scale roll-out of district heating than countries from cluster 1, there are certainly attractive areas where district heating can play an important role, e.g. to supply urban centres or to use individual large-scale RES sources.

Cluster 4 (BG, CZ, DE, IT, PL, SK, ES): Good physical suitability for large-scale use of DH with high heat densities, high RES potentials and many multi-family houses in the building stock. This cluster consists of countries with a good suitability for a large-scale roll-out of district heating. Most countries have mature DH markets, but compared to cluster 1 a lower share of RES in district heating. The settlement structure in terms of building stock and heat demand densities is very suitable for district heating with an important role of multi-family houses and high heat demand densities. Also most countries show large potentials to use RES in DH (less so Bulgaria and Spain). All countries have several policies in place to support DH. Despite these common aspects, individual countries can be highlighted. Especially Germany shows a very good physical suitability for district heating with many high heat demand density areas and very good RES potentials (especially geothermal). Also Italy, Spain and Czech Republic have a settlement structure with many multi-family houses and high heat demand densities that can be well supplied by DH. Overall, DH can play an important role in the decarbonisation of the H&C sector in this cluster.

Cluster 5 (AT, BE, FR, HU, IE, LU, NL, SI): Diverse suitability for large-scale use of district heating with a building stock that is dominated by single-family houses. This cluster gives a more diverse picture, but includes countries with good physical suitability for DH like France, Belgium or the Netherlands with high heat demand densities and sufficient RES potentials. Overall, however, countries in this cluster have a high share of single-family houses, which are less attractive for DH supply. By far the highest share of single-family houses is observed in Ireland.

Overall, it needs to be underlined that the analysis ranks the countries according to their suitability to use district heating as a large-scale option for decarbonisation. It is certainly true that also in countries with low suitability results, district heating can play an important role, especially in urban areas and to make use of large RES-based heat sources.

The potentials to use RES in DH need more explanation. We have included one aggregated indicator reflecting the aggregated RES potential from individual sources, because including the individual sources as separate indicators in the clustering would have resulted in too scattered results and a very high weighting of potentials in the overall suitability. In order to better understand the role of different potentials for the individual countries, Figure 29 shows the country rankings for individual sources. It is important to note that the RES potentials considered are matched with high heat density areas in order to exclude RES potentials that cannot be exploited by district heating. Further, the RES sources considered all reflect RES that can only be exploited by district heating and are not well suited to supply individual buildings.

Country	Cluster	Sum	Average in each cluster
DK	1	6.6	5.4
EE	1	5.2	
FI	1	5.1	
LV	1	5.0	
LT	1	5.3	
SE	2	6.8	6.8
HR	3	1.9	2.5
CY	3	2.3	
EL	3	2.3	
MT	3	3.9	
PT	3	3.0	
RO	3	1.7	
BG	4	4.5	4.2
CZ	4	4.2	
DE	4	5.0	
IT	4	4.2	
PL	4	4.0	
SK	4	3.7	
ES	4	4.1	
AT	5	4.8	4.0
BE	5	3.4	
FR	5	5.2	
HU	5	4.2	
IE	5	3.0	
LU	5	4.0	
NL	5	4.5	
SI	5	3.1	

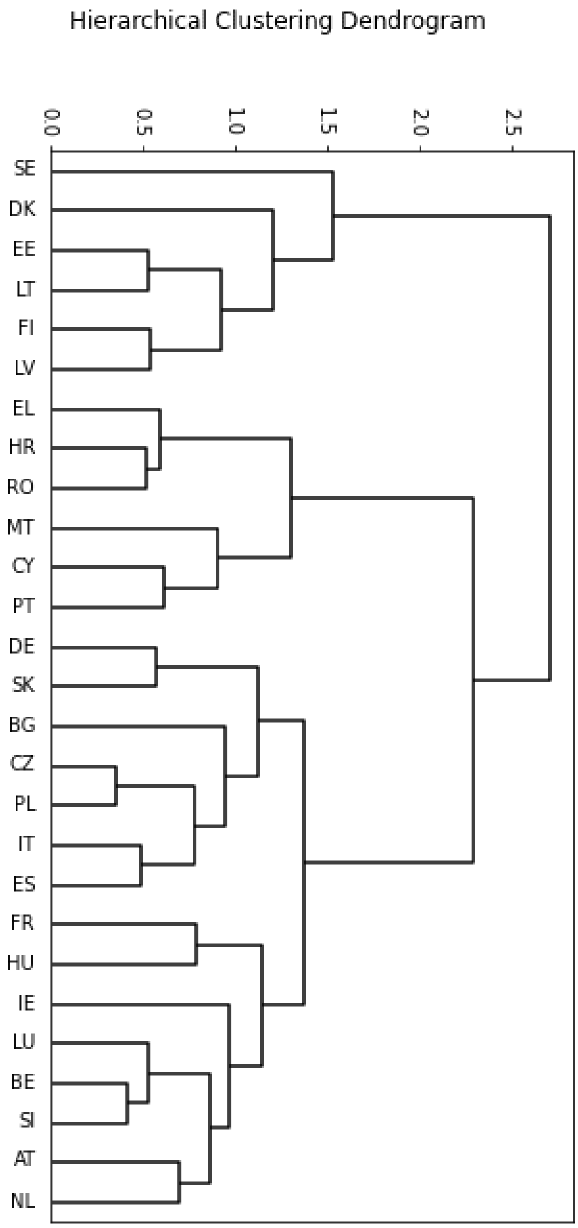


Figure 29: Results of hierarchical clustering for decarbonisation strategy "District heating"

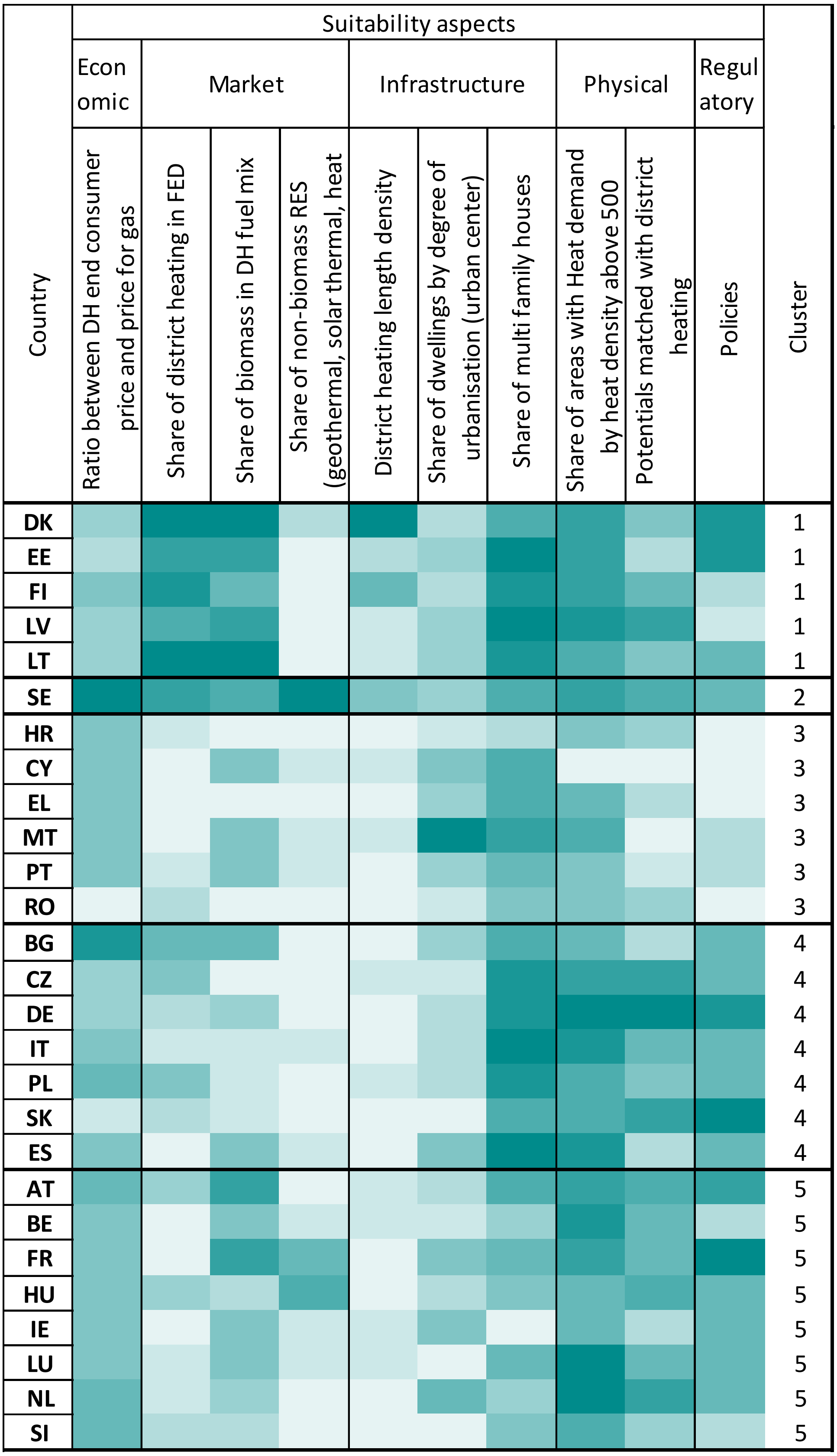


Figure 30: Overview of results for individual suitability indicators by country as used in the hierarchical clustering for the decarbonisation strategy "District heating"

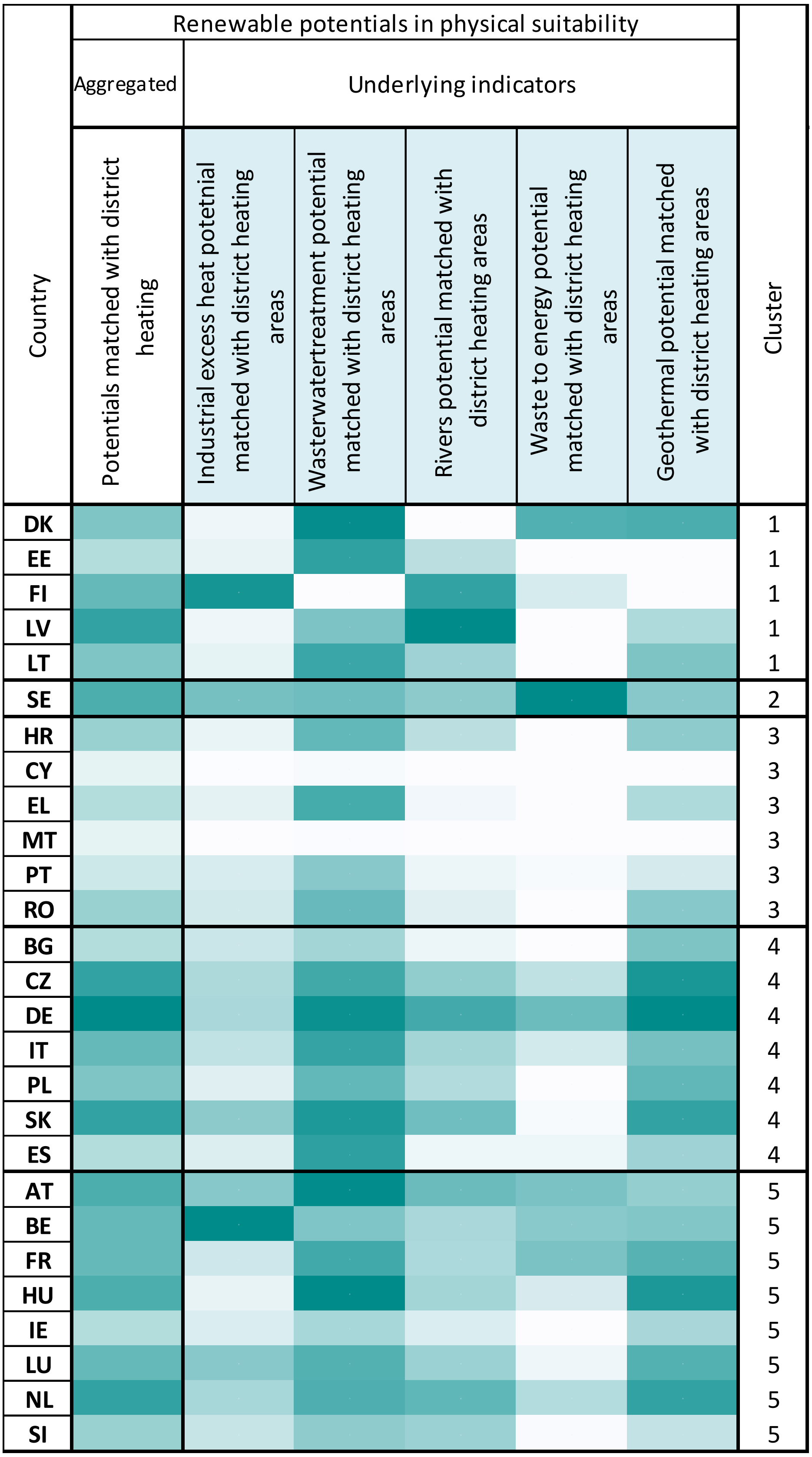


Figure 31: Overview of individual RES sources calculated matched with potential future DH areas (high heat demand areas)

4.2.3. Decarbonisation strategy "Direct use of RES"

The strategy "Direct use of RES" describes a decarbonisation strategy of the H&C sector that strongly builds on the use of biomass and solar thermal energy, in centralised and decentralised supply. Certainly, such a strategy needs to be accompanied by strong elements of other strategies like electrification, district heating or clean gas.

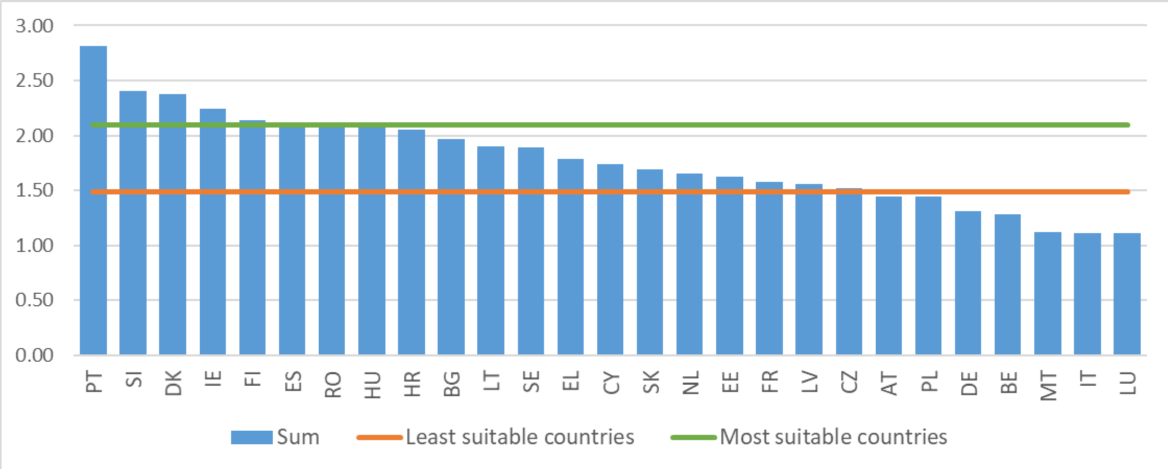


Figure 32: Total suitability ranking of countries for direct use of RES

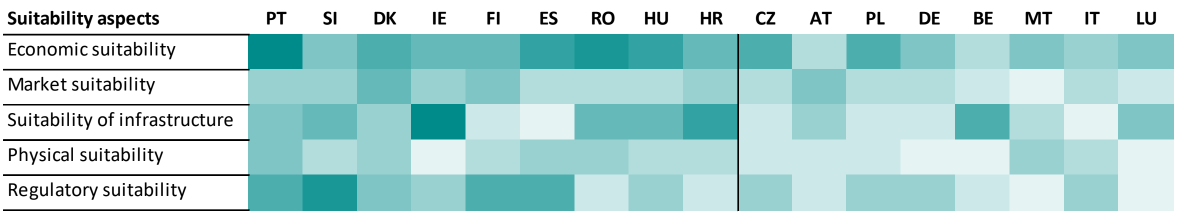


Figure 33: Ranking of different suitability aspects for direct use of RES

Figure 34 and Figure 35 provide results of the clustering analysis. Based on these results, the clusters can be summarised as follows.

Cluster 1 (DK, EE, FI, LV, LT, SE): Northern countries with a strong role of biomass in centralised and decentralised heat supply. This cluster shows a very high suitability for the direct use of RES, namely biomass. This is reflected by very good biomass potentials and already today a high share of biomass in centralised heat supply. Here, Denmark is the exception with rather low biomass potentials and the only country in this cluster with a substantial share of solar thermal in the supply of DH. The high share of process heat below 200°C is driven by a strong pulp and paper industry and allows to decarbonise large shares of industrial process heating via the direct use of RES.

Cluster 2 (AT, CY, DE, EL, IT, MT, PL, PT, SK, ES): Southern and other countries with an important market or potential for solar thermal energy. This cluster gives a mixed picture on the suitability for the direct use of RES. The current use of solar thermal or biomass in district heating is limited to selected countries. Especially Austria uses a high share of biomass and some solar thermal for the central heat supply. In contrast to cluster 1, many countries in this cluster already have very mature markets for decentralised solar thermal energy, namely Austria, Cyprus, Germany, Portugal and Greece, although Germany and Austria have relatively low solar irradiation and, thus, lower cost-effectiveness of solar thermal energy use. Many of the Southern European countries with high solar irradiation like Italy, Malta, Portugal and Spain still have a lower share of solar thermal installations in the heating technology stock. Overall, direct use of RES in this cluster mainly focuses on solar thermal energy and less on biomass. For most countries, biomass potentials are very limited.

Cluster 3 (BG, HR, CZ, HU, RO): Central-Eastern countries with a high share of biomass in decentralised heating and moderate potentials for both biomass and solar thermal. This cluster consists of countries from Central-Eastern Europe. These countries are described by a high importance of biomass for decentralised supply of buildings, driven by a very good cost-effectiveness compared to natural gas-based heating. Also the higher share of single-family houses supports the decentralised use of biomass. At the same time, the biomass resource potentials are moderate. Solar thermal potentials and markets are less pronounced but also show a higher suitability than in cluster 1. The current use of solar thermal energy or biomass in district heating supply is still low compared to cluster 1 or 4. Overall, countries in this cluster have both: sufficiently good biomass as well as solar thermal potentials, which results in an overall good suitability for the direct use of RES.

Cluster 4 (BE, FR, IE, LU, NL, SI): Lower suitability for the direct use of RES driven by lower biomass and solar thermal resource potentials. Countries in this cluster show relatively low suitability to decarbonise via direct use of RES (except Slovenia). The countries are characterised by a high importance of single-family houses in the building stock, at the same time, the current use of biomass or solar thermal for the supply of individual buildings is relatively low (except Slovenia). Also, resource potentials for biomass and solar energy are comparably low (except Slovenia). Despite the low potentials for the direct use of RES, some countries have many policies in place. France and the Netherlands, for example, have several policies in place to support the direct use of RES, while the markets for both solar thermal and decentralised biomass are yet very small.

Country	Cluster	Sum	Average in each cluster
DK	1	5.6	4.5
EE	1	3.9	
FI	1	4.9	
LV	1	4.0	
LT	1	4.4	
SE	1	4.4	
AT	2	3.9	3.5
CY	2	4.0	
DE	2	2.9	
EL	2	3.7	
IT	2	2.5	
MT	2	2.2	
PL	2	2.7	
PT	2	5.9	
SK	2	3.0	
ES	2	4.0	
BG	3	4.4	4.0
HR	3	4.0	
CZ	3	3.1	
HU	3	4.1	
RO	3	4.3	
BE	4	2.0	2.8
FR	4	2.8	
IE	4	3.5	
LU	4	1.9	
NL	4	2.4	
SI	4	4.4	

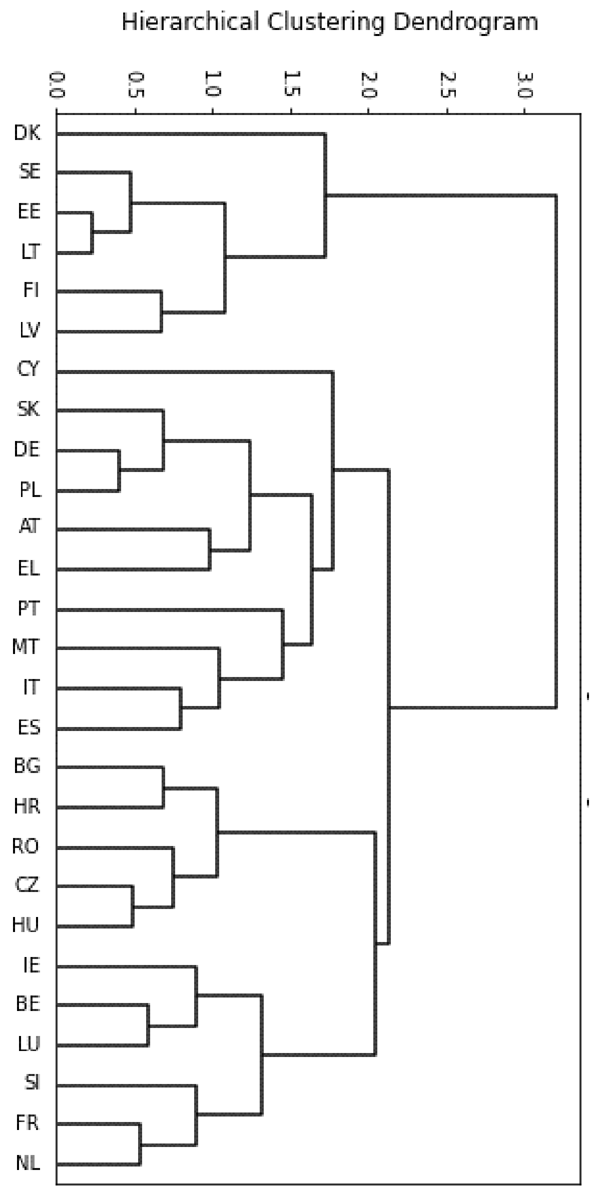


Figure 34: Results of hierarchical clustering for decarbonisation strategy "Direct RES"

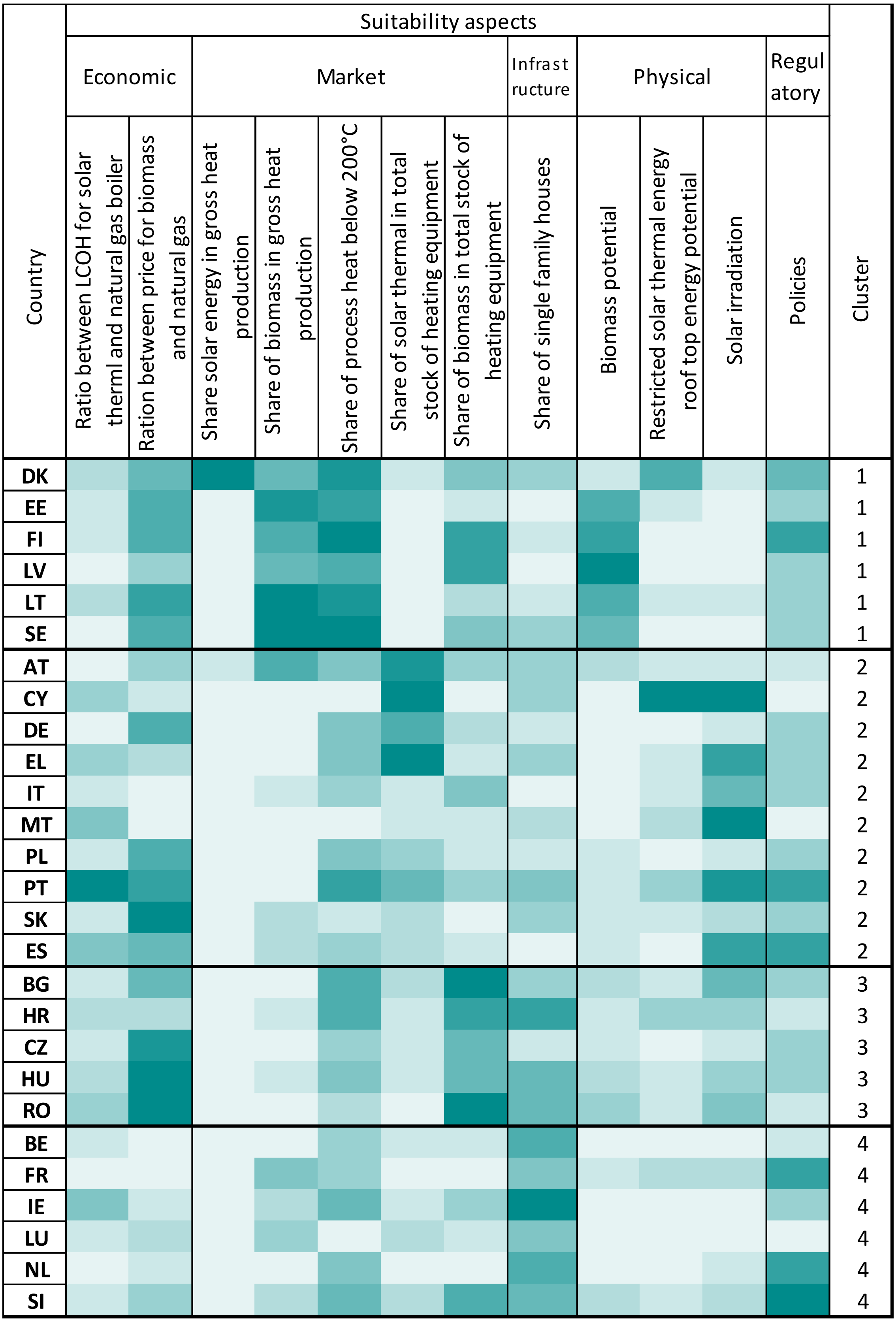


Figure 35: Overview of results for individual suitability indicators by country as used in the hierarchical clustering for the decarbonisation strategy "Direct RES"

4.2.4. Decarbonisation strategy "e-fuels and hydrogen"

The decarbonisation strategy "e-fuels and hydrogen" includes the use of all kinds of CO_2-neutral electricity-based fuels and gases. For the H&C sector, clean gas such as CH_4 will certainly have a more important role than fuels. Due to the low maturity of the markets that are only now developing, there are no indicators on the economics of this strategy included. Also regulatory suitability is not included, because policies are only emerging now or are very general in nature.

Results show large differences across the countries as seen in the overall suitability in the following figures. The Netherlands show the highest overall suitability, driven by mature markets, developed infrastructure and the regulatory instruments in place. On the other hand, the physical suitability, which reflects RES-E potentials to produce e-fuels/hydrogen domestically, is comparably low. Lithuania and Latvia on the other hand show a very high suitability due to the physical conditions with high RES-E potentials, while the market suitability is lower than in the Netherlands.

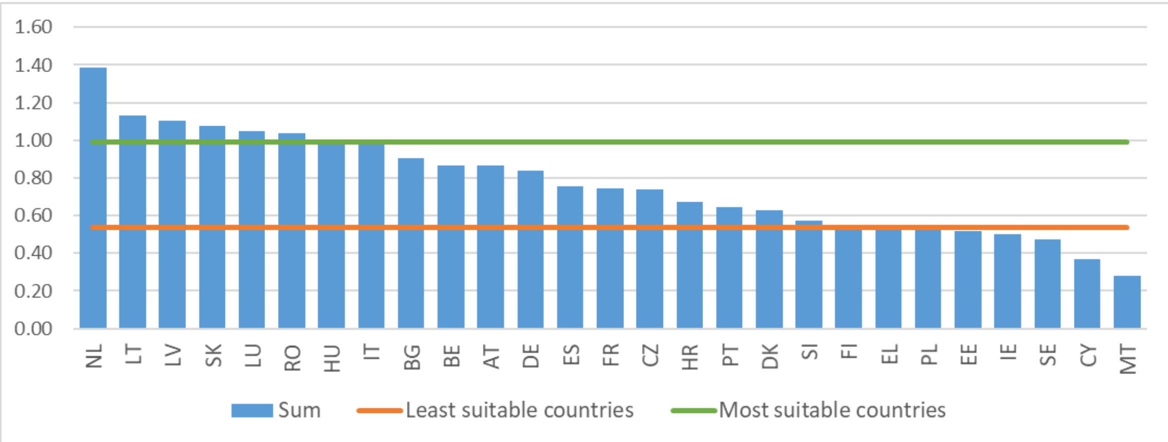


Figure 36: Total suitability ranking of countries for e-fuels and hydrogen

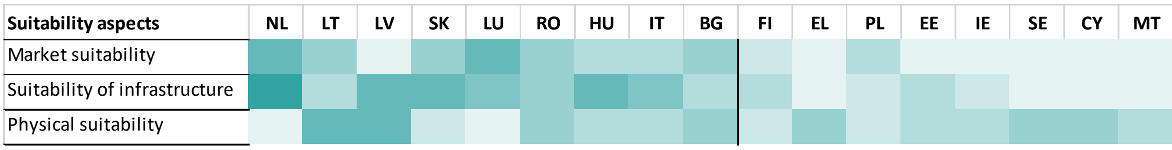


Figure 37: Ranking of different suitability aspects for e-fuels and hydrogen

The previous figures provide results of the clustering analysis. Based on these results, the clusters can be summarised as follows.

Cluster 1 (LV and LT): High suitability driven by very good wind and PV potentials. Both Latvia and Lithuania show very high potentials for the use of wind and PV which can be a strong basis for domestic hydrogen/e-fuels production. The gas infrastructure is developed as natural gas plays an important role in centralised heat supply. However, at the distribution grid level, the gas infrastructure seams less developed as it plays a less important role in the residential market.

Cluster 2 (CY, EL, MT, PT, ES): Least suitability for e-fuels/hydrogen due to undeveloped gas markets and infrastructure. This cluster shows the lowest suitability to decarbonise via e-fuels/gases or hydrogen. The gas markets and infrastructure are not well developed and also the industrial structure seems not to push for clean gases with low importance of basic chemicals and steel production. Solar irradiation is high, but other RES potentials like wind and hydropower are low, which are needed as a basis for the large-scale production of e-gases/hydrogen.

Cluster 3 (AT, HR, FI, SI, SE): Countries with very good RES-E potentials, but undeveloped gas infrastructure. This cluster includes countries with some use of gas in centralised heat supply, but generally not very extensively developed gas distribution infrastructure, as the use of gas for residential sector heating is low. Despite low solar irradiation (except HR), overall RES-E potentials of these countries are good with high potentials for hydropower and good solar or wind potentials. Judging from a RES resource perspective, these countries have good potentials to also produce e-fuels/hydrogen domestically, while gas markets and infrastructure are not yet so well developed and the large-scale roll-out would require a much higher investment in infrastructure than in most other countries. Also, the transition of the industry sector is not expected to be a large driver for hydrogen use with lower importance of the chemical industry in these countries. Except for Austria, these countries show a rather low suitability for the strategy e-fuels and hydrogen.

Cluster 4 (BE, BG, CZ, DK, EE, FR, DE, HU, IE, PL, RO): Relevant natural gas markets and infrastructure but diverse renewable energy potentials. Countries in this cluster have very developed markets for natural gas indicated by a high share of gas in centralised heat supply (except Poland and Ireland). With basic chemicals and steel industry located in most countries also the industry will likely have a substantial demand for clean gases in the future (except Estonia and Ireland). Also the infrastructure down to the gas distribution grid is well developed in most countries (less in Bulgaria and Estonia), which is reflected by a high share of natural gas in residential sector final energy demand. The RES-E potentials give a mixed picture. While some countries have substantial solar energy potentials (especially Bulgaria and Romania), others have higher wind potentials (Ireland, Denmark, Estonia) while some countries have in total lower RES-E potentials (like Belgium and Germany). In summary, this gives a mixed picture. Also the overall suitability for using clean gas and hydrogen shows a huge range in this cluster with some countries having a high suitability (Romania, Bulgaria and Hungary), but most countries showing rather low suitability (lowest in Poland, Ireland, Estonia and Denmark).

Cluster 5 (IT, LU, NL, SK): Extensive infrastructure available but low renewable energy potentials: This cluster comprises countries with mature gas markets and well developed infrastructure also at the distribution grid level. Potentially, these countries will need to develop green hydrogen markets to supply the steel and petro-chemical industries. However, all countries in this cluster only have limited RES-E potentials potentially requiring a strong role of hydrogen/e-fuel imports. Still, these countries have a comparably good suitability for the decarbonisation strategy e-fuels and hydrogen.

Country	Cluster	Sum	Average in each cluster
LV	1	3.3	3.3
LT	1	3.3	
CY	2	1.5	1.7
EL	2	1.9	
MT	2	1.0	
PT	2	2.0	
ES	2	2.2	
AT	3	2.3	1.8
HR	3	1.9	
FI	3	1.5	
SI	3	1.6	
SE	3	1.6	
BE	4	1.8	1.9
BG	4	2.5	
CZ	4	1.7	
DK	4	1.6	
EE	4	1.5	
FR	4	1.9	
DE	4	1.8	
HU	4	2.4	
IE	4	1.5	
PL	4	1.3	
RO	4	2.8	
IT	5	2.5	2.5
LU	5	2.2	
NL	5	2.9	
SK	5	2.5	

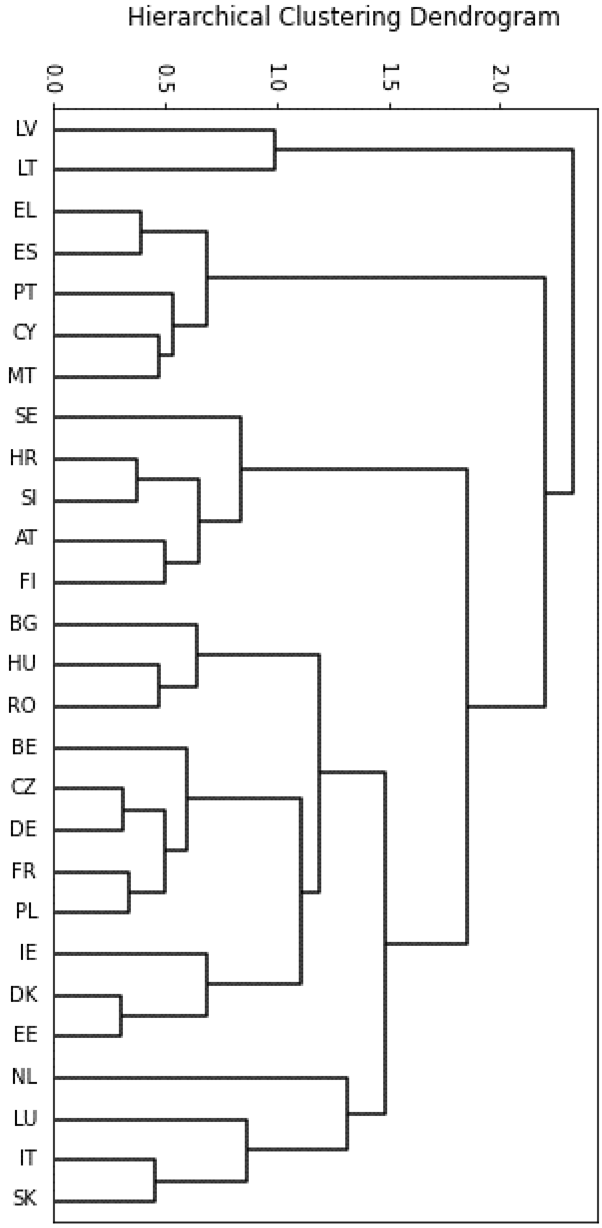


Figure 38: Results of hierarchical clustering for decarbonisation strategy "E-fuels and hydrogen"

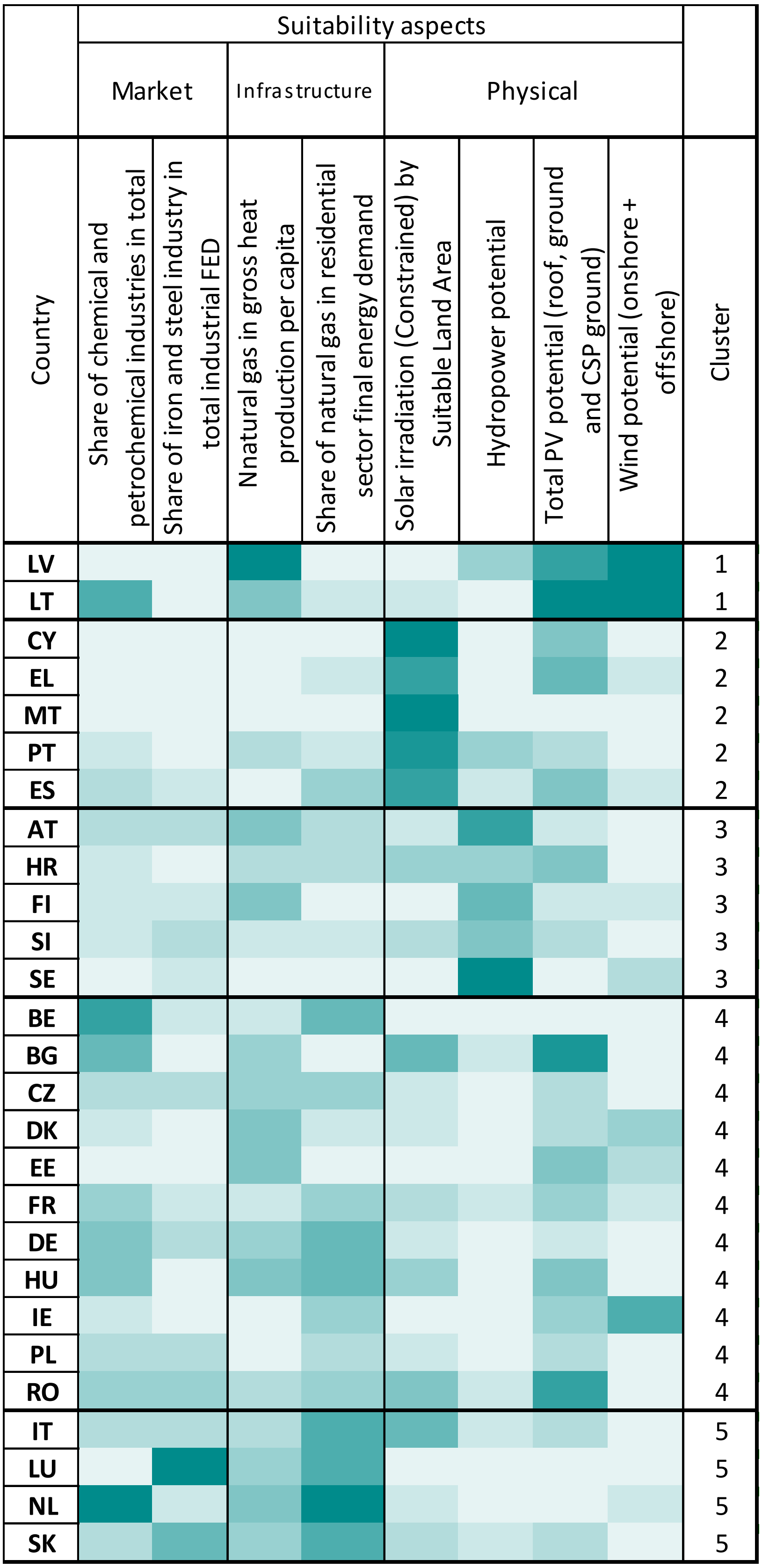


Figure 39: Overview of results for individual suitability indicators by country as used in the hierarchical clustering for the decarbonisation strategy "E-fuels and hydrogen"

4.2.5. Overview of results across decarbonisation strategies

In this section an overview of the suitability analysis and the clustering results across all strategies and for all member states is shown. Figure 40 presents the overall suitability ranking of all strategies across the countries. These aggregated results have to be interpreted with caution.

- The results allow for a comparison between countries within one strategy, but do not allow a comparison across strategies. E.g. it cannot be concluded that district heating is a more suitable strategy than electrification for Germany. In general, the calculated absolute suitability is not a meaningful result, it simply is high with a larger number of individual indicators considered as input for the calculation.
- Comparison across indicators can likely be biased. Outliers of individual countries can move all other countries up or down the suitability scale. E.g. Cyprus has virtually no heat demand, which makes all other countries appear is if they have a high heat demand density and differences among the other countries are neglected (see district heating expansion results above).
- Further systematic biases are possible. E.g. large countries often end up in the "remaining group", because they aggregate over a larger population and region.

Figure 40 shows that the suitabilities are very unevenly spread across countries. Some countries have a high suitability for several strategies like Sweden, Denmark or Bulgaria (electrification, district heating, direct RES) or even all strategies like Latvia and Lithuania (driven by high wind and solar energy potentials). Other countries, though, only have less suitable strategies available like Belgium, Luxembourg or Germany (somewhat suitable options in district heating).

	Suitability results				Selected underlying qualitative results		
Country	Electrification	District heating	Direct RES	E-fuels and hydrogen	Solar rooftop potentials	Biomass potentials and large-scale central use today	Likely combined H2 demand for steel and chemicals
SE	8.8	6.8	4.4	1.6		high	very high
DK	6.5	6.6	5.6	1.6			
BG	6.0	4.5	4.4	2.5			
LT	5.7	5.3	4.4	3.3		high	very high
FI	5.6	5.1	4.9	1.5		high	very high
EL	5.6	2.3	3.7	1.9	Very high		
HR	5.3	1.9	4.0	1.9	Very high		high
CY	5.3	2.3	4.0	1.5	Very high		
FR	4.9	5.2	2.8	1.9			high
IE	4.8	3.0	3.5	1.5			
LV	4.8	5.0	4.0	3.3		high	
ES	4.8	4.1	4.0	2.2	Very high		high
PT	4.5	3.0	5.9	2.0	Very high		
IT	4.5	4.2	2.5	2.5			high
NL	4.4	4.5	2.4	2.9			very high
RO	4.4	1.7	4.3	2.8			high
EE	4.4	5.2	3.9	1.5		high	
AT	4.4	4.8	3.9	2.3			very high
SI	4.3	3.1	4.4	1.6			
MT	4.3	3.9	2.2	1.0	Very high		
HU	4.2	4.2	4.1	2.4			high
SK	4.1	3.7	3.0	2.5			very high
PL	3.8	4.0	2.7	1.3			high
CZ	3.7	4.2	3.1	1.7			very high
DE	2.8	5.0	2.9	1.8			very high
BE	2.8	3.4	2.0	1.8			very high
LU	2.8	4.0	1.9	2.2			

Figure 40: Ranking of different decarbonisation strategies for each Member State plus selected underlying indicators (Left: Green fields indicate high suitability for a certain strategy and red fields lower suitability. Suitability is not to be interpreted in "absolute" terms, but only relative in comparison to other countries. Comparison can only be made within one strategy across countries. Comparison across strategies is not valid.)

It needs to be underlined that a country can typically not only follow one decarbonisation strategy but a combination of different strategies with different prioritisations. Also, the four strategies are not to be regarded as equal. **Electrification** is the one strategy which has a large potential in most (if not all) countries and with a huge efficiency advantage, especially compared to the strategy e-fuels and hydrogen. Figure 40 reveals that many countries show a relatively good suitability for electrification with only **Luxembourg, Belgium and Germany** being the least suitable countries, but also the **Czech Republic and Poland** with relatively low scores. However, even these countries have strong policies in place to electrify space heating via using heat pumps.

District heating is a strategy that requires to be accompanied by other strategies to reach decarbonisation of rural areas with lower heat demand densities as well as industrial process heating demand. Still, it can play an important role in many countries. It fits well with electrification, which can reach low heat density areas and supply DH with RES. District heating allows to exploit additional RES resources that are not accessible to a decentralised heating infrastructure. Particularly the northern countries **Sweden, Denmark, Estonia, Finland, Latvia and Lithuania** show great potentials for DH use (in terms of RES potentials, but also settlement structure). Even more, they already have very mature DH markets and developed infrastructure. Also **Germany** has very good feasibility for DH as a central strategy, explained by very good RES potentials (matched to DH areas), very suitable settlement structure and already strong developed markets and infrastructure. On the other hand, some countries can show low suitability for the large-scale use of DH (i.e. focus to support selected large urban areas only). These are mainly southern countries including **Romania, Croatia, Greece, Cyprus, Portugal** (cluster 3), but also **Slovenia, Belgium and Ireland**. All these countries have comparably low RES potentials, which would particularly qualify for district heating (waste-to-energy, industrial waste heat, geothermal, ambient heat from rivers and lakes and wastewater plants). In addition, the southern countries have lower heat demand densities and many have less mature district heating markets today (more though in eastern countries). The remaining countries show mostly high feasibility for the large-scale use of DH focused on the higher heat demand density areas (see cluster 4). For most of these countries, the combination of electrification and district heating is a very suitable integrated strategy.

The strategy "**direct use of RES**" is to interpreted with caution. It mainly covers the use of solar thermal energy and biomass. Solar thermal, though, can only be used in combination with other RES, and **biomass** heavily depends on the availability of resources and sustainability aspects. To allow for more separated conclusions on both sub-strategies, Figure 40 highlights in addition countries with very high solar rooftop potentials as well as large-scale biomass potentials (see right side). Only the **Baltic countries, Finland and Sweden** (see cluster 1 in Figure 35, except DK) have sufficient biomass resources to substantially build on this strategy. Indeed, these countries are using large quantities of biomass already today for centralised heating supply. However, also these countries show very high suitability for electrification and district heating strategies with very good wind, solar and partly hydropower potentials. So they simply do not need to go for a biomass-based strategy and thus can avoid potential sustainability problems. They even have the potential to reduce the biomass use for district heating and space heating in the future, replacing it by more efficient sources using heat pumps. **Process heating**, however, is a different topic. Here, the same countries are characterised by a very high process heat demand at low-temperature level below 200°C (or even 150°C), mainly coming from the pulp and paper industry. The pulp and paper industry mainly uses production residues for energetic purposes, which is a sustainable use of biomass in line with cascading principles. On the other hand, the temperature level up to 150°C can possibly be supplied also by efficient high-temperature heat pumps in the future. So electrification can also here be an efficient alternative to the use of biomass in those countries.

A different situation with regard to biomass is observed in the countries **Bulgaria, Croatia, Romania, Hungary and Czech Republic** (cluster 3 in Figure 35). Here, biomass plays an important role for decentralised space heating (very likely large share of inefficient stoves), while compared to e.g. the Baltic countries they do not show a high biomass potential. Thus, here, an integrated H&C strategy should rather focus on reducing the use of biomass in decentralised space heating.

The use of **decentralised solar thermal** energy can only support other forms of heat supply, strongly limiting the scalability of this strategy. Some countries with high solar irradiation show very good economic competitiveness compared to fossil supply, particularly **Portugal, Spain, Malta, Greece, Croatia and Cyprus**. Here, the direct use of solar energy can support the RES supply. This can be both solar thermal technology and/or combinations of heat pumps with photovoltaics.

To understand the role of the strategy **e-fuels and hydrogen** it is fundamental to distinguish between space heating and high temperature process heating (plus other industrial uses). For space heating, the use of e-fuels or hydrogen requires about 6 times more green electricity than the use of heat pumps. For (high temperature) process heating, the efficiency advantage is substantially smaller (1-2 times) so that other advantages like the possibility to continue using large parts of today's production assets as well as available infrastructure and seasonal storage become more relevant and can outbalance the efficiency losses. Furthermore, the picture will be fundamentally affected by the transition in the steel industry and the feedstocks for chemicals (ammonia and high-value chemicals like ethylene). The right column in Figure 40 is based on today's production capacity of basic oxygen furnace steel, ammonia and ethylene. It summarises the likely hydrogen demand for the transition of these industries if they remain in these countries. The countries with high or even very high potential hydrogen demand from the chemicals and steel industry are spread across the full spectrum of suitabilities. And conclusions are very different. Countries with a high potential hydrogen demand from industry and good suitability scores for electrification / e-fuels and hydrogen as well as high RES-E potentials might be able to domestically produce H_2 needed. On the other hand, countries with a high hydrogen demand combined with low RES potentials and low suitability scores will likely focus more on imports.

Results on countries' suitability for e-fuels and hydrogen reveal that particularly those countries with low suitability for electrification also do not score high on e-fuels and hydrogen (**Luxembourg, Belgium, Germany, Czech Republic, Poland**). On the other hand, many of the countries with good scores anyway also score well on electrification and/or district heating, which is the preferred strategy combination for space heating (e.g. Lithuania, Latvia, the Netherlands).

5. Policy packages for the decarbonisation of heating and cooling

5.1. Objectives and approach

Based on the analysis of the decarbonisation pathway archetypes (see Chapter 4), this chapter elaborates packages of measures addressing the specific challenges, potentials and characteristics of the decarbonisation of heating and cooling. Portfolios of measures are developed in line with the following steps:

1. Identification of key elements of the transition and policy needs
2. Identification of barriers and key challenges
3. Identification of policy options to address barriers and target groups
4. Matching of policy matrix with results of suitability analysis to identify country cluster-specific policy sets.

In the following, the first four steps are carried out for decentralised heating and cooling (section 5.2), centralised heating and cooling (section 5.3) and process heat (section 5.4).

5.2. Decentralised heating and cooling

5.2.1. Elements of the transition and policy needs

The transition of decentralised heating and cooling requires

- **Rapid decline of fossil fuel boilers:** The use of fossil fuel for individual heating needs to decline rapidly -> A regulatory framework is needed to ensure the phase-out of fossil fuels for heating.
- **Strong increase of the market share of heat pumps:** The role of heat pumps increases rapidly -> Policies to support the deployment of heat pumps are needed.
- **Strong increase of solar thermal:** The role of solar thermal increases rapidly -> Policies to support the deployment of solar thermal are needed.
- **Limitation of the role of biomass:** The use of biomass is limited due to the restricted availability -> Policies for the allocation of biomass and for limiting its use are needed.

5.2.2. Key challenges

The deployment of renewable energies in individual space and water heating faces several barriers (see also TU Wien et. al 2022[46]).

[46] TU Wien et. al. (2022): Renewable Space Heating and Cooling under Revised Renewable Energy Directive. Forthcoming.

- **Economic barriers** for the decarbonisation of individual heating and cooling in buildings cover two main items:
    - Higher upfront costs: High investment costs as compared to fossil heating equipment pose a barrier for the deployment of heating and cooling equipment based on renewable energies.
    - Low fossil fuel prices: During the use-phase of renewable heating equipment, economic barriers arise if the operation costs are higher than for fossil heating and cooling.
- **Barriers related to technology maturity** occur where the required decarbonisation technologies are not fully developed. For heat pumps, where technologies are largely developed, further development may be needed for certain segments, such as buildings with low efficiency and large multi-family buildings. The **impact on the electricity system** may further be a technologcal barrier for the deployment of heat pumps. At the same time, heat pump technologies provide flexibility options for the electricity system, where digital technologies may help to support the use of flexibility options and demand side management as well as to continuously control the efficient operation.
- Barriers related to **market maturity (including technology, fuel and installer markets)** are an important barrier for the deployment of heat pumps. In many EU MS, heat pumps currently have a low market share and a rapid increase is needed to meet the decarbonisation pathways.
- **The suitability of the building stock** poses a barrier for the deployment of most renewable heating technologies: For heat pumps, an efficient deployment requires low-temperature heating systems. For solar thermal installations, rooftops may be unsuitable for the installation.
- **End-user and investor barriers** cover a variety of barriers for investments in decarbonisation technologies. Such barriers include a lack of access to capital, imperfect information, bounded rationality and split incentives[47].

5.2.3. Policy options

Phase-out policies for fossil fuels in individual heating in buildings

Regulatory measures for phasing out fossil fuels in individual heating are needed to shape the transition towards clean heating. The proposal for the recast EPBD highlights the need for phasing out fossil fuels in heating and cooling and states that a “clear legal basis for the ban of heat generators based on their greenhouse gas emissions or the type of fuel used should support national phase-out policies and measures”.

There are three key approaches for phasing out fossil fuels for individual heating and cooling in buildings:

[47] For an overview see e.g. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/mapping-eu/Mapping-HC-Final-Report-WP5.pdf

1. Bans on the use of fossil fuels or the installation of the respective heating equipment
2. Use obligations for renewable energies for heating
3. Minimum levels of CO_2 emissions in buildings

The report "Phase-out regulations for fossil fuel boilers at EU and national level" summarises key options for phase-out legislation (Oeko-Institut 2021)[48]:

- The most common approach for restricting the use of fossil fuels for heating are **use obligations for renewable energies**, mandating that a given share of heat demand needs to be supplied by renewable energies (and thus restricting the remaining use of fossil fuels). Use obligations have been implemented in several EU Member States (e.g. Denmark, Germany) and are already partly addressed at EU level in the Renewable Energies Directive Art. 15a.
- Another option to increase the share of renewable heating is by **setting minimum efficiency levels for heating systems exceeding 100%**. This approach has been proposed as an option to phase out fossil boilers through the Ecodesign implementing regulations for fossil boilers[49]. Furthermore, the Dutch government has announced a regulation for phasing out stand-alone fossil boilers based on minimum levels for the efficiency of the systems.
- **Restrictions of heating equipment** using fossil fuels are another common approach for phasing out fossil fuels and include bans for the installation of fossil boilers or bans for placing equipment on the market. The former approach has been implemented by several EU Member States (e.g. Austria, Germany).
- A **ban for selling or using fossil fuels for heating** after a specified date means that after this end date, fossil fuels cannot be sold or used, implying a full phase-out covering all heating installations. While to our knowledge no such regulations are currently implemented or planned in any of the EU Member States, a legislative proposal for introducing an end-date for the use of fossil fuels was developed by the German Climate Neutrality Foundation[50] based on an assessment of legal options[51]. The study assesses the legal feasibility of implementing an end date for the use of fossil fuels in Germany and concludes that there are no fundamental legal constraints as long as a sufficiently long time span is foreseen between the legal enshrinement of the phase-out and the actual end date to have enough time for the transformation process[52]. Norway, for instance, prohibited the use of mineral oil for heating of buildings.
- Another approach for restricting the use of gas for heating are restrictions on the **connection of buildings to the gas grid**. This approach has been implemented in

[48] Oeko-Institut (2021): Phase-out regulations for fossil fuel boilers at EU and national level. Available online at: https://www.oeko.de/fileadmin/oekodoc/Phase-out_fossil_heating.pdf

[49] ECOS (2020): FIVE YEARS LEFT - How ecodesign and energy labelling can decarbonise heating. Available online at: https://ecostandard.org/wp-content/uploads/2020/12/Five-Years-Left-How-ecodesign-and-energy-labelling-Coolproducts-report.pdf

[50] Stiftung Klimaneutralität (2021): Fehlinvestitionen vermeiden: Klimaneutralität 2045 und das Ende des Einsatzes fossiler Brennstoffe. Available online at https://www.stiftung-klima.de/app/uploads/2021/05/2021-05-18-Fehlinvestitionen-vermeiden.pdf.

[51] BBH (2021): Fehlinvestitionen vermeiden–Eine Untersuchung zu den rechtlichen Möglichkeiten und Grenzen zur Defossilisierung der deutschen Volkswirtschaft bis 2045. Available online at https://www.stiftung-klima.de/app/uploads/2021/05/2021-05-12_Gutachten-Fehlinvestitionen-vermeiden.pdf.

[52] The study foresees an end date by 2045 according to the German target to achieve climate neutrality by 2045.

the Netherlands, where new buildings cannot be connected to the gas grid since July 2018. Another example is Denmark, where no fossil fuel heating equipment can be installed in district heating areas.

- Moreover, there are indirect approaches to address the installation or use of fossil fuel heating. For example, the French government passed a law defining a **CO_2 efficiency threshold**, specifying a threshold for CO_2 emissions per square metre and year.

Economic instruments

Economic instruments address the two key economic barriers outlined in Section 5.2.2:

- To address the barrier of higher upfront costs when investing in renewable H&C equipment, financial support programmes are key policies implemented in various forms across EU Member States. Financial incentive schemes include grants, loans, guarantees as well as innovative financing instruments, such as on-bill schemes and energy performance contracting (for an overview see e.g. Oeko-Institut et. al., 2022)[53]. Several Member States have introduced grants and loans for specific target groups, where especially programmes addressing low-income households play an increasing role. This includes, among others, programmes in Austria[54], Ireland[55] and France[56]. While financial support for renewable heating and cooling equipment can support the transition, it is essential that financial support for the installation of fossil fuel-based heating equipment is phased out. According to a recent report[57], 19 out of the 27 EU Member States currently provide funding for fossil fuel-based heating equipment.
- To address the barrier of higher operation costs for renewable heating, energy and carbon pricing can support the economic viability of investments in renewable heating equipment. Carbon pricing is currently in place for the heating fuels in some EU Member States such as for example Sweden and Germany, and an EU-wide introduction of carbon pricing for buildings and transport has been proposed in the context of the revision of the ETS Directive[58]. The revenues of carbon pricing schemes can be used to support energy efficiency and heat decarbonisation policy measures. For the EU proposal for carbon pricing in the buildings sector, the use of part of the revenues to introduce a Social Climate Fund supporting vulnerable households is proposed. Next to carbon pricing, heat pump tariffs, i.e. lower rates for electricity used in heat pumps, can support their economic viability.

---

[53] Oeko-Institut, Trinomics, DTU (2022): Policy Support for Heating and Cooling Decarbonisation. Meta-Study Part 1. Forthcoming.

[54] Subsidy scheme “sauber heizen für alle“, see e.g. https://www.land-oberoesterreich.gv.at/270992.htm

[55] Better energy warmer homes scheme, see e.g. https://www.seai.ie/publications/Scheme-and-Application-Guidelines.pdf

[56] Prime Energie scheme, see e.g. https://www.aide-sociale.fr/prime-energie/

[57] Coolproducts (2020): Mapping Europe’s subsidies for fossil fuel heating systems. Online available at https://www.coolproducts.eu/failing-rules/mapping-europes-subsidies-for-fossil-fuel-heating-systems/

[58] For information on the revision of the ETS Directive see https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2021/0211(COD)&l=en

Market transformation policies

Market transformation programmes may support the market development of RES-H/C technologies. This includes a supportive policy framework to increase awareness and skills across different market actors. This may include[53]:

- the communication of low-carbon transformation plans at the local level, e.g. by implementing visible demonstration projects;
- consumer empowerment and transparency of costs and benefits;
- intensifying policies for crucial change agents such as craftsmen, architects and planners, e.g. through regional training programmes, the initiation of local networks, changes in the education system for craftsmen and by addressing change agents in RES policies;
- capacity building and supporting tools for the municipal level. Furthermore, the development of one-stop shops facilitating retrofit measures are highlighted in various studies.

Table 16: Policy matrix for decentralised heating and cooling

Supporting measures	(1) Challenges/ Barriers				(2) Target groups				(3) Technologies			
	Economic barriers	Technology maturity	Market maturity	Regulatory barriers	Building owners (owner occupied)	Building occupants	Buildings owners or property developers (new buildings)	Installers	Fossil fuel phase-out	Heat pumps	Solar thermal	Biomass
Fossil fuel phase-out												
Ban of fossil fuel boilers	(x)	(x)	(x)	(x)	x		x	(x)	x	(x)	(x)	(x)
Minimum renewable obligation in buildings	(x)	(x)	(x)	(x)	x		x	(x)	x	(x)	(x)	(x)
Minimum standards for carbon efficiency	(x)	(x)	(x)	(x)	x			(x)	x	(x)	(x)	(x)
Requirement for fossil-free new buildings	(x)	(x)	(x)	(x)			x		x	(x)	(x)	(x)

Supporting measures	(1) Challenges/ Barriers				(2) Target groups				(3) Technologies			
	Economic barriers	Technology maturity	Market maturity	Regulatory barriers	Building owners (owner occupied)	Building occupants	Buildings owners or property developers (new buildings)	Installers	Fossil fuel phase-out	Heat pumps	Solar thermal	Biomass
Economic instruments												
Carbon pricing	x				(x)	x			x	(x)	(x)	
Heat pump tariffs	x				(x)	x				x		
Removing subsidies for fossil boilers	x				x		x		x			
Subsidies for RES-H technologies	x		(x)				x			x	x	x
Market transformation policies												
Support for market transformation programmes (e.g. procurement groups)		x	x		x		x	x		x	(x)	(x)
Capacity building programmes			x		x			x	x	x		
Heat planning and allocation strategies	(x)	(x)	(x)	x	x	(x)	x	(x)	x	x	x	x
Pilot studies for heat pumps in existing buildings and multi-family buildings		x	x	(x)	(x)			(x)		x		

5.2.4. Country-cluster specific policy sets

The various EU Member States face differing barriers for the deployment of renewable heating and cooling and thus have differing policy needs. Based on the policy options the policy matrix for decentralised heating and cooling (Table 17) and on the suitablilty analysis (see Chapter 4), policy sets are developed for different sets of countries that face similar barriers.

Phase-out policies

Regulatory measures for phasing out fossil fuels in individual space and water heating are relevant in all countries. However, such policies are of particular importance in countries where these technologies account for a significant share of heating and cooling in buildings. Figure 41 shows the shares of fossil fuel-based individual space heating in the EU Member States. The figure shows that in five countries (Ireland, Luxembourg, Netherlands, Belgium and Germany), individual heating using fossil fuels accounts for more than 70% of the total space heating demand. Only four countries (Estonia, Portugal, Finland and Sweden) show shares of less than 10%.

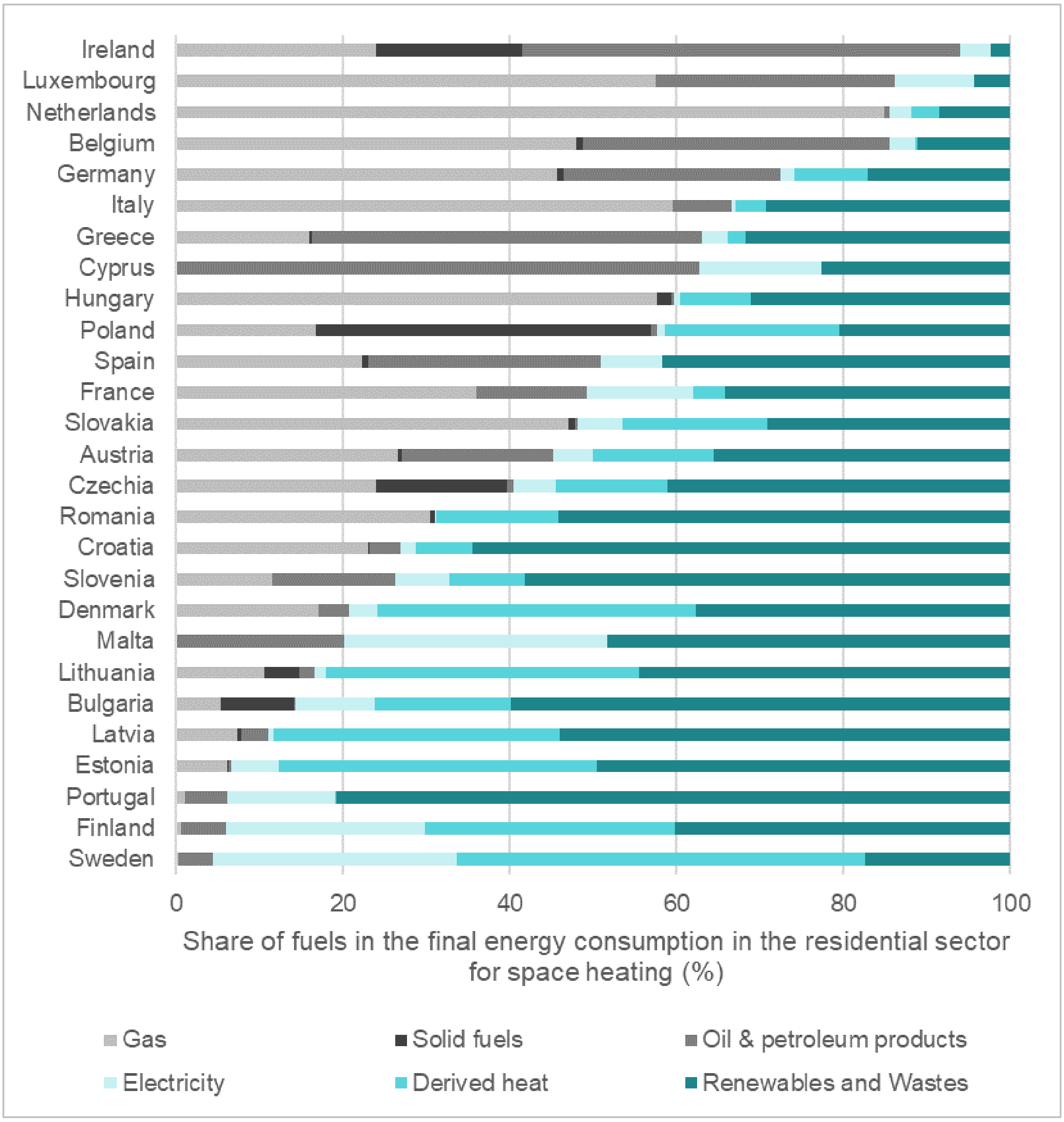


Figure 41: Share of fuels in the final energy consumption in the residential sector for space heating (2019). Source: own elaboration based on Eurostat data.

Economic instruments

Economic instruments are relevant to address economic barriers for the deployment of renewable energy technologies for individual heating and cooling in buildings. The extent to which such instruments are relevant in the EU Member States depends on two main factors:

1. The difference between the investment costs of RES-H equipment and fossil fuel-based technologies.
2. The difference between the operation cost of renewable heating vs. fossil fuel-based heating. For heat pumps, this refers to the difference between the electricity price and the prices for fossil fuels.

To assess the relevance of financial support measures in the EU Member States, Figure 42 shows the investment cost of a gas boiler as compared to a heat pump, where financial support programmes are not included. The figure shows that in all countries the investment in a gas boiler is lower than that for a heat pump, however the difference ranges from a rather minor increase of 20% to 500% in Romania.

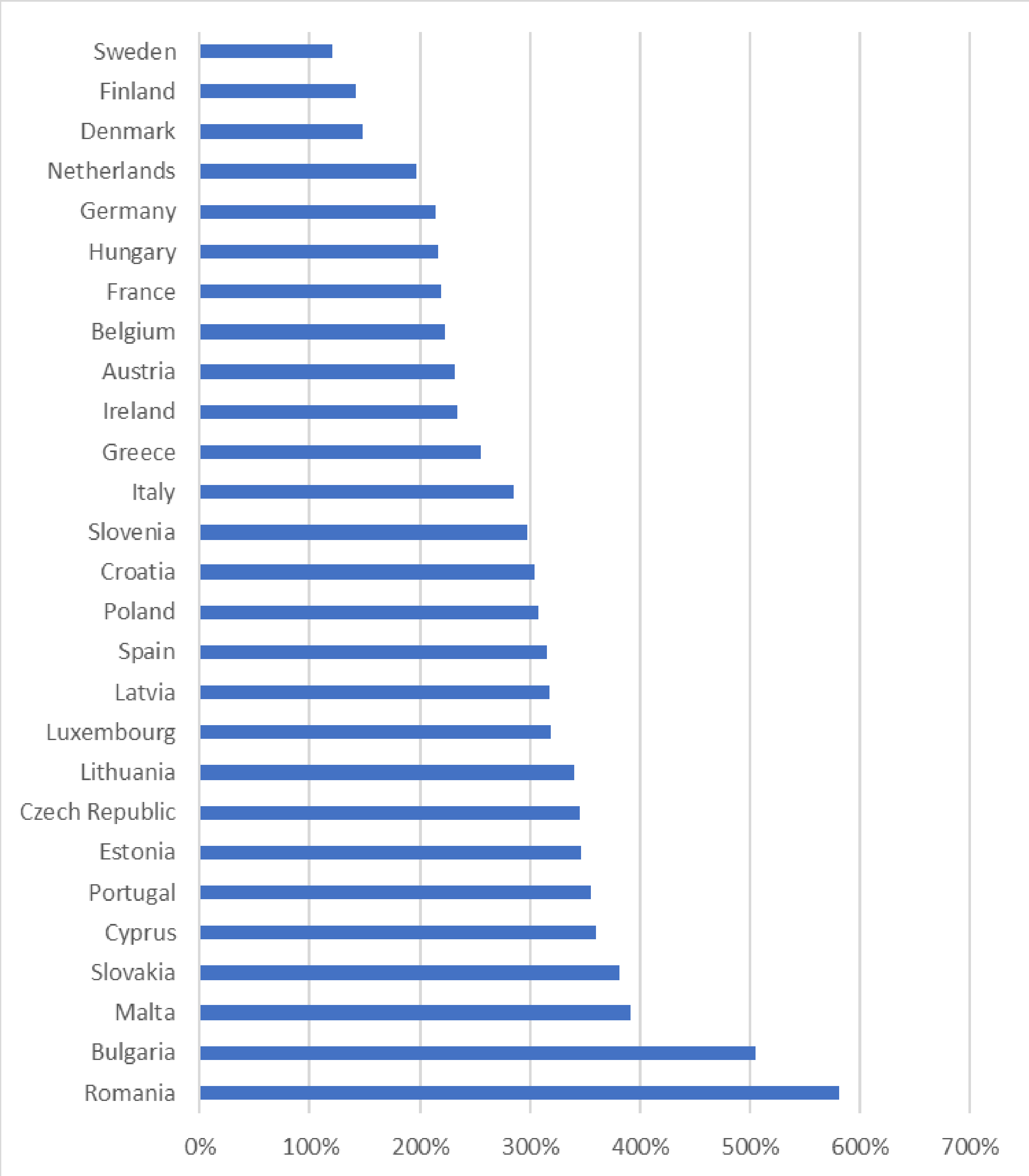


Figure 42: Investment cost for a heat pump as compared to a gas boiler. Source: Data collected under Task 2 of the study Renewable space heating under the revised Renewable Energy Directive [59]

To assess the need for economic instruments addressing the operation phase in the EU Member States (e.g. carbon pricing or heat pump tariffs), Figure 43 shows the difference in operating costs between heat pumps and gas boilers in the EU Member States. The figure shows the ratio of the heating costs with a heat pump and a gas boiler, where a uniform seasonal performance factor of 3 has been assumed. In countries where the ratio is larger

---

[59] European Commission, Directorate-General for Energy, Kranzl, L., Fallahnejad, M., Büchele, R., et al., *Renewable space heating under the revised Renewable Energy Directive : ENER/C1/2018-494 : final report*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/525486

than one, the operation of a heat pump is more costly than for gas boilers. The calculation is based on 2020 prices and does not include future price increases, e.g. though the introduction of CO_2 pricing.

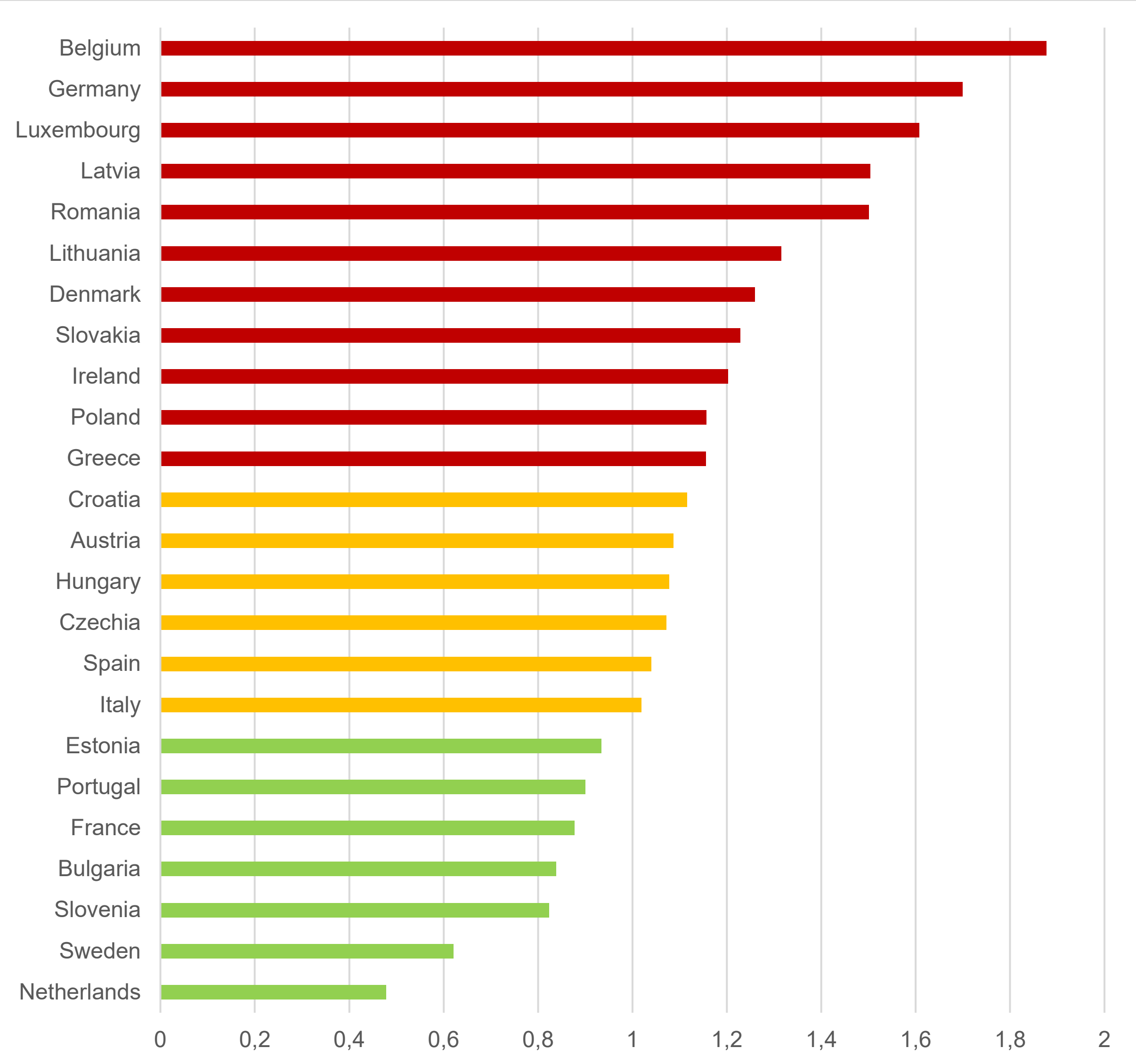


Figure 43: Difference in operation cost for heat pumps vs. gas boilers. Source: Own calculations based on Eurostat data.

Market transformation

The need for an (additional) policy framework for supporting the market development of renewable heating technologies largely depends on the maturity of such markets within the Member States. Especially in Member States with a current low market penetration, the transformation needs to be supported with extensive efforts to ensure the availability and quality of installation workforce and to facilitate information to end-consumers.

Figure 44 shows the number of heat pumps sold per 1000 households in the year 2020 in selected EU Member States. The figure shows considerable differences between the Member States, where the Nordic countries Finland, Estonia, Denmark and Sweden take a leading role.

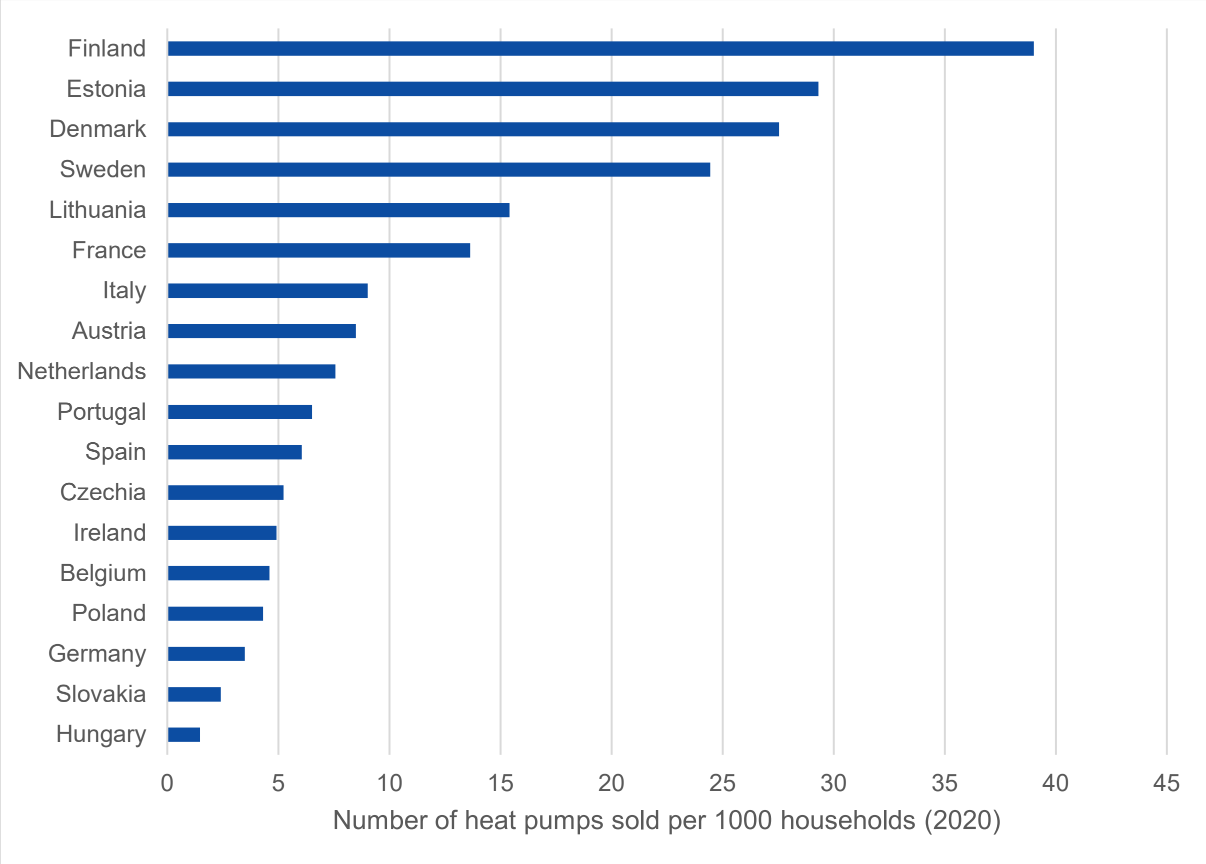


Figure 44: Number of heat pumps sold per 1000 households (2020). Source: EHPA data.

Table 18 summarises the specific policy needs for the deployment of heat pumps as the leading technology for decarbonising individual heating and cooling in buildings, differentiating between different groups of countries with differing policy needs.

Table 18: Country-specific policy needs for the deployment of heat pumps

Policy set	Short description	Role of policy set in different MS
Phase-out regulations	This policy set includes regulatory measures to phase out fossil fuels in individual heating and cooling. This may include bans on heating equipment based on fossil fuels, use obligations for renewable energies and/or minimum requirements for carbon emissions in buildings.	While phase-out policies are recommended in all EU Member States, they are particularly relevant in Member States with high shares of individual heating using fossil fuels. These include Ireland, Luxembourg, the Netherlands, Belgium, Germany and Italy (Figure 41).
Economic instruments	Economic instruments include instruments addressing the investment side (i.e. subsidy schemes) as well as the operation	Subsidy schemes are particularly relevant in countries where the difference between investments in fossil fuel-based heating and heat pumps is high. This is currently the case in most EU Member States. The exceptions

Policy set	Short description	Role of policy set in different MS
	side (i.e. energy and carbon pricing).	are Sweden, Finland and Denmark, where the difference is more moderate (Figure 42). In terms of operating costs, heat pumps are economically competitive with current (2020) prices in only six countries, whereas in the majority of countries the operation costs for heat pumps are higher in the absence of carbon pricing and/or heat pump tariffs (Figure 43).
Market transformation policies	Market transformation policies support the market development of RES-H/C technologies and include support for increasing awareness and skills across different market actors.	Market transformation policies are particularly relevant in countries where the current deployment is low and where a strong increase in market shares is required. The latter is the case for countries with high transformation needs (Figure 41). In all countries with high transformation needs, the market for heat pumps is currently significantly less developed than in the leading countries, i.e. Finland, Estonia, Denmark and Sweden.

5.3. Centralised heating and cooling

Centralised heating and cooling includes centralised heat and cold generation (incl. use of waste heat) and district heating and cooling infrastructure.

5.3.1. Key elements of the transition and policy needs

- **Expanding DHC infrastructure**: Higher shares of district heating and cooling require the expansion and densification of heating and cooling networks (more consumers connected), the development of new grids and the transformation of the infrastructure towards low-ex systems. -> Policies are needed supporting the infrastructural development and switching from decentralised (fossil-fuelled) heating and cooling to DHC.
- **Rapid decline of fossil fuels:** The use of fossil fuels for DHC production needs to decline rapidly. -> Policies are needed to ensure the phase-out of fossil fuels for DHC including DHC generation from fossil-fuelled CHP.
- **Strong increase of centralised renewable DHC production:** The role of centralised renewable DHC generation (biomass, large heat pumps, solar thermal, geothermal etc.) needs to increase rapidly. -> Policies are needed to support the deployment of centralised renewable DHC production.
- **More use of industrial excess/waste heat in DHC:** The use of industrial excess/waste heat for DHC needs to be expanded. -> Policies are needed to support the deployment of excess/waste heat.

5.3.2. Barriers and key challenges

The development of the DHC grid infrastructure as well as the deployment of renewable energies and excess/waste heat in district hreating and cooling faces several barriers (see also TU Wien et. al 2022[60]).

Economic barriers for the development of DHC infratsructure and the decarbonisation of centralised heating and cooling generation cover several items:

- Higher upfront costs: High investment costs for selected low-carbon HC technologies (e.g. large heat pumps, geothermal drillings) as compared to fossil-fuelled heating units; upfront costs for expanding the DHC infrastructure.
- Low fossil fuel prices: Low prices for gas, coal and heating oil disadvantage HC generation if renewable fuel (e.g. biomass) or electricity face higher prices.
- The use of excess/waste heat might require investments in back-up capacities in order to counter the risk of fluctuating/intermitting heat delivery; moreover, high grid connection costs of the waste heat sources might occur due to large distances between source and heating grid.
- Partially low incentives for excess/waste heat producers to make excess/waste heat available for heat utilisation in DHC as heat emissions to the environment are free of charge.

Barriers related to **technology maturity** occur where decarbonisation technologies are not fully developed, e.g. concentrated solar district heating; the extraction of excess heat from production processes can turn out to be complex as the technical implementation of heat extraction often requires to intervene with the ongoing production process. In many DHC systems digitalisation has not been sufficiently integrated yet, e.g. remote metering and monitoring of system parameters, customer demand parameters etc.) -> Since the network operator does not know the exact system parameters, their ability to control the DH system to balance generation and storage with the real demand situation is limited.

Barriers related to **market maturity** (including technology, fuel and installer markets) include technology availability (for selected technologies, e.g. river water heat pumps, there are only a few technology providers so far; low-ex DHC infrastructure is not common yet in many DHC markets).

Resource and space availability can pose a barrier for the deployment of most centralised renewable heating technologies; domestic resources of biomass are limited; for solar collector fields space availability close to settlements is generally limited and associated to high costs (suitable areas tend to be expensive due to competition with other uses such as new construction, recreation); large heat pumps need to have access to an ambient heat source (e.g. river, lake, ground water, soil) and have an impact on the overall electricity demand; geothermal heat is restricted to geologically suitable regions.

Regulatory barriers cover several items:

- Centralised RES-HC (e.g. space requirement for solar collector fields) is often not sufficiently considered in local planning processes.

[60] TU Wien et. al. (2022): Renewable Space Heating and Cooling under Revised Renewable Energy Directive. Forthcoming.

- For geothermal energy there is often only limited availability of or access to data on geological conditions which is at the expense of the investor's risk.
- Complex and partly unclear regulation on licensing conditions and processes, diverging regulations at the sub-national level, or insufficient expertise by public authorities dealing with the applications of DHC-related topics.
- For excess/waste heat, in many Member States companies are not obliged to provide data on their waste heat quantities; waste heat registers are not available.
- Partly unclear regulations for third-party access (especially for RES and waste heat).
- Integrated planning processes (in the sense of local strategic heat planning) often lack access to information/data on the demand side (e.g. quality of building stock, age structure of boilers etc.) which poses a hurdle for developing grid infrastructures.

The suitability of the building stock poses a barrier for the development of low-ex DHC which require low-temperature heating systems in the connected buildings. Furthermore, a trade-off exists between efficiency measures (lowering energy density) and the profitability of DHC expansion.

End-user barriers include imperfect information, bounded rationality and the partially low reputation of DHC due to non-transparent pricing, inefficiency, etc.

5.3.3. Policy options

Expanding the share of DHC in heat supply requires the expansion as well as modernisation of the infrastructure (increasing the connection rate in existing grids, expanding existing grids, constructing new grids), decarbonising DHC generation by replacing fossil fuels by renewables and excess/waste heat, and the modernisation of old grids to enable them to cope with the new sources as well as the changed topology of generation.

Regulatory instruments

Regulatory approaches for the expansion of the DHC infrastructure include

- setting quantitative infrastructural expansion targets (e.g. based on the number of new connections, scope of grid expansion etc.);
- spatial zoning and mandatory connection rules to DHC systems (e.g. in new development areas, existing DHC areas or areas for which an extension of a DHC network is planned);
- the obligation to implement local strategic heat planning (see below).

Regulatory policies that aim at decarbonising DHC generation involve

- setting binding quantitative targets for the whole DHC sector of a country, e.g. binding decarbonisation targets or targets for the development of the share of renewables/excess heat in the DHC generation mix (similar to Art. 24 of the proposed revised Renewable Energy Directive[61]);

[61] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557

- setting binding quantitative targets on level of companies (e.g. in the form of renewable/excess heat quota/obligations for DHC companies);
- obliging DHC companies to develop transformation/decarbonisation plans;
- regulating Third Party Access (TPA) to DHC, e.g. by
  - implementing mandatory TPA for renewables and/or excess/waste heat production (similar to the proposed new Art. 24 (4c) in the proposal for a revised Renewable Energy Directive) ;
  - establishing minimum technical specifications for the connection of renewables and/or excess/waste heat production to existing heat grids (aiming at incentivising TPA by ensuring transparency) ;
- enhancing the use of industrial excess/waste heat by e.g. obliging companies (excess heat sources) to provide data on their excess/waste heat flows and/or to develop excess/waste heat utilisation concepts.

Economic instruments

Economic instruments include a broad basket of different policy options including carbon or energy taxes, investment support (e.g. subsidies, soft loans), support of operating costs. Economic instruments can be applied at different levels in the DHC system.

On the level of the infrastructure, financial support can be awarded to consumers or grid operators to connect additional customers to DHC; grid operators could be supported for grid expansion and/or low-ex grid transformation, support could also be given to make buildings fit for low-ex DHC (by reducing the system temperatures in the buildings' heating systems).

Economic approaches aiming at the decarbonisation of DHC generation include CO_2 pricing, energy taxes or levies (e.g. waste heat levies), direct financial investment support for centralised RES-HC plants or the connection of excess/waste heat sources, financial support of the operating costs of clean heat sources (e.g. in the form of a feed-in tariff). Additional policy options cover risk-hedging instruments (especially for heat supply projects with large upfront investments such as geothermal projects or projects that are associated with considerable risk, e.g. some projects using excess/waste heat).

Market transformation instruments

Market transformation policies support the market development and market penetration of DHC technologies and infrastructure. Policies include strategic local/municipal heat planning. This approach mainly consists of developing spatially resolved strategies for decarbonising a municipality's heat supply. In this context municipalities will screen which areas could be used for centralised RES-HC generation, systematically screen potential excess/waste heat potentials; furthermore, municipalities will be encouraged to make public areas available for centralised RES-HC generation and seasonal storage.

Moreover, market transformation approaches involve policies supporting digitalisation and awareness-raising across market actors, policy measures encouraging and facilitating new ownership/operator models (e.g. energy communities) and participation.

Table 19: Policy matrix centralised heating and cooling

Supporting measures	(1) Challenges/ Barriers					(2) Target groups				(3) Technologies			
	Economic barriers	Technology maturity	Market maturity	Resource and space availability	Regulatory/administrative barriers	Building owners	DHC grid operators	Investors and operators of centralised RES-HC	Waste heat producers	Centralised fossil fuel phase-out	Centralised RES-HC	Waste heat	DHC infrastructure
Regulatory instruments for the expansion of DHC infrastructure													
Quantitative infrastructural expansion targets	(x)	(x)	(x)		(x)	(x)	x	(x)	(x)				x
Spatial zoning / mandatory connection rules					(x)	x	x						x
Regulatory instruments for the decarbonisation of DHC generation													
Quantitative targets for the whole DHC sector	(x)	(x)	x	(x)	(x)		x	x	x	(x)	x	x	(x)
Renewable/excess heat quota/ obligations for DHC companies	(x)	(x)	(x)	(x)	(x)		x	x	x	(x)	x	x	(x)
Transformation/ decarbonisation plans		(x)	(x)	(x)			x	(x)	(x)	(x)	(x)	(x)	(x)
Mandatory Third Party Access					x		x	x	x	(x)	x	x	(x)
Excess/waste heat utilisation concepts		(x)	(x)	x			(x)		x			x	(x)
Economic instruments													
CO_2 pricing	x	(x)	(x)			(x)	(x)	(x)	(x)	x	(x)	(x)	
Investment support for infrastructure	x	(x)	(x)				x						x
Investment support for centralised	x	(x)	(x)					x	x		x	x	

Supporting measures	(1) Challenges/ Barriers					(2) Target groups				(3) Technologies			
	Economic barriers	Technology maturity	Market maturity	Resource and space availability	Regulatory/administrative barriers	Building owners	DHC grid operators	Investors and operators of centralised RES-HC	Waste heat producers	Centralised fossil fuel phase-out	Centralised RES-HC	Waste heat	DHC infrastructure
RES-HC/excess heat													
Support of operating costs	x	(x)	(x)					x	x		x	x	
Risk hedging instruments	x	(x)	(x)					x	x		x	x	
Market transformation instruments													
Local strategic heat planning				x	x	(x)	x	(x)	(x)	x	x	x	x
Energy communities			(x)				(x)						
Awareness raising						x	(x)	(x)	(x)		(x)	(x)	(x)

5.3.4. Country-cluster specific policy sets

The various EU Member States face differing barriers for the expansion and decarbonisation of district heating and cooling and thus have differing policy needs. The following sections develop policy sets for different groups of countries that face similar barriers.

Regulatory measures for DHC decarbonisation

Regulatory measures for phasing out fossil fuels in existing DHC systems are relevant in all countries with DHC. However, these measures are particularly important in those countries that have a high share of fossil heat generation today (especially gas, oil, coal) in DHC. Figure 45 shows the shares of fossil fuel-based DHC generation in 20 EU Member States. Data is missing for Belgium, Ireland, Luxembourg, Portugal and Spain. There is no district heating in Malta and Cyprus. The figure shows that in three out of four countries fossil fuel heat generation accounts for more than half of the total DHC supply. Only four countries (France, Lithuania, Denmark, Sweden) have a share of renewables and industrial excess heat in their DHC supply greater than 50%.

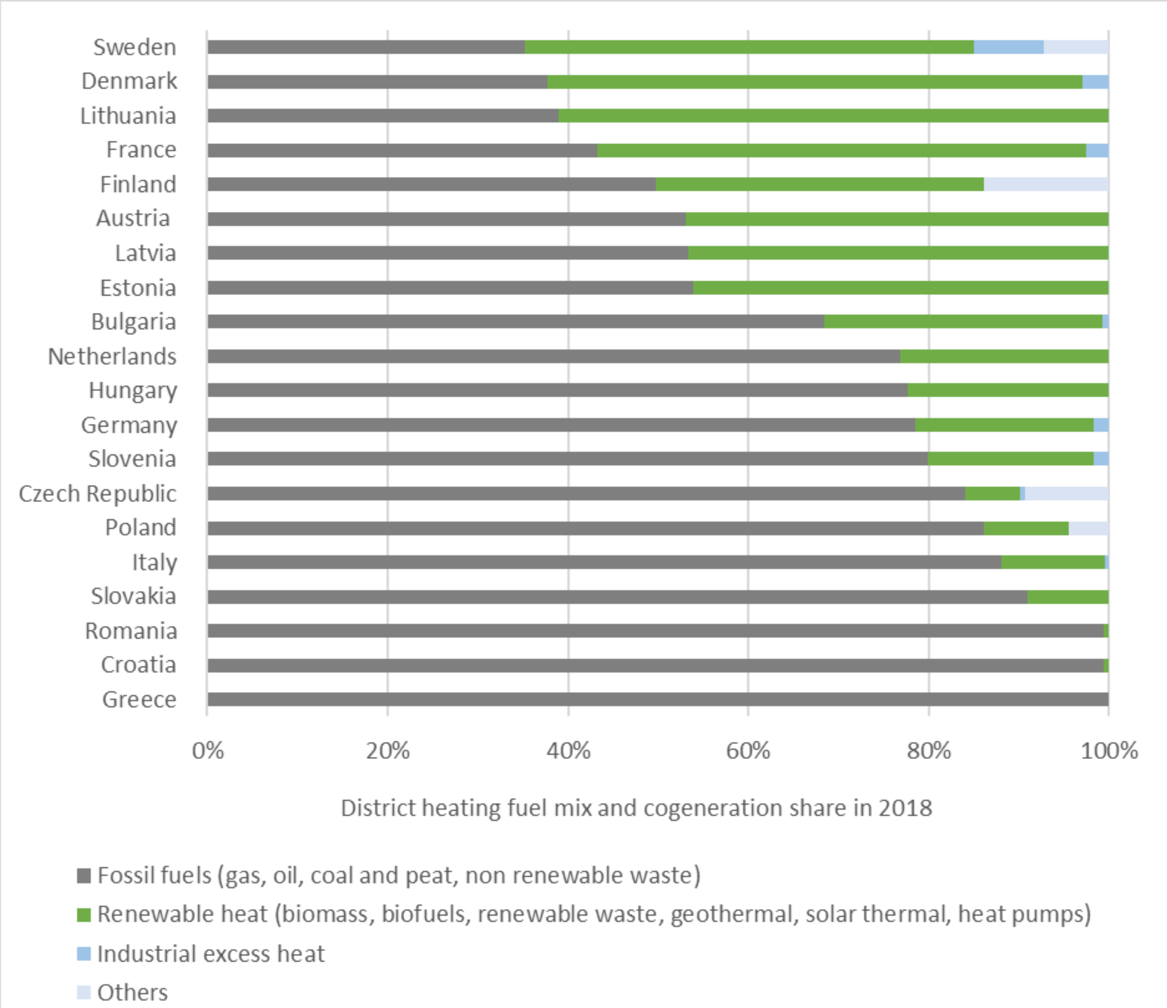


Figure 45: District heating fuel mix in 2018. Source: Data from study "Overview of District Heating and Cooling Markets and Regulatory Frameworks under the Revised Renewable Energy Directive (DHC Trend)"[62]

Regulatory measures for expanding DHC infrastructure

Regulatory measures for expanding DHC infrastructure (expansion and densification of heating and cooling networks, development of new grids) are particularly relevant in those countries that have a suitable demand structure. Areas with higher heat densities are more suitable for DH supply than areas with low heat densities. Thus, a suitable indicator is how the total heat demand of a country is distributed among different heat density categories. Figure 46 shows the respective distribution.

According to Persson et al. (2019)[63] heat density classes 3-5 capture mainly high concentrations of heat demands in towns and cities. These three heat density classes are particularly well suited for district heating supply. In eight countries (Sweden, Spain, Belgium, Latvia, Italy, Germany, Luxembourg, Netherlands), more than 75% of the heat demand is in the heat density classes suitable for district heating.

[62] https://op.europa.eu/en/publication-detail/-/publication/5e1fd499-eabf-11ec-a534-01aa75ed71a1/language-en

[63] Persson, U.; Wiechers, E.; Möller, B.; Werner, S. (2019): Heat Roadmap Europe: Heat distribution costs; Energy 176 (2019)

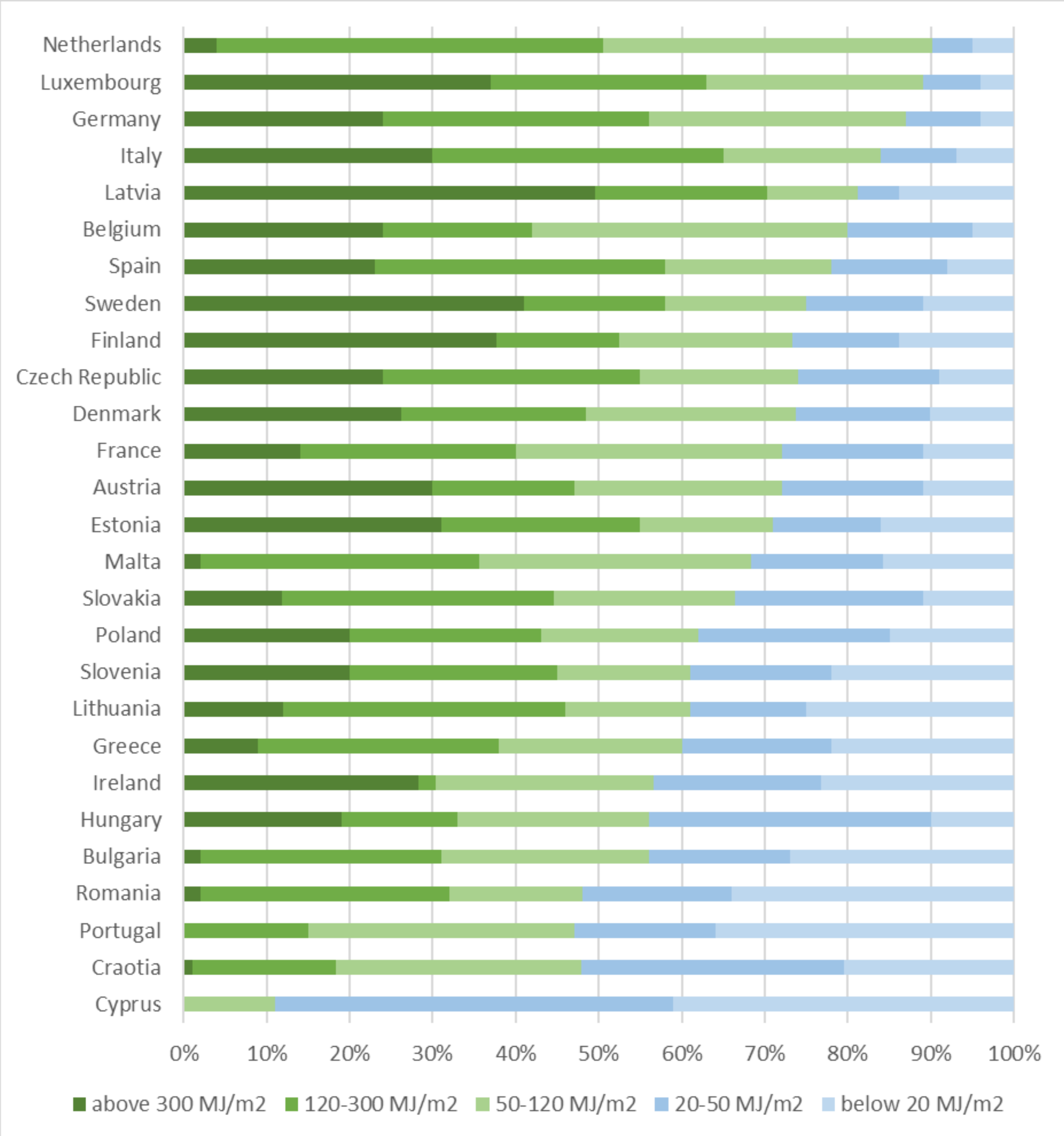


Figure 46: National heat demand distributed among different heat density classes. Source: Data from Persson et al. (2019)"[64]

Economic measures for DHC deployment

Economic incentives for decarbonising DHC generation are particularly necessary in countries where the heat production costs for district heating from renewable energies or industrial excess heat are higher than the comparable costs from generation from fossil fuels. Due to a lack of data on energy carrier or technology-specific heat production costs in Member States' DHC markets, this cost comparison can not be considered extensively but only as a proxy. The comparison of the DHC heat production costs from a large gas boiler and a large-scale heat pump (in many countries one of the key technologies for decarbonising DHC) should serve as an example.

[64] Persson, U.; Wiechers, E.; Möller, B.; Werner, S. (2019): Heat Roadmap Europe: Heat distribution costs; Energy 176 (2019)

The operating costs per kilowatt hour of heat for a gas boiler and a large heat pump are compared. An efficiency of 95% is assumed for the gas boiler. The heat pump has a sesaonal performance factor of 3.5. For the heat pump the electricity price for industry (consumption band IE 20-70 GWh/a; prices excluding VAT and other recoverable taxes and levies) is used, for the gas boiler the gas price for non-household consumers (consumption band I4 27,7 - 277 GWh/a, excluding VAT and taxes). The calculation reflects energy prices in the second half of 2020, based on Eurostat data.

As shown in Figure 49, the operating costs of a large heat pump are higher than those of a gas boiler in nine countries. For these countries this implies the need for economic incentives to compensate for the cost difference. For the evaluation, however, it must be taken into account that both electricity and gas prices are currently subject to strong fluctuations. The cost comparison is therefore only a snapshot of the situation in the second half of 2020.

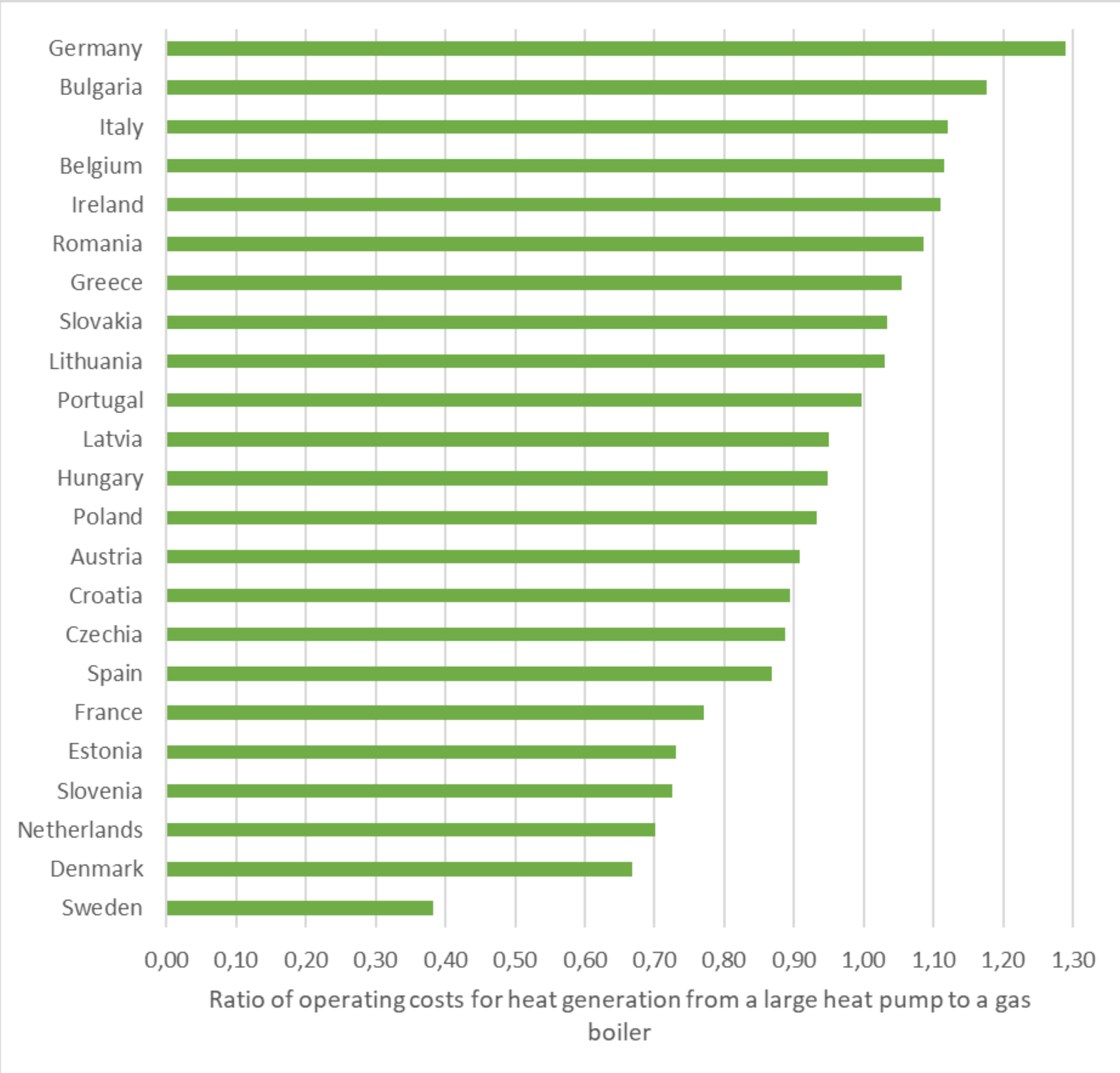


Figure 47: Cost comparison of operating costs between a large heat pump and a centralised gas boiler. Source: Own calculations based on Eurostat data

Market transformation

Market transformation measures are particularly needed in countries that have a good potential for district heating expansion but where district heating has not been widely used to date. In these countries, it is necessary to design the DHC market framework and manage market forces in such a way as to ensure DHC infrastructure expandsion rapidly. In doing so, it should be ensured that the corresponding DHC systems meet the requirements of 4th generation DHC right away.

One indicator for identifying these countries is the current DHC market shares in the various sectors. Figure 48 shows the share of DHC in final energy consumption for space heating and hot water in the residential sector (left panel). In the right part, the DHC share in the overall final energy consumption of the service sector is plotted.

In about half of all Member States, the DHC market share for space heating and domestic hot water supply is below 10% in the residential sector. In the service sector, the DHC share is below 10% in eleven Member States.

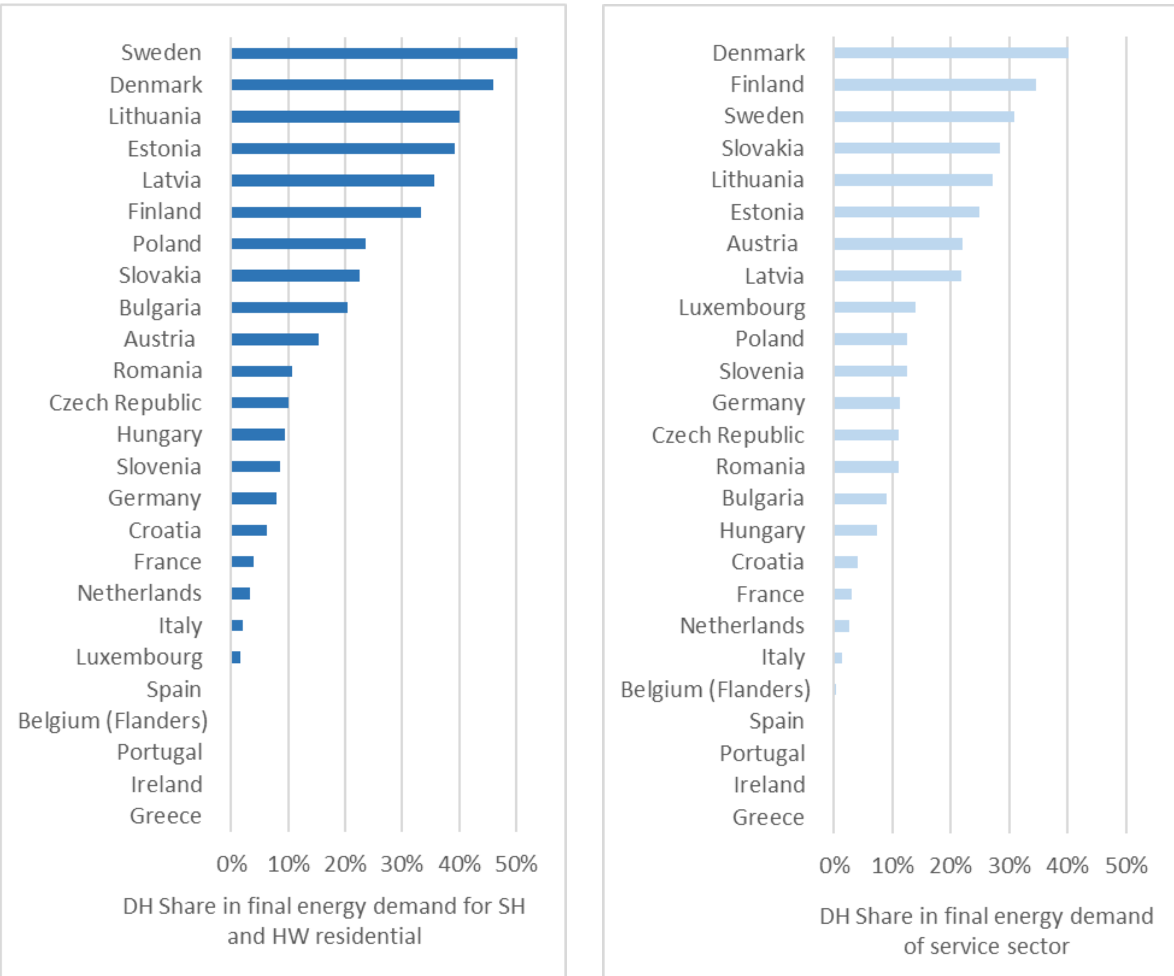


Figure 48: DH share in final energy consumption for space heating and hot water in the residential sector (left) and the DH share in the overall final energy consumption of the service sector (right). Source: Data from study "Overview of District Heating and Cooling Markets and Regulatory Frameworks under the Revised Renewable Energy Directive (DHC Trend)"[65]

[65] https://op.europa.eu/en/publication-detail/-/publication/5e1fd499-eabf-11ec-a534-01aa75ed71a1/language-en

Table 20 summarises the specific policy needs for expanding and decarbonising district heating and cooling, differentiating between different policy approaches as well as groups of countries with differing suitabilities and thus differing policy needs.

Table 20: Country-specific policy needs for the expansion and decarbonisation of district heating and cooling

Policy set	Short description	Role of policy set in different MS
Regulatory measures for DHC decarbonisation	Regulatory measures for DHC decarbonisation include regulations aiming at replacing fossil fuels in centralised heat generation by renewables and industrial excess heat. Policies may include quota/obligations for DHC companies, mandatory grid access for third-party generation from climate-friendly heat generation, obligations to develop transformation strategies and to expand the use of excess heat.	Regulatory measures for DHC decarbonisation are particularly relevant in Member States with a considerable market penetration of DHC (Figure 48) but high shares of fossil fuels in the DHC generation mix (Figure 45). These include countries like Poland, Czech Republic, Germany, Slovenia, Bulgaria, Latvia, Estonia, Austria (mainly countries from clusters 4 and 5, see Section 4.2.2).
Regulatory measures for expanding DHC infrastructure	Regulatory measures for expanding the DHC infrastructure aim at densification of heating grids, expansion of existing grids and development of new grids. Policy instruments include mandatory expansion targets, spatial zoning, mandatory connection to DHC systems.	Regulatory measures for expanding DHC infrastructure are particularly suitable in those countries in which DHC market shares are still low while the countries have a suitable demand structure (areas with high heat densities, Figure 46, are more suitable for DH supply than areas with low heat densities). Suitable countries include the Netherlands, Germany, Italy, Luxembourg, Belgium, Spain (mainly countries from clusters 4 and 5, see section 4.2.2).
Economic measures for DHC deployment	Economic instruments for expanding DHC infrastructure and decarbonising DHC generation include policy measures addressing the investment side (e.g. investment support) as well as the operation side (e.g. energy and carbon pricing).	Investment support is particularly relevant in countries where the difference between investments in centralised fossil fuel-based heat generation and centralised renewable heat generation is high. This is currently the case for most technologies (exceptions for biomass). In terms of operating costs, heat generation from large heat pumps (in many countries one of the key technologies for DHC decarbonisation) is economically competitive with 2020 prices in 4 out of 10 countries, whereas in the remaining countries the operation costs for heat pumps are higher than for fossil-fuelled boilers (Figure 49).

Policy set	Short description	Role of policy set in different MS
Market transformation policies	Market transformation policies support the market development and market penetration of DHC technologies and infrastructure; policies include strategic (local) heat planning approaches, awareness-raising across different market actors, participation.	Market transformation policies are particularly relevant in Member States that show good suitability for DHC (e.g. sufficiently high heat densities, sufficient potentials of renewable energies and excess heat) while current market shares of DHC are quite low (Figure 50). Market transformation policies pave the way for rapid market growth by transparently demonstrating the potential of DHC to municipalities and market actors, enabling market actors to implement it, and encouraging new ownership/operator models and participation to expand the actor spectrum. Market transformation policies are particularly suitable for countries from clusters 4 and 5 (see Section 4.2.2).

5.4. Process heat

5.4.1. Key elements of the transition and policy needs

- Main share of energy demand for process heat from **highly energy-intensive processes that operate at high temperatures** not suitable for direct use of RES via solar thermal, geothermal or heat pumps. Also, the potentials for use of district heating are limited.
- Biomass shows higher potentials, but due to limited resource potentials prioritisation across sectors and uses might be needed policies for the allocation of biomass
- Specific role for the use of direct RES to supply **low temperature process heating** below 100°C e.g. in the food industry. Solar thermal, geothermal and heat pumps are suitable.
- Very important role of **CO_2-neutral secondary energy carriers including electricity, hydrogen and syngas** for the supply of process heat, but still uncertainty about the respective role, national strategies and (local) availability for investors. → Clear policy strategies needed that reduce uncertainty for investors
- **Electrification of process heat** might be the most efficient way, however, in most cases it also requires a more comprehensive re-investment than switching to hydrogen or clean gas. Clean gas is the strategy with least intervention at industrial plants, however, also with the lowest overall efficiency. → Policies that provide investment support for electrification solutions
- Technologies to use electricity or hydrogen for process heating in **industrial furnaces** are in many cases **not yet available at industrial scale**. The maturity of such technologies depends less on needed technical breakthroughs, but rather on

upscaling and demonstrating as many technologies are currently at least on Technology Readiness Level (TRL) 4 or 5 (or higher). → Policies for upscaling and market introduction are needed

- Technologies to use electricity or hydrogen for process heating **via steam generation are available also at industrial scale** (electric boiler, hydrogen boiler).
- Making CO_2-neutral process heating cost-competitive requires **CO_2 prices in the range of 100-200 euro/tonne of CO_2**, which is substantially higher than current prices. Main reason is the difference in the prices of fossil versus CO_2-neutral energy carriers. → Higher CO_2 prices or accompanying policies that ensure a level-playing field also in the short and medium term for key decarbonisation technologies
- In most cases, **main driver of costs are OPEX** and less CAPEX, due to highly scaled units and long annual operation times. The share of CAPEX in total heat supply costs is often below 10%. → Policies need to consider OPEX
- In the **transition phase, hybrid systems that integrate electric steam boilers** in steam supply systems together with CHP units or gas boilers allow for an early roll-out of technologies, while risk for investors is low. → Policies need to make sure that such hybrid systems can efficiently operate in the electricity market; investment grants might speed up the market introduction
- Similarly, using **windows of opportunity along modernisation cycles and re-investing in CO_2-neutral steel production** via direct reduction technology is a low-risk strategy as natural gas and hydrogen can be used flexibly.

5.4.2. Barriers and key challenges

Table 21 outlines the key barriers and challenges for the decarbonisation of process heat. Note that not all barriers are applicable/relevant in all MS. Solar thermal energy and DHC are niche solution and are therefore not considered in this section. The main focus is on the major strategies to supply CO2-neutral process heating

Table 21: Barriers and key challenges for process heat

Type of barrier	Hydrogen for high temp. process heat in furnaces	Power-to-gas for high temp. process heat	Elec. furnaces for high temp. process heat	Elec. steam boilers for process heat	Heat pump (incl. geothermal energy)
Economic Investment (incl. infrastructure) Fuel costs	High fuel costs likely Investment in infrastructure and supply needed Also substantial investment at industrial facility needed in many	Very high fuel costs likely; no investment on the demand side (except steel) Major investment in supply tech needed	Higher fuel costs compared to gas; Investment in electricity grids depends	Higher fuel costs compared to gas boilers are main barrier; Investment in electricity grids depends on	High investment and potentially complex integration in processes

Type of barrier	Hydrogen for high temp. process heat in furnaces	Power-to-gas for high temp. process heat	Elec. furnaces for high temp. process heat	Elec. steam boilers for process heat	Heat pump (incl. geothermal energy)
	cases (e.g. steelmaking)		on local situation Re-building and investment at industrial facilities needed (new furnaces)	local situation	
Technology maturity	TRL 4-5 → pilot and demonstration plants needed	Demand side: TRL9 → no technical barriers Supply side: R&D needed	TRL 3-9 → R&D, pilot and demonstration plants needed	TRL9 → no technical barriers	<100°C: TRL9 100-150°C: More R&D needed
Market maturity: technology, fuel and installer markets	No green hydrogen available at large scale, no technologies available at industrial scale, no transport infrastructure for hydrogen	Demand side: Gas is dominant technology; Supply side: Supply of CO_2-neutral gas uncertain	Only market for small-scale and specialised units established (e.g. glass, metal processing)	Market is still niche / depends on country	Market is still niche / depends on country
Impact on electricity sector Load implications (incl. grid) RES-E availability	A) hydrogen can contribute to load shifting; especially seasonal storage B) if domestic H_2 generation: Very high additional RES-E needed; seasonal storage can contribute to RES integration	A) - B) if domestic generation: Very high additional RES-E needs; seasonal storage can contribute to RES integration	A) limited load shifting potential due to high capacity utilisation B) High additional RES-E need	A) Contribution to load shifting only in hybrid systems B) High additional RES-E need	A) - B) Moderate additional RES-E need
Resource availability (potentials) and space availability	If domestic H_2 generation: Very high additional RES-E needs; large potential for imports	If domestic H_2 generation: Very high additional RES-E needs; large potential for imports	High additional RES-E needs	Very high additional RES-E needs	Moderate additional RES-E needs
Regulatory barriers (planning regulations, data availability)	Clear strategy and planning needed to reduce uncertainty at national level;	Clear perspective needed: Will clean gas be available?	Transport infrastructure planning often slow	Transport infrastructure planning often slow	-

Type of barrier	Hydrogen for high temp. process heat in furnaces	Power-to-gas for high temp. process heat	Elec. furnaces for high temp. process heat	Elec. steam boilers for process heat	Heat pump (incl. geothermal energy)
	H_2 market needs to be established and regulated Transport infrastructure planning				

5.4.3. Target groups

In this section, the main target groups relevant for the decarbonisation of process heat are described.

- Industry, divided by:
  - Heavy industry, i.e. industry with high energy demand and covered by EU Emission Trading System (EU ETS); with (mostly) high temperature process heat; e.g. steel, chemical, cement industry
  - Light industry, i.e. industry with low/(lower) energy demand and not part of EU ETS; with (rather) low temperature process heat, e.g. machinery, food industry
- Manufacturers / technology developers, divided by:
  - Manufacturers of standardised plants like electric boilers, heat pumps
  - Technology developers, i.e. manufacturers of not standardised plants like electric furnaces for high temperature process
- Third-party investors and/or operators of plants (i.e. contracting)
- Infrastructure developers/providers, divided by:
  - Hydrogen/syngas grid providers
  - Electricity grid providers

5.4.4. Policy options

This section describes key policy options for decarbonising process heat and provides an overview of the barriers, target groups and technologies that are addressed by the respective policies.

(1) Carbon and energy pricing

- Revision of EU ETS with higher targets (i.e. lower cap and higher certification prices) and new/adapted regulation of carbon leakage

- Introduction of EU/national CO_2 price for heat in order to create level playing field also in the non-ETS sectors
- Revision of political energy price components in order to create level playing field, i.e. adaption of exemptions from energy taxes and levies or increase of taxes

(2) Technology development and deployment, i.e. support for technology upscaling and market introduction (demand side)

- Research funding, i.e. technology development with a focus on pilot projects and demonstration projects (less basic research)
- Financial incentives for investments (investment grant) in renewable/carbon-free process heat technologies (e.g. for technologies like electric furnaces, electric steam boilers, heat pumps, hydrogen furnace and boilers etc.)
- Financial incentives focusing on operating costs for renewable/carbon-free process heat (for energy demand, e.g. demand of electricity, hydrogen, syngas)
- Financial incentives addressing investment and operating costs like carbon contracts for differences or green product markets
- Quotas / mandatory share of renewable/carbon-free process heat (including biomass, solar thermal, renewable electrification of process heat, green (and blue) hydrogen, power-to-gas etc.)

(3) Technology development and deployment (supply side), i.e. production of energy carriers

- Clear policy strategies that reduce uncertainty for investors
- Research funding, i.e. technology development of supply technologies with focus on pilot projects and demonstration projects
- Green certificate scheme/guarantee of origin for hydrogen and/or syngas
- Feed-in-tariffs / feed-in premiums for green (and blue) hydrogen/syngas producers, e.g. H_2 global initiative
- Financial incentives for investments / investment support for energy carrier production technologies (e.g. electrolyser)
- Allocation strategies for limited resources (etc. biomass, hydrogen)

(4) Infrastructure

- Financial funding for hydrogen (and/or syngas) infrastructure / hydrogen grids
- Accelerated expansion of electricity grid infrastructure

Table 22: Policy matrix for process heat

Supporting measures	(1) Barriers				(2) Target groups							(3) Technologies							
	Economic barriers	Technology maturity	Market maturity	Regulatory barriers	Heavy industry	Light industry	Manufacturers of standardised plants	Technology developers	Investors and/or operators of plants	Hydrogen/syngas grid providers	Electricity grid providers	Hydrogen furnaces (for process heat)	Syngas (for process heat)	Electric furnaces	Electric steam boilers	Heat pumps (incl. geothermal energy)	Direct RES (solar thermal, biomass)	Infrastructure (hydrogen and elec. grids)	Electrolysers
Carbon and energy pricing																			
Revision of EU ETS with higher targets	x	(x)	(x)		x							x	x	x	x	(x)	(x)		
Introduction of CO_2 price for heat	x	(x)	(x)		x	x						(x)	(x)	(x)	(x)	x	x		
Introduction of energy price components	x	(x)	(x)		x	x						x	x	x	x	x	x		
Technology development and deployment – demand side																			
Research funding (demand side)	x	x	x	x	x	x		x	x			x	x	(x)	(x)	(x)	(x)		
Financial incentives for investments	x	x	x		x	x	x		x			x	x	x	x	x	x		
Financial incentives focusing on operating costs	x	x	x		x	x	x		x			x	x	x	x	x	(x)		
Financial incentives addressing investment and operating costs	x	x	x		x	x	x		x			x	x	x	x	x	x		

Supporting measures	(1) Barriers				(2) Target groups							(3) Technologies							
	Economic barriers	Technology maturity	Market maturity	Regulatory barriers	Heavy industry	Light industry	Manufacturers of standardised plants	Technology developers	Investors and/or operators of plants	Hydrogen/syngas grid providers	Electricity grid providers	Hydrogen furnaces (for process heat)	Syngas (for process heat)	Electric furnaces	Electric steam boilers	Heat pumps (incl. geothermal energy)	Direct RES (solar thermal, biomass)	Infrastructure (hydrogen and elec. grids)	Electrolysers
Quotas / mandatory share	x	x	x		x	x	x		x			x	x	x	x	x	x		
Technology development and deployment - supply side																			
Clear policy strategies	x	x	x	x	(x)	(x)		x	x	x	x	(x)	(x)					x	x
Research funding (supply side)	x							x	x									(x)	x
Green certificate scheme for hydrogen and/or syngas	x							x	x										x
Feed-in-tariffs/ premiums for hydrogen/ syngas producers	x							x	x										x
Financial incentives for investments for energy carrier production technologies	x							x	x										x
Allocation strategies for limited resources				x	x	x	(x)	(x)	(x)			(x)	(x)				x		x
Infrastructure																			

Supporting measures	(1) Barriers				(2) Target groups							(3) Technologies							
	Economic barriers	Technology maturity	Market maturity	Regulatory barriers	Heavy industry	Light industry	Manufacturers of standardised plants	Technology developers	Investors and/or operators of plants	Hydrogen/syngas grid providers	Electricity grid providers	Hydrogen furnaces (for process heat)	Syngas (for process heat)	Electric furnaces	Electric steam boilers	Heat pumps (incl. geothermal energy)	Direct RES (solar thermal, biomass)	Infrastructure (hydrogen and elec. grids)	Electrolysers
Financial funding for hydrogen (and/or syngas) infrastructure	x									x		(x)	(x)					x	(x)
Accelerated expansion of electricity grid infrastructure	x										x		(x)	(x)	(x)	(x)		x	(x)

5.4.5. Country-cluster specific policy sets

The EU Member States face different barriers for the decarbonisation of process heating, and the structure of processes and sectors also varies strongly across countries. Thus, they have different policy needs. Based on the policy options in the policy matrix for process heating (Table 22) and on the suitability analysis (see Chapter 3), policy sets for process heat are developed for different sets of countries that face similar barriers / patterns.

Economic instruments

Key policies for process heat are of economic nature, making climate-friendly process heat technologies cost-effective (EU ETS, subsidies, taxes, etc). Depending on the specific application and the temperature level, process heat supply requires different technologies:

- **High** temperature heat (>500°C) means use in specialised furnaces where hydrogen is often the preferred CO_2-free option, but also electrification possible in many cases.
- **Medium** temperature heat (100-500°C) is mostly steam, where electrification is available on the market (electric steam boilers); high-temperature heat pumps can also play a role.
- **Low** temperature heat (<100°C) can be supplied efficiently by district heating or high-temperature heat pumps.

Figure 49 shows the process heat demand by temperature level and country. Differences between countries are huge: Countries like Latvia, Sweden or Finland have a huge steam demand (~100-500°C) with 60-70% of overlall FED for H&C. Only less than 20% of demand are used to supply heat above 500°C (which is in high-temperature furnaces), where hydrogen is an attractive supply option in the long term. On the other hand, 12 countries have more than 50% of FED for H&C in high temperature heat above 500°C. For these countries, a strong hydrogen strategy to supply industrial demands is important.

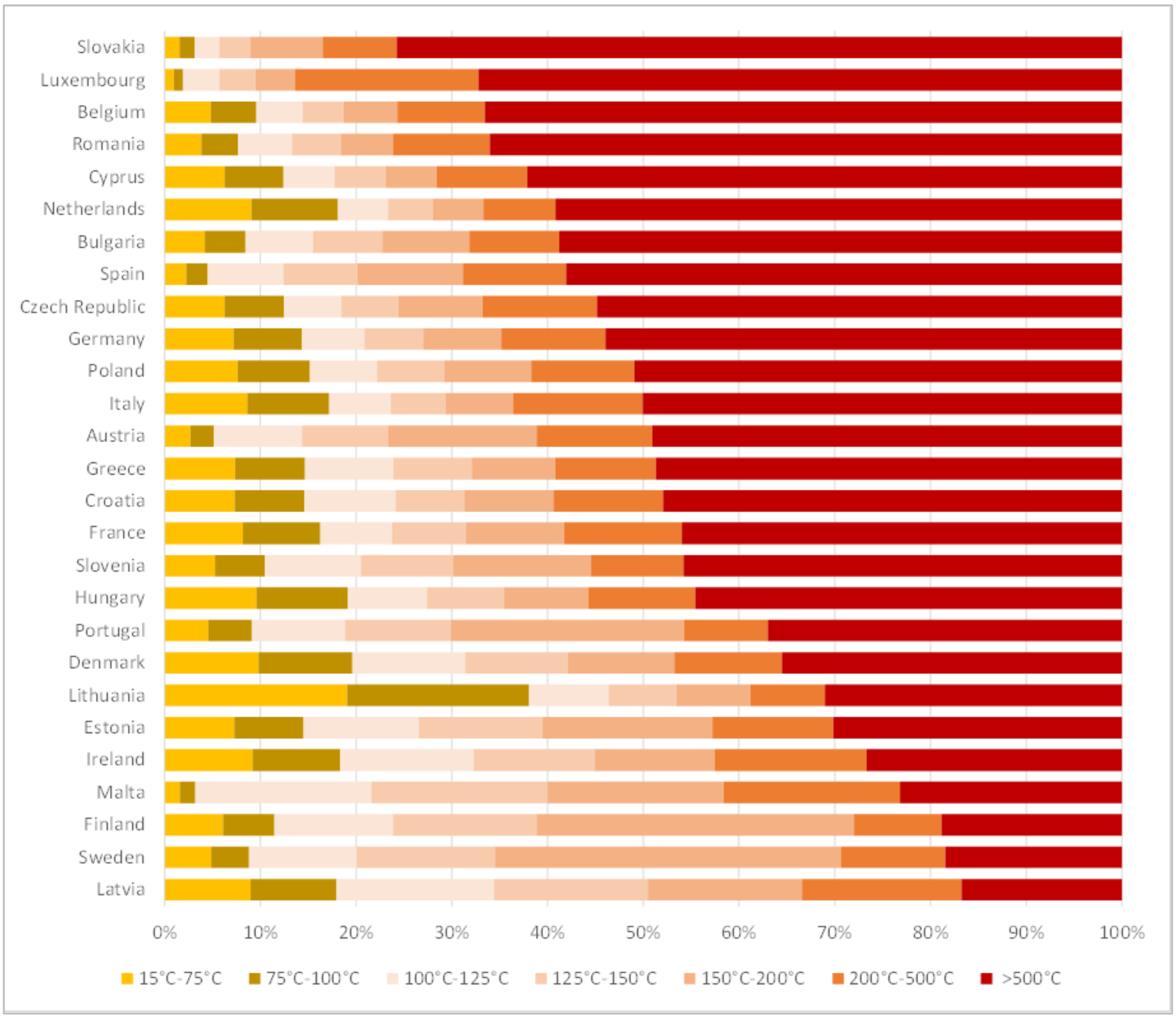


Figure 49: Final energy demand for H&C Industry process heating by temperature level 2018 (Source: Eurostat and Rehfeldt et al. 2017[66])

Most facilities of the energy-intensive industries are covered by a carbon price within the EU ETS. Smaller facilities (emission sources) are not included in the ETS and in most countries do not face a carbon price. Industries like engineering, food and other industries are nearly entirely outside the EU ETS, but their importance varies strongly by country (as shown in Figure 50). As a result, in 9 countries (see Figure 50) more than 30% of industrial FED is not covered by a CO_2 price and, thus, lacking incentives to switch to low-carbon

[66] Rehfeldt, M.; Fleiter, T.; Toro, F: (2017): A bottom-up estimation of the heating and cooling demand in European industry. In: Energy Efficiency 45 (2012), S. 786. DOI: 10.1007/s12053-017-9571-y

fuels. Here, a national CO_2 price or an ETS II that extends a price towards these non-energy intensive industries can have a substantial impact and fills a significant policy gap. Most important to mention are Latvia, Denmark and Ireland. On the other hand, in 12 countries including Belgium, Netherlands and Bulgaria more than 80% of industrial FED is covered by the EU ETS. Here, the introduction of a CO_2 price for the remaining industries has a lower impact and should have less priority.

At the same time, CO_2-neutral technologies are currently not cost-competitive in most countries and sectors. Thus economic policies for process heat are highly needed. The gap in carbon pricing needs to be closed basically in all countries, but in countries with a large share of FED within industries outside the ETS, this should receive a very high priority.

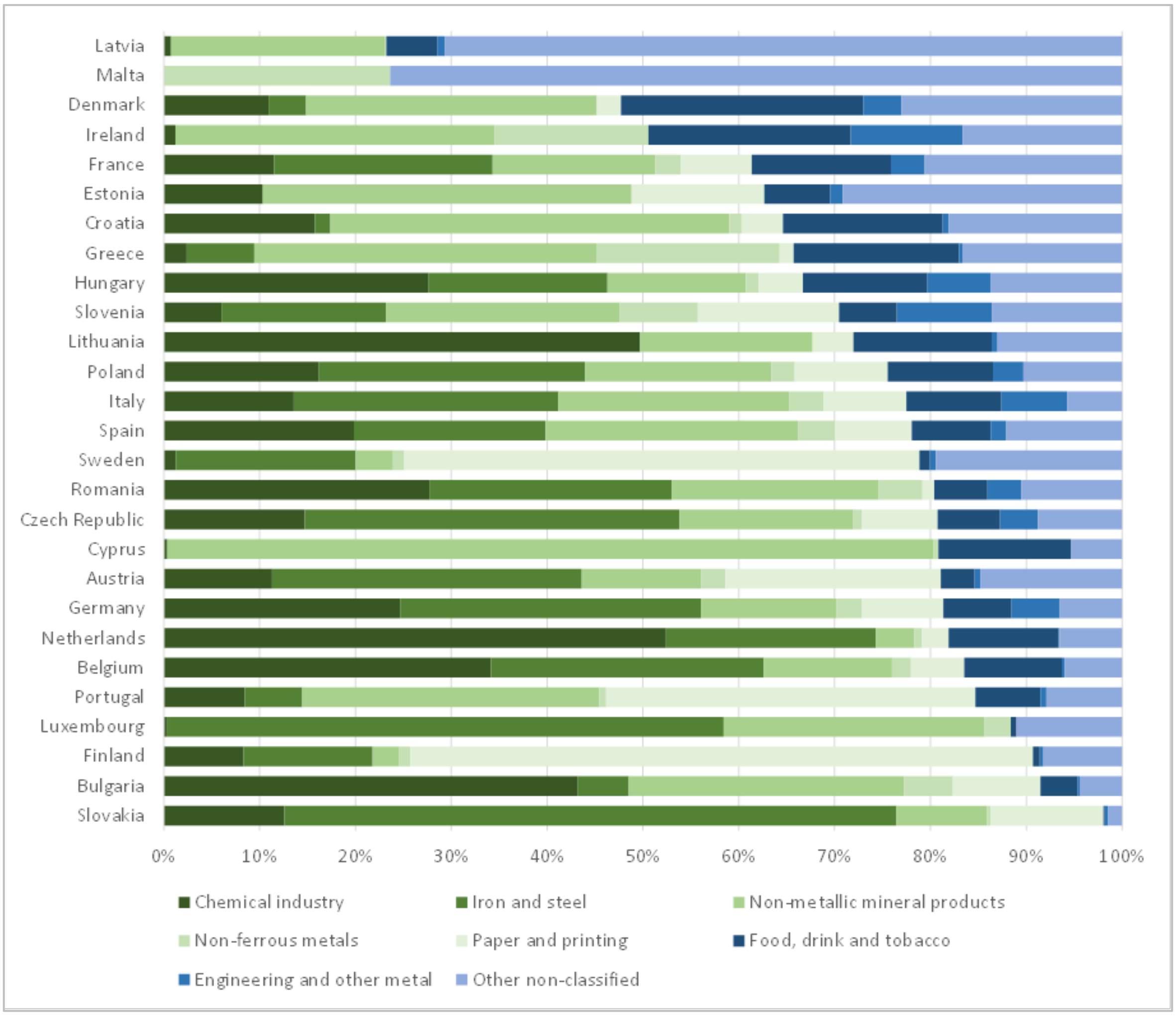


Figure 50: Final energy demand for process heating by subsector 2018 (Source: Eurostat)

Electrification of process heating is a key strategy in all countries to decarbonise process heating. Investment support for electric process heating alone is not sufficient. OPEX also needs to be competitive. In most countries, however, electricity is yet too expensive compared to natural gas, coal and fuel oil. Figure 51 shows electricity and gas prices for industrial consumers for the years 2020 and 2021 based on Eurostat statistics. Developments have been dynamic in recent months. It can be observed that already in 2021 natural gas prices were two to three times higher in many countries than they were in 2020. For the year 2022, wherestatistical data is not yet available, Figure 51 shows assumptions of the scenario modelling for this year. At the same time, increases in electricity prices from 2020 to 2021 have been rather moderate for industrial consumers but have increased considerably in 2022.

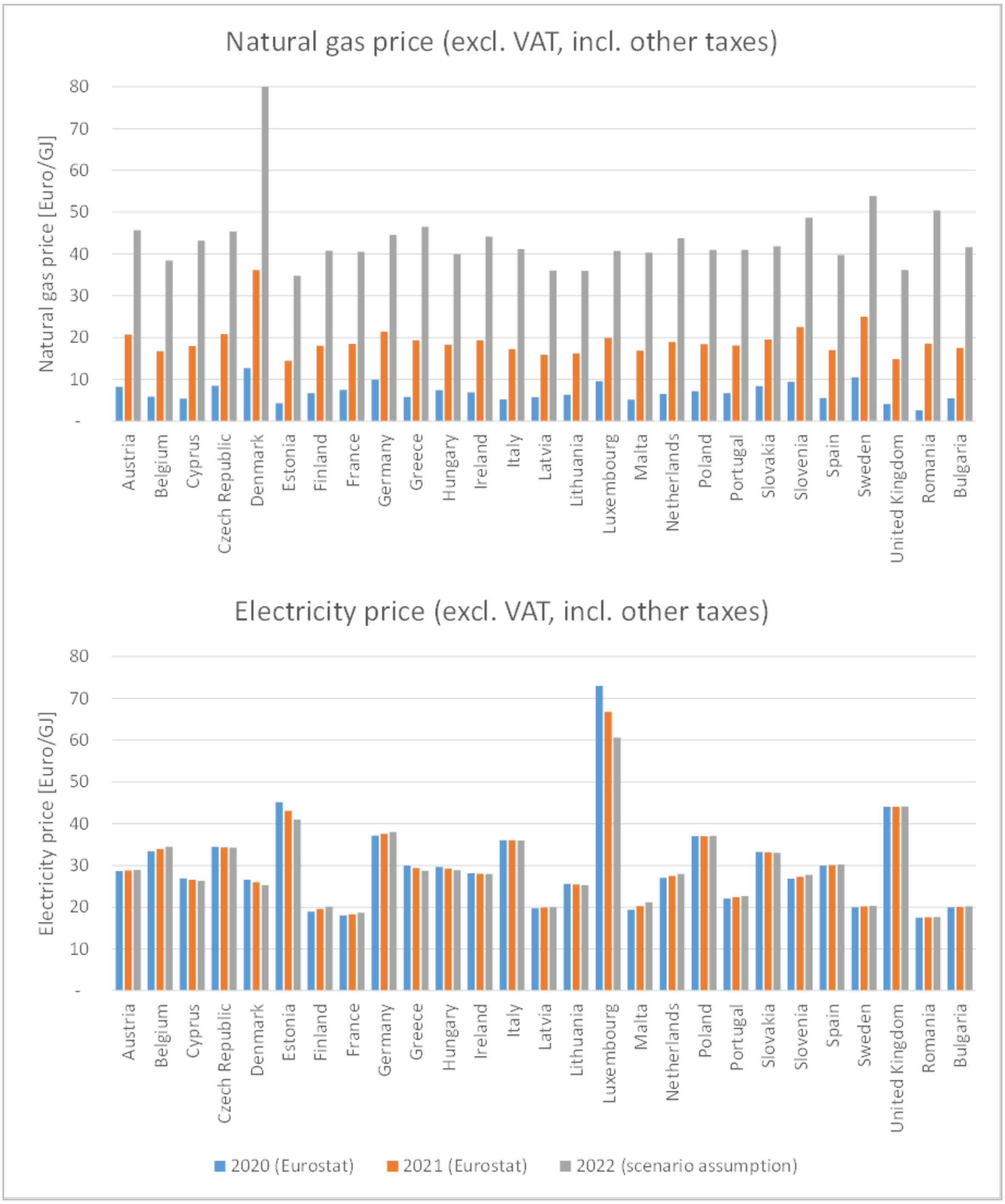


Figure 51: Electricity price and natural gas price for industry both excl. VAT but incl. other taxes (Eurostat and own assumptions)

The price ratio of electricity to natural gas is a good indication of the cost-effectiveness of electric process heating and varies heavily by country indicating the different importance of policies (see Figure 54). In the year 2020, the electricity price for industry was more than three times higher than the natural gas price in all countries except Sweden, Denmark, France, Finland and Slovenia. But even in these five countries, electricity was about two times more expensive than natural gas. Even including current levels of CO_2 prices on top of the natural gas prices does not allow for a business case for electric process heating. With the increase in natural gas prices in 2021, the situation changed drastically. In countries like Denmark, Sweden, Romania and France, electric process heating was cost-competitive with natural gas. However, in most countries, electricity was still substantially more expensive than natural gas. For example, Germany or Italy had an electricity price that is more than 7 times higher than the natural gas price in the year 2020. The picture curently changes with the short-term increase in gas prices, but as also electricity prices increase, the general pattern does not fundamentally change and electricity is still too expensive compared to natural gas in most countries. Finland and Sweden are exceptions, where electricity prices are in the same order of magnitude as gas prices are, making electrification a competitive option.

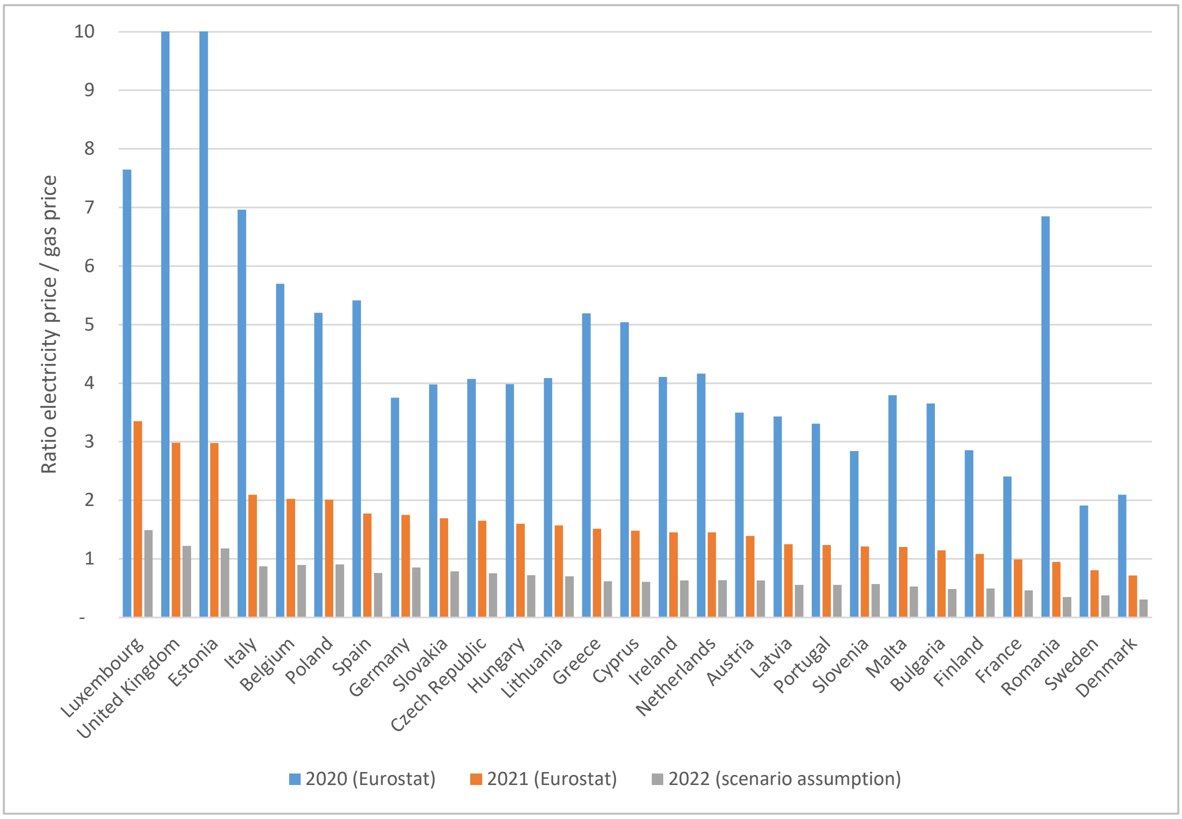


Figure 52: Cost-efficiency of electric process heating - ratio electricity price divided by gas price both excl. VAT but incl. other taxes (Eurostat and own assumptions)

Hydrogen can play an important role in decarbonising industry. It is particularly required to transform the primary steel production and chemical feedstock (ammonia, ethylene/olefines) production to CO_2 neutrality. The large steel/chemical clusters will determine the update of hydrogen infrastructure. Also in furnaces / high-temperature applications in industries like glass, metal processing, cement, ceramics, hydrogen can play an important role.

In countries with a large steel/chemical industry, it is likely that also other industries will have hydrogen available. Countries with large primary steel production capacity per capita are Austria, Slovakia, Czech Republic, Finland, Sweden, Belgium and the Netherlands. The basic chemical production per capita is exceptionally high in the Netherlands and Lithuania. These countries need to prioritise hydrogen use and develop strategies to improve investment perspectives. Thus, strong strategies and allocation for hydrogen, but also rapid upscaling of hydrogen infrastructure are key policies.

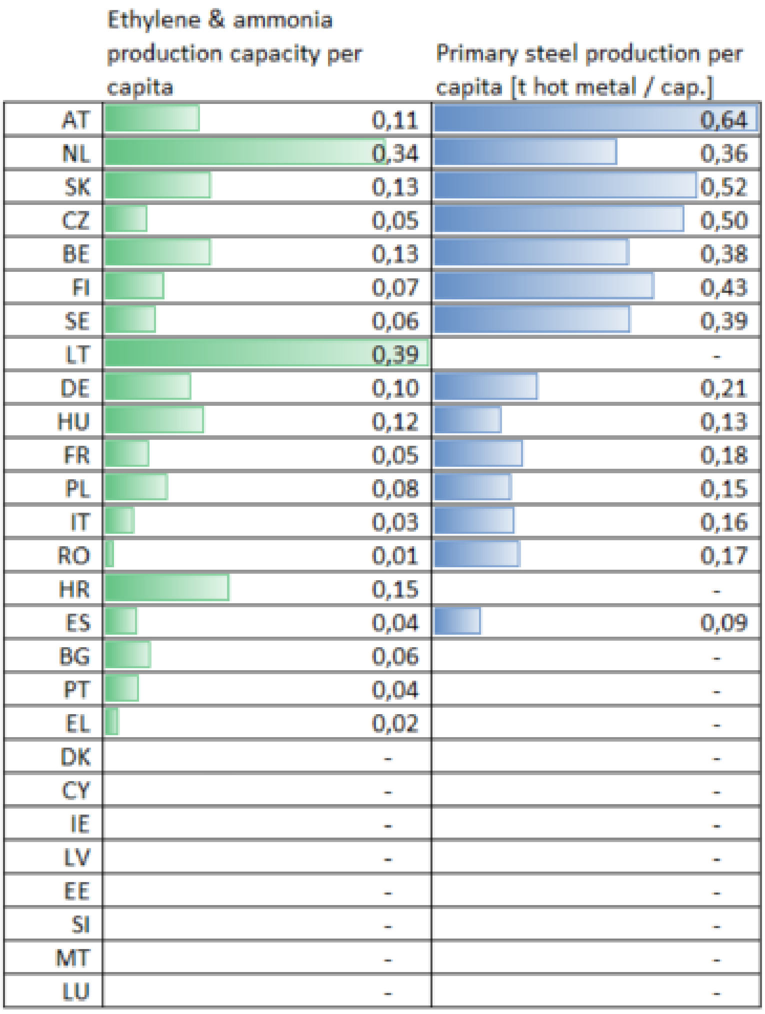


Figure 53: Current production capacity for basic chemicals (ethylene and ammonia) and primary steel per capita (Fraunhofer ISI database)

Table 23: Country-specific policy needs for process heat

Policy set	Short description	Role of policy set in different MS
Economic instruments: **Carbon and energy price regime**	Basically includes all taxes and levies for energy carriers as well as the carbon price from ETS I and potentially ETS II.	Electrification of process heating is economically competitive compared with past gas prices only in two countries (Finland and Sweden), whereas in the majority of Member States the operational costs of electric process heating are currently higher (no consideration of carbon pricing etc.). A comprehensive reform of energy taxes and levies can substantially improve the competitiveness of electric process heating. The countries with the highest need of such a reform seem to be Germany, Italy, Slovakia, Belgium, Portugal, Denmark, Romania. But also other countries except Sweden and Finland need to make electric process heating more cost-competitive.

Policy set	Short description	Role of policy set in different MS
		A strong CO_2 price within the ETS, but also outside the ETS is needed. This involves a reform of ETS I and the introduction of ETS II to also cover the industry sector (instead of buildings and transport only). In case ETS II is not expanded to industry, Member States should implement national CO_2 prices for the non-ETS industry. This is particularly important for Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany.
Economic instruments: Technology support programmes	Technology development and deployment, i.e. support for technology upscaling and market introduction (demand side)	Investment support with a focus on pilot projects and demonstration projects (less basic research) is particularly relevant to enable the quick market entry of low-carbon technologies. Financial operational support should be provided in almost all Member States, particularly in areas where currently low-carbon technologies are not yet market-ready. E.g. new hydrogen-based chemical processes or steel production would require CO_2 prices above 100 Euro/t CO_2 and, thus, need additional support of operational costs at current prices. Carbon contracts for difference (CCfDs) can play an important role. They do not only provide financial support, they also reduce uncertainty and risks related to CO_2 prices and competitiveness of low-carbon technologies. They are very relevant in all countries with large basic chemical and steel industries. Among them are Austria, Slovakia, Czech Republic, Finland, Sweden, Belgium and the Netherlands, but also others like Germany.
Market and information-based measures	Market and information-based measures support the market development of process heat technologies, increase awareness and reduce uncertainties. Industry faces major uncertainties with regard to the local and regional availability of green hydrogen. A clear and concrete strategy that evolves into a hydrogen upscaling plan can significantly reduce uncertainty and lead to realistic expectations. Other important market and information-based instruments relate to the labelling of CO_2 footprints on products, which allows consumers to consider CO_2 emissions in purchase decisions and, thus, can create lead markets for low-carbon products.	So far only six Member States have developed a hydrogen strategy (or similar). On the other hand, many countries will need huge quantities of hydrogen for the supply of chemical and steel industries. Among them are Austria, the Netherlands, Slovakia, Czech Republic, Belgium, Finland, Sweden, Lithuania, Germany, Hungary, France, Poland, Italy, Romania, Croatia and others with a lower priority. While quantities are huge, hydrogen demands might be focused on a few locations only. These countries require a planned and strategic development of hydrogen infrastructure and markets. Other countries depend less on hydrogen in their transition. Here, a clear strategy can also mean that hydrogen will not play a significant role and actors need to use other solutions.

6. Modelling of pathways and measures for heating and cooling decarbonisation archetypes

6.1. Objectives and approach

This chapter presents the approach and results of the modelling of pathways for the decarbonisation of heating and cooling until 2050, with an outlook until 2070. The modelling in this work builds on a set of well-established and validated models, interfaces, and data. The building sector is covered by the model Invert[67] and the sector of industrial process heat is modelled in FORECAST[68]. The modelling of the district heating sector considers district heating expansion requirements and decarbonisation of supply. Models developed in the project Hotmaps[69] are adapted and used for this purpose. The electricity sector is included in a simplified way, which still allows to capture its major impacts on the H&C sector. More precisely, the output of electricity sector modelling as performed e.g. in the project SET-Nav, RES Heat or Elec Heat[70] is used as input for the heat sector modelling. The results of all models and model runs are brought together in a synthesis, presenting the results of the heating/cooling sector in line with definitions used in the Renewable Energy Directive and related legislation. Figure 54 shows this overall modelling framework in the analysis.

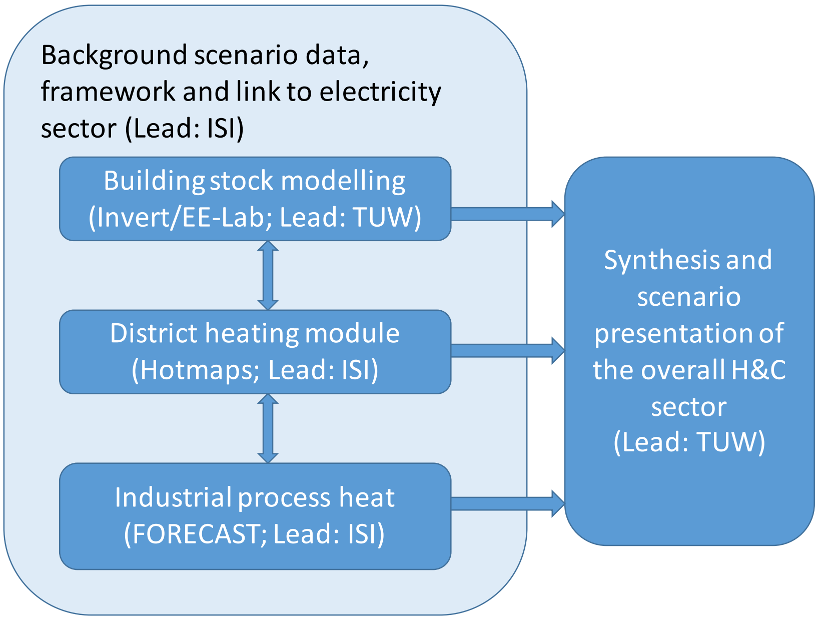


Figure 54: Overall modelling framework and modelling tools applied

The models Invert and FORECAST calculate on the country level (B1 & I1). Results from the models are then broken down to a higher geographical detail (B2 and DH3) to be used in the district heating (DH) modelling. The DH modelling hereby includes a sequence of steps (DH1 – DH6) for deriving potential DH demand and supply scenarios. In the different

[67] www.invert.at
[68] www.forecast-model.eu
[69] www.hotmaps-project.eu
[70] www.set-nav.eu; Renewable Space Heating under the Revised Renewable Energy Directive (ENER/C1/2018-494); Potentials and levels for the electrification of space heating in buildings (ENER/C1/2019-481)

modelling steps the effect of applying different policy frameworks is taken into account, as also shown in the figure. Further details on the models can be found in the annex of this report (see Annex C3).

6.2. Scenario design and input data

6.2.1. Overview scenario design

Baseline scenario:

The baseline scenario considers policies in place before the implementation of the Fit-for-55 package and in particular assumes no strong ambitions of MS in the implementation of climate and energy policies. Thus, neither 2030 nor 2050 decarbonisation targets are achieved. The approach allows to estimate the impact of increased measures in the decarbonisation pathway scenarios.

The baseline scenario considers main drivers like population growth, economic development and key evolution lines of the energy system to be the same as in the draft reference scenario 2020 of PRIMES[71]. Although decarbonisation targets by far are not achieved in this scenario, still some significant changes occur, e.g. with respect to the heat generation mix of district heating grids.

As far as more detailed assumptions are required, similar assumptions as in the project Elec Heat[72] are being made for the space heating sector. Furthermore, technology data and sectoral data from the reference scenario of the project RES Heat[73] are being used.

Decarbonisation pathway scenario:

The decarbonisation pathway scenario achieves full decarbonisation by 2050, and thus also in the H&C sector. Moreover, the targets described for 2030 in the Fit-for-55 package are achieved:

- 49% of RES in the building sector (Art 15a of the proposal for a recast Renewable Energy Directive, 2021);
- Increase the share of renewable sources in the amount of energy sources used for final energy and non-energy purposes in the industry sector by an annual increase of 1.1 percentage points by 2030 (Art 22a of the proposal for a recast Renewable Energy Directive, 2021) ;
- Increase the share of renewable energy in the H&C sector by at least 1.1 percentage points annually. This increase shall be at 1.5 percentage points for Member States where waste heat and cold is used (Art 23 of the proposal for a recast Renewable Energy Directive, 2021);

[71] E3 Modelling 2020; This scenario reflects national planning as postulated by EU MS's in National Energy and Climate Plans as submitted in the years 2019 and 2020. In practical terms modelling is here aligned to the outcomes of the PRIMES reference scenario as provided in draft by end of January 2021, i.e., EC 2020 Reference Scenario.

[72] Potentials and levels for the electrification of space heating in buildings (ENER/C1/2019-481)

[73] Renewable Space Heating under the Revised Renewable Energy Directive (ENER/C1/2018-494)

- Increase the share of energy from renewable sources and from waste heat and cold in district heating and cooling by at least 2.1 percentage points annually. (Art 24 of the proposal for a recast Renewable Energy Directive, 2021).

Moreover, the constraints, assumptions, policies and potentials on MS level as described in Chapter 5 are implemented and considered in the scenario development.

The decarbonisation pathways will be triggered and characterised by the policy packages identified and described in the other tasks. In the following, we will describe in which level of detail these policy packages will be explicitly modelled in the different sectors.

Price sensitivity scenario:

The price sensitivity scenario follows the same storyline as the decarbonisation pathway scenario, however, with energy prices in the range as they have been observed since late 2021. Thus, this scenario allows to depict the potential impact of high energy prices on a scenario with high decarbonisation efforts.

6.2.2. Main input data and cross-cutting scenario assumptions

In the baseline scenario, the following cross-cutting assumptions were made:

- Energy prices: based on PRIMES reference scenario 2020. As far as relevant for the different sectors (buildings, industry, district heating), taxes and grid fees are added. Hourly profiles of electricity prices are being used in line with the modelling in the study “Potentials and Levels for the Electrification of Space Heating in Buildings” (reference scenario Elec Heat Project).
- CO_2-Prices: based on PRIMES draft reference scenario 2020 (starting with 30€/tCO_2 in 2030 increasing to 150 €/tCO_2 in 2050).
- Biomass constraints and allocation between sectors: moderate constraints in the building and district heating sector; low constraint in the industry sector. We assume that in the baseline scenario certain roundwood fractions are still part of the available biomass resources in the heating sector (i.e. the Fit-for-55 policy package is not yet implemented). Under this assumption, the total biomass consumption in the baseline scenario does not exceed the biomass potentials.

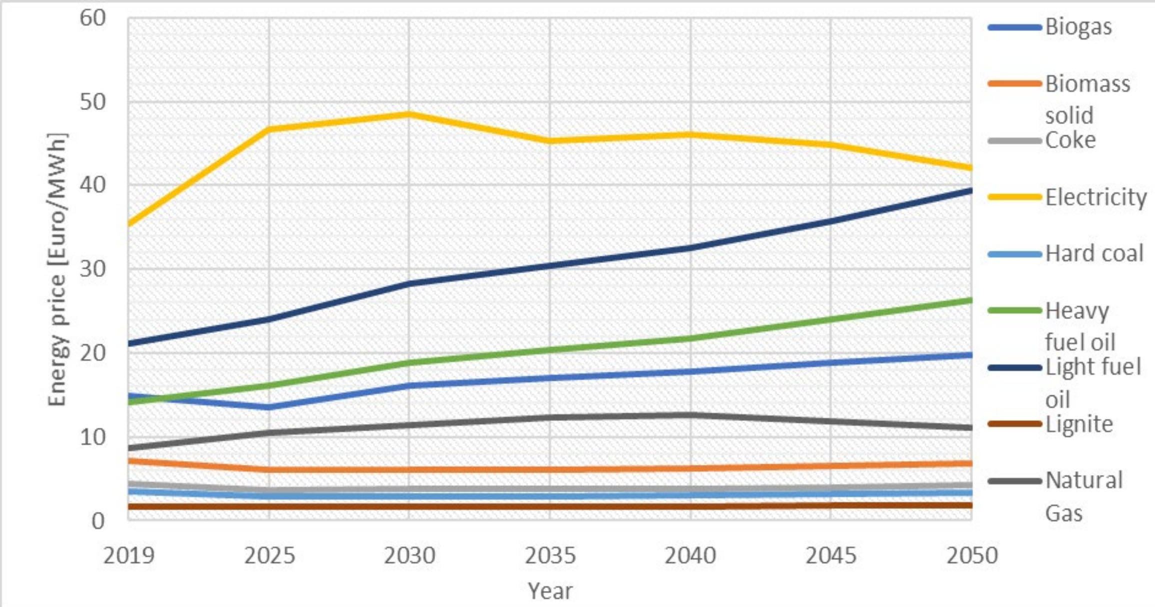


Figure 55: Energy carriers price projections (2019 based on Eurostat; projection: own assumption taking into consideration the EU Reference Scenario 2020 and limited recovery scenario)

In the price-sensitivity scenario, we carry out a model run to reflect better prices like averages of the last quarter of 2021 and first quarter of 2022. For this purpose, we consider a constant price mark-up on top of the price scenario described above. The main assumption of this scenario is that energy prices will remain high until 2030. After 2030 prices converge to a main price scenario by 2050. Table 24 shows the price mark-ups for the different energy carriers and related sources which were consulted to depict price differences of the period from October 2021 until March 2022 and the period 2019-2020.

Table 24: Price mark-ups in the price-sensitivity scenario

Energy carrier	Price mark-up (until 2030) [€/MWh]	Sources
Natural gas	70	European Commission 2022[74], IEA 2022[75]
Fuel oil	18	European Commission 2022[74]
Biomass	10	ProPellets AT 2022[76], Baltpool 2022[77], weighted average over different solid biomass fuels
Electricity	120	European Commission 2022[74]
District heating	40	Assuming an average of natural gas and biomass

[74] European Commission, Quarterly report on European electricity markets with focus on developments in annual wholesale prices. https://energy.ec.europa.eu/system/files/2022-04/Quarterly%20report%20on%20European%20electricity%20markets_Q4%202021.pdf, 2022

[75] IEA, Natural gas prices in Europe, Asia and the United States, Jan 2020-February 2022, IEA, Paris https://www.iea.org/data-and-statistics/charts/natural-gas-prices-in-europe-asia-and-the-united-states-jan-2020-february-2022 , April 2022

[76] www.propellets.at, access on 30 May 2022

[77] https://www.baltpool.eu/en/, access on 30 May 2022

In the decarbonisation pathway, the following cross-cutting assumptions were made:

- Energy prices are in line with the modelling in the study "Potentials and Levels for the Electrification of Space Heating in Buildings" (anchor scenario Elec Heat project). As far as relevant for the different sectors (buildings, industry, district heating), taxes and grid fees are added; partly, taxes were adjusted according to the more specific assumptions described below for the different sectors.
- CO_2 prices: increase to 500€/tCO_2 in 2050 for industry and district heating and to 200 €/tCO_2 in buildings (in line with the study Potentials and Levels for the Electrification of Space Heating in Buildings).
- Biomass constraints and allocation between sectors: high constraints (leading to a reduction of currently used biomass) in the building sector; medium constraints for district heating (using the regional "conditioned potentials" for residues, see Chapter 3) in district heating and low constraint in the industry sector. In the decarbonisation pathway, we assume that roundwood fractions will be gradually phased out and by 2035 are not part of the biomass potential anymore. Overall, the biomass use across all sectors covered must not exceed the available potentials.

6.2.3. Main input data and scenario assumptions for the building sector

This chapter presents calibration and input data for the different scenarios for the sector space heating, domestic hot water and cooling derived by the Invert/EE-Lab model.

The aim of the **baseline scenario** is to present a trajectory for the future energy consumption of the sector in focus under the current policy conditions as well as presenting an Invert/EE-Lab model run that is in line with the Primes Reference Scenario 2020. At this point it is important to keep in mind that the input data set as well as the methodology of the applied Invert/EE-Lab model is independent of that of the Primes (buildings) model. The scope of the Invert/EE-Lab model includes the calculation of energy demand and final energy consumption based on energy-performance properties of buildings, such as U-values and surface areas, climate conditions, user needs, and technology performance data. The evolution of the energy consumption considers the drivers and barriers of investing in energy-related investments of investors in the building stock (refurbishment, newly constructed buildings, building demolitions) as well as factors which influence the associated energy consumption independent from investment activities such as climate change, change in comfort expectations triggered by either increasing income or changing energy price levels. While we aligned many of the input parameters, we did not force the model to derive exactly the same results as the Primes model does. That is to say, decisions are still anticipated endogenously within the Invert/EE-Lab model and are not taken from the Primes model results as exogenous parameters. Thus, the model results differ to some extent from that of the Primes model, yet the overall direction is similar.

The energy consumption for space heating and domestic hot water preparation in the draft baseline scenario was calculated assuming that all existing policy measures related to the

European building stock are implemented in their current form and continue to be valid until the year 2050. As the main source for implemented policies the Mure database[78] was used.

In order to **calibrate the renovation activities**, we used the results of a European-wide study on renovation activities (IPSOS Study, 2019). In this study, the renovation activities in the building sector during the period 2012 – 2016 were assessed for the housing and non-residential sector. A survey approach was used in this study to derive the share of households which have performed different kinds of building refurbishment depths. Besides non-energy-related refurbishments, four types of energy-related refurbishment activities were distinguished:

- “Below threshold”: Activities which reduced the primary energy demand by less than 3%, with average primary energy savings of about 0.2%.
- “Light renovations”: Energy savings in the range of 3% to 30%, with average primary savings of 12.7%.
- “Medium renovations”: Savings in the range of 30% to 60% with average primary energy savings of 41.1% and a range of 37%-45% on the level of individual MS.
- “Deep renovations”: Activities which achieved savings of more than 60% and saved about 66% on average on the EU-28 level, with a range of 62% - 73% on the level of MS.

The energy savings of measures were assessed based on calculated energy demand reductions using the Navigant Building Energy Performance Model (based on ISO 52016) and do not refer to primary energy savings measured. The primary energy savings in relative as well as absolute terms as well as associated annual refurbishment rates for the period 2012 – 2016 and investment costs are distinguished for the residential and the non-residential sector and are reported for each country.

The Invert/EE-Lab model, which we apply in our study, considers refurbishment measures related to the reduction of energy needs as well as the measures that target the heat supply and heat distribution system. With respect to the activities which reduce the energy needs, we consider in this study for each building archetype three different refurbishment options, which are defined by the energy needs for space heating. The standard refurbishment options are assigned to target energy needs for space heating, which should be achieved after renovation. These target requirements are outlined in Table 42. On (EU) average, these settings aim at annual energy needs for space heating of about 50 kWh/m² for single-family homes and about 30 kWh/m² for compact apartment buildings. However, we adopt these targets by setting a range of 10% to no more than 50% for the energy needs savings which can be achieved by renovation measures. With this restriction, we try to tackle the common observations that energy demand in buildings tend to decrease less than what has been calculated based on the initial energy performance certificate and the country-specific energy performance requirements for refurbished buildings. Several underlying reasons can add to this effect. First, it has been observed by many publications that the initial final energy consumption of buildings with a poor energy performance is significantly lower than that according to the energy performance certificate (Majcen et al, 2013; Loga and Stein,

[78] www.measures-odyssee-mure.eu/

2022) [79]. While we tried to account for this in the applied Invert/EE-Lab model, we might still underestimate the effect. In addition to the deviations with respect to the initial status quo, also the energy consumption after a refurbishment might exceed the prior level calculated, be it either due to a rebound effect or that the actual refurbishment performed was not in all details as ambitioned as on paper.

In addition to that, we have implemented, based on observed data, a method to adjust the target indoor temperatures in dependence of the specific energy needs and annual consumption-dependent energy costs per dwelling area. With that, we account (to some extent) for the observation that buildings with high energy needs and/or energy costs tend to reduce the average indoor temperature[80] level, while the target temperatures in efficient buildings and/or buildings with low energy costs is typically above the set-point temperature of 20°C commonly referred as standard.

Considering the energy needs for domestic hot water preparation, the upper limit of energy needs savings achieved by the standard renovation option is set (on average) at about 44% for single family homes and 40% for apartment buildings. Primary as well as final energy savings are even lower, as the energy supply efficiency of the hot water system is usually lower than that of the space heating systems (stand-by losses).

In addition to the standard refurbishment option, we consider an option with less ambitious measures (70% of savings compared to the standard option) and a deeper refurbishment option (energy needs for space heating are 70% of that of the standard refurbishment option).

With these settings, the model approximately covers (conservatively) the two more ambitious renovation activities as assessed by Ipsos (2019)[81]. Regarding the refurbishment rates, we build on the before-mentioned study. Since the study looked at primary energy reductions, which can be achieved by other measures such as more efficient lighting or appliances or switching to a more efficient heating system, we cannot directly take the refurbishment rates as derived by the study. Based on the presumption that energy "light" and "below threshold" refurbishment activities did not target the energy needs for heating but rather lighting, appliances and new heating systems, we focused on the "medium" and "deep" energy-related refurbishments only (heating system replacement is modelled explicitly in Invert/EE-Lab). For the period 2012-2016 we derived a refurbishment rate (for the share of heated floor area that reduces the energy needs for space heating) by taking the 100% (residential buildings) and 80% (non-residential buildings) of renovation rates (derived by the study) for "deep" refurbishment as well as 80% (residential buildings) and 60% (non-residential buildings) for "medium" refurbishments. We decreased the refurbishment rates for the non-residential buildings since this sector has additional options

[79] Majcen, D., Itard, L.C.M., Visscher, H., 2013. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. Energy Policy 54, 125–136.

Loga, T. and Stein, B., 2022. Use of energy performance certificates for realistic prognoses – A method to calibrate the national calculation procedure by the average actual consumption. In proceedings of the eceee Summer Study 2022, June, 2022.

[80] With indoor temperature we refer to the operative indoor temperature, which comprises the surface temperature of walls, ceilings, and floor (70%) and the air temperature (30%). In most cases, the surface temperatures are lower than the air temperature, therefore the operative temperature is below the temperature level, which is typically observed in buildings using a thermometer. This effect is larger in buildings with a low energy performance since surface temperatures are lower due to the lower thermal resistance of the components. This means that the operative temperature of a building with a low energy performance is lower than that of a building with a higher energy performance (ceteris paribus) if both buildings have the same measured air temperature.

[81] IPSOS, 2019: Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU. Report prepared for the EC DG Energy. contract No ENER/C3/2016-547/02/SI2.753931. Available at: https://ec.europa.eu/energy/en/studies/comprehensive-study-building-energy-renovation-activities-and-uptake-nearly-zero-energy

to reduce its primary energy consumption due to a higher electricity consumption by appliances (in our understanding, process heat has not been covered by the study). Furthermore we define that the refurbishment rate must not exceed 2.2% p.a.. For the share of the three renovation options in the Invert/EE-Lab model on the energy-related refurbishment activities, we made the assumption that 100% (residential buildings) and 80% (non-residential buildings) of the energy-related "deep" refurbishment activities of the Ipsos study correspond to the most ambitious renovation measure in the Invert/EE-Lab model, the remaining renovations are assigned to 40% to less-than-standard renovation measures (with average energy needs reductions for space heating and domestic hot water preparation of less than 35%) and the remaining shares are given to the standard refurbishment option.

To derive the share between energy-related and non-energy-related refurbishment options in the Invert/EE-Lab model we derived the annual activity rate of 2.2 % for a steady-steady building stock[82] considering the average lifetime of energy-related building shell components of 45 years. The ratio of this 2.2% and the refurbishment rate derived above is used to calibrate the share between energy-related and non-energy-related refurbishment options in the Invert/EE-Lab model.

Table 43 and Table 44 in the Annex document the target renovation rates in residential and non-residential buildings for the period 2012-2016 used to calibrate the Invert/EE-Lab model.

For the **baseline scenario**, we calibrated the refurbishment activities in the Invert/EE-Lab model, so that it derived the targeted shares for the period 2012-2016 considering the energy prices for that period (yet keeping the refurbishment costs of 2019).

For space cooling, our approach refers to existing scenarios considered in the project "Renewable Cooling under the revised Renewable Energy Directive"[83]. For the base year, we used the cooling consumption data derived in the same study[84] and for the baseline scenario the useful cooling energy demand in the base year 2019 is increased by the absolute cooling energy demand growth according to the HRE scenario[85], resulting in a growth of useful energy by about a factor of 4.5 by 2050 for the whole EU-27.

The mix of cooling technologies is also based on the above-mentioned study[84]. In the base year, the cooling market is dominated by vapour compression systems and these systems are likely to keep dominating the market in the future. Therefore, cooling technologies included in this study consist of various vapour compression systems with different energy input, with most of the energy input being electricity.

Main technology data as well as the share of technologies in the scenarios is shown in the Annex. Also, descriptions on the techno-economic data and assumptions of cooling technologies are provided in the Annex.

---

[82] While the model considers also new building construction and demolition, for this calibration we assumed no change in the total number of buildings.

[83] Kranzl L., Mascherbauer P., Fallahnejad M., Pezutto S., Novelli A., Zambito A., Miraglio P., Belleri A., Bottecchia L., Gantioler S., Riviere P., Etienne A., Stabat P., Berthou T., Viegand J., Jensen C., Hummel M., Müller. Analysis of the impacts of the renewable cooling energy definition. Report 3 of the study Renewable Cooling under the Revised Renewable Energy Directive ENER/C1/2018-493, 2021

[84] Pezutto S., Kranzl L., Mascherbauer P., Fallahnejad M., Novelli A., Zambito A., Miraglio P., Belleri A., Bottecchia L., Gantioler S., Riviere P., Etienne A., Stabat P., Berthou T., Viegand J., Jensen C., Hummel M., Müller A., Cooling Technologies Overview and Market Shares, Report 1 of the study Renewable Cooling under the Revised Renewable Energy Directive ENER/C1/2018-493, 2020

[85] HRE4 project, 'Horizon 2020 Heat Roadmap Europe 4 - HRE4 - project'. 2016 [Online]. Available: https://heatroadmap.eu/. [Accessed: 28-Feb-2020]

In the **decarbonisation pathway scenario**, we implemented a stringent package of policies and boundary conditions in the model, leading to full decarbonisation by 2050. It turns out that in the model strong regulatory measures in addition to economic support and other accompanying measures are required. More concrete policy settings for the sectors building renovation (envelope), direct RES-H support, district heating and e-fuels/H_2 are described below.

For renovation of the building envelope, we implemented minimum energy performance standards (MEPS), - corresponding to an obligation of building renovation – for those 25% of buildings within each building category performing worst. The MEPS are designed in a way that the affected buildings need to be renovated within a period of 10 years. The refurbishment obligation is introduced in 2025; our implementation assumes that owners buildings start to refurbish the buildings 5 years later, with a peak after 8 years. The energy performance of refurbished buildings is in between the energy performance class threshold levels of B and C (closer to B) in the 2020s and early 2030s. By 2035 the standards are tightened and are set in between the two energy performance class threshold levels A and B. Due to the continuous renovation of the building stock, gradually more buildings fall into the 25% range of least performing buildings. Investment subsidies are granted in order to ensure public acceptance and affordability but are not main drivers in the scenario. We consider subsidies of 15% for a standard refurbishment level, and 35% for a refurbishment level that leads to an energy performance level of (about) A. We assume that buildings constructed before 1945 face higher renovation barriers due to technical, economical and/or cultural constraints and are unable to reach an energy performance level of A.

As support for direct RES-H solutions, an obligation for RES-H systems in case of new building construction, renovation and heating system replacement is implemented as a policy instrument in the model. Thus, after a heating system exceeds a certain lifetime, it needs to be replaced by a renewable one. In order to ensure public acceptance and affordability, we assumed moderate investment subsidies for RES-H investments (20% for wood pellet boilers and ground source heat pumps, 10% for air source heat pumps). In addition, we assume that constraints for installing PV and solar thermal are reduced, thus allowing the installation of PV and solar thermal in principle on every roof. The scenario assumes that there is a clear priority for using biomass in high-temperature applications and not for space and water heating, thus, biomass is gradually moved out of the building sector by appropriate settings of the before-mentioned policy settings. For more information on how the efficiencies of heat pumps are modelled in the Invert model, see Annex C3.

In order to ensure a high use of district heating infrastructure, we assume that stringent spatial energy planning is enforced, establishing district heating priority zones. This leads to high connection rates in the range of 70-90% (depending on the level in the base year) and – as a consequence – it leads to reduced specific grid costs in terms of €/MWh.

For renewable e-fuels and H_2 in buildings, we assumed that no specific support measures are implemented. This follows the rationale that these high-exergy energy carriers should be used for high-exergy applications and not so much for low-temperature heating.

For space cooling, also in the pathway scenario we referred to a scenario developed in the above-mentioned study[83], i.e. the RES-C scenario, showing only a moderate increase of space cooling demand of about 50% by 2050 in EU-27. It implies a strong uptake of efficiency measures and passive cooling, in particular shading, free cooling and measures to allow higher indoor temperature levels at the same comfort level, e.g. by appropriate increase of air velocity.

In the Baseline scenario the share of systems with electrical energy input from the grid is high whereas in the Pathways scenario cooling generators which are powered by local renewable energy and waste heat experience a significant uptake, which further reduces the demand of delivered energy for cooling in the form of electricity. Main technology data as well as the share of technologies in the scenarios is shown in the annex.

6.2.4. Main input data and scenario assumptions for the industry sector

Overview

We use the FORECAST model to calculate scenarios for the transition of the industry sector. FORECAST is a bottom-up simulation model for analysing the long-term development of energy demand and emissions of the industry considering a broad range of mitigation options to reduce CO_2 emissions, combined with a high level of technological detail. The model requires a broad set of input data, which combines a variety of data sources. The model database was first developed in 2008 and since then has been continuously expanded and updated to reflect most recent developments, policies and statistics. If available, energy balances, employment, value added, and energy prices were calibrated to most recent Eurostat statistics. For a more detailed model description we refer to Fleiter et al. (2018)[86] and Rehfeldt et al. (2020)[87].

The main scenario assumptions include economic framework data, CO_2 and energy prices as well as policy and technology assumptions. These are described in the following for both scenarios.

Economic framework and production data

The economic forecasts (GDP and industrial gross value added) used in the Baseline scenario and the Pathway scenario, are defined in line with the most recent EU reference scenario (2020). An average annual growth rate in (gross) value added of around 1.6% p.a. is assumed for the industry until 2030, afterwards the growth rate declines to 0.8% p.a. The equipment goods industry (engineering) is projected to be growing at a steady higher pace compared to the energy-intensive basic industries. In addition, in the long run, a moderate decoupling of the value added and the physical production volumes in the basic industry is projected.

[86] Fleiter, T.; Rehfeldt, M.; Herbst, A.; Elsland, R.; Klingler, A.-L.; Manz, P.; Eidelloth, S. (2018): A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In: Energy Strategy Reviews, 22 (2018), S. 237-254.

[87] Rehfeldt, M.; Fleiter, T.; Herbst, A.; Eidelloth, S. (2020): Fuel switching as an option for medium-term emission reduction - A model-based analysis of reactions to price signals and regulatory action in German industry. In: Energy Policy 147, S. 111889. DOI: 10.1016/j.enpol.2020.111889.

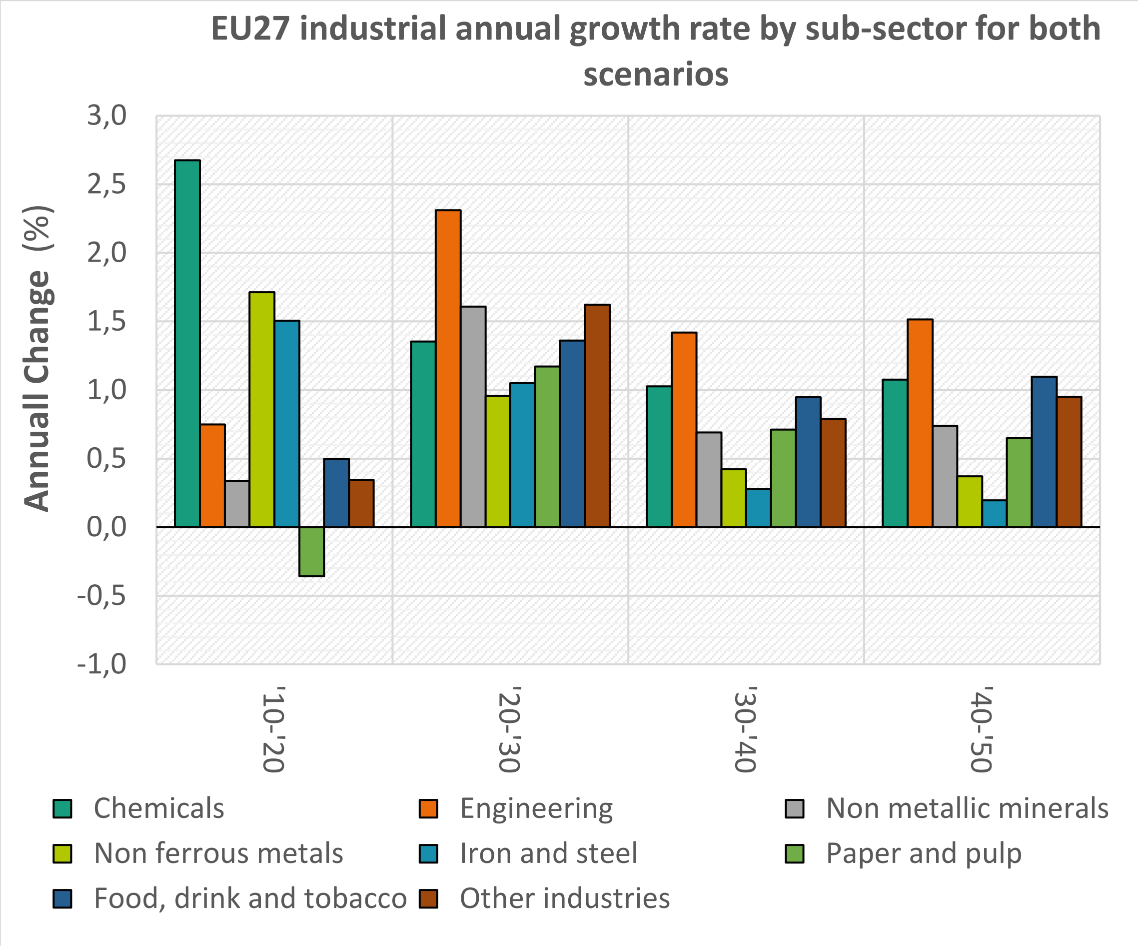


Figure 56: Development of industrial annual growth by subsector Primes Ref 2020.

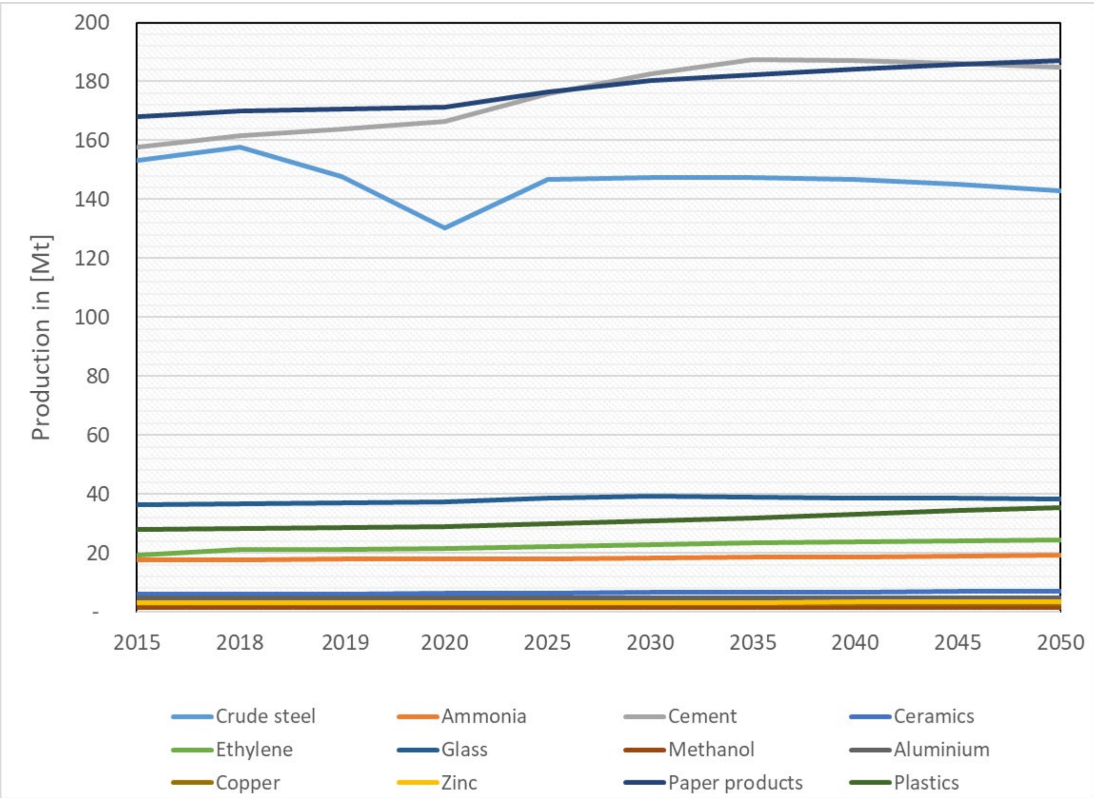


Figure 57: EU 27 Development of the production of the main industrial products (source: FORECAST)

CO_2 and energy carrier prices

A key exogenous input to the model are energy carrier prices, which include current taxes and levies for industrial users as well as CO_2 prices, because the FORECAST model makes choices for fuels, investments or energy efficiency measures largely based on cost-competitiveness. Figure 55 compares the projections of industrial energy prices over time for different energy carriers. The future evolution of energy prices follows the overall trends of the EU Reference Scenario 2020. Towards 2050 most fossil energy carriers show an increasing trend, while the electricity price decreases starting from 2030. In the pathway scenario, the energy carrier price was updated based on Eurostat until 2022, thus reflecting the current energy price peak.

The CO_2 price is an exogenous assumption, which affects the speed of fuel-switching and energy efficiency improvement. In the Baseline scenario, the CO_2 price for the EU ETS is at around 30€/tCO_2-eq in 2030, 80€/tCO_2-eq in 2040 and 150€/tCO_2-eq in 2050, which is in line with the EU reference scenario (2020). The pathway scenario assumes a higher CO_2 price for the EU ETS: around 110€/tCO_2-eq in 2030, 235€/tCO_2-eq in 2040, and 390€/tCO_2-eq in 2050. Furthermore, in the pathway scenario, we assume in addition a CO_2 price for the non-ETS industry sector. The trajectory of the non-ETS CO_2 price is assumed to be equal to the EU ETS price. This is needed in order to drive the fuel switch towards low-carbon energy carriers in the less energy-intensive industries like machinery, food, and others. In the Baseline scenario, we do not assume a CO_2 price for the non-ETS industries. Depending on the country, this can be 20 to 50% of industrial final energy demand that is not under a CO_2 price regime and thus lacking incentives for switching to low-carbon fuels (see policy section).

Policy and technology assumptions

Table 25 and Table 26 summarise the key technology assumptions for both scenarios. The Baseline scenario aims to capture today's level of policy implementation at the EU level, but does not yet include instruments that were proposed or are being discussed within e.g. the Fit for 55 package if they had not been implemented by January 2022. The Baseline scenario presents a narrative that strongly builds on energy efficiency. A fuel switch towards hydrogen is limited to some use in steel production and as feedstock in the chemical industry which is in line with the EU Hydrogen Strategy[88] and current company plans. The pathway scenario outlines a path that would allow the industry sector to reduce its GHG emissions by at least 95% by the year 2050 compared to 1990. In order to achieve this goal, the scenario assumes a significant expansion of policy support and regulation. It draws on a relatively balanced mix of mitigation strategies including energy and material efficiency, circularity, electrification, hydrogen, and carbon capture utilisation and storage (CCUS).

[88] European Commission (2020): A hydrogen strategy for a climate-neutral Europe. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

Table 25: Overview of the major technologies' assumptions for the industry

Measure	Assumption	
	Baseline Scenario	Pathway Scenario
Energy Efficiency	Fast deployment of best-available-techniques (BAT) efficiency	
Process innovation	No fundamental break-through; some technologies at high TRL above (6-7) will become available soon (e.g. H_2-based DRI steelmaking)	Diffusion of innovative technologies with Technology Readiness Level (TRL) above 4
Material strategies	Continuation of current trends in recycling but no fundamental switch to circular economy. Material efficiency along the value chain only improves in line with past trends	Ambitious progress
CCU/S	No CCU/S	CCU/S where no technical alternative with TRL higher than 4 available -> Cement and lime industries
Fuel switch	Driven by costs and prices	Driven by costs and prices to fully phase out fossils

Table 26: Overview of the major technology assumptions for specific products in the industry in the scenario

Product	Scenario	Process switch	Material strategies	CCS
Steel	baseline	32% of the primary steel production is produced through H-DR by 2050	Increase EAF share of the total steel production from 41% (2019) to 45% by 2050, and more efficient steel use and substitution result in a 7% decrease in the total production	-
	pathway	100% of the primary steel production is produced in H-DR by 2050	High-quality EAF, increase EAF share from 41% (2019) to 61% by 2050.	-
Cement and lime	baseline	BAT efficiency	Decrease in the clinker share from 78% to 64%. 13% increase in the total production by 2030.	-
	pathway	Low-carbon types of cement enter the market and substitute around 15% by 2050, BAT efficiency	An ambitious decrease in the clinker share by 58%, efficient concrete use and substitution, concrete recycling, and re-use result in a 5% decrease in production by 2050.	CCS for lime and clinker
Chemicals	baseline	BAT efficiency, 60% feedstock H_2 for ammonia	A slow increase in plastics recycling	-
	pathway	100% feedstock H_2 for methanol, ethylene, and ammonia	A higher increase in plastics recycling, plastics substitution, reduced fertiliser demand, and more efficient material use.	-

Product	Scenario	Process switch	Material strategies	CCS
Glass	baseline	BAT energy efficiency	A slow increase in recycling	-
	pathway	70% electric furnaces by 2050	Increase flat glass recycling and more efficient glass use	-
Paper	baseline	BAT energy efficiency	Ambitious recycling	
	pathway	Innovative efficiency (paper drying, enzymatic pre-treatment, black liquor gasification)	Ambitious recycling	

Policies in the Pathway scenario and country-specific considerations

Table 27 summarises the main policy assumptions and their connection to technology parameters. It also shows how differentiation in Member States is included in the model. It is important to keep in mind that the model approach allows some policies to be fully endogenously modelled, like energy or CO_2 prices, but others are more exogenous like material efficiency or circularity. Differentiation by Member States can, in many cases, be done based on endogenous consideration of e.g. industrial structure of energy prices. In other cases, however, less knowledge is available about differences between countries, e.g. when it comes to national policies.

Table 27: Policy assumptions for the industry sector in the Pathway scenario linking to country differences

Strategy	Policy assumptions	Technology and other assumptions	Differentiation by Member State
Energy and material efficiency and circularity	Effective implementation of circular economy action plan. Break-through in material efficiency via among others: Transparent tracking and labelling of embodied carbon emissions along the value chain. Demand-side pull: green product markets. Pass-through of carbon costs along value chain.	Ambitious progress, in particular for basic materials like steel, plastics, cement, glass	Differences among Member States emerge via different industrial structures and different starting points in terms of shares of secondary materials (e.g. electric steel). No differences in energy or material efficiency progress, because no empirical data
Electrification of process heat	Revision of energy taxes from taxing electricity to taxing carbon/fossils. Short-term programmes to expand electric and hybrid steam generation systems.	Strong electrification of process heating involving substantial replacement of existing furnaces, boilers and CHP units.	Differentiation is based on current price spreads between gas and electricity.

Strategy	Policy assumptions	Technology and other assumptions	Differentiation by Member State
	Strengthening of electricity transport infrastructure and preparing for higher electric loads at industry consumers. Ambitious increase in RES-E across Europe.	Hybrid systems to increase flexibility and reduce uncertainty	
Hydrogen for process heat	Transparent and specific hydrogen strategy including plans for the infrastructure expansion to reduce uncertainty among industrial consumers when and if hydrogen will be locally available. Financial support for industries switching to hydrogen to account for higher energy expenses compared to gas or coal.	Strong hydrogen focus for chemicals (feedstocks) and steel, but also potential use across other industries	Differences via industrial structure and hydrogen availability in chemical and steel industry. Countries that need to build up hydrogen infrastructure for these two industries are more likely to also use hydrogen for process heating in other industries.
CCU and CCS	Adopt strategy to build up pan-European CO_2 transport and storage infrastructure to connect CO_2 hot-spots with storage and possible uses Political and societal consensus for CCS in industry in all Member States Adopted framework for balancing and monitoring negative CO_2 emissions	Diffusion of carbon capture in cement and lime industries and connection with offshore storage and uses in chemical industry BECCS as possible strategy for negative CO_2	Differences via industrial structure, more particularly the importance of the cement and lime industry
Biomass use	Prioritise cascading use of biomass starting with construction material and industry feedstock For energetic use, focus on production residues (e.g. wood processing industries). No support to use biomass in process heat. Reconsider carbon neutrality of biomass in existing legislation.	Limit biomass use to today's use levels, which mainly is production residues.	Strongly determined by today's structure of paper industry Only countries with good biomass resource will use this strategy
Diffusion of near CO_2-neutral processes: Cross-cutting policies	• High EU ETS price trajectory (min 150 euro in 2030) • ETS innovation fund that also allows support beyond first-of-a-kind implementation • Functioning carbon border adjustment mechanism (CBAM)		

Strategy	Policy assumptions	Technology and other assumptions	Differentiation by Member State
	• Substantial national funding via national programmes, carbon contracts for difference (CCfDs) and IPCEIs • Ensuring clear directionality and trust towards CO_2 neutrality to allow large-scale strategic investments		
Industrial policy	• Industrial strategy aims to keep basic material producers in Europe		

Country-specific assumptions were made for the support of hydrogen and electrification in the pathway scenario. These are closely linked to how the FORECAST model decides on new investments. The fuel switch in FORECAST is modelled using a discrete choice approach: Basically, the choice for energy carriers is determined by their cost as well as other residual parameters that include many more qualitative determinants including the dynamics or inertia of technical changes, perceived security of supply, the handling of energy carriers or simply the infrastructural availability. A more detailed description of the method is available in Fleiter et al. (2018)[89] and Rehfeldt et al. (2018)[90].

Countries with a large chemical and steel industry will require hydrogen for CO_2-neutral production. These countries will need to invest in hydrogen supply anyway and will need to build up transport infrastructures. Here, we assume that in these countries hydrogen is also more attractive to other process heating uses. Therefore, we increase the attractiveness of hydrogen as compared to other countries. This covers the countries Austria, Belgium, Czech Republic, Finland, Germany, Lithuania, Netherlands, Slovakia, and Sweden.

Furthermore, in Croatia, France, Hungary, Italy, Poland, Romania, and Spain hydrogen is less favoured as an energy carrier choice for high-temperature processes. As a result, it is assumed that the attractiveness (price sensitivity and infrastructure) of hydrogen has medium attractiveness. while for Bulgaria, Cyprus, Denmark, Estonia, Greece, Ireland, Latvia, Luxembourg, Malta, Portugal, and Slovenia hydrogen has a low attractiveness.

6.2.5. Main input data and scenario assumptions for the district heating sector

The modelling of district heating consists of three parts:

- Modelling the DH expansion: Future possible DH areas are identified, based on distribution costs.
- Renewable and waste heat potentials for district heating generation: Identified biomass and geothermal potentials (see Chapter 3) are processed and mapped.

[89] Fleiter, T.; Rehfeldt, M.; Herbst, A.; Elsland, R.; Klingler, A.-L.; Manz, P.; Eidelloth, S. (2018): A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In: Energy Strategy Reviews, 22 (2018), S. 237-254.

[90] Rehfeldt, M.; Fleiter, T.; Worrell, E. (2018): Inter-fuel substitution in European industry: A random utility approach on industrial heat demand. In: Journal of Cleaner Production, June 2018, pp. 98 - 110. https://doi.org/10.1016/j.jclepro.2018.03.179 .

Other renewable and waste heat sources are identified, calculated and mapped in high spatial resolution. These potentials are spatially mapped to future possible DH areas.

- Modelling the DH supply mix: The optimal DH generation mix and dispatch is calculated with the focus on 2050. For each MS, up to five different DH clusters are modelled reflecting typical renewable and waste heat potentials available.

(i) Modelling the DH expansion

Main input data for the **DH expansion model** are:

- Assumptions for the costs of DH expansion
- Assumptions for the market shares and distribution cost thresholds

For spatial mapping of DH areas and potentials as well as for temperature and irradiation profiles, the Local Administrative Unit classification (LAU) and the NUTS classification were used[91]. For the identification of potential DH areas in EU Member States, evolving heat demand and DH market shares from 2020 to 2050 were considered. Accordingly, an area is identified as a potential DH area if its average DH network costs (distribution grid and service pipes) is below a pre-defined threshold. In case of the baseline scenario, only those areas could have been identified as potential DH areas that had an annual heat demand of at least 10 GWh. Details of the methodology and consideration of the evolving demand and DH market shares are explained thoroughly in Annex B. The market share values (definded as shares on total stock and not annual installations) in 2020 are assigned based on the existing energy values delivered [92]. In order to derive the district heating expansion of the reference scenario provided by the Invert/EE-Lab model (which is a reimplementation of the Primes reference scenario), we used the market share values along with the cost ceiling parameter to calibrate the DH expansion model for each country. All of these values were compared with the values in the literature[93]. Based on the baseline scenario, no DH development is expected in Cyprus, Ireland, Malta and Spain.

[91] https://gisco-services.ec.europa.eu/distribution/v2/lau/geojson/LAU_RG_01M_2019_3035.geojson and https://gisco-services.ec.europa.eu/distribution/v2/nuts/geojson/NUTS_RG_01M_2021_3035_LEVL_0.geojson

[92] The existing market shares are defined by the heating degree day corrected district heating demand in the residential and commercial sector according to the energy balances provided by Eurostat, divided by the calculated final energy demand for space heating and domestic hot water preparation.

[93] See e.g. Persson, U. (2021). Assessment of DH connection rates for 2015 (Internal promemoria, not published). Based on the Halmstad University District Heating and Cooling Database_version 5 (HUDHC_v5: 2016 update by date 2019-09-30). Halmstad University, Sweden.

Table 28: Summary of input parameters (baseline scenario)

	Total demand [GWh]		DH market share in DH areas [%]		Cost ceiling [EUR/MWh]
Country	2020	2050	2020	2050	
AT	84,200	70,862	55.0%	53.0%	30
BE	115,203	90,508	15.0%	13.0%	28
BG	24,331	19,946	64.0%	46.0%	32
CY	2,656	2,380	0.0%	0.0%	N/A
CZ	92,259	88,056	44.0%	44.0%	29
DE	805,824	649,205	32.0%	32.0%	30
DK	58,773	58,215	88.0%	72.0%	33
EE	12,529	11,287	58.0%	56.0%	30
ES	145,749	130,862	0.0%	0.0%	N/A
FI	76,562	74,980	63.0%	63.0%	31
FR	487,490	477,148	15.0%	46.0%	34
EL	38,458	36,777	29.0%	20.0%	26
HR	25,186	19,297	37.0%	36.0%	27
HU	80,035	68,117	33.0%	38.0%	25
IE	34,008	30,926	0.0%	0.0%	N/A
IT	383,381	343,432	17.0%	36.0%	30
LT	17,409	13,793	78.0%	90.0%	27
LU	7,823	7,433	29.0%	31.0%	27
LV	15,363	12,587	57.0%	57.0%	27
MT	837	734	0.0%	0.0%	N/A
NL	135,620	124,158	26.0%	33.0%	32
PL	244,171	254,784	51.0%	47.0%	26
PT	27,928	23,093	33.0%	34.0%	34

	Total demand [GWh]		DH market share in DH areas [%]		Cost ceiling [EUR/MWh]
Country	2020	2050	2020	2050	
RO	83,830	68,780	43.0%	52.0%	27
SE	86,180	93,469	86.0%	54.0%	35
SI	12,210	11,960	52.0%	58.0%	26
SK	30,764	26,039	74.0%	51.0%	27

The results of the DH expansion model for the baseline scenario, using the input parameters presented in the table above, are summarised in Table 29. Based on the baseline scenario, an average network cost of 26.6 EUR/MWh can be expected for EU27. Generally, the average network costs in the Member States lies between 23 and 30 EUR/MWh. The average network costs in the Netherlands and Portugal are relatively higher than in other Member States. This is due to the fact that these countries have a low starting market share, leading to lower heat supply over the period of 2020 to 2050 and – in connection with lower connection rates - higher average network costs. An opposite situation is imposed by the scenario for the case of Sweden, where a decrease in the market share through the investment period leads to higher average network costs. Three Member States, namely Estonia, Latvia and Luxembourg, have relatively low average network costs. This is due to the fact that heat demand density within DH areas in these countries is very high and the DH market share remains high through the study horizon. Furthermore, it should be noted that no DH areas with an annual heat demand of below 10 GWh/year were considered in this calculation.

Table 29: Results of running the model with above input parameters (baseline scenario)

	Demand in DH areas [GWh]		Share of heat demand in DH areas from total demand [%]		DH share from total demand [%]		Demand covered by DH [GWh]		Average network costs
Country	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**[EUR/ MWh]**
AT	32,760	26,042	38.9%	36.8%	21.4%	19.5%	18,018	13,803	23.9
BE	7,928	5,973	6.9%	6.6%	1.0%	0.9%	1,189	777	28.0
BG	7,818	7,211	32.1%	36.2%	20.6%	16.6%	5,004	3,317	28.6
CY									

	Demand in DH areas [GWh]		Share of heat demand in DH areas from total demand [%]		DH share from total demand [%]		Demand covered by DH [GWh]		Average network costs
Country	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**[EUR/ MWh]**
CZ	39,590	37,537	42.9%	42.6%	18.9%	18.8%	17,420	16,516	24.6
DE	207,100	168,342	25.7%	25.9%	8.2%	8.3%	66,272	53,869	28.7
DK	28,625	26,559	48.7%	45.6%	48.8%	37.4%	28,666	21,790	27.6
EE	8,660	7,701	69.1%	68.2%	40.1%	38.2%	5,023	4,312	12.1
ES									
FI	52,225	50,277	68.2%	67.1%	43.0%	42.2%	32,902	31,675	26.7
FR	161,004	154,476	33.0%	32.4%	5.0%	14.9%	24,151	71,059	28.7
EL	1,957	1,930	5.1%	5.2%	1.5%	1.0%	568	386	25.7
HR	4,805	3,948	19.1%	20.5%	7.1%	7.4%	1,778	1,421	26.9
HU	23,182	19,704	29.0%	28.9%	9.6%	11.0%	7,650	7,487	24.3
IE									
IT	91,386	81,030	23.8%	23.6%	4.1%	8.5%	15,536	29,171	29.3
LT	10,052	7,961	57.7%	57.7%	45.0%	51.9%	7,841	7,165	13.8
LU	3,489	3,068	44.6%	41.3%	12.9%	12.8%	1,012	951	25.6
LV	10,525	8,489	68.5%	67.4%	39.0%	38.4%	5,999	4,838	15.1
MT									
NL	22,554	22,426	16.6%	18.1%	4.3%	6.0%	5,864	7,401	31.0
PL	119,065	121,774	48.8%	47.8%	24.9%	22.5%	60,723	57,234	24.6
PT	962	832	3.4%	3.6%	1.1%	1.2%	317	283	33.1
RO	26,734	23,883	31.9%	34.7%	13.7%	18.1%	11,496	12,419	24.9
SE	54,057	55,896	62.7%	59.8%	53.9%	32.3%	46,489	30,184	30.0
SI	2,764	2,762	22.6%	23.1%	11.8%	13.4%	1,437	1,602	25.8

	Demand in DH areas [GWh]		Share of heat demand in DH areas from total demand [%]		DH share from total demand [%]		Demand covered by DH [GWh]		Average network costs
Country	2020	2050	2020	2050	2020	2050	2020	2050	[EUR/ MWh]
SK	9,501	8,083	30.9%	31.0%	22.9%	15.8%	7,031	4,122	25.2
Total	**926,742**	**845,905**	**29.6%**	**30.1%**	**11.9%**	**13.6%**	**372,383**	**381,782**	**26.6**

(ii) Renewable and waste heat potentials for district heating generation

A decarbonised district heating supply can be achieved by utilising available renewable or waste heat sources. The most important renewable heat sources are solar thermal, deep geothermal, biomass and ambient heat from the air, water resources or near surface ground sources. Waste heat, even with lower temperatures, can be utilised in district heating, stemming from industrial plants, thermal treatment of waste (Waste-to-Energy), and also from the treatment of waste water (temperature of the sewage water and biomass in sludge). Heat sources with low temperature combined with a heat pump are suitable also for district heating systems with high system temperatures up to 90°C (water temperature that is provided to the connected houses), but are more efficient with a lower system temperature.

In the following, an overview of the different input data for the modelling of district heating (DH) generation in high spatial and temporal resolution is provided, as well as the data processing and spatial allocation is described. For detailed information on the technical assumptions for the potentials, the reader is referred to Annex C3.

From Chapter 3, the spatial data on deep geothermal temperatures, locations of underground aquifers and biomass potentials are used to calculate technical potentials for DH generation. Futher data sources are included for other potentials (see Table 30). The geothermal data from task 1 were provided as temperature data in the underground in the resolution of 1000 x 1000m, as spatial data (raster format). Additionally, the locations of hydrothermal potential reservoirs are identified and provided as spatial data (vector format). These two data sets were combined to calculate the technical geothermal potentials, separated by hydro- and petrothermal technology, based on typical flow rates and other parameters. The biomass potentials for DH were provided as conditioned biomass potentials per NUTS2 region from task 1. These potentials were used directly as technical potentials, and mapped to the corresponding DH areas, that lie within the NUTS 2 region, assuming that these biomass potentials for DH can be utilised regionally.

Table 30: Generation potentials in the DH areas

Generation Potential	Spatial resolution (grid size)	Temporal resolution	Temperature level considered	Source
Geothermal (petro- and hydrothermal)	1000 x 1000m	Annual, full load hours considered	> 60 °C	Task 1: Geothermal Atlas[94], GeoDH[95]
Biomass	NUTS 2	Annual	Direct combustion/biogas	Task 1: ENSPRESO - Biomass (JRC)[96]
Industrial waste heat	Coordinates	Annual, monthly profile considered	> 55 °C	ISI Industrial Database[97]
Wastewater treatment	Coordinates	Annual	10-25 °C	Peta 5[98]/Hotmaps[99]
Waste-to-energy plants	Coordinates	Annual	100 °C	Peta 5
Rivers and lakes	5000 x 5000m	Annual, full load hours considered	2-8 °C	Copernicus[100]

Figure 58 depicts these potentials, i.e. technical potentials for geothermal heat (hydrothermal and petrothermal potentials with the minimum temperature of 65°C or 85°C in the underground), heat from rivers and lakes, wastewater treatment plants and waste heat from industrial sites and waste incineration plants (waste-to-energy, WtE) in Europe for the baseline scenario. Solar and roundwood biomass potentials as well as air source heat pumps were not assumed to be limited by spatial availability and therefore not mapped. The technical potentials are visualised based on the amount of energy they could provide per year, which was used for the mapping to the DH areas. The minimum temperature for geothermal projects was assumed at 85°C for the baseline, and at 65°C for the policy scenario.

---

[94] European Commission, Atlas of Geothermal Resources in Europe, 2002.

[95] Geothermal District Heating project (GeoDH) - Map: https://map.mbfsz.gov.hu/geo_DH/

[96] JRC-EU-TIMES - JRC TIMES energy system model for the EU: https://doi.org/10.5281/zenodo.3544900. 2019.

[97] P. Manz, K. Kermeli, U. Persson, M. Neuwirth, T. Fleiter, W. Crijns-Graus, Decarbonizing District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites?, Sustainability 13 (2021) 1439. https://doi.org/10.3390/su13031439.

[98] Europa-Universität Flensburg, Halmstad University, Aalborg University, Pan-European Thermal Atlas 5.1 (PETA 5.1), sEEnergies, 2021.

[99] https://www.hotmaps-project.eu/

[100] Copernicus, Copernicus Climate Change Service Information: Hydrology-related climate impact indicators from 1970 to 2100 derived from bias adjusted European climate projections, European Commission, 2021.

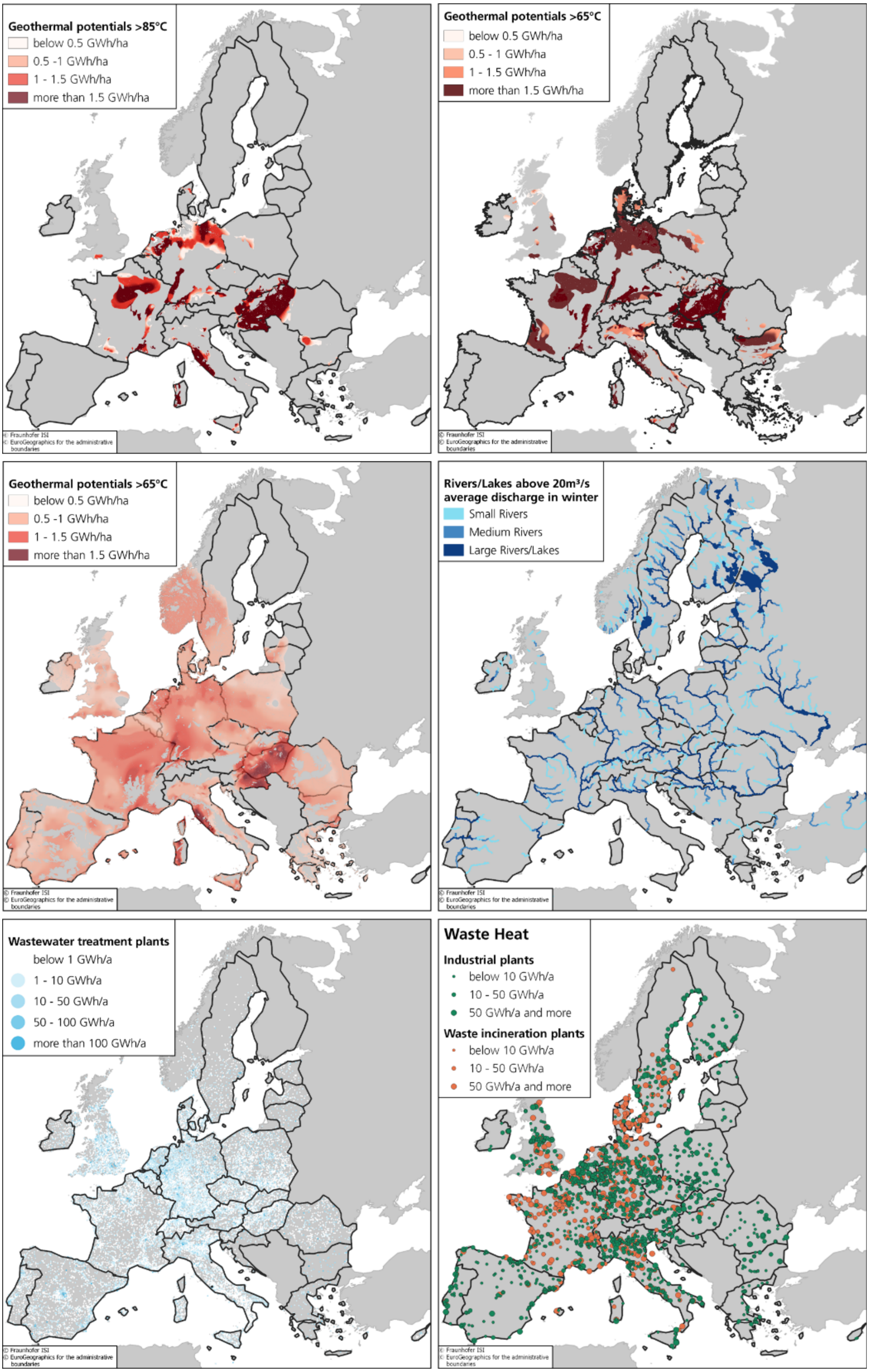


Figure 58: Technical RES and waste heat potentials for DH utilisation in EU in the baseline scenario

The potentials of solar thermal and ambient heat utilised in heat pumps were not mapped, instead it is assumed they are not limited by spatial availability.

The open-source software QGIS is used for the mapping of the identified regional heat potentials with the DH areas identified in step (i): Modelling the DH expansion. These data are transferred in the format of shapefiles, identifying potential DH areas in 2050 for the baseline and policy scenario, together with the heat demand served by DH. Distribution losses in the grid are added to the annual heat demand, resulting in the needed heat supply of the DH generation. A minimum distance was defined for each of the potentials (the reader is referred to Annex C3 for more details). Based on this distance, for each of the point sources of renewable or waste heat, the closest DH area was calculated that is within this distance. Additionally, for sites with high waste heat (WtE plants and industrial sites with excess heat), DH areas with high annual heat demands are prioritised and sequenced, taking into account the distance and heat demand of each potential DH area. The result of the mapping algorithm is a table-based list of the DH areas, with the cumulated annual renewable or waste heat potential. These spatial available technical potentials are used as the input to the clustering of DH areas.

Other low-temperature waste heat sources are not included, even though these could provide a considerable share for waste heat utilisation on a regional level. Especially non-energy-intensive industries, service sector (hospitals, cooling, server centres) or metro stations could provide waste heat, often on a low-temperature level. Combined with a heat pump, they are comparable with air source heat pumps that are assumed here, decreasing costs by improving the efficiency.

(iii) Modelling the DH supply mix

For modelling the DH generation, **the DH supply optimisation model** requires the following input data to optimise DH generation investments and dispatch in 2050: techno-economic data for the heat generation technologies, energy carrier prices, system temperatures and hourly profiles for RES and waste heat potentials as well as for the DH demand of the DH areas identified in the previous step.

The technological data includes data for different boilers, CHP plants and renewables. OPEX and CAPEX, efficiencies, lifetimes are based on Task 2 from Braungardt et al. (2022) (RES Heat project[101]). For waste-to-energy, it was assumed that it provides the baseload if available.

The energy carrier prices for DH generation in 2050 consist of wholesale prices and surcharges like taxes and grid fees. The hourly electricity prices are based on results from the ongoing Elec Heat project[102]. The respective scenarios are chosen for the baseline and pathways scenarios (reference and anchor scenario).

The temperature level of DH grids is decisive for the efficient utilisation of low-temperature renewable and waste heat sources. In 2050, it was assumed that the temperature is similar to the current level for the baseline scenario (flow temperature 90 to 70°C), while in the pathway scenario a decrease of system temperature is assumed (flow temperature 60 to 70°C).

[101] Renewable Space Heating under the Revised Renewable Energy Directive (ENER/C1/2018-494)

[102] Potentials and levels for the electrification of space heating in buildings (ENER/C1/2019-481)

The hourly profiles for weather data like ambient temperature and irradiation are taken from the JRC data set[103] with a resolution of LAU2. The heating profiles are taken from Hotmaps load profiles[104], with a resolution of NUTS 2. In the clustering and aggregation of DH areas, the profiles consider the demand modelled for DH in the LAU2 regions.

In the baseline scenario the potentials of the following RES sources are included: hydrothermal (direct), wastewater (with heat pump), waste-to-energy (CHP), industrial excess heat (direct), rivers and lakes (with heat pump). Biomass is not spatially allocated and it is assumed that biomass use is reduced to 50% of the current use in the Member States. Solar thermal energy as well as air source heat pumps are also not spatially allocated and the deployment is not restricted in the modelled scenarios. For solar thermal a minimum level in line with the current use is assumed.

In the pathways scenario, in addition to the potentials of the baseline scenario, petrothermal energy is included. Furthermore, biomass and biomethane are included (based on task 1) and allocated. Biomethane is based on biomass as well as sludge from wastewater treatment (e.g. in anaerob digesters).

6.3. Space and water heating and cooling in the building stock (Invert)

In the following chapters we present the sectoral model results for buildings, industry and district heating. Subsequently, a consolidated view for the whole heating and cooling sector is discussed.

6.3.1. Baseline scenario

The final energy demand for space heating, cooling and domestic hot water preparation in residential and tertiary buildings amounts to about 3340 TWh for the EU-27 countries in 2020. In the baseline scenario, the final energy consumption decreases until 2050 to about 2800 TWh. While the share of solid and liquid energy carriers decreases, they still hold a share of about one third of final energy demand in 2050. The share of heat pumps and solar increases (together about one third of final energy demand in 2050) and the share of biomass and district heating remains on a more or less constant level. The electricity demand for cooling increases significantly and holds a share of 10% of total final energy demand by 2050. Overall, the scenario fails to take up efficiency potentials and fails to decarbonise (unless huge amounts of synthetic gases and liquids would be supplied, which however was not assumed in this scenario).

The baseline scenario results on MS-level for 2050 (Figure 60) in comparison with the base year (Figure 59) shows the inertia of the stock of heating systems and related energy carriers which dominates the baseline scenario. Countries with a currently strong focus on fuel oil and gas still have a high share of these fuels in 2050 (e.g. BE, DE, IE, NL), countries with a long district heating tradition continue to show high shares of district heating (mainly Scandinavian and Baltic countries), and countries with a currently significant share of

[103] 'Typical Meteorological Data access service', European Commission, Joint Research Centre, 2017 (updated 2017-07-24), http://data.europa.eu/89h/jrc-tmy-tmy-download-service

[104] https://www.hotmaps-project.eu/

biomass continue to use biomass for space and water heating (e.g. AT, the Baltic countries, PT).

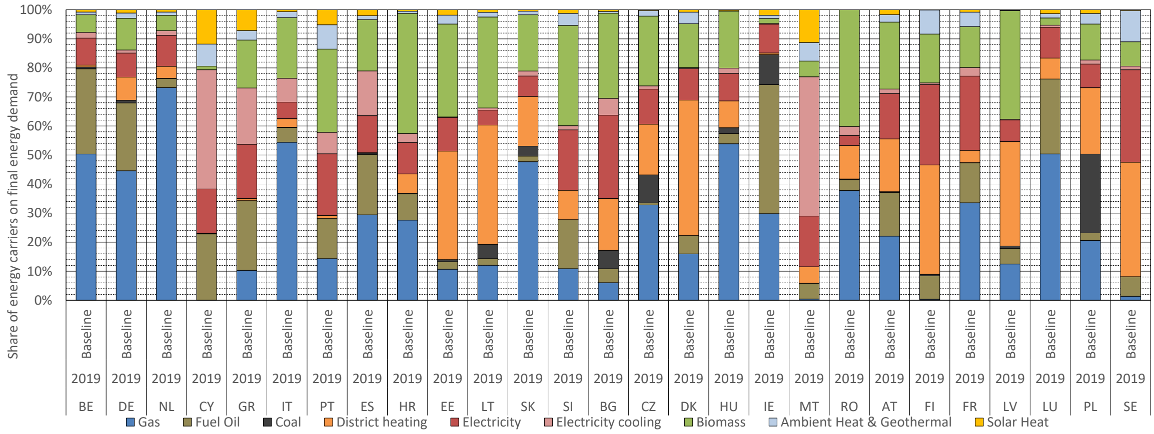


Figure 59: Share of energy carriers in final energy demand for space heating, cooling and hot water in residential and tertiary buildings by EU-27 Member States, baseline scenario, 2019[105]

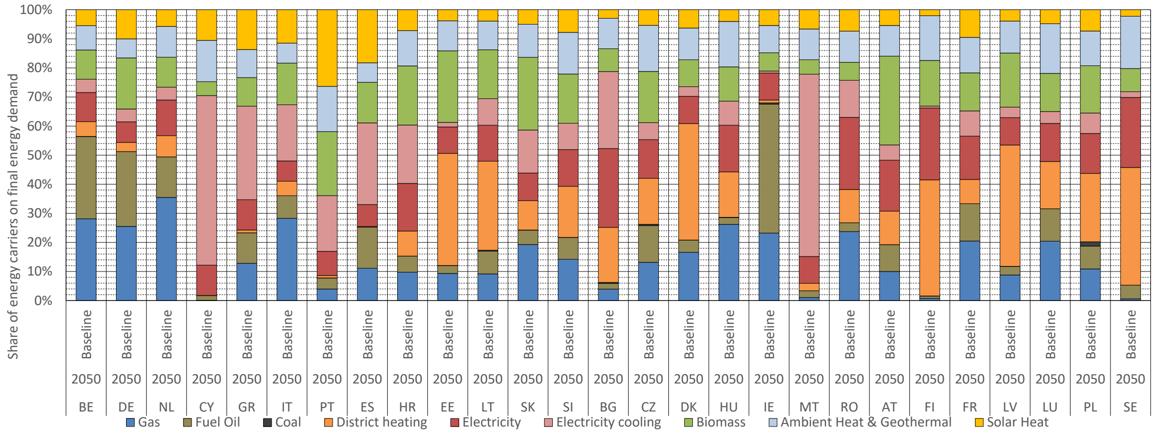


Figure 60: Share of energy carriers in final energy demand for space heating, cooling and hot water in residential and tertiary buildings by EU-27 Member States, baseline scenario, 2050

6.3.2. Decarbonisation pathway scenario

The decarbonisation pathway scenario achieves significantly higher efficiency gains through building renovation, mainly triggered by the ambitious implementation of renovation obligations (minimum energy performance standards). This results in a final energy demand for space heating, cooling and hot water of 2000 TWh in 2050.

The transition towards renewable heating systems, not based on gases and liquids, is achieved by stringent regulatory instruments for the gas and oil phase-out (see Section 5.2.4).

While the use of biomass is restricted, assuming that this resource is more and more needed for materials and higher-exergetic end uses, a strong increase in heat pump capacities takes place and in particular in southern countries solar energy. The share of district heating doubles from the base year until 2050. Due to the strong uptake of heat pumps and solar, the energy delivered (i.e. total final energy demand minus solar and

[105] The countries are ordered according to the clustering result presented in Figure 65.

ambient energy supply) decreases from 3200 TWh in the base year to about 1250 TWh in 2050.

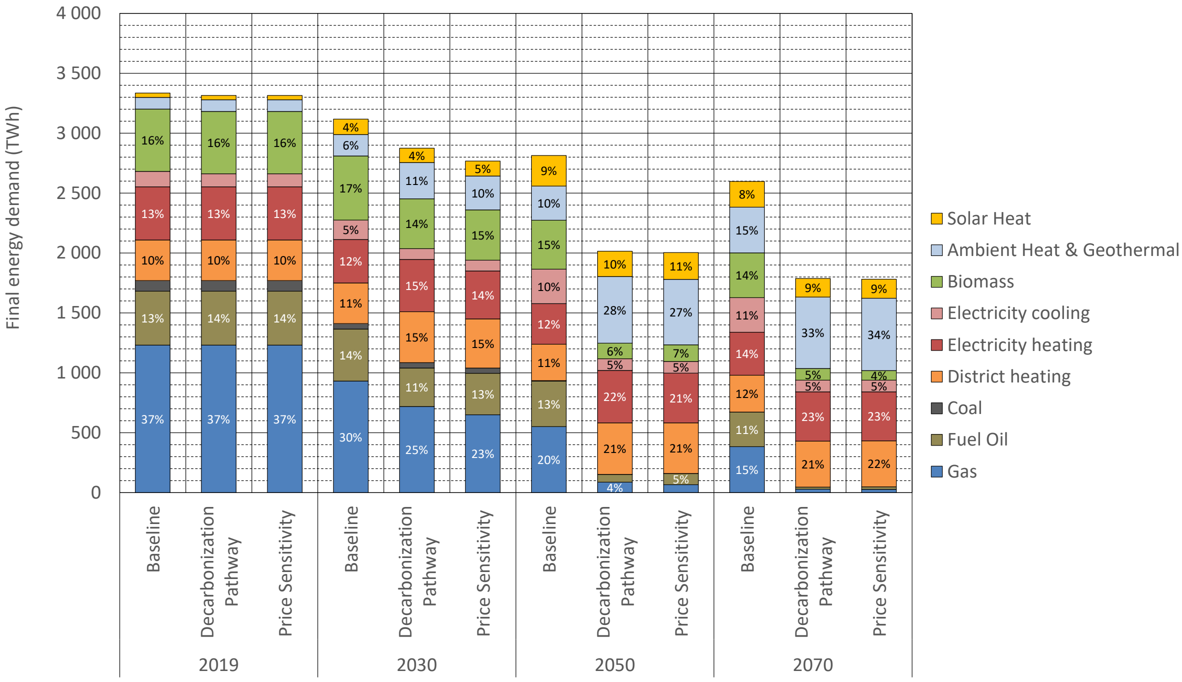


Figure 61: Final energy demand for space heating, cooling and hot water in residential and tertiary buildings, EU-27 in scenarios up to 2070

Overall, the scenario achieves full decarbonisation by strong regulatory policies for building insulation and the phase-out of gases and liquids (see policy package described in Section 5.2.4). The share of gases and liquids in this scenario declines to only 7% of final energy demand in 2050, or 9% of the demand for gas and liquids in the base year. The scenario assumes that this remaining share of gases and liquids is provided by renewable fuels such as e-fuels or biomethane. The modelling shows that the considerable increase in building retrofitting measures, heat pumps, solar and district heating requires very stringent regulatory measures and a complete paradigm shift in the choice of heating systems and the quality of building construction and renovation works.

It is worth emphasising that despite the huge increase of heat pumps, the electricity consumption of this sector can be kept on a similar level in 2050 as it was in the base year 2019. The main reason is that in the base year, a significant share (13%) of the final energy demand for space heating and hot water is covered by electricity, of which most is used for direct electric resistance heating. By phasing out these inefficient direct electric resistant heaters and by increasing the share of heat pumps, a much higher share of buildings can be heated, using approximately the same amount of electricity in the sector as it is today. Of course, this also requires the uptake of renovation measures as modelled in this scenario, first to reduce the space heating energy needs and second to achieve low supply temperature levels and thus correspondingly high seasonal COPs of heat pumps.

Figure 62 shows that there are still significant differences in the energy mix of the sector in this scenario in 2050. However, the strong increase of heat pumps and at least a certain share of solar heat are robust tendencies across all Member States. Moreover, district heating increases in most Member States, depending on the heat densitities, cheap renewable district heat potentials and policies to achieve high connection rates in district heating areas.

In the baseline scenario, the share of cooling strongly increases to 10% of the total final energy demand for H&C in buildings in 2050. In contrast, in the decarbonisation pathway scenario, substantial efforts of passive and free cooling measures are assumed to be implemented, stabilising the final energy demand for cooling. However, the differences between Member States are significant. Even in the decarbonisation scenario, in some countries (CY, ES, GR, MT) the share of cooling in final energy demand is about 20% or higher. In terms of energy delivered (i.e. subtracting ambient and solar heat), the share in these countries is even 1/3 to more than 50%.

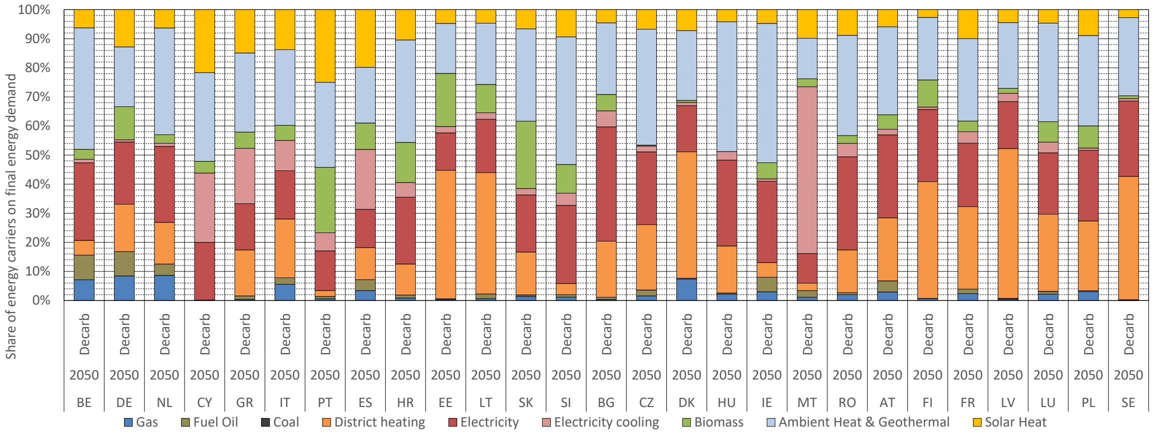


Figure 62: Share of energy carriers in final energy demand for space heating, cooling and hot water in residential and tertiary buildings by EU-27 Member States, decarbonisation pathway scenario, 2050

The price sensitivity run shows changes mainly in the period around 2030 whereas in 2050, when the energy prices are again on the same level in the decarbonisation pathway and in the price sensitivity scenario, the results are rather similar. The main reason for that are the stringent regulatory policies which in the pathway scenario enforce a strong uptake of building retrofitting measures anyway and fossil fuel phase-out policies. Thus, the price signal does not provide much incentive for a change in energy carriers (despite of a slight shift from gas to oil, biomass and solar). Rather, the main effect resulting from the price increase are short-term behavioural changes, forcing occupants to lower effective indoor temperature levels during the heating season.[106]

The outlook until the year 2070 indicates that in the baseline scenario building renovation activities and fossil heating system replacement continues after 2050, but the speed is not sufficient to achieve carbon neutrality even in 2070. 40% of the gas and fuel oil demand in the base year still remains in the system by 2070. In the decarbonisation scenario, it turns out that still not the full potential of efficiency improvements was achieved by 2050, i.e. further building renovation and heating system replacement leads to even lower energy demand levels and an almost complete phase-out of gases and liquids by 2070. Final and delivered energy demand decrease to 1700 TWh and to less than 1000 TWh, respectively, by 2070.

[106] The model Invert/EE-Lab includes endogenous short-term price elasticities reflecting user behaviour and their choice for lower indoor temperature levels triggered through energy price increases.

In order to illustrate the dynamics of building retrofitting and achieved energy savings, Figure 63 and Figure 64 show the floor area of existing buildings which are not renovated between 2019 and 2070 (in black), buildings which are renovated but only undergo maintenance measures, i.e. no improvement of buildings' energy performance (in grey), buildings which are renovated (in blue) and new building construction (in red), as well as their corresponding specific energy needs for space heating and the savings after building renovation (in green).

In the case of Sweden and Luxembourg (Figure 63) we see a strong increase in the heated floor area of about 60% (SE) and more than 70% for Luxembourg. In addition, both countries show a low thermal renovation rate in the baseline scenario, which derives from the historical data on which the baseline runs have been calibrated. France's stronger decrease derives from a lower growth of newly constructed buildings and a higher share of thermal renovation acitivities compared to Luxembourg and higher energy saving rates compared to Sweden in the baseline scenario. The development of energy consumption levels of the two countries depicted with higher energy savings already in the baseline scenario (Italy and Bulgaria, Figure 64) is strongly driven by no additional heated floor areas, high refurbishment rates in the baseline scenario and in the case of Bulgaria, rather high initial energy needs per heated floor area considering the mild climate conditions of Bulgaria.

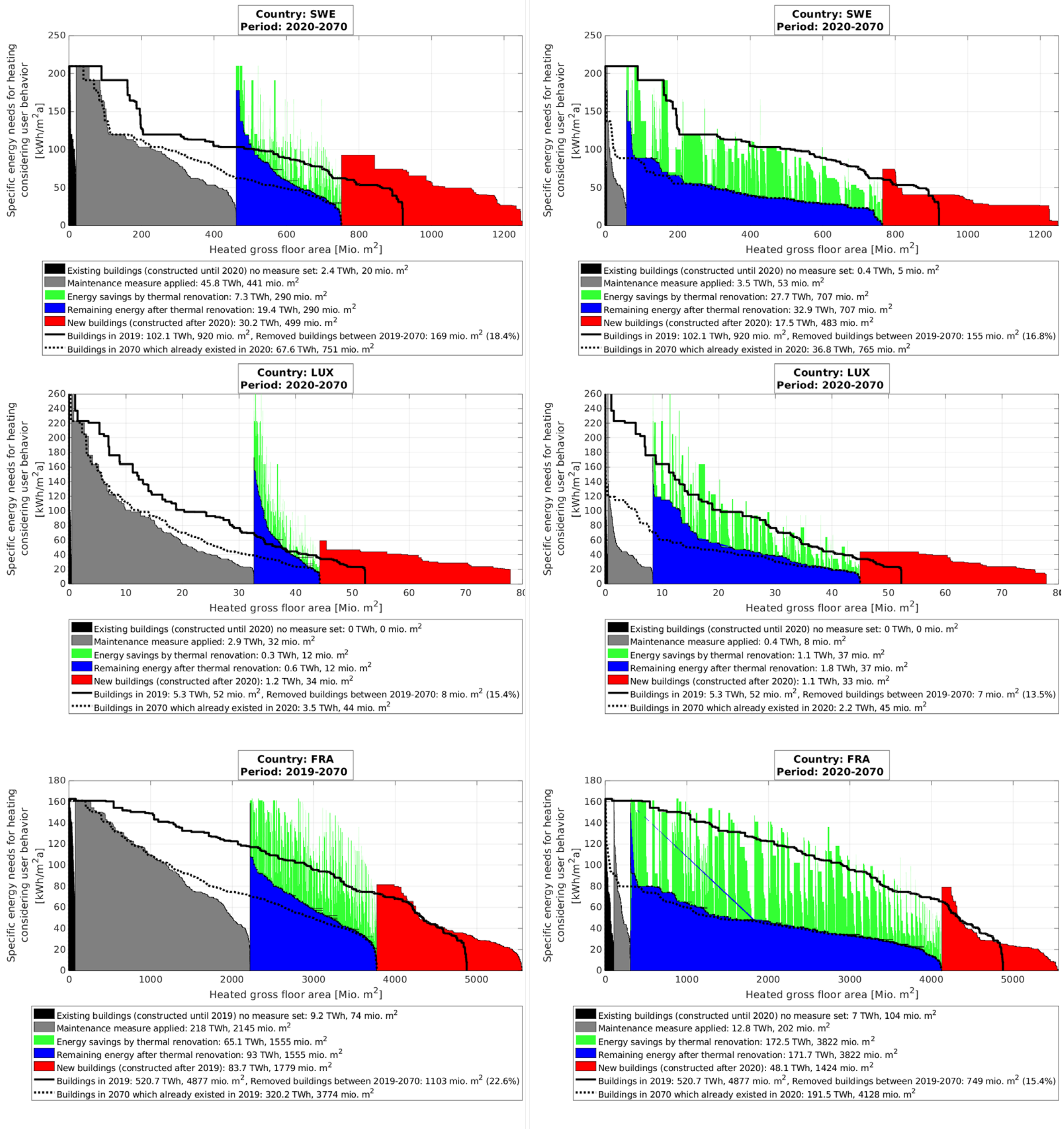


Figure 63: Heated gross floor area by different construction activities and resulting energy demand (and savings in case of building renovation) in the baseline scenario (left side) and the decarbonisation pathway (right side) in selected countries: Sweden, Luxembourg, and France.

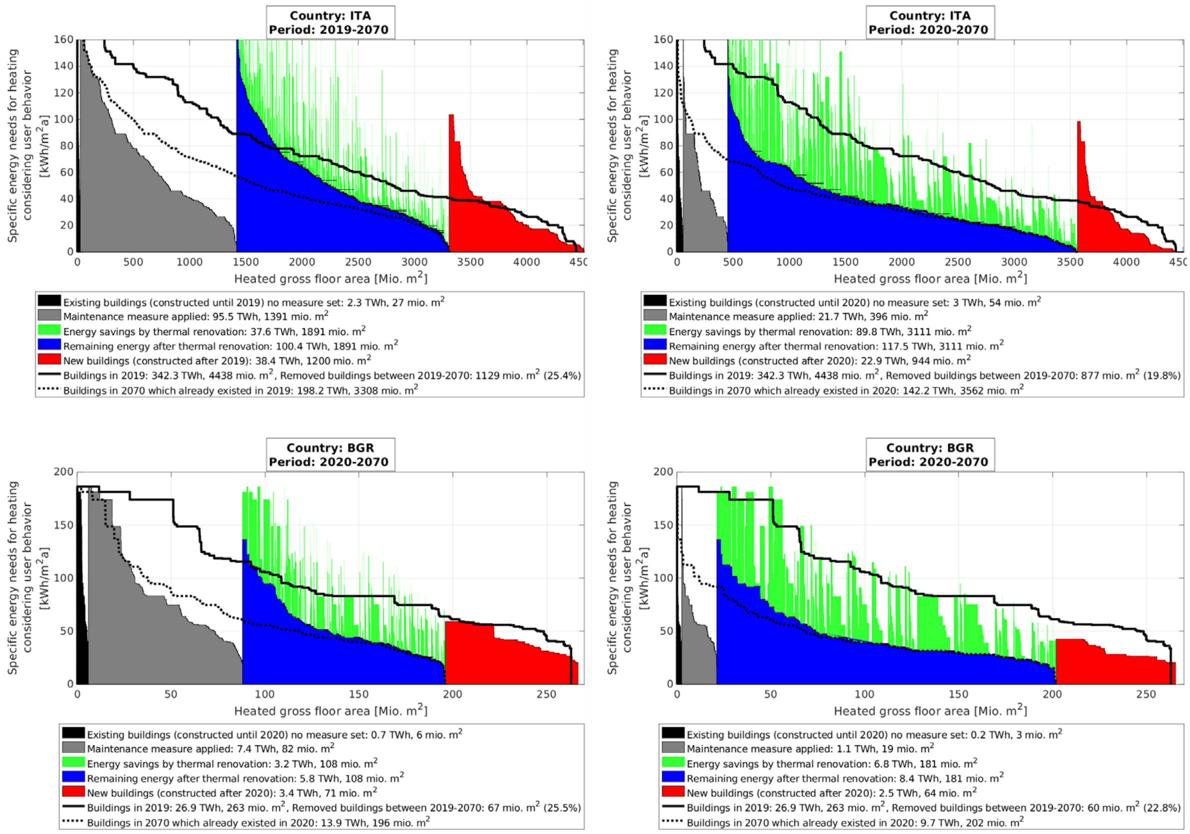


Figure 64: Heated gross floor area by different construction activities and resulting energy demand (and savings in case of building renovation) in the baseline scenario (left side) and the decarbonisation pathway (right side) in selected countries: Italy and Bulgaria.

Limitations of the modelling approach and the possible impact on the insights and conclusions are discussed in the discussion and summary chapter of the modelling activities.

MS clustering based on modelling results of the building sector

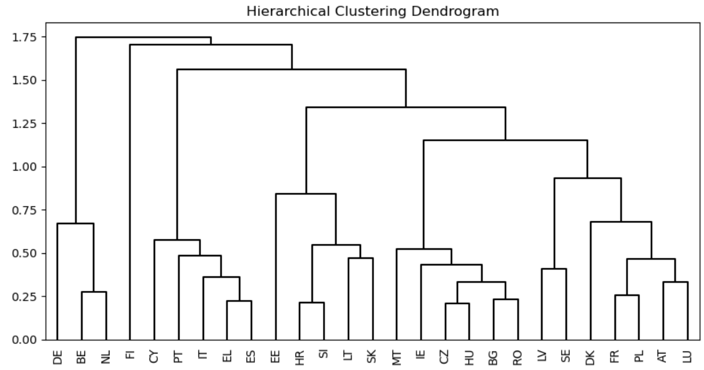
The country-based results of the building sector modelling are clustered to identify similarities in the MS (see Figure 65). As input parameters for the clustering algorithm we chose the final energy demand per capita for the main energy carriers.

The clustering shows that the MS can be divided into 5 different groups[107]:

- Group 1: relatively high share of remaining gases and liquids
- Group 2: mainly southern countries, low demand per capita, high share of solar
- Group 3: strong role of biomass (and to some extent district heating), low gas and liquids
- Group 4: lower biomass, balanced mix of other energy carriers

[107] The dendogram in Figure 65 classifies FI as a country with a very unique position, suggesting FI as a separate group, mainly due to the high demand per capita. Still, in order to define country clusters with approximately similar order of magnitude, we decided to manually re-assign Finland to the group of countries with higher demand per capita (group 5).

- Group 5: higher demand per capita, medium biomass, higher relevance of district heating



Country	Biomass_per-capita	District heating_per-capita	Electricity_per-capita	Hydrogen, E-gas, E-Fuel_per-capita	Solar_per-capita
EU27	7%	24%	51%	8%	11%
BE					
DE					
NL					
CY					
EL					
IT					
PT					
ES					
HR					
EE					
LT					
SK					
SI					
BG					
CZ					
DK					
HU					
IE					
MT					
RO					
AT					
FI					
FR					
LV					
LU					
PL					
SE					

Figure 65: MS clustering based on modelling results of the building sector

6.4. H&C in industry (FORECAST model)

In the following, results are presented first by showing the impact on GHG emissions and then by diving into the different areas of final energy demand in industry.

Figure 66 shows the development of total GHG emissions by sources for the baseline and the pathway scenarios for the EU27. The baseline scenario, which considers currently implemented policies and trends, shows a further reduction of GHG emissions towards 2030 resulting in about 622 Mt CO_2-eq by 2030. Compared to 1990, industrial GHG emissions in the baseline scenario are reduced by 47% by 2030. By 2050 a reduction of about 64% compared to 1990 is achieved. Thus, the baseline scenario is falling short of the ambition as laid out in the EU Green Deal, which requires all sectors to achieve near zero GHG emissions by 2050.

In the pathway scenario, which includes additional and more ambitious decarbonisation policies compared to the baseline scenario, industry sector GHG emissions decrease to 416 Mt CO_2-eq by 2030, representing a 64% decrease with respect to 1990. This reflects a substantial increase in ambition, given that towards 2030 only a few years are left to accelerate the transition. Towards 2050, the reduction in GHG emissions is further accelerated resulting in a reduction of about 94% by 2050 compared to 1990. This includes about 100 Mt CO_2 in carbon capture and storage (CCS) from cement and lime plants.

The two main drivers for the additional GHG reduction by 2030 in the pathway scenario are the accelerated gas and coal phase-out. The reduction in gas is driven by high gas prices, while the reduction in the use of coal is driven by increasing CO_2 prices and support for the introduction of hydrogen-based steelmaking replacing coal-intensive blast furnaces. By 2040 most fossils are close to being phased out already, while they are completely phased out in 2050, when only process-related GHG emissions remain. These mainly come from the cement and lime industries, where most are then captured, while also a few more heterogenous sources of process emissions remain that are too small to use for CCS. Overall, the pathway scenario shows very fast and comprehensive decarbonisation of process heating that is even accelerated by the high gas prices. Although, in the short term towards 2030, the higher gas prices also induce a certain switch from gas to fuel oil. This, however, does not sustain in the long term.

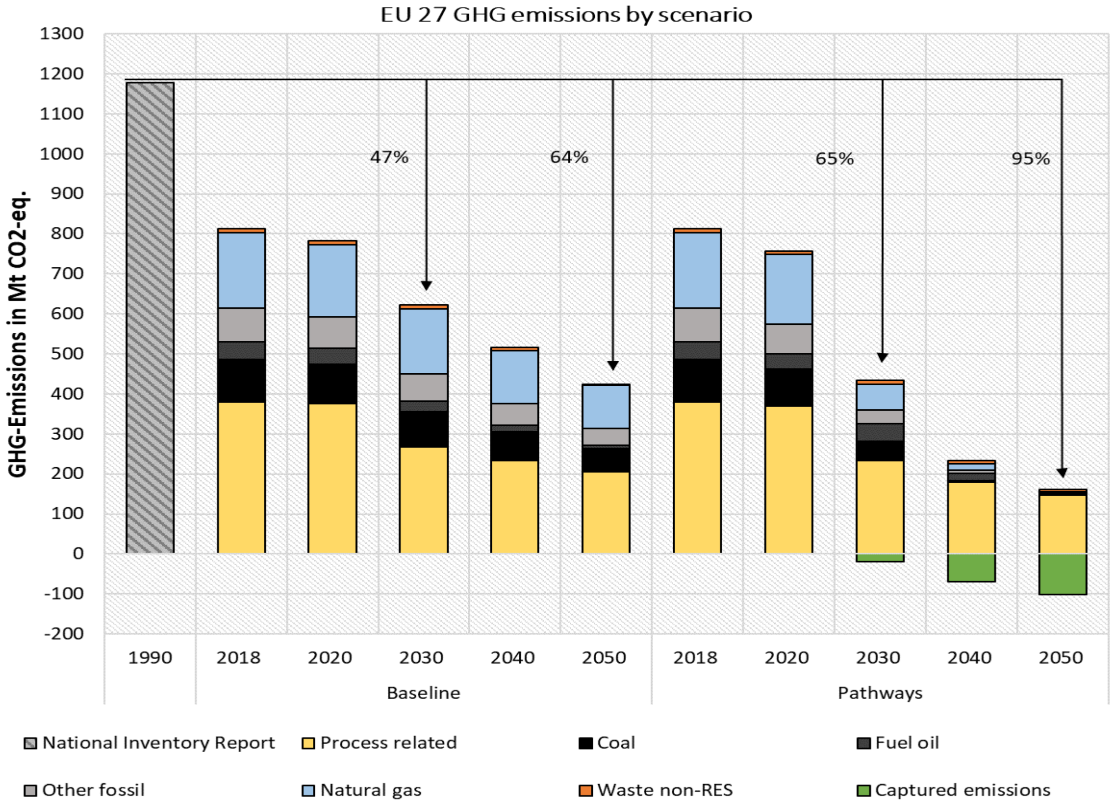


Figure 66: Overview on the development of GHG emissions in the Pathway and the Baseline scenario in the industry sector (source: FORECAST)

The **resulting final energy demand (FED)** is shown in Figure 67 and includes the final energy demand for heating and cooling as well as other uses like mechanical energy. Both scenarios show a steady decrease in the FED, while it flattens from 2035 onwards in the baseline scenario. In the baseline scenario, the FED decreases by 7% from 3,051 TWh in 2018 to 2,849 TWh by 2050. In the pathway scenario, FED decreases by 16% to 2,552 TWh by 2050. This decrease is driven by the use of the best available technologies and efficiency improvements, but also accelerated circularity and material efficiency play important roles. In the pathway scenario, the energy mix changes substantially, fossil fuels are completely phased out by 2050 and electricity is the dominant enegy carrier with more than 50% of total FED. Also hydrogen plays a relevant role, but is substantially less important. Biomass, district heating and ambient heat are used in niches, where supply potentials are very high or where process temperatures are low.

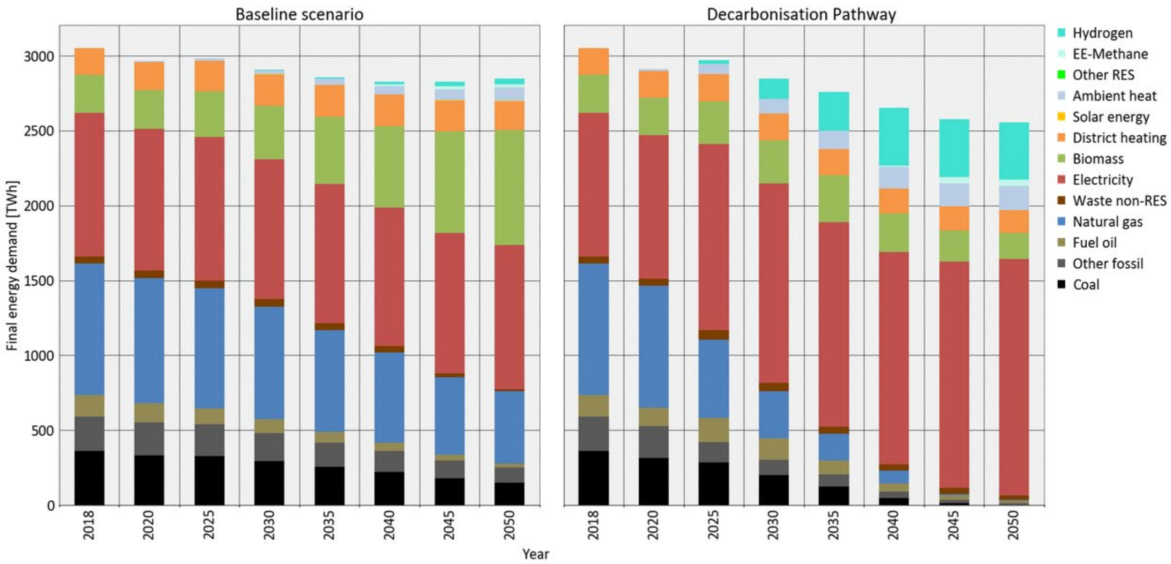


Figure 67: Resulting final energy demand in industry excluding feedstocks (EU27, 2018-2050)

In 2018 almost 73% or 2,213 TWh of the final energy demand in the industry is used for **heating and cooling**. Here, the observed change is even more pronounced. While the baseline scenario still sees an important role of natural gas by 2050 and electrification does not accelerate, the pathway scenario looks very different, with fast electrification that compensates most of the fossil phase-out. But also hydrogen has a large share by 2050. Biomass shows a very strong increase in the baseline scenario: it almost triples to 766 TWh by 2050 making biomass one of the most important energy carriers. The strong increase in biomass is driven by the CO_2 price. At these price levels, solutions like hydrogen and (to a lesser extent) direct electrification are not yet cost-effective, so biomass gains large market shares, as possible (domestic and international) limitations to biomass supply are not considered in the baseline scenario. Without restrictions on the biomass use, it potentially "explodes" in the baseline scenario.

The pathway scenario considers a stronger prioritisation of biomass and stronger support for electrification and hydrogen. As a result, biomass even falls in the long term, because it is technically not needed and economically not attractive compared to electrification and hydrogen under the assumed support and price regime.

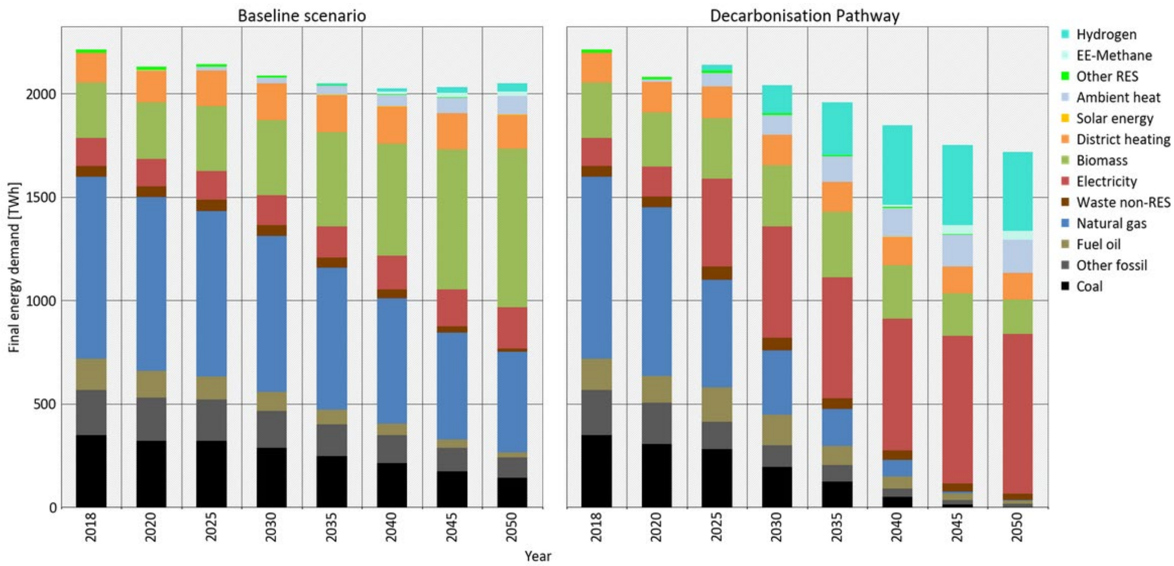


Figure 68: Resulting final energy demand for heating and cooling in the industry sector (EU27, 2018-2050)

The challenges, energy mix and technologies for the decarbonisation of industrial H&C differ substantially for the different applications. The two most relevant applications are low- and medium-temperature process heating in boilers and CHP units on the one hand and high-temperature process heating in furnaces on the other hand. Both are shown in more detail in the following.

Final energy demand for the supply of **low- and medium-temperature process heat** accounts for about 32% (961 TWh) in 2018 as shown in Figure 69. In 2018 the main energy source for steam and hot water generation were natural gas at 36% (342 TWh) and biomass at 26% (249 TWh). Both scenarios showcase different developments for low and medium temperatures. In the baseline scenario, biomass becomes the most significant energy carrier accounting for more than 60% (626 TWh) of the low- and medium-temperature process heating. On the other hand, the decarbonisation pathway scenario illustrates a substantially higher electricity demand, with a rapid increase from 21 TWh in 2018 to 249 TWh and 544 TWh by 2030 and 2050 respectively. The important role of electrification is suppoted by the fact that technologies are ready and available (electric boilers) and that a certain share of the lower temperature heat demand can be efficiently supplied by industrial-size heat pumps, which is indicated by the role of ambient heat in the FED mix.

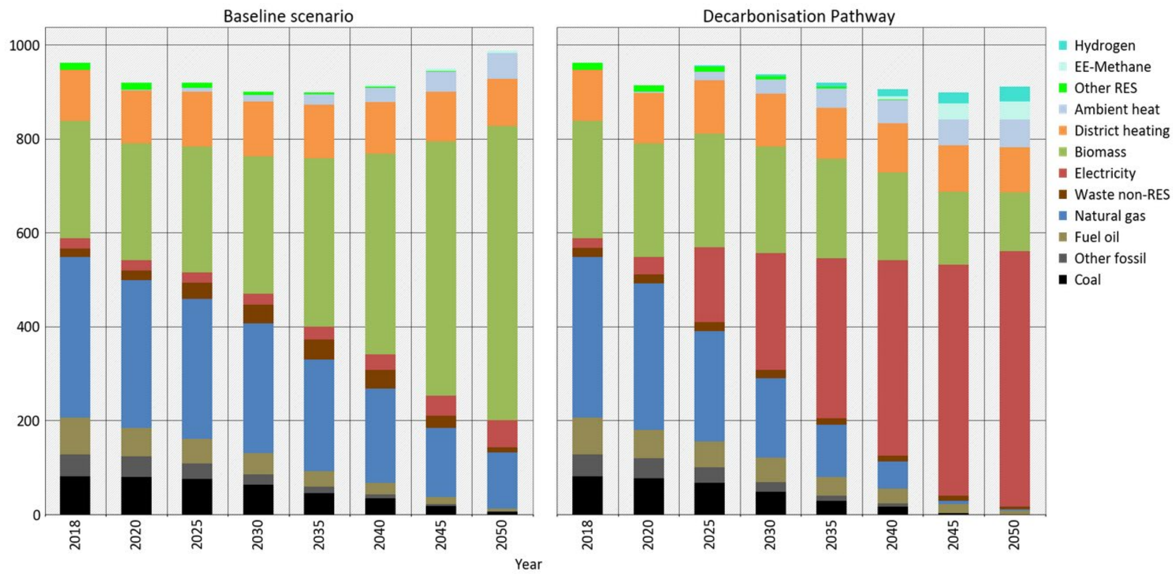


Figure 69 Final energy demand for steam and hot water generation in industry by scenario and energy carrier (EU27, 2018-2050)

High-temperature process heating takes place in different types of industrial furnaces and kilns. The different sectors and processes vary in the degree they can electrify. For some, electrification technologies are mature, while for others they are still under development or face major technical and economic barriers.

High-temperature heat demand acounts for almost 31% (948TWh). Figure 70 compares the energy carrier used for high-temperature process heating in the EU27 industry. By 2050, the high-temperature energy demand in the baseline and pathway scenarios declines by 14% and 39%, respectively, compared to 2018. The introduction of state-of-the-art technologies for existing industrial sites has resulted in efficiency gains which are primarily responsible for the energy demand decrease in the baseline scenario, whereas in the decarbonisation pathways scenario the switch towards new low-carbon processes such as hydrogen direct reduction of iron (H-DR) with electric arc furnace (EAF) steelmaking route and the circular economy modelling assumption play vital roles in decreasing the energy demand for high-temperature heat.

High-temperature processes are characterised by a very high reliance on hydrocarbons, around 90% of the energy demand in 2018. In 2018 natural gas is the most important energy carrier for high-temperature furnaces covering 39% (371 TWh) of the EU27 high-temperature energy demand. In the decarbonisation pathways scenario, most gas-fired furnaces are replaced by electricity or hydrogen by 2035, resulting in a substantial increase in electricity demand by 2030 (203 TWh). On the other hand, fossil fuels and coal start decreasing by 2025 and phase out by 2050. Hydrogen starts to increase from 2030 and becomes the most important energy carrier (350 TWh) by 2050 in this segment. The electricity demand peak in 2030 is due to the decrease in the attractiveness of natural gas, and as other alternatives such as hydrogen are not yet available everywhere. Overall, hydrogen plays a substantially larger role in high-tempererature process heating, driven by the transition in the steel industry, but also by the technical requirements of furnaces and processes in other branches. While it is a very robust result that high-temperature process heating will be dominated by hydrogen and electrification, the share of each solution is unceratin to some degree. While much hydrogen will be needed for the steel industry, other branches will be more flexible in using hydrogen or electricity, partly based on what is nationally cost-effective and locally available.

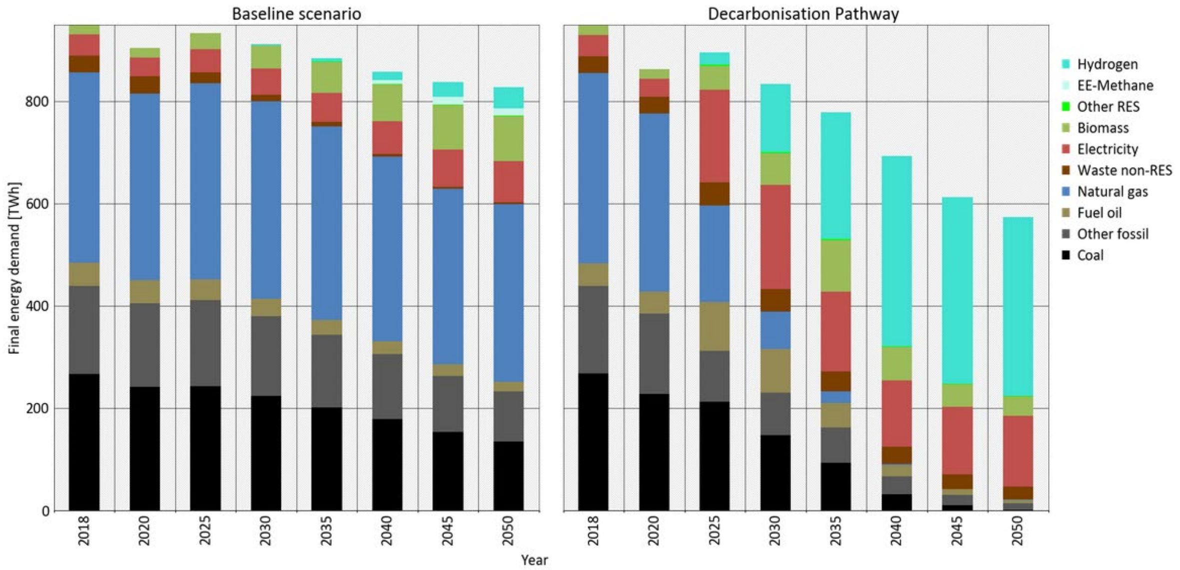


Figure 70: Final energy demand for high-temperature process heat in industrial furnaces by scenario and energy carrier (EU27, 2018-2050)

The **direct electrification** of process heating is a dominating strategy in the pathway scenario. The share of direct electricity in total final demand reaches 62% (1581 TWh) in the decarbonisation pathway scenario by 2050 (compared to 31% in 2018). Figure 71 shows the evolution of the overall electricity demand in industry by end uses. It becomes obvious how electrification of low and medium process heat supply (steam and hot water) drive the overall increase, but also electrification in high-temperature applications (furnaces) plays an important role. This rapid increase in electricity is attributed to the financial support policies for electric process heating and the decrease in the attractiveness of natural gas. Overall, electrification of process heating adds roughly 700 TWh to the electricity demand, which increases to about 1600 TWh in the pathways scenario.

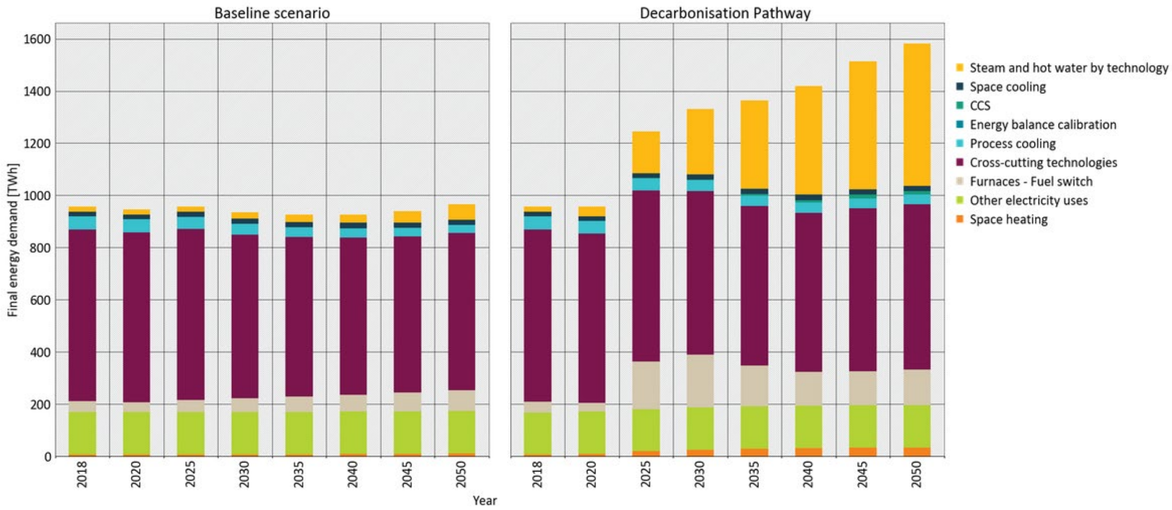


Figure 71: Electricity demand in industry by application (EU27, 2018-2050)

The evolution of hydrogen demand by end use is shown in Figure 72. In the baseline scenario hydrogen is only used to a limited extent. Here, it is mainly used in the iron and steel industry. In the pathway scenario, it is assumed that the steel and chemical industries are the first to transform their production routes to hydrogen-based technologies resulting in 136 TWh for high-temperature process heat by 2030. Afterwards the demand scales up to reaching 380 TWh by 2050. This does not include the potential demand for feedstocks, which can be a lot higher, but is out of scope in this study.

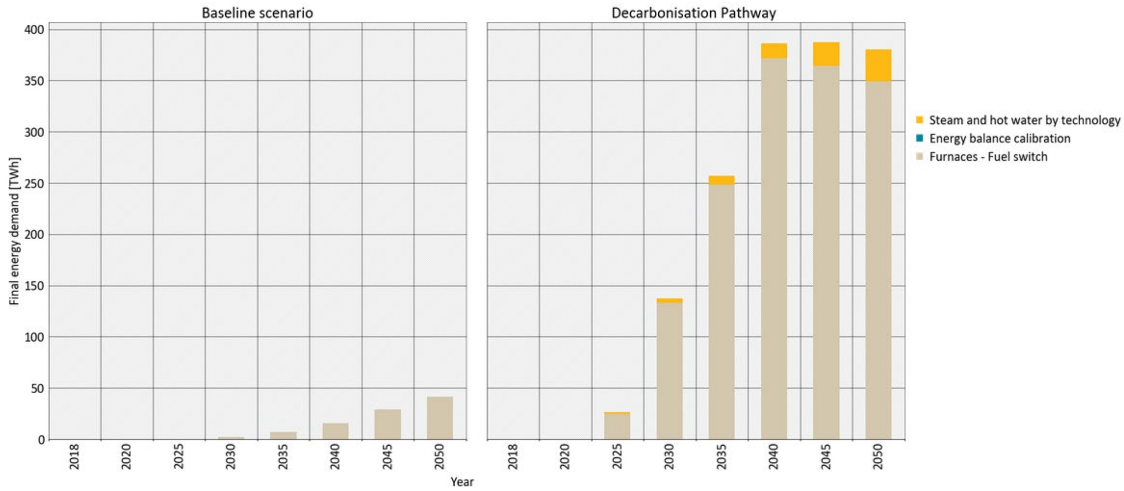


Figure 72: Hydrogen demand for process heating in industry by application (EU27, 2018-2050) Forecast

Results substantially vary by Member State, because industrial structure, energy supply, strategies and opportunities are also very different across the Member States. Still, certain groups of Member States share similar elements of the decarbonisation pathway. The results of the industry sector scenarios are clustered to develop more homogeneous groups of Member States and allow more generalised recommendations on strategies and the policy mix. Input parameters are the shares of the main technologies, i.e. biomass-based generation technologies, geothermal energy plants and heat pumps. The clustering shows that the MS can be divided into 3 different groups according to Figure 73:

- Strong industrial base and high demand for hydrogen

- Lower importance of energy-intensive industries like steel and cement
- Diversified supply mix - high energy demand in industry but mostly low temperature

Note, however, that such grouping always includes simplifications and that even within a group there is substantial heterogeneity. Every country needs tailor-made strategies, but the countries within one group also have certain overarching elements in common.

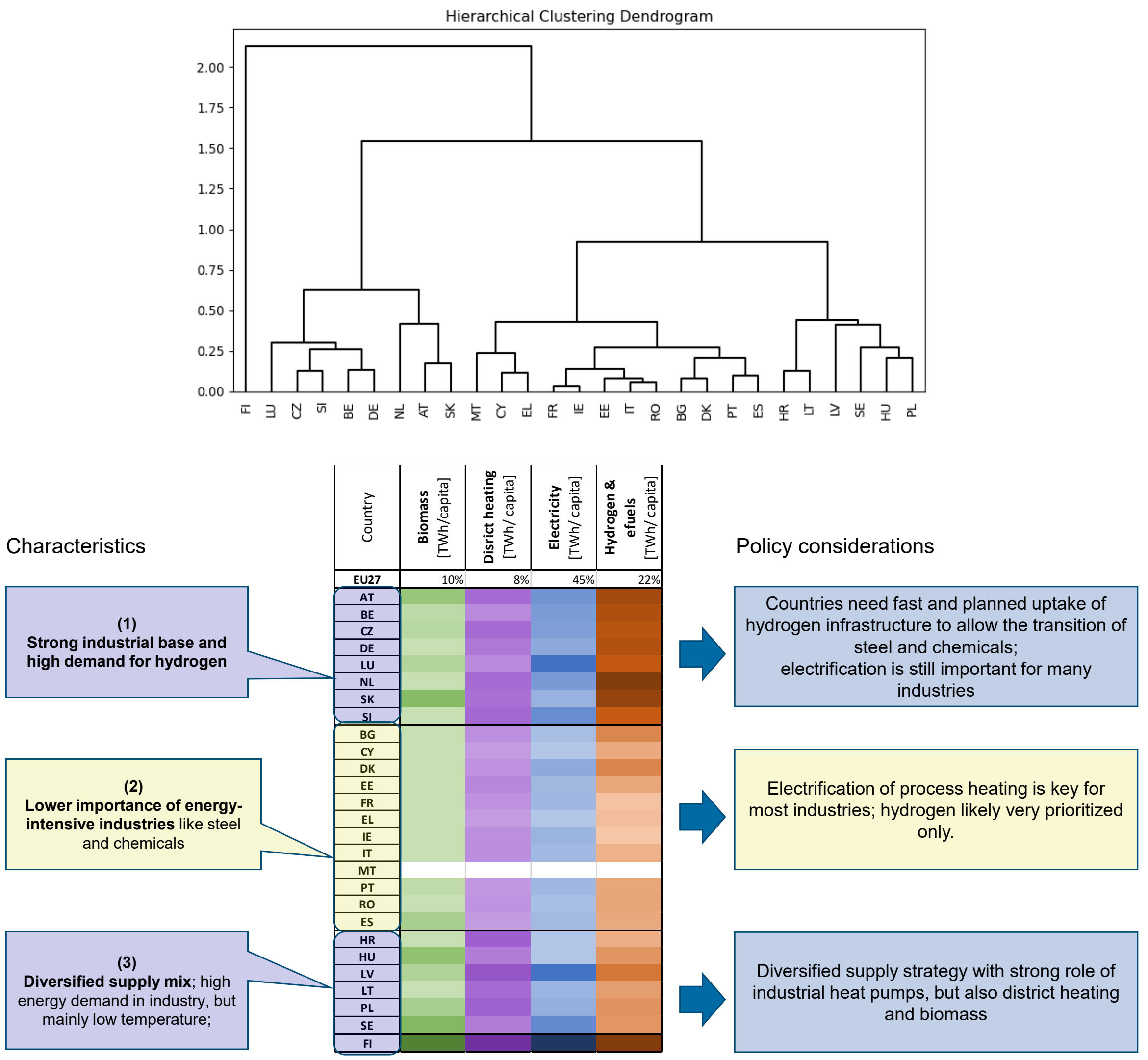


Figure 73: Results of country clustering for industrial final energy demand (bottom) incl. Dendogram (top)

Figure 74 shows results of final energy demand in 2050 for the decarbonisation pathway scenario by Member State. Countries are grouped according to the three clusters identified. It is striking that electricity is the dominant technology in the energy mix in all countries - even in those that stronger focus on hydrogen (group 1). Still, countries in group 1 have a higher share of hydrogen than other countries. This result is strongly driven by the industrial structure: Most of these countries also have a strong steel and/or chemical industry, which stronger depend on hydrogen for the transition. Countries in groups 2 and 3 often have a more relevant demand for low- and medium-temperature process heat. Figure 75 and Figure 76 add similar results for the baseline scenario and for the year 2018 for comparison.

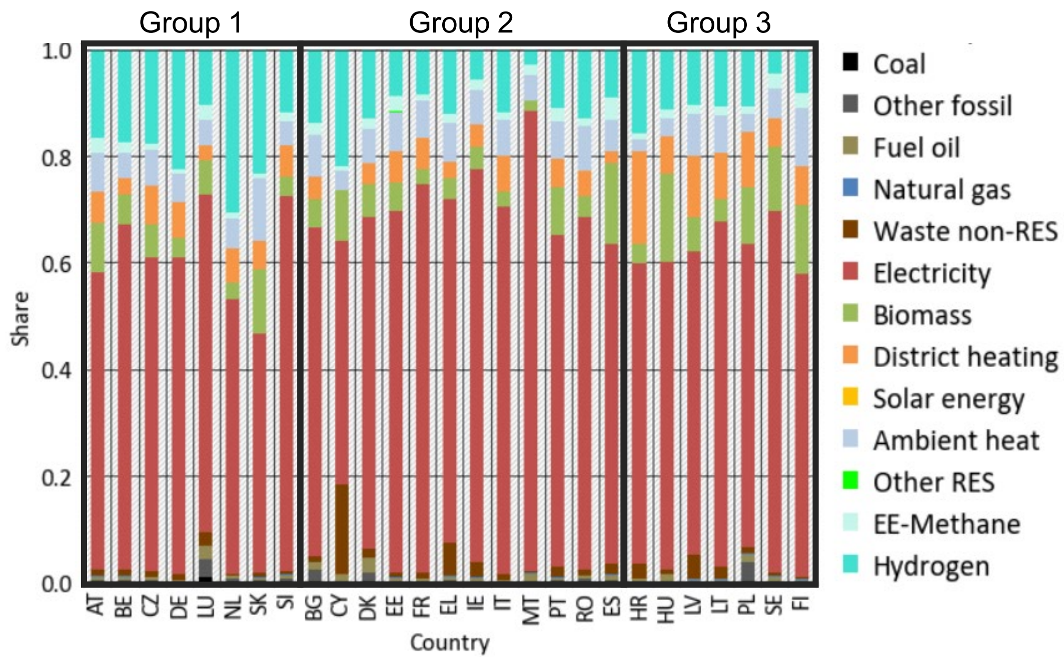


Figure 74: Share of energy carriers in final energy demand by 2050 in the pathway scenario by Member State incl. country grouping (EU27, 2050)

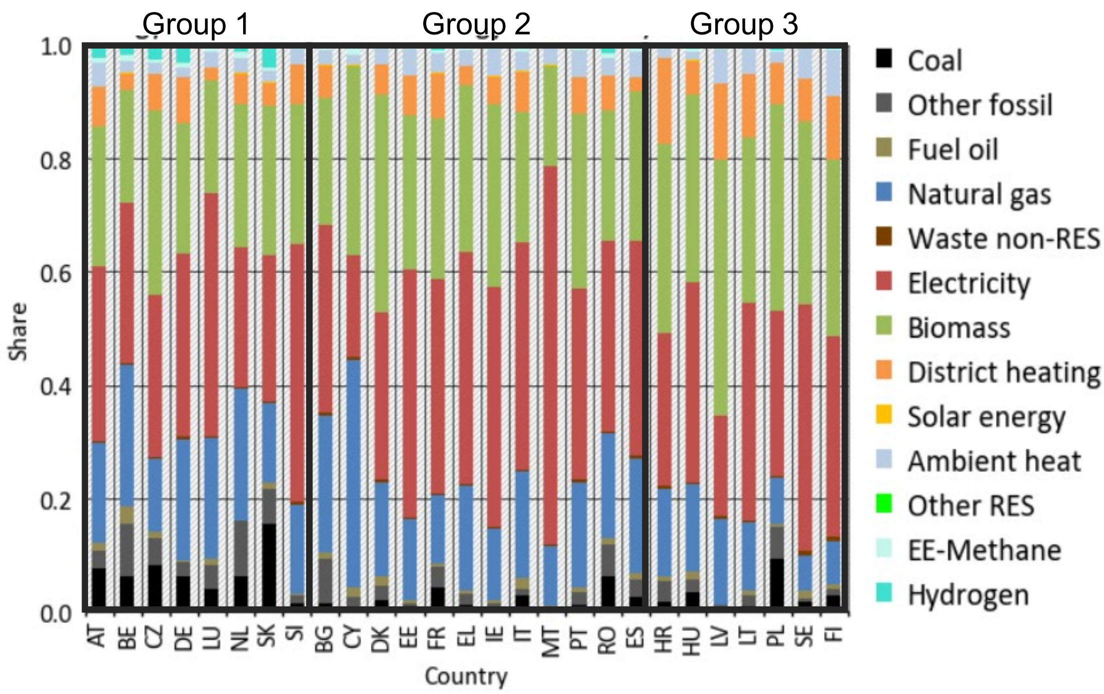


Figure 75: Share of energy carriers in final energy demand by 2050 in the baseline scenario by Member State (EU27, 2050)

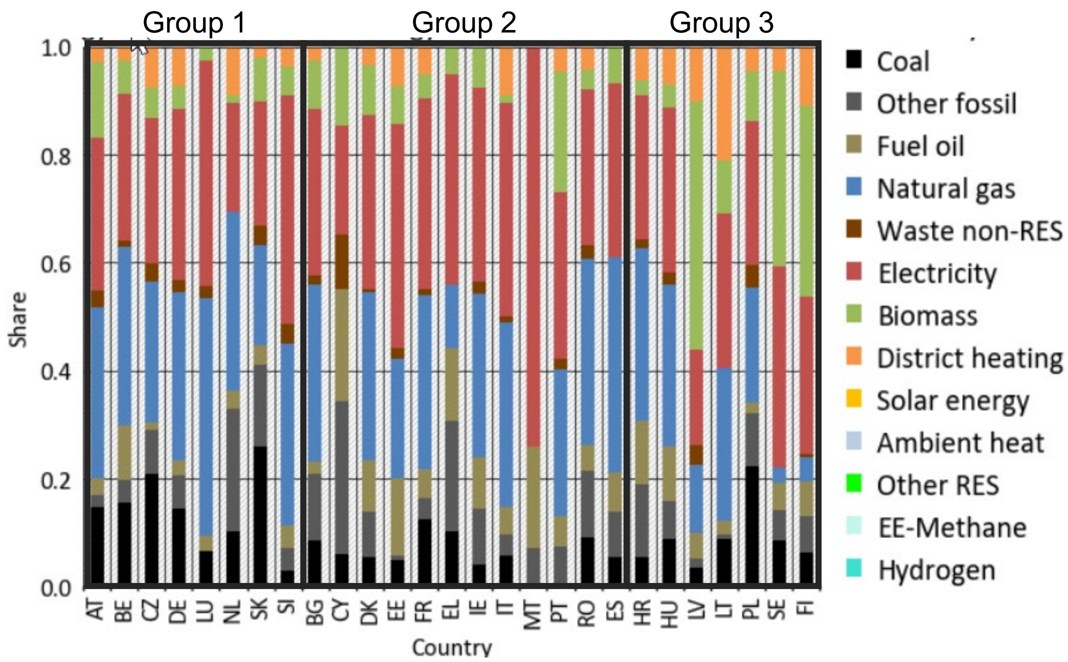


Figure 76: Share of energy carriers in final energy demand in 2018 by Member State (EU27, 2018)

6.5. District heating (Hotmaps)

(i) Modelling the DH expansion

As a first step, the current share of the heat demand that is supplied by DH in different locations across Europe is determined. After the estimation of current market shares of DH with an existing DH grid, areas are identified that are potentially suitable for DH in the future (in 2050). For this, a calculation module developed within the Hotmaps project is used, the CM DH potential – economic assessment (see methodology in Annex C3).

In the baseline scenario, only those areas could be identified as potential DH areas that had an annual heat demand of at least 10 GWh. The following figures demonstrate the potential DH areas identified for four Member States: Germany, Italy, Sweden and the Netherlands. The potential district heating areas are depicted in yellow.

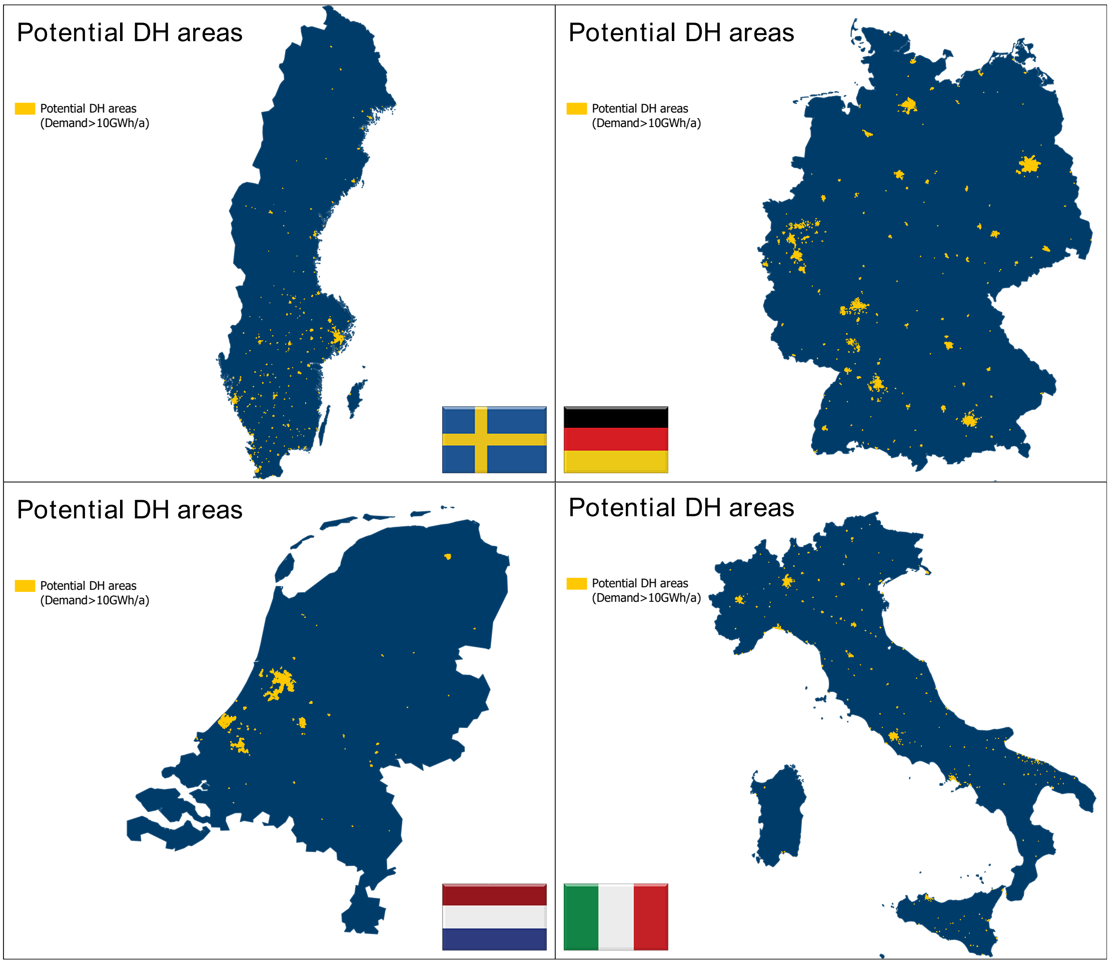


Figure 77: Potential DH areas for Germany, Italy, Sweden and the Netherlands

Based on the baseline scenario, heat demand changes from 2020 to 2050. Furthermore, the DH market share changes during this period. Thechanges in the DH market shares in 2050 compared to 2020 are presented in Figure 78. With regard to the heat demand covered by DH systems, Figure 79 illustrates the changes of heat supply by DH within identified potential DH areas in 2050 compared to 2020. Based on this figure, only in France, Italy, the Netherlands and Romania an increase in the heat supplied via DH can be expected. Based on the investment made for the DH networks and delivered heat by DH system from 2020 to 2050, the average cost of DH networks per unit of delivered heat in each country is calculated. The corresponding values are presented in Figure 80.

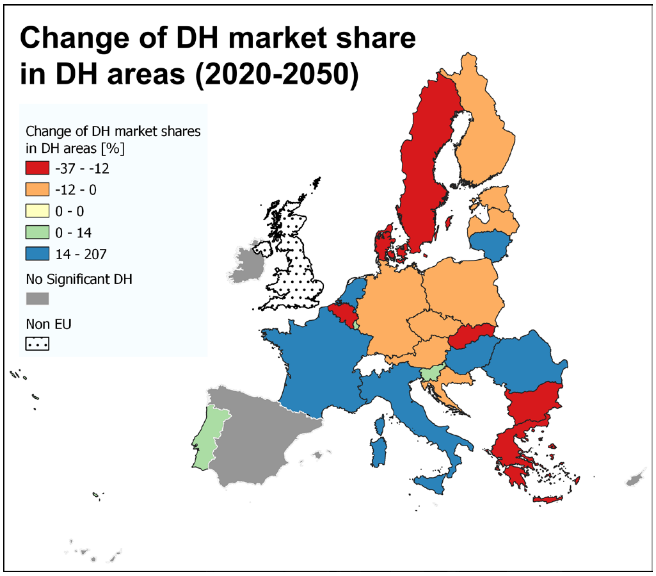


Figure 78: DH market share in DH areas, baseline scenario

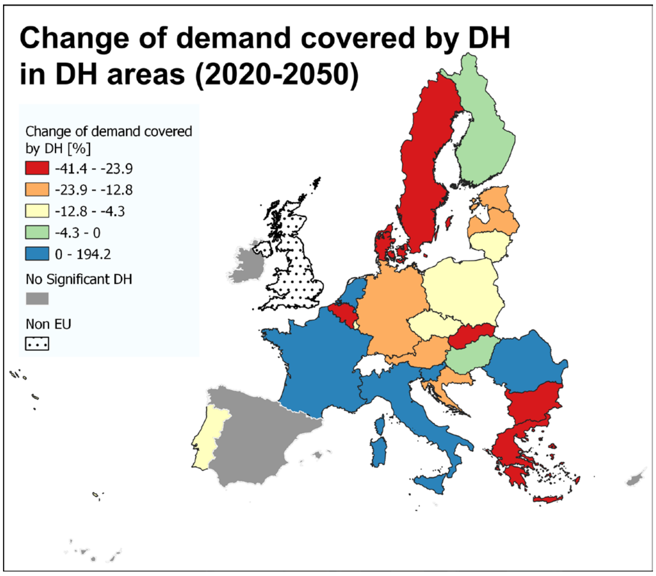


Figure 79: Change of demand covered by DH in DH areas, baseline scenario

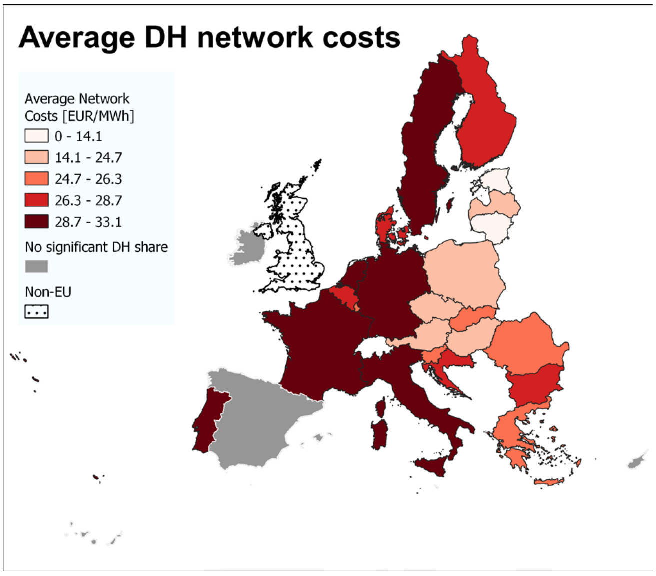


Figure 80: Average DH network costs, baseline scenario

In the last two decades, the share of district heating in heat consumption in EU-27 countries and the UK has remained constant at around 12%.[108] The installed DH generation capacity of 350 GW supplied ca. 450 TWh_{th} annually from 2000 to 2019[109]. While the share of natural gas in DH supply has remained almost constant, other fossil fuels have been replaced by biomass, other renewables and waste. The share of waste heat has also increased in the last years, although the overall share has remained small. Despite the plateau in heat supply by district heating, the district heating pipelines have been extended from ca. 150.000 km in 2005 to 200.000 km in 2019, as reported by IEA. IEA reports average annual grid investments of USD 6 billion from 2000 to 2019, including refurbishment costs. Denmark, France, the Netherlands, and Sweden have the highest investments in district heating pipelines. Depending on the connection rates, a greater or smaller part of the investment may flow into the refurbishment or new developments.

[108] JRC. Techno-economics for smaller heating and cooling technologies. Techno-Economics Smaller Heat Cool Technol 2017. http://data.europa.eu/euodp/da/data/dataset/jrc-etri-techno-economics-smaller-heating-cooling-technologies-2017 (accessed March 26, 2019).

[109] European Commission, Directorate-General for Energy, Bacquet, A., Galindo Fernández, M., Oger, A., et al., *District heating and cooling in the European Union : overview of markets and regulatory frameworks under the revised Renewable Energy Directive*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/962525;

IEA (2020), World Energy Investment 2020, IEA, Paris https://www.iea.org/reports/world-energy-investment-2020

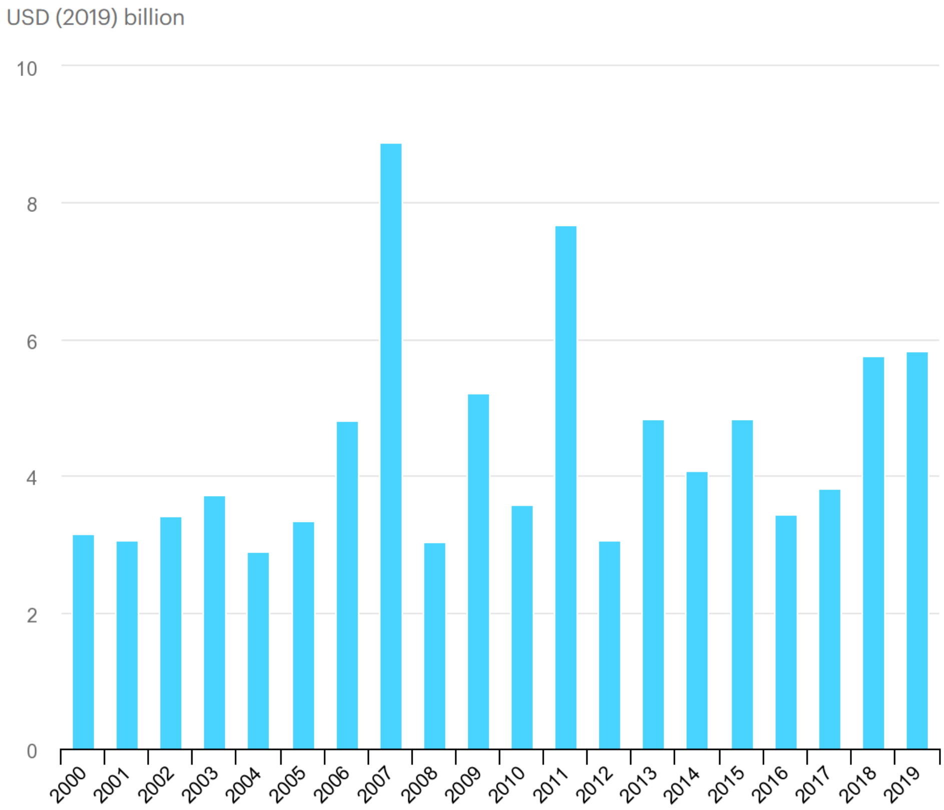


Figure 81: Estimated investment in district heating pipelines in Europe, 2000-2019[110]

The calculations performed in this study result in an annual investment of EUR_{2020} 6.94 billion for both distribution and service pipes in EU-27 countries for the baseline scenario. However, if DH market shares from the decarbonisation pathway scenario are followed, additional investments are required. In this case, an additional investment of EUR_{2020} 4.85 billion is necessary, leading to an annual investment of EUR_{2020} 11.79 billion for distribution and service pipes in EU-27 countries.

Looking into the grids (only pipes and pipe works; excluding investments such as buying land), the following aspects should be considered:

- Today's investments in DH grids lead to future refurbishment costs.
- In case of an increase in the DH market share within DH areas, additional investments are required; therefore, future refurbishment costs will also increase.
- In this study, it is assumed that existing grids are not dismantled nor demolished; but rather are refurbished and renewed.
- The calculations are done with a grid lifetime (=depreciation) of 40 years.
- The DH areas obtained under the baseline and decarbonisation pathway scenarios are different.

[110] IEA, Paris https://www.iea.org/data-and-statistics/charts/estimated-investment-in-district-heating-pipelines-in-europe-2000-2019

Table 31 Compliance of scenarios with different 2030 targets

		Baseline		Decarbonisation Pathway	
Country	2020 DH market share in DH areas	2050 DH market share in DH areas	Annual investments [MEUR 2020 / yr] for distribution & service pipes	2050 DH market share in DH areas	Annual investments [MEUR 2020 / yr] for distribution & service pipes
AT	55%	53%	261	80%	332
BE	15%	13%	19	70%	133
BG	64%	46%	82	75%	112
CY	0%	0%	0	0%	0
CZ	44%	44%	292	80%	448
DE	32%	32%	1,196	75%	2,701
DK	88%	72%	395	90%	483
EE	58%	56%	39	80%	41
ES	3%	0%	<1	70%	466
FI	63%	63%	596	90%	662
FR	15%	46%	1,004	75%	1,481
EL	29%	20%	9	70%	117
HR	37%	36%	30	80%	57
HU	33%	38%	129	80%	248
IE	0%	0%	0	70%	11
IT	17%	36%	479	70%	1,232
LT	78%	90%	69	90%	77
LU	29%	31%	17	80%	38
LV	57%	57%	55	80%	57

		Baseline		Decarbonisation Pathway	
Country	2020 DH market share in DH areas	2050 DH market share in DH areas	Annual investments [MEUR 2020 / yr] for distribution & service pipes	2050 DH market share in DH areas	Annual investments [MEUR 2020 / yr] for distribution & service pipes
MT	0%	0%	0	0%	0
NL	26%	33%	144	75%	386
PL	51%	47%	1,005	80%	1,113
PT	33%	34%	7	70%	62
RO	43%	52%	210	75%	225
SE	86%	54%	779	90%	1,134
SI	52%	58%	28	80%	30
SK	74%	51%	96	90%	144
Total			**6,940**		**11,789**

(ii) RES Potentials

To cover the DH demand of residential and service buildings (Invert) and industry (Forecast), investments and operation of a portfolio of heat supply technologies is modelled (for the year 2050/2070). For that, regional RES and waste heat potentials (see main input data) are mapped to the future DH areas (see methodology in Annex C3). Figure 82 and Figure 83 show the aggregated potentials in the MS in comparison to the total DH demand for the baseline scenario and decarbonisation pathway scenario respectively.

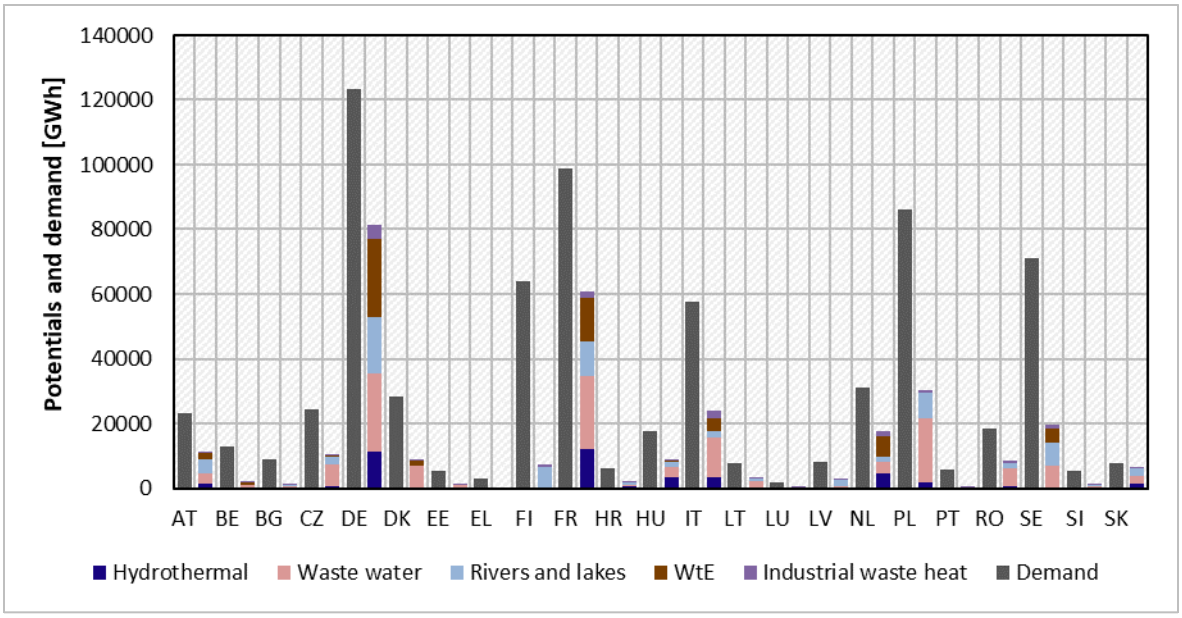


Figure 82: Potentials of renewables and waste heat for DH systems in 2050 in European countries in the baseline scenario

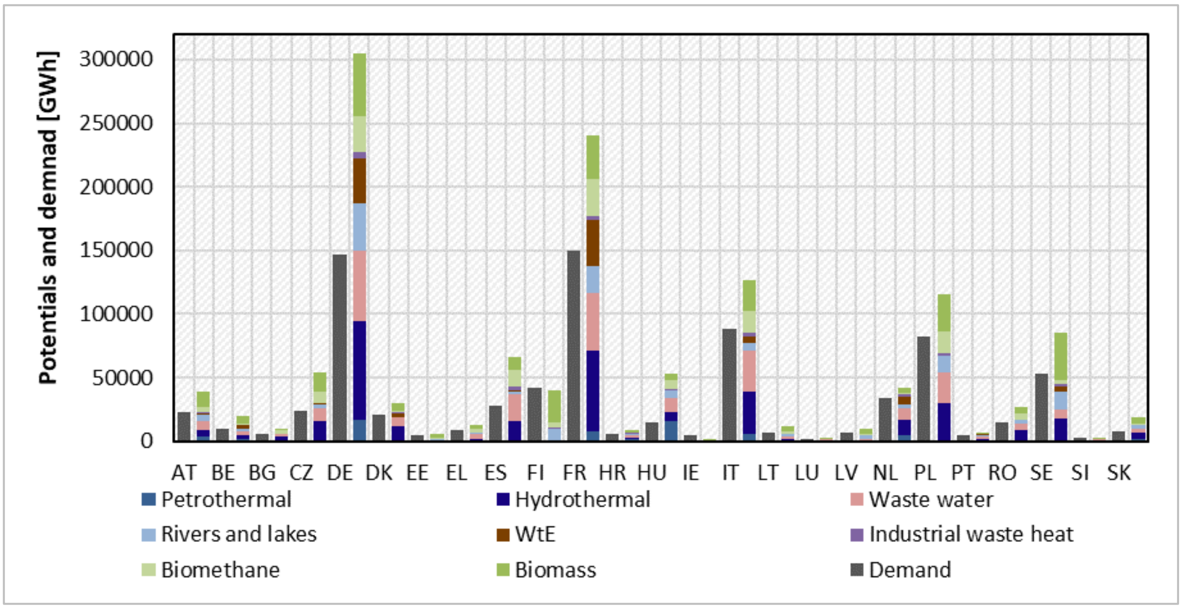


Figure 83: Potentials of renewables and waste heat for DH systems in 2050 in European countries in the decarbonisation pathway scenario

(ii) Modelling the DH supply mix

After deriving the potentials, DH types are developed using a clustering approach, for which subsequently the dispatch of heat supply is calculated (see methodology in Annex C3). The DH types represent DH areas with similar RES and industrial waste heat potentials. For both scenarios, five different DH types are derived using the potentials as input figures (compare Figure 82 and Figure 83).

From a qualitative perspective, the DH types in the baseline scenario can be described as follows:

- DH type 1 - WtE: DH areas with high waste-to-energy potentials

- DH type 2 - low RES potentials: DH areas with overall low (mapped) potentials (hydrothermal, waste water, waste to energy, industrial waste heat and rivers & lakes)
- DH type 3 - wastewater: DH areas with high wastewater potentials (with heat pumps)
- DH type 4 - rivers & lakes: DH areas with high rivers and lakes potentials (with heat pumps)
- DH type 5 - hydrothermal: DH areas with high hydrothermal potentials

Figure 84 and Table 32 show the shares of the potentials in the five different DH types in the baseline scenario. In Figure 84, the DH areas are arranged along their cluster (x-axis) and the share of potentials to cover demand is displayed (y-axis).

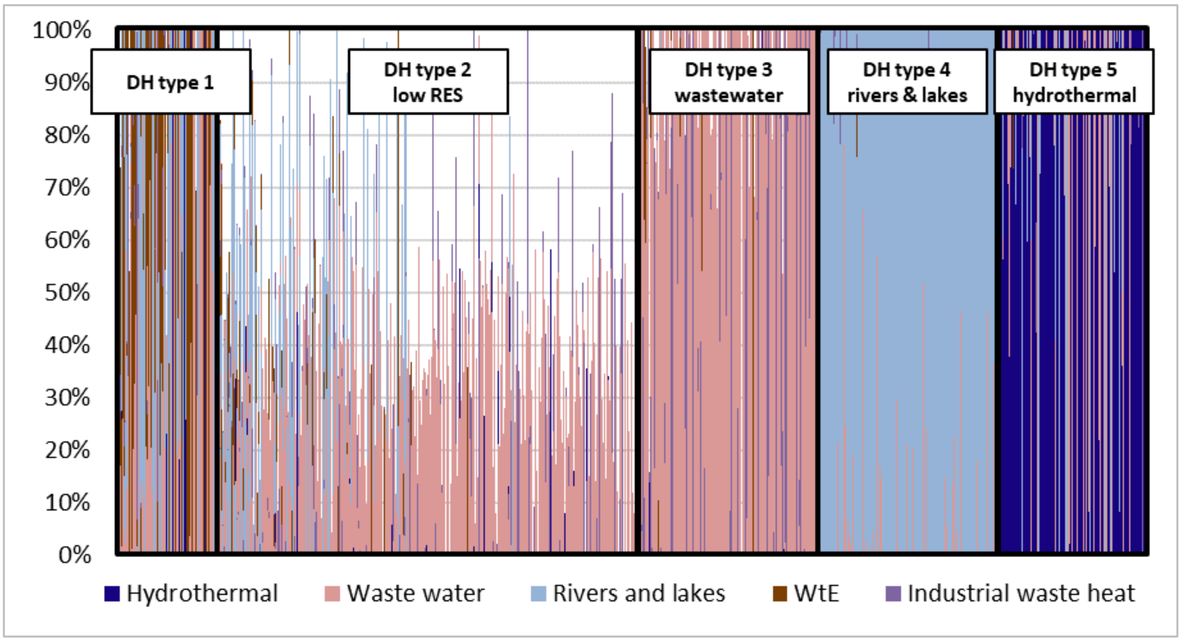


Figure 84: Visualisation of the potentials in the five different DH types in the baseline scenario

Table 32: Share of potentials in the five DH types in the baseline scenario

DH Type		Share of potentials				
		Hydro-thermal	Wastewater	WtE	Industrial excess heat	Rivers & lakes
1	WtE	20%	35%	**43%**	9%	34%
2	Low RES	1%	17%	1%	2%	4%
3	Wastewater	4%	**60%**	2%	11%	0%
4	Rivers & lakes	2%	28%	2%	4%	**98%**
5	Hydrothermal	**87%**	39%	2%	12%	45%

In the decarbonisation pathway scenario biomass and biomethane as well as petrothermal potentials are included in the clustering. From a qualitative perspective, the DH types in the decarbonisation pathway scenario can be described as follows:

- DH type 1 - petrothermal: DH areas with high petrothermal as well as hydrothermal and wastewater potentials
- DH type 2 - rivers & lakes: DH areas with high rivers and lakes potentials (with heat pumps) as well as higher hydrothermal potentials
- DH type 3 - biomass: DH areas with high biomass potentials
- DH type 4 - hydrothermal and wastewater: DH areas with high hydrothermal and high wastewater potentials (with heat pumps)
- DH type 5 - hydrothermal: DH areas with high hydrothermal potentials

Figure 85 and Table 33 show the shares of the potentials in the five different DH types in the pathway scenario. The DH types are more diverse, i.e. in all clusters more than one RES source reaches higher shares and can be used to cover the demand, compared to the baseline scenario.

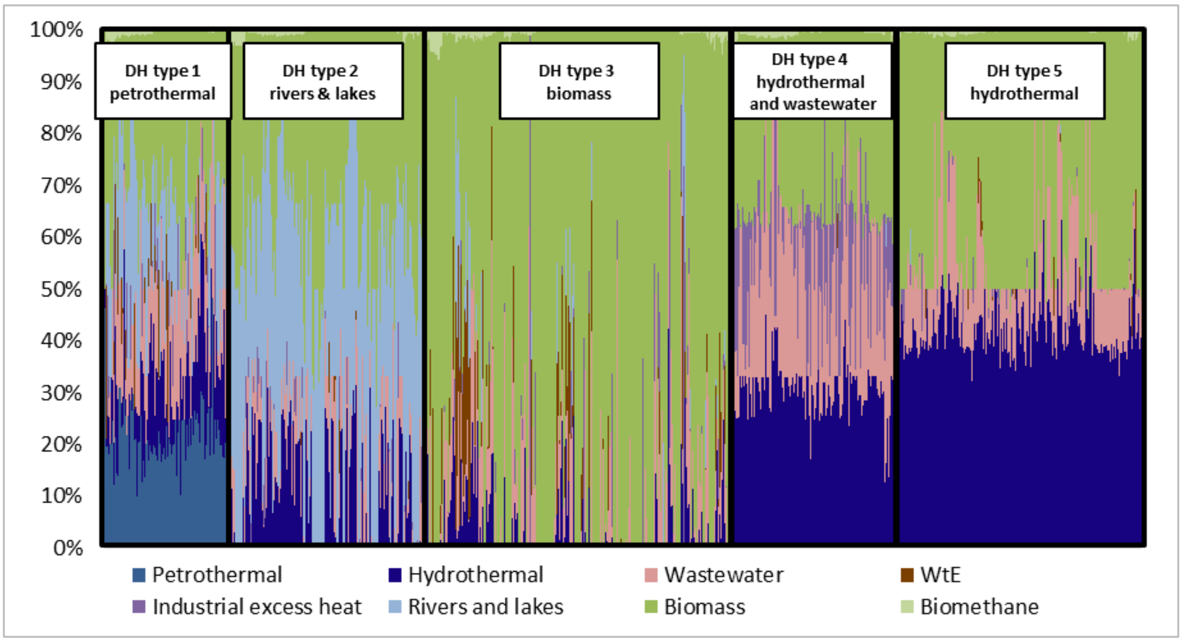


Figure 85: Visualisation of the potentials in the five different DH types in the decarbonisation pathway scenario

Table 33: Share of potentials in the five DH types in the pathway scenario

DH Type		Share of potentials							
		Petro-thermal	Hydro-thermal	Waste-water	WtE	Industrial excess heat	Rivers & lakes	Bio-mass	Bio-me-thane
1	Petrothermal	**97%**	65%	55%	6%	7%	39%	72%	1%
2	Rivers & lakes	0%	66%	40%	1%	7%	**96%**	79%	1%
3	Biomass	1%	23%	34%	13%	3%	6%	**65%**	1%
4	Hydrothermal and wastewater	0%	**99%**	**89%**	0%	12%	0%	79%	2%
5	Hydrothermal	0%	**99%**	23%	1%	1%	0%	75%	0%

For each of the DH types in each of the MS, the supply of the heat from the different available sources is derived with the calculation module DH supply dispatch initially developed in the Hotmaps project (see methodology in Annex C3). The module calculates the cost-minimal investments and operation of a portfolio of heat supply technologies in a defined DH system for each hour of the year. **For the calculations average values of heat demand and potentials per DH type in each MS are used.** The average country-specific potentials, thereby, serve as maximum restrictions. Thus, the amount of heat provided from DH is an input (i.e. equals DH demand and grid losses) and the technology mix is an output of the optimisation. Finally, the results are aggregated to MS and EU-27 level. In this aggregation, absolute values reflecting a typical DH type are multiplied by the number of coherent DH areas per DH type and, thus, summarised for all existing DH types (see methodology in Annex C3).

The aggregated results for DH are presented in the following. Figure 86 shows the thermal generation mix and the capacities in the DH networks per MS and in the EU in 2050/2070 in the **baseline scenario**.

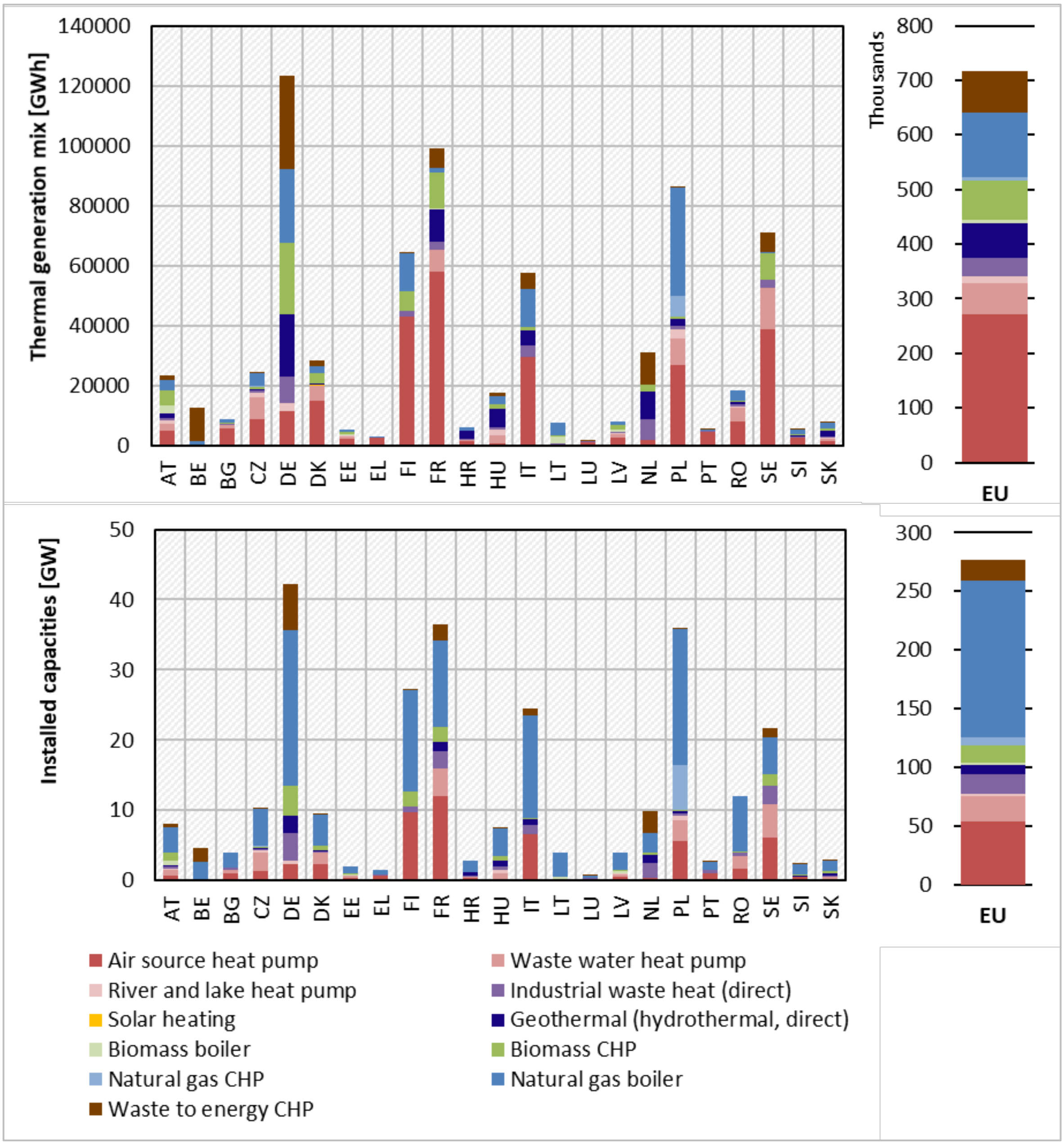


Figure 86: Thermal generation mix and capacities in district heating per MS and in EU-27 in 2050/2070 in the baseline scenario

Figure 86 shows that in the baseline scenario heat pumps can provide a high share of the heat in the DH systems in several MS and in the EU in 2050/2070. Thereby air source heat pumps have the highest share, followed by waste water heat pumps and river & lake heat pumps. Complementary heat generation technologies are solar thermal and hydrothermal plants as well as biomass and waste CHP. In addition, natural gas boilers and CHP have a share of 17% in the generation mix. In line with the generation, heat pumps have a high share in the capacity mix in the EU. Furthermore, natural gas reaches rather high capacities compared to the lower generation share, indicating its back-up role for DH. The baseline scenario already shows a deep reduction of fossil energies in DH supply compared to today. This is mainly driven by the increasing CO2 price (100 €/T CO2). Coal is completely phased out, while natural gas remains, mainly to provide peak-loads with low annual full load hours. RES potentials are sufficiently available.

Figure 87 shows the thermal generation mix and the capacities in the DH networks per MS and in the EU in 2050/2070 in the **decarbonisation pathway scenario**.

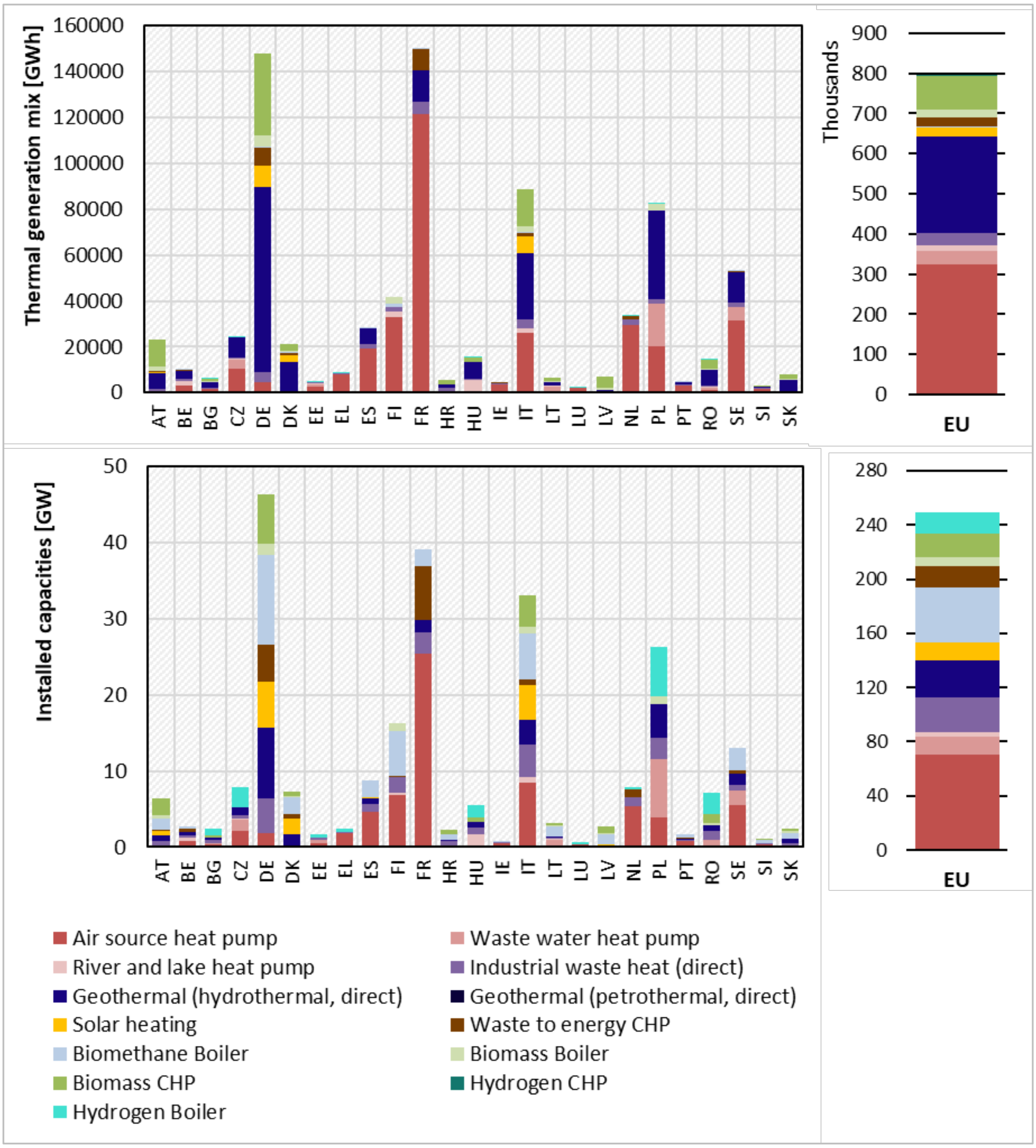


Figure 87: Thermal generation mix and capacities in district heating per MS and in EU-27 in 2050/2070 in the decarbonisation pathway scenario

In contrast to the baseline scenario, the decarbonisation pathway scenario reaches a fully decarbonised heat supply, i.e. coal and natural gas are phased out completely. Heat pumps (47%) and geothermal (hydrothermal) plants (30%) reach the highest shares in the EU thermal generation mix. Complementary heat generation technologies are industrial excess heat, solar thermal plants, biomass and waste CHP as well as biomethane and hydrogen-based technologies. At the same time, heat pumps have a high share in the capacity mix in the EU. Furthermore, biomethane and hydrogen reach high capacities but low generation. Thus, both technologies have a clear back-up role for DH, i.e. are used to cover peak loads.

The results are connected with **several uncertainties**:

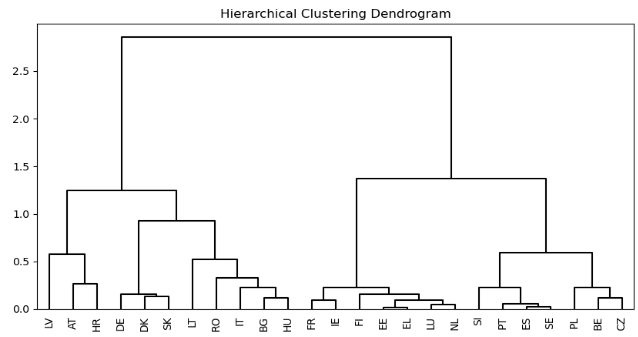
- Electricity prices: In the scenarios modelled, Member State-specific electricity prices including taxes and grid fees are assumed. These prices are quite high in some Member States, e.g. in Germany or Denmark, while other Member States, e.g. France and the Netherlands, have relatively low electricity prices. Because of high electricity prices, heat pumps are less cost-competitive in the respective Member States. Lower electricity prices, i.e. with lower taxes and fees, would lead to higher shares of heat pumps with accordingly lower shares of RES, especially geothermal (hydrothermal) energy.
- Geothermal (hydrothermal) energy: In the scenarios modelled, relatively high, conservative cost assumptions are made for hydrothermal and petrothermal plants. With lower costs (still in the range of the literature) geothermal would increase and could reach shares of more than 45% of the thermal generation mix of the EU. Higher shares of geothermal energy would accordingly lead to lower shares of heat pumps. Overall, it can be concluded that geothermal (hydrothermal) energy can make a substantial contribution to DH generation in several Member States.
- Solar thermal energy: In the model, relatively high cost assumptions are made for solar thermal energy. In some publications, cost estimations are lower. With lower costs, solar thermal could reach more than 10% of the thermal generation mix of the EU with accordingly lower shares of heat pumps.
- Biomass: In the model framework, it is assumed that stricter biomass regulations will lead to a biomass price increase to 35 €/MWh. The use of biomass is quite sensitive to this assumption. With lower biomass prices, the use of biomass could increase to around 25% of the generation mix and with higher biomass prices, the use of biomass would decline to below 10%.
- Thermal storage: The scenarios modelled include a significant increase in thermal storage, which is, however, still below other estimations. The high use of geothermal is linked to the use of thermal storage. At the same time, with lower costs of thermal storage, higher shares of solar thermal would be achievable.
- WtE: The share of WtE in the heat generation mix is lower than the potentials in all Member States, i.e. not all WtE potential is used to cover the heat supply. At the same time, the WtE potentials are quite conservative, as current waste volumes form the basis for the potentials in 2050/2070. A reduction in waste volumes and an increase in recycling could justify the low utilisation of WtE potentials. Furthermore, it should be noted that WtE in the model is associated with emissions (144 kg CO_2/MWh in the pathway scenario), and with the high CO_2 price, full exploitation of the potential is not cost-optimal. Consequently, lower emission factors for WtE would lead to higher shares of up to 100% potential exploitation.

Concluding, the baseline scenario already shows a strong reduction of fossil fuels and the pathway scenario reaches a fully decarbonised DH supply. This development is mainly driven by the increasing CO_2 price that makes RES-based alternatives cost-effective (150 €/T CO_2 in the baseline and 500 €/T CO_2 in the pathway scenario). RES potentials for DH are sufficiently available. In 2050/2070 DH can be provided carbon-free by a mix of heat pumps, geothermal (hydrothermal) plants, solar heating, WtE, industrial excess heat and backup technologies based on methane and hydrogen.

MS clustering based on modelling results of the DH dispatch

The results of the DH dispatch are clustered to identify similarities in the MS (see Figure 88). Input parameters are the share of the main technologies, i.e. biomass-based generation technologies, geothermal energy plants and heat pumps. The clustering shows that the MS can be divided into 4 different groups:

- Group 1: MS with balanced supply of DH through biomass, geothermal, electricity
- Group 2: MS with balanced supply and a focus on geothermal
- Group 3: MS with a focus on large-scale heat pumps
- Group 4: MS with a focus on geothermal and large-scale heat pumps



Country	Share biomass	Share geothermal energy	Share electricity (heat pumps)
EU27	13%	30%	47%
AT			
HR			
LV			
BG			
DE			
DK			
HU			
IT			
LT			
RO			
SK			
EE			
EL			
FI			
FR			
IE			
LU			
NL			
BE			
CZ			
ES			
PL			
PT			
SE			
SI			

Figure 88: MS clustering based on modelling results of the DH dispatch

6.6. Consolidated scenario results of the H&C sector

This section presents the consolidated results of the sectoral modelling presented above. We show aggregated results for demand, GHG emissions and costs für EU-27 by energy carriers and sectors as well as selected results on MS level. We focus on the scenario results until 2050. Also, we analyse to which extent the decarbonisation pathway scenario fulfills targets suggested in the proposal of the revised Renewable Energy Directive (COM(2021) 557 final).

The results are presented and distinguished by the sectors industry, buildings and district heating. While industry and buildings are end-use sectors, district heating represents an energy conversion sector, supplying space heating and hot water end-uses in industry and buildings. This could be an argument to show the results only for the end-use sectors buildings and industry, including district heating. However, there are specific policy needs of the district heating sector, which are completely different from the policies required for the decarbonisation process in industry and buildings. In order to support the policy analysis in this project with the corresponding modelling results, we decided to cover the three sectors in consolidated graphs. It needs to be emphasised that for buildings and industry we show final energy demand, while for district heating the figures show energy input for the heat generation.

Figure 89 shows the baseline scenario of energy use for heating and cooling by sectors and energy carriers in the EU-27 by 2050[111]. According to the scenario definition (see Chapter 6.2), the scenario is far from reaching carbon neutrality in 2050. Still, the scenario shows some progress in terms of energy savings (17% lower demand in 2050 than in 2018), mainly triggered through savings in the building sector. Moreover, the scenario is characterised by a slightly higher share of district heating (below 11% in 2018, above 16% in 2050), with a significant shift of the district heat generation mix towards large-scale heat pumps, holding a share of more than 50% in 2050. Biomass use increases to about 20% and 25% in 2030 and 2050, respectively.

[111] Results are also provided until 2070. Due to the focus of the modelling on the periods 2030 and 2050, the outlook to 2070 is shown in the Annex (see Figure 116 and Figure 117).

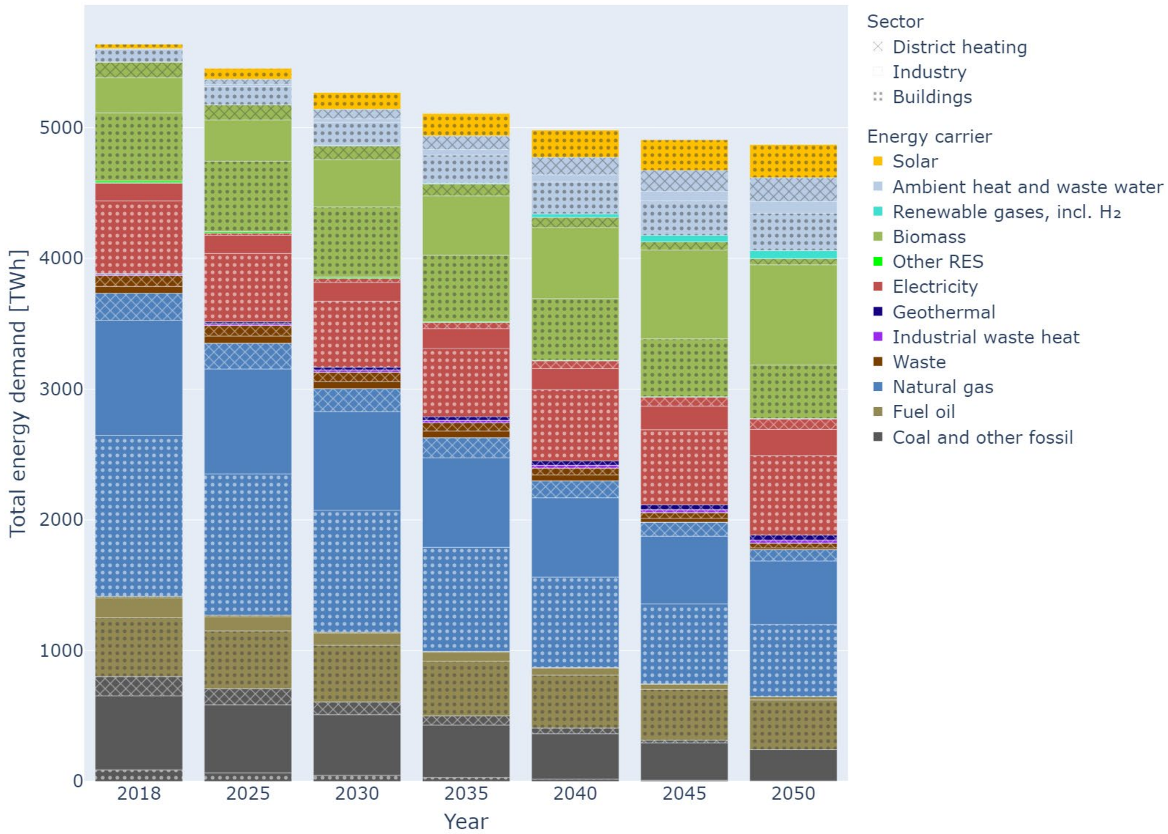


Figure 89: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, baseline scenario, EU-27

The results in terms of energy demand by energy carriers translate into corresponding GHG emissions. Overall in the baseline scenario, GHG emissions decrease by about 50% from 2018 to 2050. The results are not only driven by the shift to renewable energy carriers, but also by some progress regarding decarbonisation of the electricity sector (see emission factors for electricity according to Table 41 in the Annex).

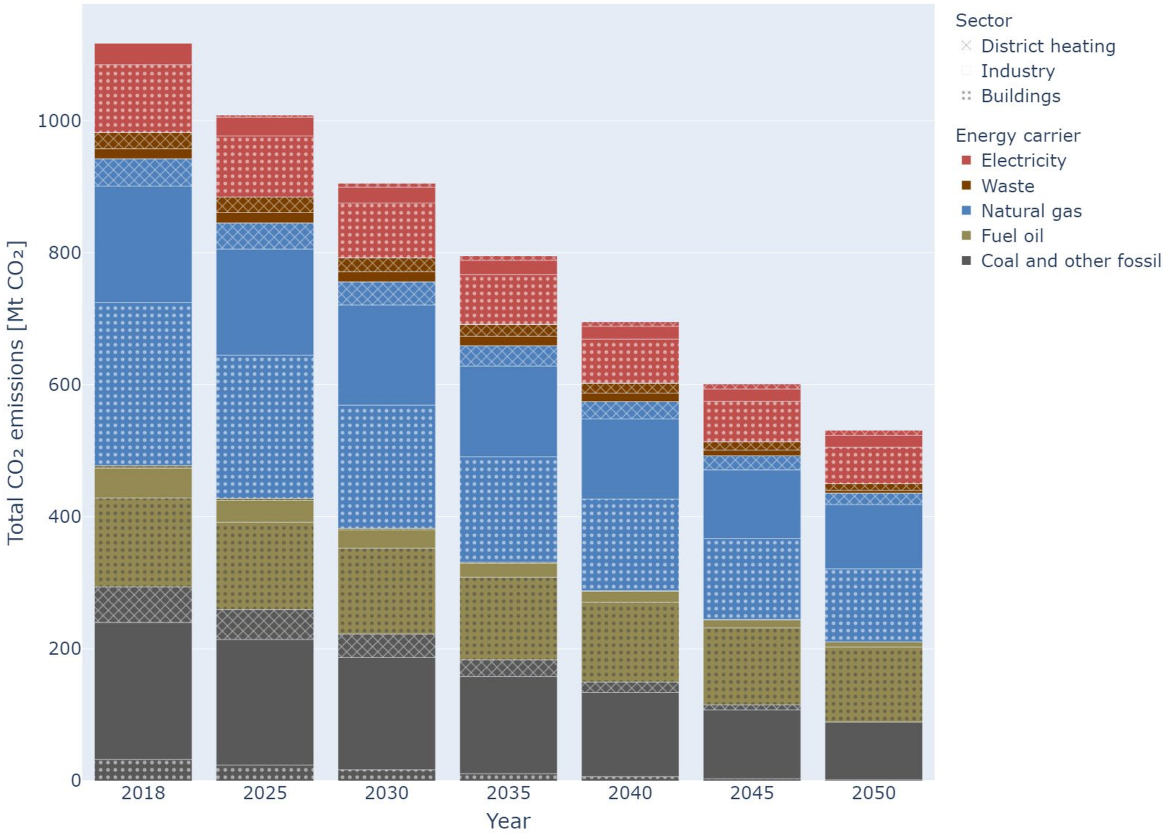


Figure 90: Greenhouse gas emissions from heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, baseline scenario, EU-27

However, the scenario shows very different characteristics in the different Member States, triggered through different starting points, potentials, policies and climatic conditions. The similarities among MS differ in buildings, industry and district heating as shown above.

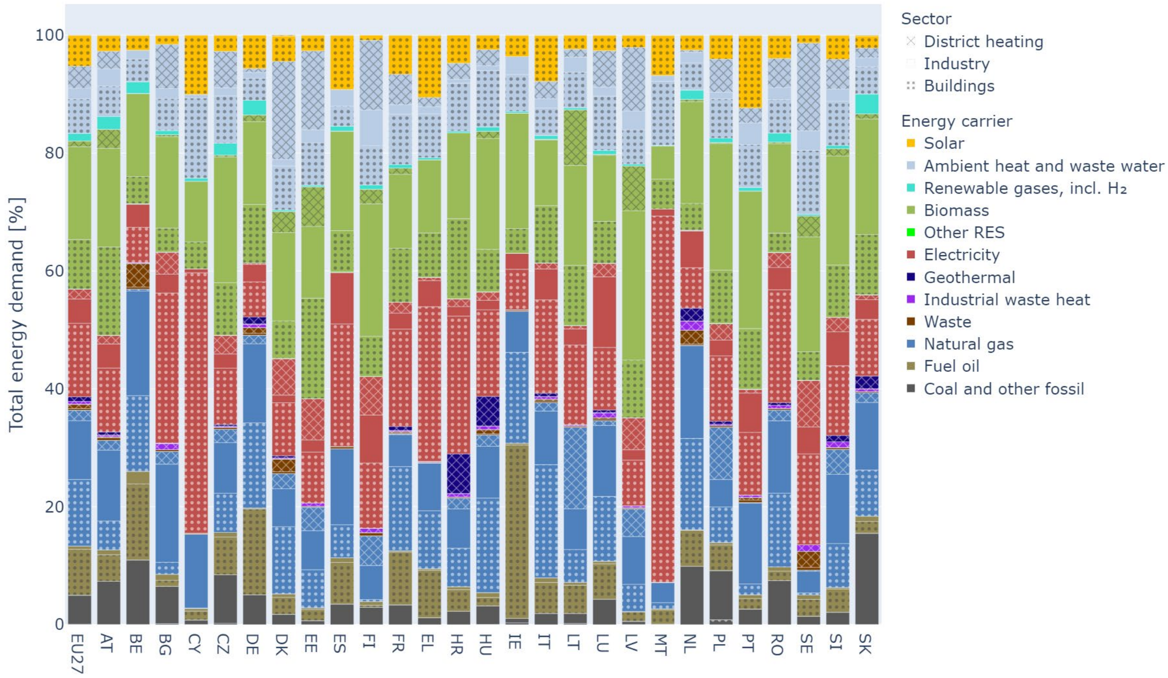


Figure 91: Share of energy carriers for heating and cooling by sectors (buildings, industry, district heating), baseline scenario, 2050

In contrast to the baseline scenario, the decarbonisation pathway scenario achieves full climate neutrality by 2050 through high-efficiency improvements and a stringent shift to renewable heating and cooling solutions (Figure 92 and Figure 94). Energy savings play a key role in achieving the model result in this scenario: the energy use for heating and cooling decreases by about 1/3 from 5600 TWh (2019) to 3800 TWh (2050). This is mainly caused by the reduction of final energy demand for space and water heating, mainly driven by renovation of the buidling envelope, but also by replacement of inefficient, old heating systems with poor efficiency. While the final energy demand for space and water heating in buildings declines by about 40% in this period (in terms of delivered energy even by 60%), in the industry sector this reduction amounts to about 22%.

A small amount of emissions remains from waste incineration. We assume that a certain share of fossil waste remains, causing a small remaining share of GHG emisisons.

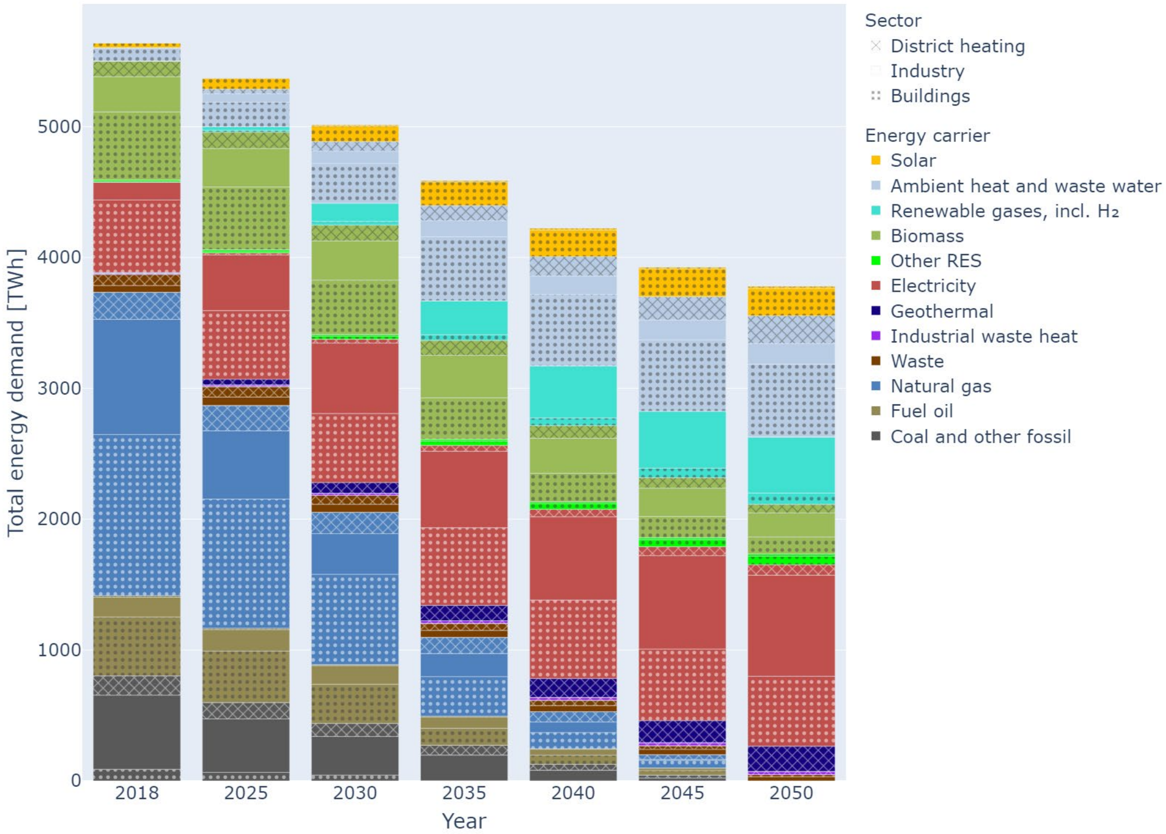


Figure 92: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, decarbonisation pathway scenario, EU-27

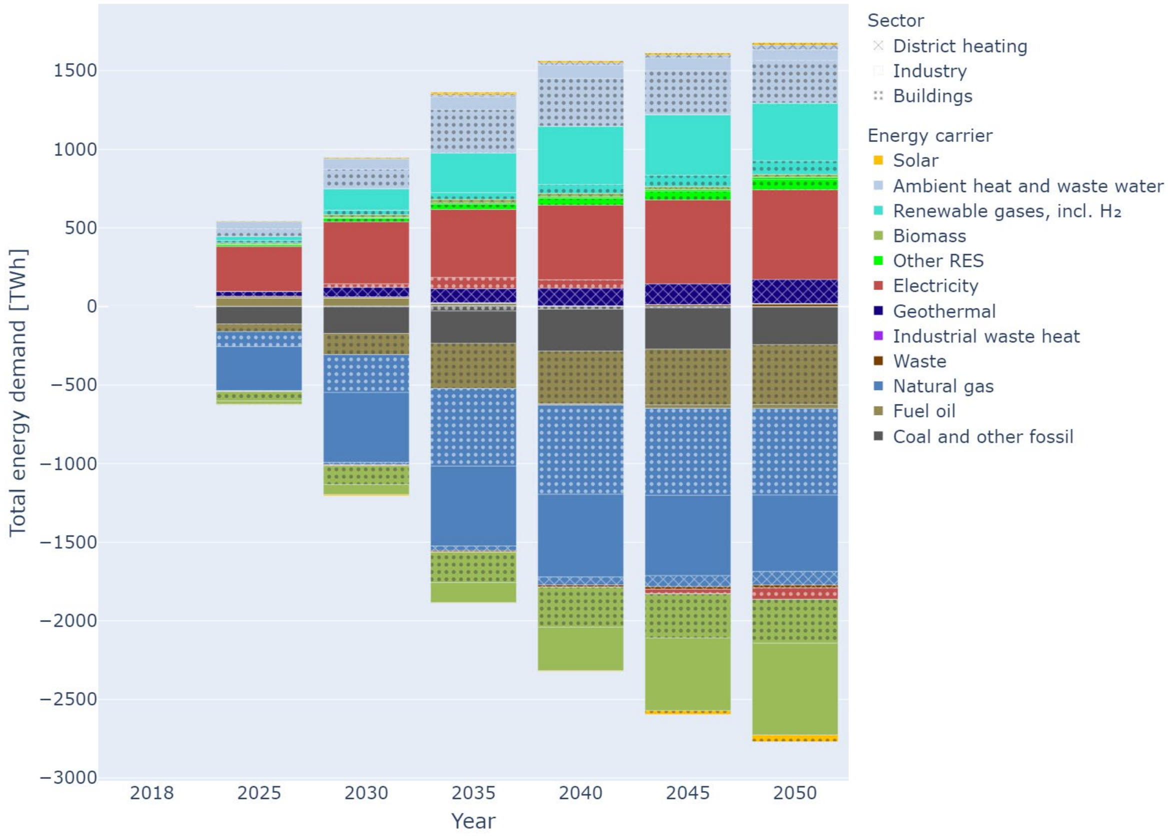


Figure 93: Difference in energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers between decarbonisation pathway scenario and baseline scenario, EU-27

Figure 94 shows GHG emissions by sector and source for the pathway scenario. Note that GHG emissions are shown for H&C only and emissions from e.g. industrial processes are excluded. For this reason, carbon capture and storage, which is part of the pathway scenario in the industry sector, is not shown here either. While it mainly addresses process emissions from cement and lime production, it also potentially captures CO_2 from the combustion of biomass and fossil waste in these plants.

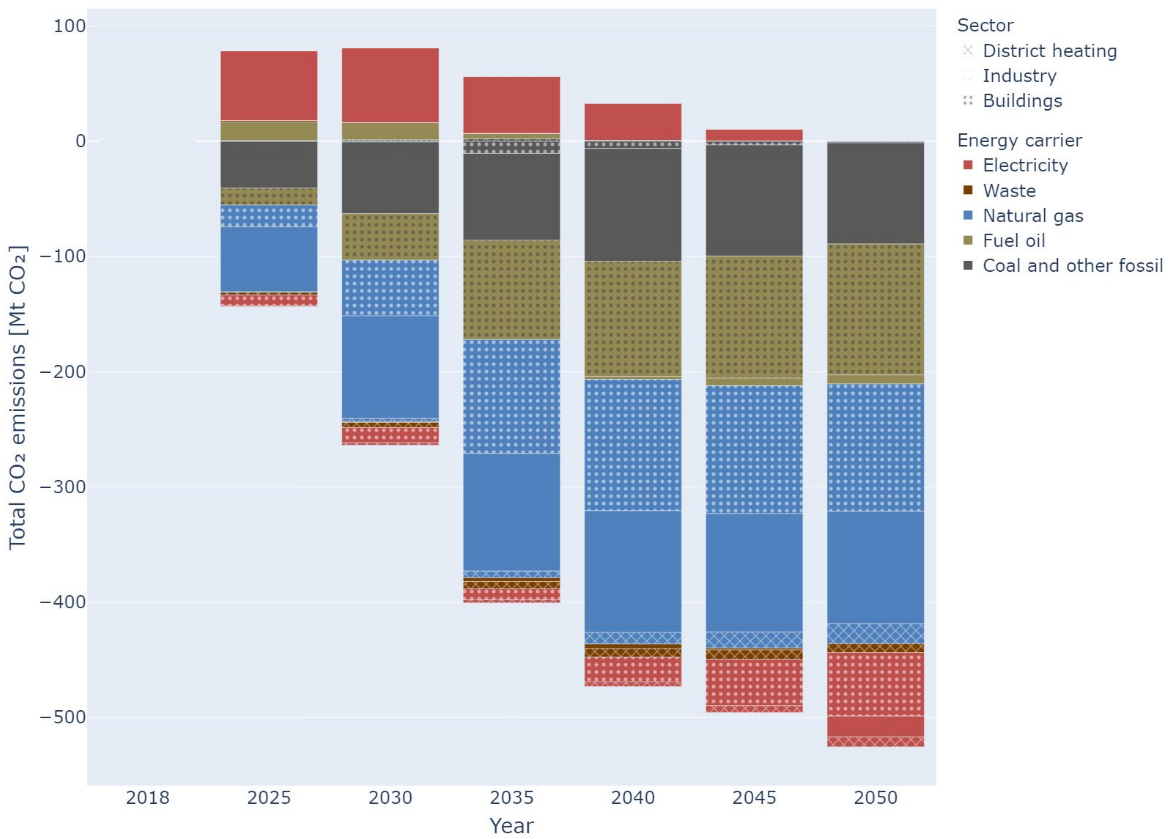


Figure 94: Difference in greenhouse gas emissions from heating and cooling by sectors (buildings, industry, district heating) and by energy carriers between decarbonisation pathway scenario and baseline scenario, EU-27

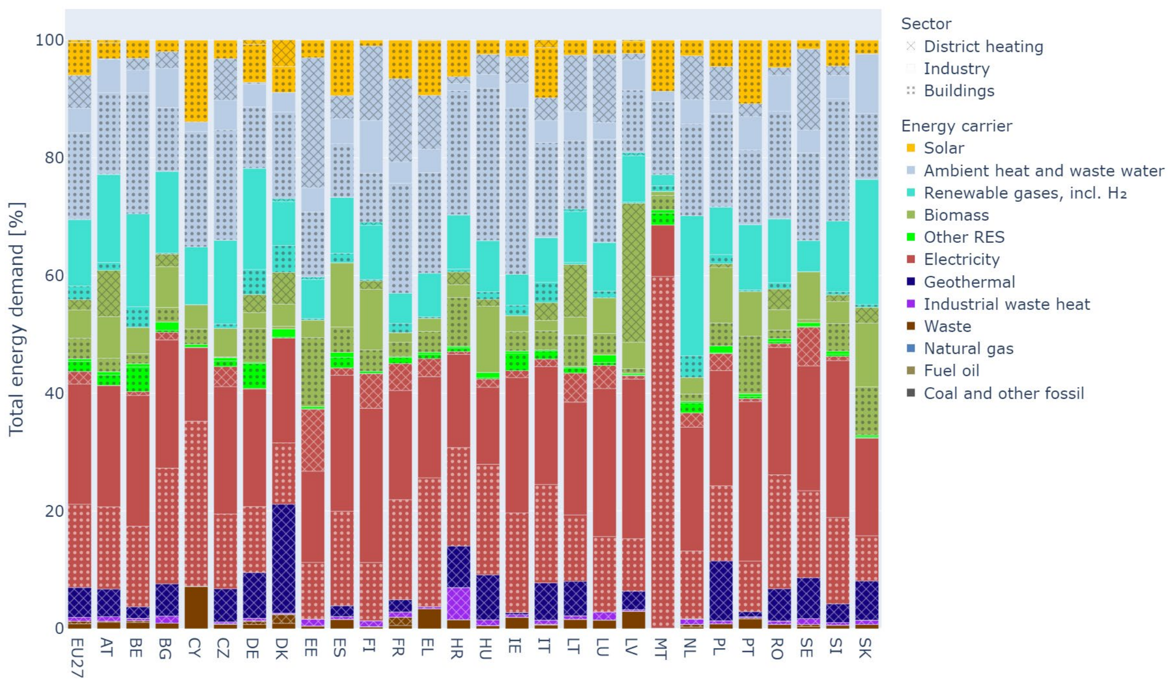


Figure 95: Share of energy carriers for heating and cooling by sectors (buildings, industry, district heating), decarbonisation pathway scenario, 2050

The price sensitivity run shows a possible impact of high energy prices, assuming that the price levels of the first half of 2022 remain approximately constant until 2030 and only then move again to the price levels assumed in the pathway scenario. The model results in an adaptation of user behaviour in buildings in terms of reduced winter indoor temperature and hot water consumption. However, due to strong regulatory measures requiring building renovation and phase-out of gas and liquids, the high prices do not trigger substantial additional long-term energy saving measures. This is why the results by 2050 do not differ strongly in the building sector.

In the industry, the high prices mainly trigger a faster reduction of gas demand with the effect of slightly higher biomass demand, but also higher oil and coal demand in the period around 2030. By 2050, the differences are again rather negligible between the two scenarios, because of the strong policy effects.

In district heating, we assumed a faster transition process, leading to earlier investments in renewable district heating, triggered by high gas prices and related policies.

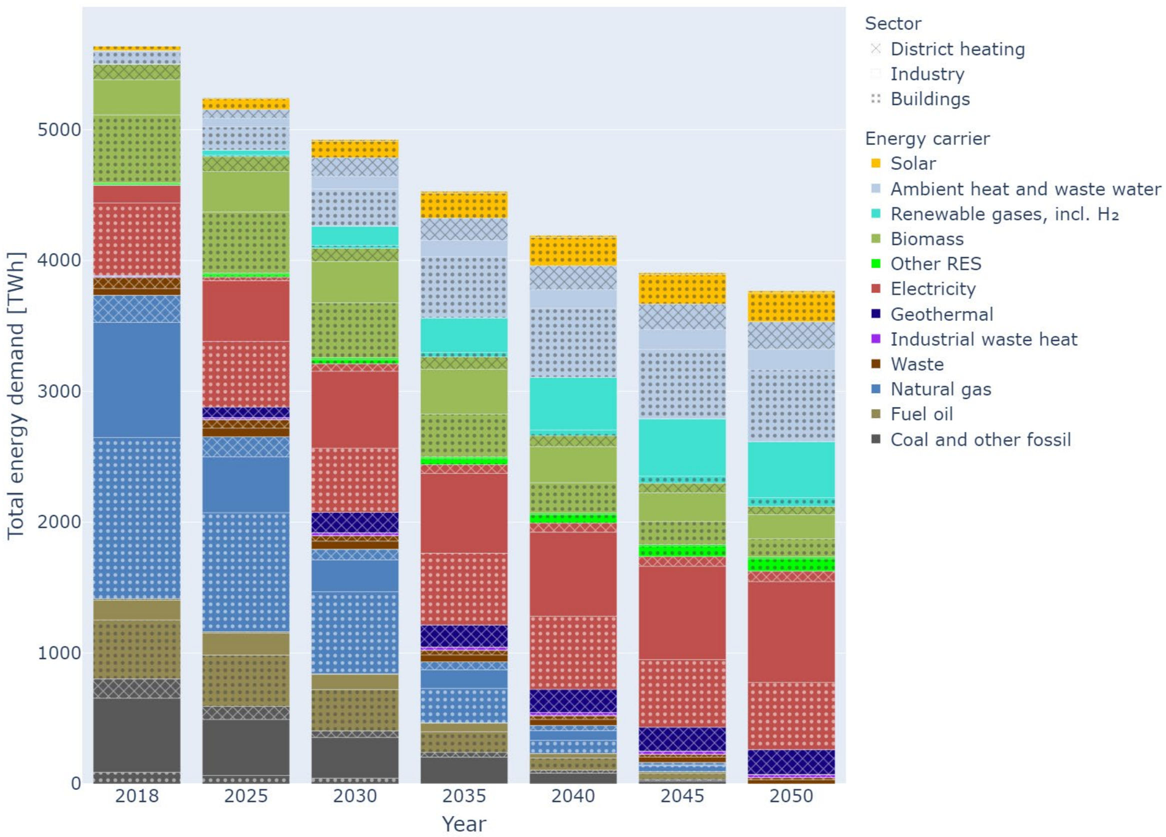


Figure 96: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, price sensitivity scenario, EU-27

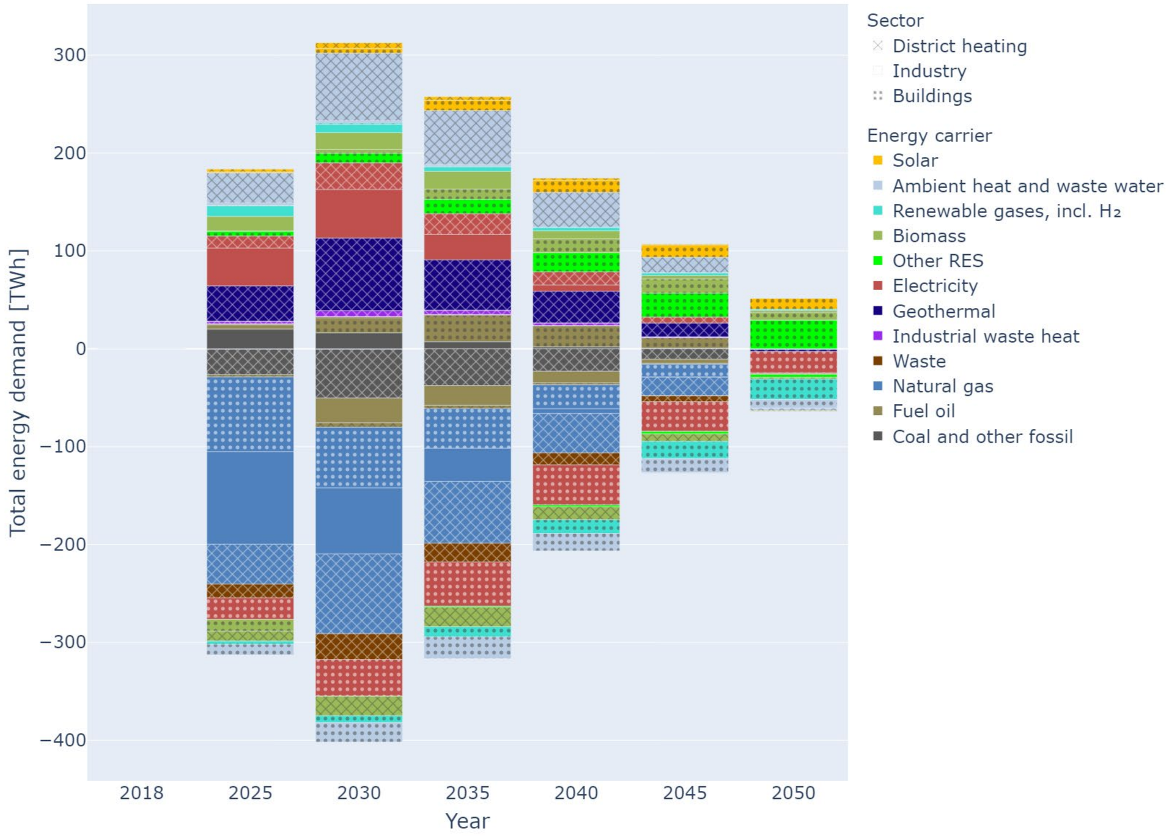


Figure 97: Difference in energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers between price sensitivity scenario and decarbonisation pathway scenario, EU-27

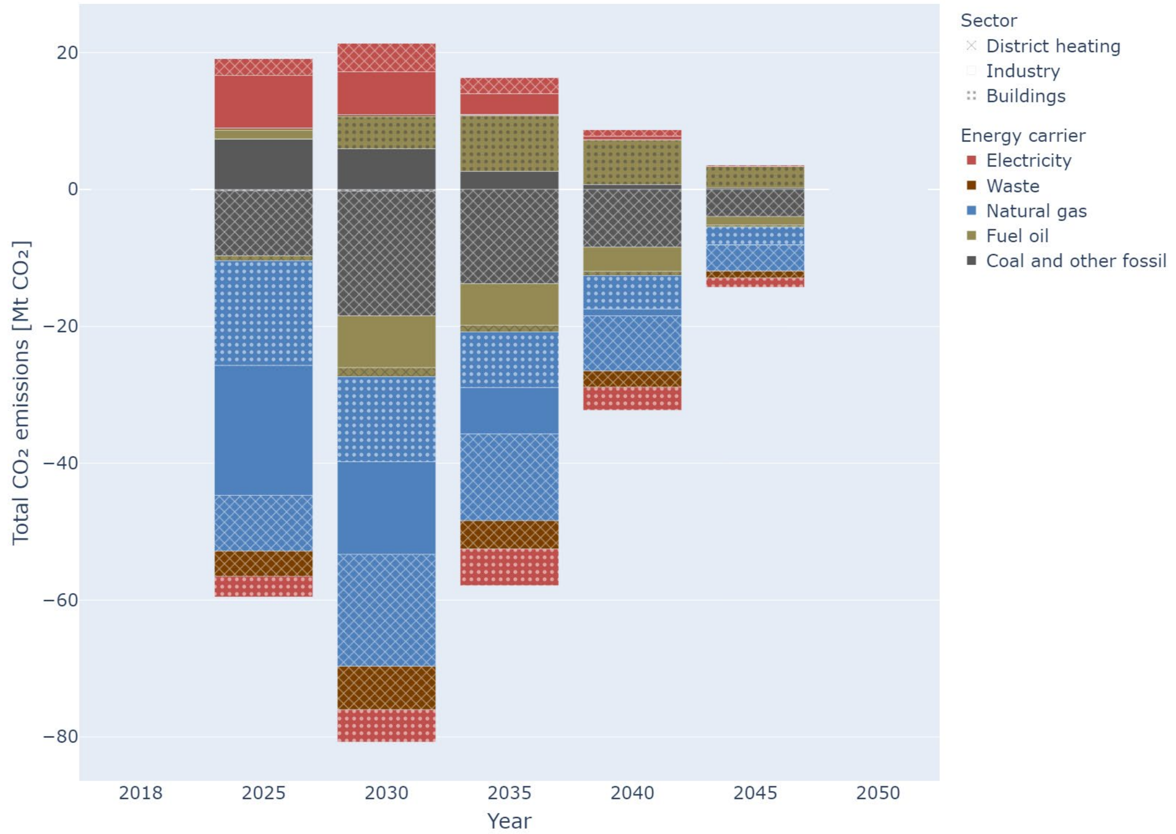


Figure 98: Difference in greenhouse gas emissions from heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, price sensitivity scenario, EU-27

In the case of low energy prices (prices before 2021), the pathway scenario leads to additional costs of about 60-80 bn Euro annually, mainly triggered by building renovation and not completely offset by corresponding savings. This corresponds to a range of about 6-10% of total system costs in the baseline scenario. It needs to be considered that this does not include co-benefits like increased supply security, resilience, comfort and health benefits etc. Also, benefits beyond the year 2050 are not factored in. These costs are considerably lower than the additional costs triggered through high prices (and not even considering the costs of gas supply cuts). The scenario with high prices (price sensitivity scenario) leads to additional costs of 100-140 bn Euro in the period until 2030, although this already assumes a quick phase-out of natural gas (see Figure 99 to Figure 101).

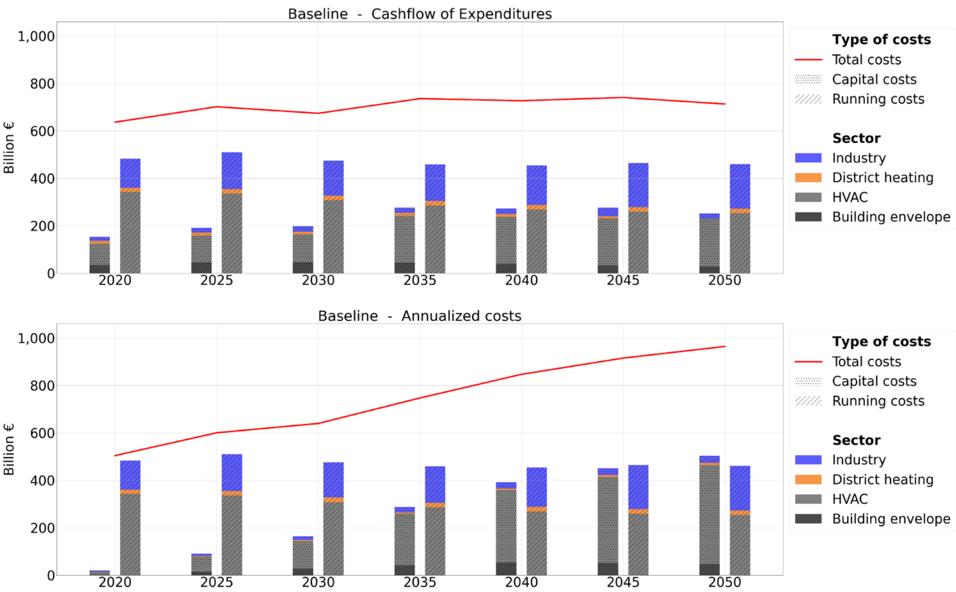


Figure 99: System costs for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, baseline scenario, EU-27

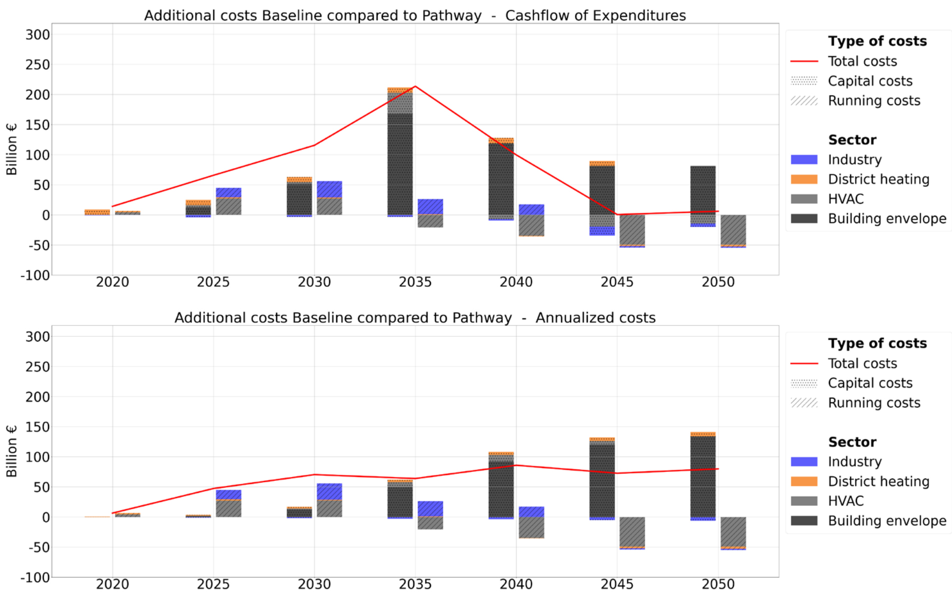


Figure 100: Additional system costs for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, decarbonisation pathway scenario compared to baseline scenario, EU-27

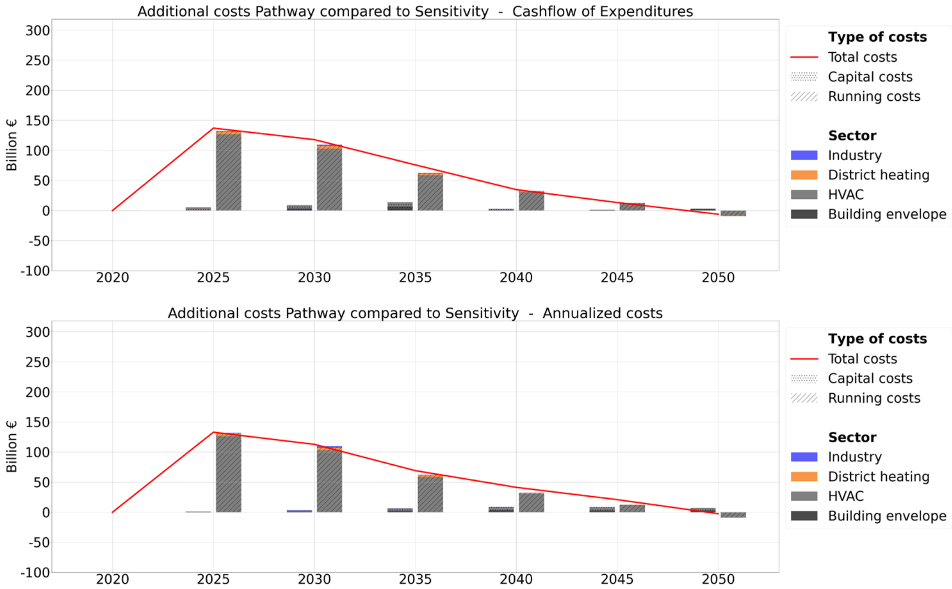


Figure 101: Additional system costs for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, price sensitivity scenario compared to baseline scenario, EU-27

The focus of our analysis was the modelling of scenarios by 2030 and 2050. In addition, an outlook to 2070 was provided (for selected results see Figure 116 and Figure 117 in the Annex). It becomes clear that the uptake of decarbonisation measures in the baseline scenario is much too low to achieve decarbonisation, even by 2070. GHG emissions from the heating and cooling sector decrease by less than 60% from 2018 to 2050. Renovation measures in the building sector continue with the moderate pace after 2050, as it was in the period before, and the slow trend towards heat pumps continues. The industry sector still relies on natural gas and coal in 2050 in the baseline scenario. The transition of the steel industry is not even half-way completed.

From the decarbonisation pathway we can learn that also after 2050 building retrofitting activities and heating system replacement continue to have an impact in terms of reduced energy demand. Moreover, gases and liquids are almost completely phased out in this scenario by 2070, while heat pumps and district heating slightly increase their share of final energy demand. This means that gases and liquids in 2050 are still in the system mainly due to the inertia of the system and the long lifetime of boilers, and not because of economic viability, while until 2070 an almost complete phase-out of these energy carriers is achieved in this scenario. In industry, fossils are phased out latest by 2050. In the longer term, hydrogen and electricity will continue to compete for market shares. CO_2 will even more become a commodity and CO_2 transport infrastructures will be extended where useful. Circularity can further improve and make use of more saturated stocks and markets, so more waste materials like steel scrap will be available. Increasing recycling rates (also in plastics) will reduce the demand for hydrogen and electricity.

7. Discussion and conclusions

7.1. Space and water heating and cooling in buildings

To achieve full decarbonisation of space and water heating and cooling in buildings by 2050, ambitious policies are needed. Table 34 summarises the key elements of the policy set required (for more details see Section 5.2.4).

Table 34: Key elements of policy set for individual heating

Policy set: Renewable heating (individual boilers)			
	Regulations	**Economic instruments**	**Complementary instruments**
EU level	Short term: Fossil-free new buildings (EPBD) Short term: Framework for national fossil fuel phase-out (EPBD/RED) Medium term: End date for selling fossil boilers at EU level (Ecodesign)	Short term: No subsidies for fossil heating technologies in any EU funding schemes From 2027: Carbon pricing ETS 2 (ETS directive) Social Climate Fund: Focus on vulnerable households	Facilitate exchange between Member States Guidelines and framework for national support schemes Technology supply chains and production of technologies
National level	Fast introduction of (gradual) phase-out regulations (use obligations, efficiency requirements, ban) Heat planning and strategy for regulatory framework for decommissioning parts of the gas grid	No subsidies for fossil boilers Subsidies for RES heating Reduce taxes on electricity, add taxes or levies on fossil energy carriers	Facilitate market transformation through information and capacity building Address shortage of workforce in the installer market Expansion of RES-E

The policy set **results in a significant reduction of greenhouse gas emissions** as compared to the reference scenario: At the EU level, GHG emissions from individual heating systems in buildings decrease by 62 Mt in 2030 as compared to the reference scenario. The impact of the policy set is particularly strong in countries with high shares of individual heating based on fossil fuels: Figure 102 shows that the reduction of greenhouse gas emissions per capita is highest in Ireland, followed by Belgium, France, Germany and the Netherlands, reflecting the fact that these are the countries with the highest shares of fossil-fuel boilers in their energy mix for space heating (see Figure 41). By contrast, the impact is relatively low in countries with low shares of fossil-fuel boilers.

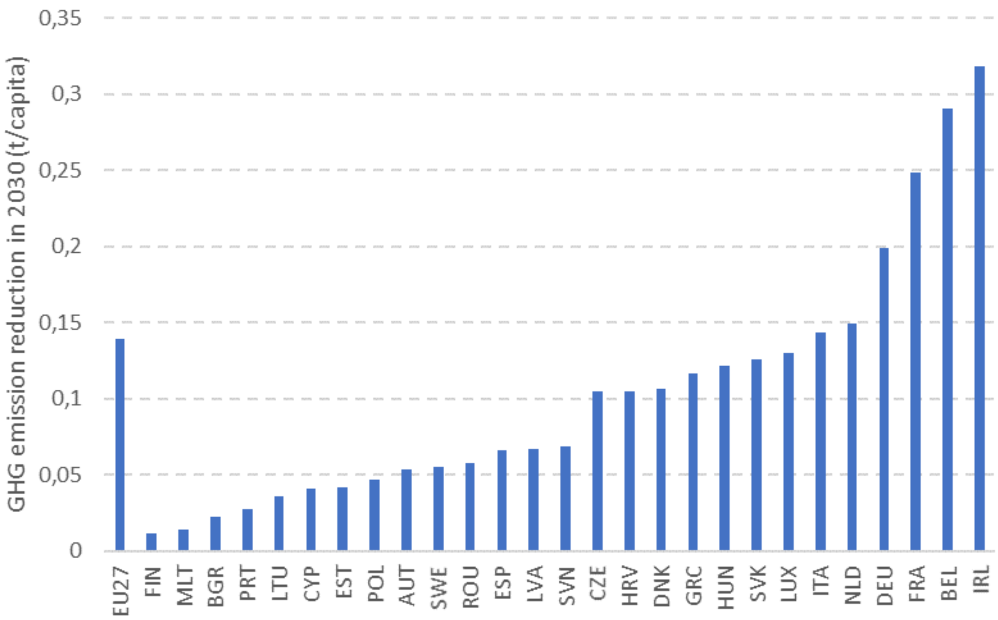


Figure 102: Reductions of greenhouse gas emissions in 2030 in the decarbonisation pathway scenario as compared to the baseline scenario.

The policy set **has a considerable impact on the use of natural gas in individual heating**. At the EU level, natural gas demand for individual heating in buildings is reduced by 212 TWh in the pathways scenario as compared to the baseline scenario. The main driver for the reduction are the regulatory measures to phase out the installation of fossil fuel boilers, combined with economic instruments to support the transition. The per capita reduction of gas demand for individual space and water heating is shown in Figure 102.

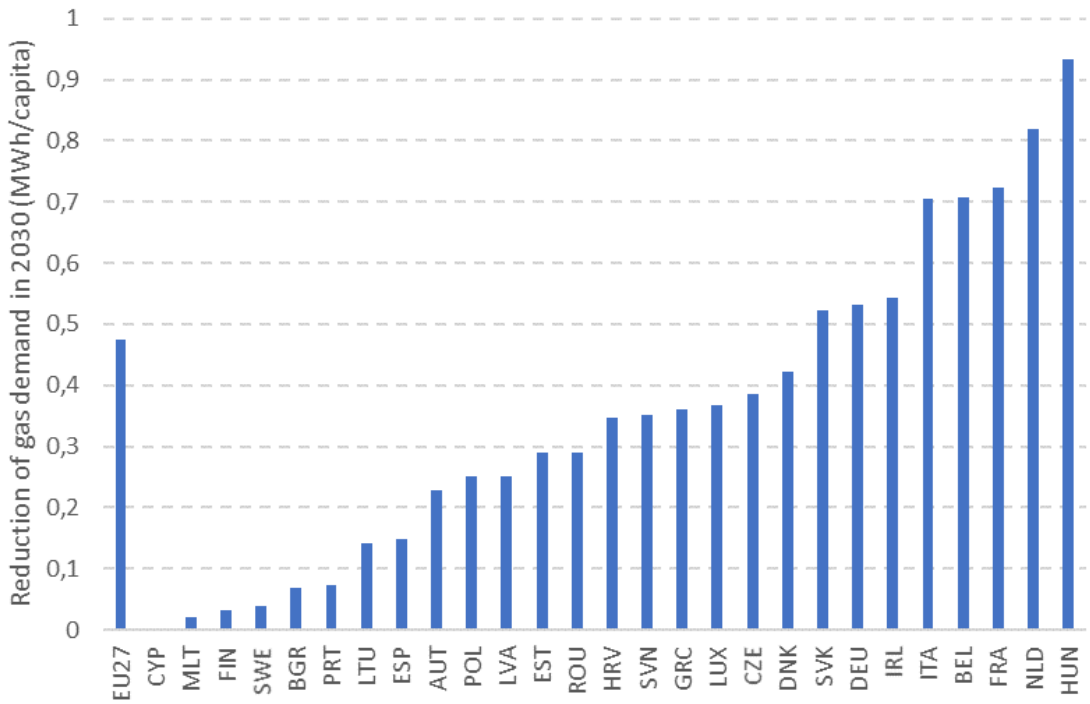


Figure 103: Reduction of natural gas demand for individual heating in buildings in the decarbonisation pathway scenario as compared to the reference scenario (2030).

The use of heat pumps increases significantly in the pathway scenario. The increase differs largely between the countries, depending on the initial share of heat pumps, the district heating share as well as climatic conditions.

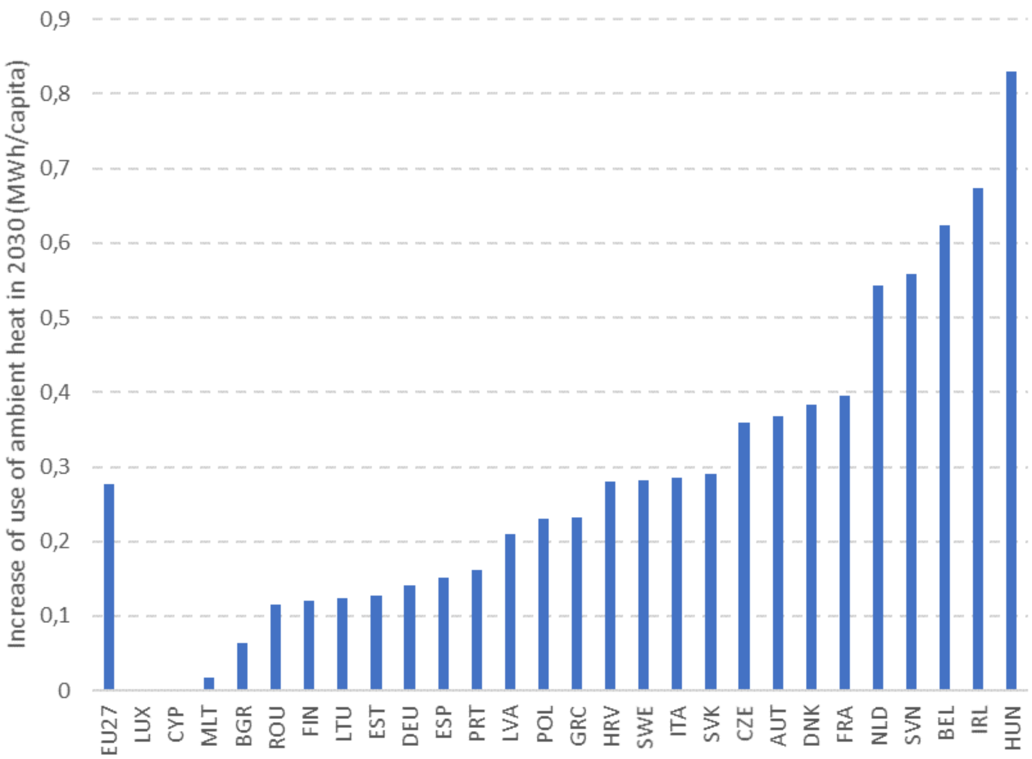


Figure 104: Increase of use of ambient heat in 2030

For individual heating in buildings, the main elements are regulatory instruments to phase out fossil fuels for heating, combined with economic incentives. In addition, a strong regulatory and support framework to support energy efficiency in buildings is needed.

As the Member States have largely differing shares of fossil fuel boilers in their current heating energy mixes, it is recommended that Member States rapidly introduce national phase-out regulations that support the transition of the market, taking into account the country-specific situations. In the medium term, a ban of the sales of fossil fuel boilers at EU level is recommended. This can be introduced within the Ecodesign framework as proposed in the Save Energy Communication. Within this framework, the ban would be introduced as a minimum requirement on energy efficiency, making (hybrid) heat pumps the standard for new heating installations. The introduction of an end date for selling heating equipment that uses fossil fuels should be communicated and legally implemented well in advance to ensure that the market actors adapt their strategies accordingly.

In terms of economic policies, a key precondition for the decarbonisation of heating and cooling in buildings is energy pricing. The analysis shows that high prices for fossil fuels strongly support the transition towards renewable heating, whereas electricity prices are key for the deployment of heat pumps. While several countries have implemented carbon pricing schemes to support the transition, an energy pricing reform can act as a key driver in many countries.

Another important driver for the transition of heating in buildings are subsidies for heating equipment. Subsidies for renewable heating systems can support the transition and can reduce the burden of households and companies in the transition. To this end, it is recommended that such policies specifically address low-income households to ensure a fair transition. In addition to ensuring financial support for renewable heating equipment, it is essential that financial support for fossil fuel boilers is phased out immediately both at EU and national level. At the EU level, this needs to be ensured by providing clear requirements and guidelines in the EU funding schemes. At the national level, for those countries that still include fossil fuel boilers in national schemes, it is recommended to immediately stop the support and redirect the funding into renewable heating technologies and energy efficiency measures.

Next to the regulatory framework and economic instruments, the market transformation needs to be supported by complementary policies. Firstly, on the supply side, this includes measures that address the shortage of skilled labour to ensure that the demand for renewable heating technologies and energy efficiency measures can be met by the market actors. This might encompass European initiatives to ensure the supply chain for equipment like renewable heating systems or control devices, if required also the production of critical products within Europe. Secondly, on the demand side, measures to facilitate retrofit work in buildings and to provide information and advice to building owners are essential, including the establishment of one-stop shops and enhancing the use and quality of Energy Performance Certificates.

7.2. Heating and cooling in industry

H&C in industry is dominated by high-temperature process heating in basic materials industries in most countries. The transition to CO_2-neutral process heating requires as key strategies both electrification and the increased use of hydrogen. Other options are also relevant for CO_2-neutral process heating but are more of a supporting nature as they can reduce the demand for hydrogen or electricity and lower the pressure on the energy supply system. Examples are solar thermal, geothermal district heating or biomass. Here, we focus on the two main strategies: Electrification and hydrogen use for process heating.

The policy mix needs to assure cost-competitiveness of both options compared to fossil-based process heating. In many cases this includes re-investment in new furnace or boiler equipment. In some cases, even a switch to another production process is required (e.g. primary steel production). Main recommended policies are summarised in Table 35. At the centre are policies that target the cost-competitiveness of CO_2-neutral process heat supply. These involve on the one hand options that make fossil technologies more expensive by e.g. adding a price on carbon emissions or increasing taxes, and on the other hand options that make CO_2-neutral solutions cheaper e.g. by providing dedicated investment or OPEX support or by reducing the price of electricity and hydrogen for industrial consumers.

Table 35 Key elements of the policy mix for CO_2-neutral process heating

Policy set: Process heating			
	Carbon and energy price regime	**Technology support**	**Complementary instruments**
EU level	Strong ETS I with robust price path ETS II also including industry that is not in ETS I Reform of energy taxes and levies to make electrification and hydrogen more attractive compared to fossils	Investment support to accelerate market entry and early diffusion. CAPEX & OPEX support, e.g. via contracts for difference to fill gaps in cost competitiveness of key decarbonisation technologies	Transition of the upstream energy system to ensure sufficient supply of renewable-based electricity and hydrogen for industry Strategies and plans for the roll-out of hydrogen infrastructure incl. regional prioritisation to allow companies to plan investments
National level	Large part of the reform of energy taxes and levies is Member State activity If the EU ETS II does not materialise or does not include the industry sector, national measures will be needed to introduce a CO_2 price for the industry outside of ETS I	Technology support programmes will need to be implemented by Member States to a large extent	The transition of the upstream system and the development of strategies and plans for the hydrogen roll-out largely falls into Member State responsibilities as well.

The scenario calculation shows that with an ambitious implementation of the policy mix, a transition towards a CO_2-neutral process heat supply in industry can be achieved. Figure 105 shows the development of final energy demand. Key insights from the scenario analysis are:

- **Electricity and hydrogen** from renewables are key to decarbonise industrial process heat supply. Here, a clear policy strategy is needed to reduce uncertainty and make investments plannable.
- **Hydrogen is important in high-temperature processes** like metal or minerals processing.
- However, technologies for using electricity or hydrogen for process heating in **industrial furnaces** are often not yet available at industrial scale. Policies for upscaling and market introduction can facilitate the transition
- **Electrification** can happen at large scale in the short term to electrifcy steam generation, if the regulatory frame allows it – technologies are ready. Still, the past has shown that prices for electricity were too high compared to fossils. The main

driver of costs are OPEX and less CAPEX. A reform of energy and CO_2 prices and accompanying support policies need to make electrification cost-competitive. Electrification of process heat might be the most efficient way, however, in most cases it also requires a more comprehensive re-investment. Here, policies can provide investment support for electrification solutions

- Use of direct RES only to supply **low-temperature process heating** below 150 or even 100°C (limited potential). **Industrial heat pumps** allow efficient electrification in this temperature range.
- **Biomass** facilitates a fast phase-out of natural gas, but is not key in the long term.
- **Energy and material efficiency improvements and circularity** overcompensate economic growth and substantially reduce the demand for clean secondary energy carriers, but are not sufficient to decarbonise.

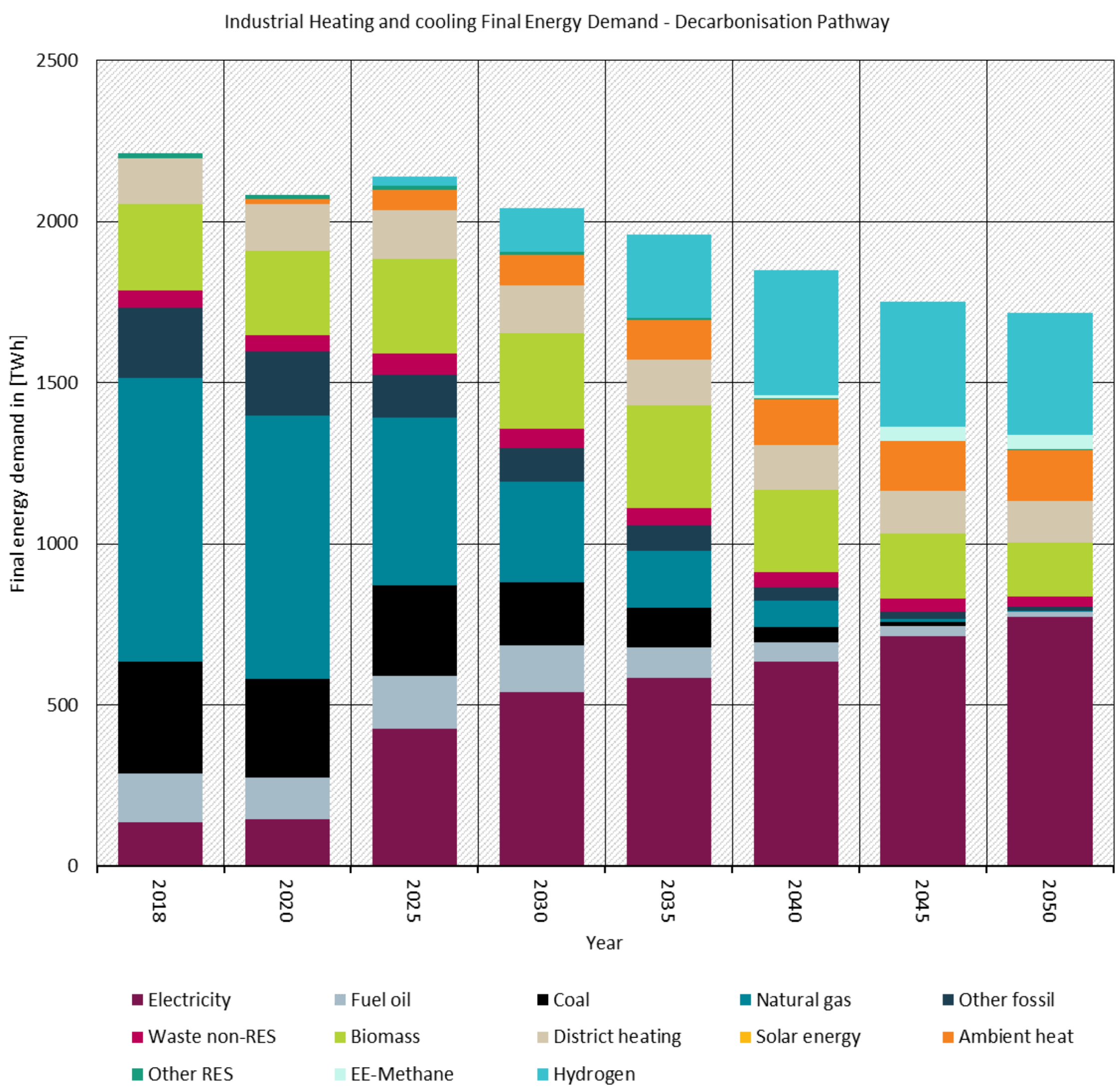


Figure 105: Final energy demand for H&C in industry in 2050 in the pathway scenario (EU27)

The impact of the policy mix is quantified in Figure 106 by calculating the additional use of electricity or hydrogen for H&C in industry in the pathway scenario as compared to the baseline scenario. These changes from the baseline to the pathway scenario are explained via additional policies making electricity- and hydrogenbased solutions for process heating more attractive. Results show that the additional impact for electrification is substantially higher than it is for hydrogen - particularly by 2030 there is already a substantial impact from electrification, replacing gas and coal in the short term. Electrification plays quite a substantial role in many countries, while the countries with the highest per capita increase are Finland, Sweden, Latvia, Austria and Slovenia. Countries with lower increase in per capita values generally have less domestic heavy industry. For hydrogen, it can be observed that the major uptake takes place after 2030. Hydrogen also plays at least a smaller role in all countries for process heating, but is very pronounced in the Netherlands, Finland, Slovakia, Austria, Germany and Belgium.

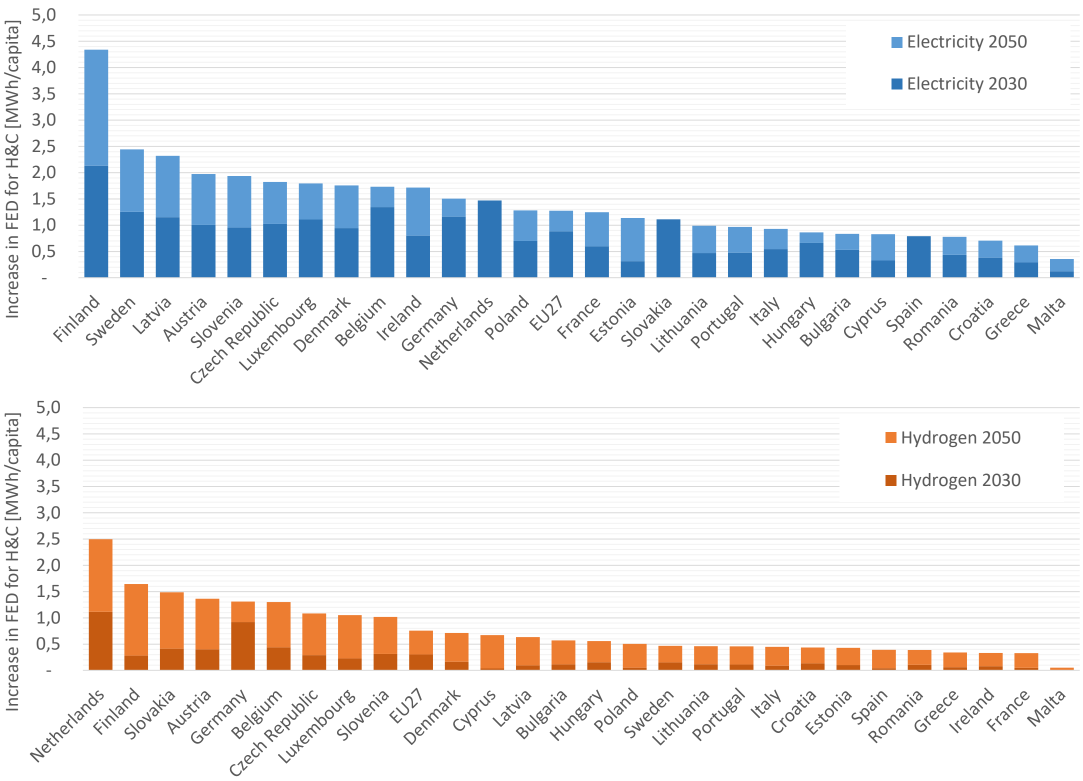


Figure 106: Increase in electricity (top) and hydrogen (bottom) demand in the pathway scenario as compared to the baseline scenario

7.3. District heating

To expand and decarbonise DH, ambitious policies are needed. Table 36 summarises the key elements of the policy set required.

Table 36 Key elements of policy set for district heating

Policy set: District heating			
	Regulations	**Economic instruments**	**Complementary instruments**
EU level	Mandatory grid access for third-party generation from	Strong ETS I with robust price path	Support for capacity building and exchange

Policy set: District heating			
	Regulations	**Economic instruments**	**Complementary instruments**
	climate-friendly heat generation Obligations to develop transformation strategies and to expand the use of waste heat.	Reform of energy taxes and levies to make electrification and hydrogen more attractive compared to fossils Specifications for efficiency district heating in EU funding context	between Member States. Financial support for research and development on innovative district heating and cooling solutions.
National level	Quota/obligations for including renewable energies in DHC Mandatory expansion targets, spatial zoning, mandatory connection to DHC systems.	Subsidy schemes for the expansion and decarbonisation of fossil-free district heating and cooling.	Strategic (local) heat planning approaches, awareness across different market actors, participation

The policy set for DH **results in a significant reduction of greenhouse gas emissions** as compared to the baseline scenario. The impact is particularly strong in countries with high shares of district heating. In 2050 a **fully decarbonised DH mix is reached** in the pathway scenario, mainly due to the high CO2 price.

Furthermore, the policy set for DH **has a considerable impact on the expansion of district heating**. Figure 107 shows the increase of the DH demand in the pathway scenario per capita until 2050/2070 compared to current levels.112 Expansion of DH per capita is especially foreseen in Italy, France, the Netherlands, Hungary, Sweden, the Czech Republic and Croatia. Thus, especially in these Member States policy measures for the growth of DH infrastructure are needed.

[112] DH demand in 2050 based on modelling results; current level based on DHC Trend report, https://op.europa.eu/en/publication-detail/-/publication/4e28b0c8-eac1-11ec-a534-01aa75ed71a1/language-en

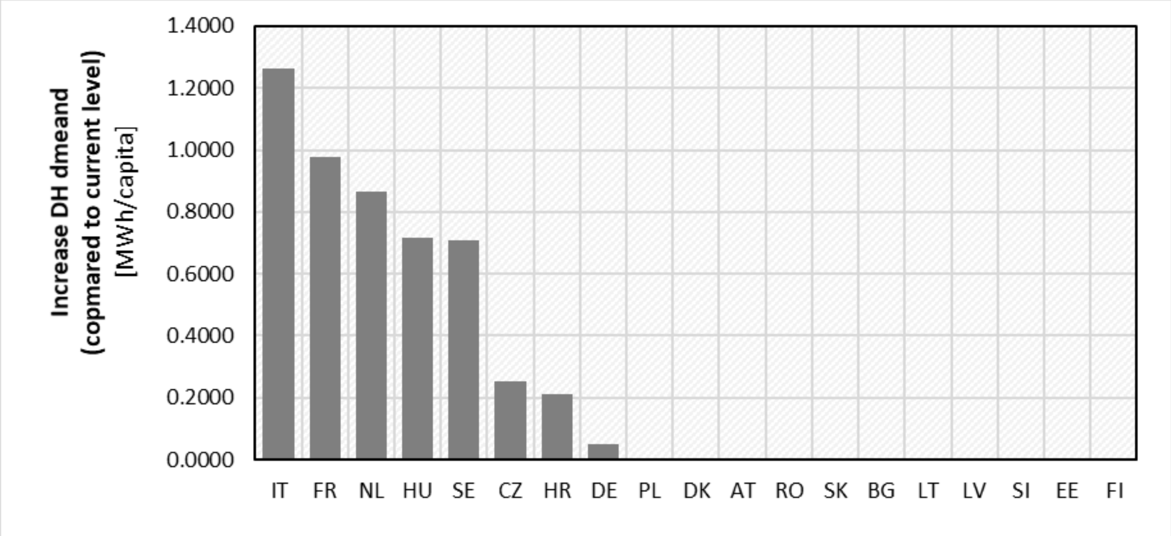


Figure 107: Increase of DH demand until 2050 compared to current level

In addition, the policy set for DH **has a high impact on the generation mix for the DH supply**. The following three figures show the shift in the technology mix in DH per capita compared to today.113 Only the shift for the three most prominent technologies are shown: heat pumps (47% on EU level), geothermal energy (30% on EU level) and biomass (13% on EU level).

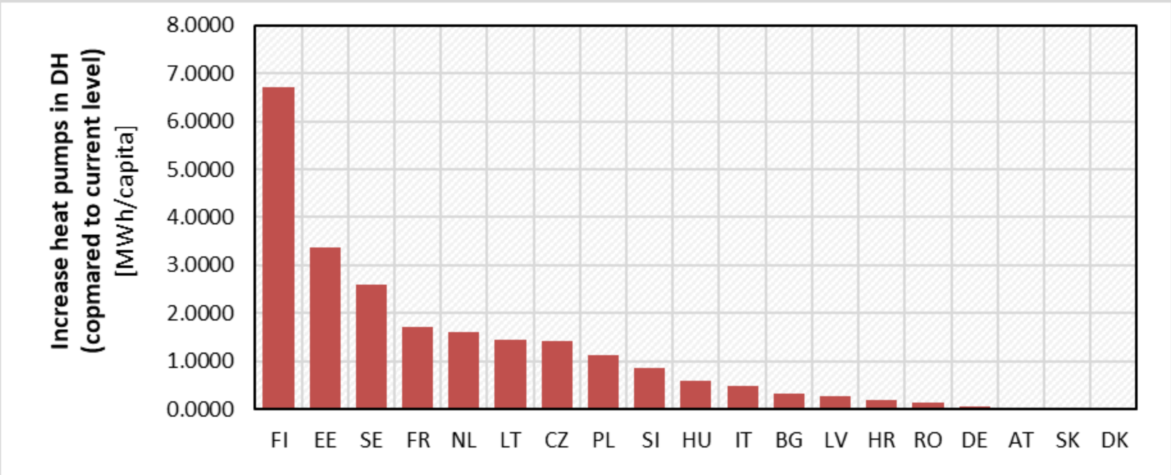


Figure 108: Increase of heat pumps in DH until 2050 compared to current level

[113] Mix in 2050 based on modelling results; current level based on DHC Trend report, https://op.europa.eu/en/publication-detail/-/publication/4e28b0c8-eac1-11ec-a534-01aa75ed71a1/language-en

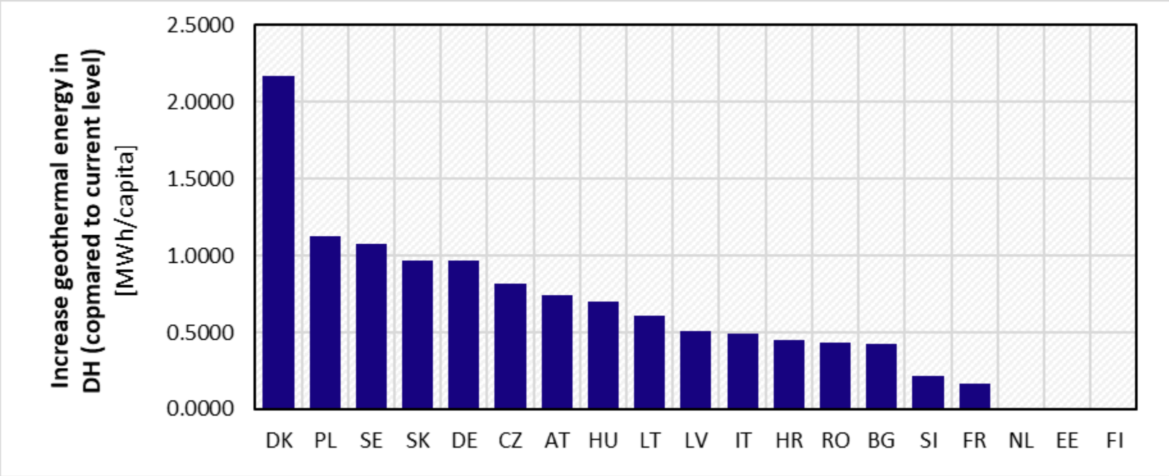


Figure 109: Increase of geothermal energy in DH until 2050 compared to current level

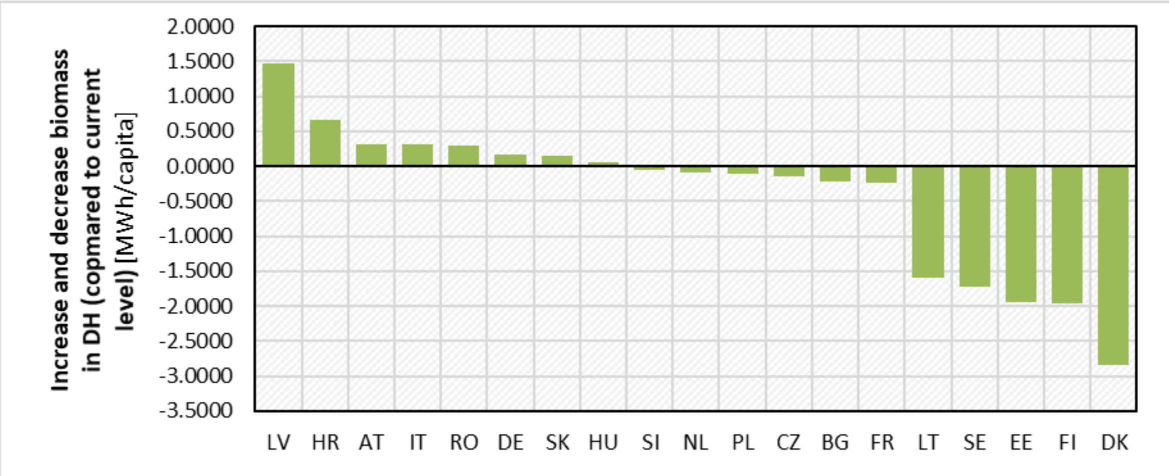


Figure 110: Increase and decrease of biomass in DH until 2050 compared to current level

Heat pumps have the highest contribution to the DH supply mix at EU level and also in several Member States in 2050. Figure 108 shows that in almost all Member States a strong uptake of heat pumps is foreseen (in the pathway scenario). In the modelling, Member State-specific electricity prices are assumed, which are quite high in some Member States. Because of high electricity prices, heat pumps are less cost-competitive in the respective Member States. Lower electricity prices would lead to higher shares of heat pumps with accordingly lower shares of RES, especially geothermal energy. Thus, we recommend policies for the uptake of large-scale heat pumps for all Member States.

An uptake of **geothermal** energy is especially prominent in Denmark (see Figure 109). However, the modelling results foresee a considerable increase of geothermal energy in almost all Member States, except the Netherlands, Estonia and Finland. Thus, policies for the uptake of geothermal energy (i.e. policies to support technical progress and minimise exploration risks to utilise potentials) are highly needed in almost all Member States.

Regarding the use of **biomass** in DH a shift in several countries can be observed (see Figure 110). In line with the modelling results, an increase of biomass is foreseen in Latvia, Croatia and, to a smaller extent, in Austria, Italy, Romania, Germany and Slovakia. In contrast, for several Member States a reduction in the use of biomass is foreseen until 2050 to reach the 2050 results of the pathway scenario. Especially in Denmark, Finland, Estonia, Sweden and Lithuania, a decrease of biomass seems to be cost-optimal in 2050 in the pathway scenario. Policies for the allocation of biomass are needed to trigger this shift.

Furthermore, other waste heat sources should be utilised either directly or together with heat pumps, depending on the temperature level. Waste-to-Energy can have a relevant contribution, so CO_2 price exemptions for waste incineration could be needed. Policies for the integration of industrial waste heat into district heating are needed to exploit the potentials. Policies to decrease system temperatures down to around 60°C may be needed, together with coordinated actions with building renovation, as renewable and waste heat potentials can be utilised more efficiently.

7.4. Cross-sectoral conclusions

The decarbonisation pathways consist of the following components:

- Energy savings
- Electrification and use of ambient heat sources
- Hydrogen, e-fuels and other renewable gases and liquids
- Solar energy
- District heating
- Solid biomass

Most of these components are present across all Member States and need specific policy considerations. The Member States, regions and sectors show significant differences regarding the importance of each of these components in our decarbonisation pathway scenario. In the following, the role of the different elements in different MS is discussed and the corresponding challenges as well as policy needs are highlighted.

Energy savings

The senario results show a signifiant reduction of total energy use for heating and cooling by about 1/3 from 2019 (5600 TWh) to 2050 (3800 TWh). This is mainly caused by the reduction of final energy demand for space and water heating, mainly driven by renovation of the building envelope, but also by the replacement of inefficient, old heating systems. While the final energy demand for space and water heating in buildings decreases by about 40% in this period (in terms of energy delivered even 60%), in the industry sector this reduction amounts to about 22%. For space cooling, the pathway scenario achieves a consolidation of the final energy demand through the very stringent use of passive measures, reducing the cooling demand strongly and increasing efficiency of cooling devices. Space heating, space cooling and process heating and cooling demand per capita vary strongly between Member States due to climatic conditions, status of the building stock and share of industrial sectors. Still, the scenario results show that the trends illustrated for the EU27 are more or less stable in all Member States. The main reason for this is that in general the building stock's envelope is better-performing in northern countries with a more severe winter climate than in southern countries. Thus, on the one hand the southern countries have lower savings potentials due to lower heating degree days, but this is compensated due to the low energy performance of the buidling stock in these countries.

On the other hand, while in northern countries in general building codes introduced more stringent energy efficiency standards at an earlier stage, due to the high heating degree days there are still high efficiency potentials untapped.

The results are related to several uncertainties and limitations due to the modelling approach:

(1) In the past, it had been observed that reductions of energy demand calculated due to building renovation are higher than energy savings measured (see e.g. Loga and Stein, 2022). At least parts of these effects have been addressed in the modelling. However, there is still an uncertainty related to the possible over-estimation of efficiency gains from building renovation. Besides model-related uncertainties and limitations, the results also depend on the question to which extent a high quality of renovation works can be achieved. Clearly, the decarbonisation pathway scenario assumes a substantial enhancement of current renovation practices in terms of quantity, quality, depth and coordination of measures.

(2) Behavioural changes in terms of indoor temperature have a strong impact on energy needs for space heating and cooling. In particular energy price increases may lead to reduced comfort levels (or the other way round), in particular – but not only – in housedholds affected by energy poverty. In our modelling, we considered the fact that building renovation leads to higher comfort levels and at the same time is able to reduce energy poverty due to lower energy needs. However, we did not assume substantial changes in comfort needs and housing functionalities.

(3) Lifestyle changes may have a significant impact on the demand for buildings and related conditioned space. E.g. higher shares of remote working may lead to higher floor space per capita in the residential sector, while it remains an open question to which extent floor space in the tertiary buildings might be reduced. Also, the shift towards common spaces in the housing sector might reduce the floor space per capita. In our modelling, we did not assume significant changes in the lifestyle affecting the demand of floor space in the residential and non-residential buildings.

(4) Industry: While efficiency potentials are well exploited in the pathway scenario, more could be possible with regard to material efficiency and circular economy, especially if entire value chains are redesigned. While this is technically possible, there is huge uncertainty if policy instruments will be designed that can effectively exploit such potentials.

<u>Electrification and use of ambient heat sources</u>

Electrification, the phase-out of direct electrical resistance heating and the strong increase in heat pumps is the most relevant change in the supply structure of heating and cooling across the EU-27 in the decarbonisation pathway scenario. Total electricty consumption almost doubles from 2019 until 2050. While the electricity consumption in the building sector remains more or less constant (or even slightly decreases), the electricity consumption for process heating in the industry increases almost by a factor of 6 to about 700 TWh by 2050. Also in district heating, the role of large-scale heat pumps becomes more important, at least in some countries.

While electricity consumption doubles from 2019 to 2050, the share of electricity and ambient heat in total energy use in the sector increases from 13% in 2019 to more than

46% in 2050. Thus, due to the more efficient use of electricity in heat pumps and the reduced energy needs on account of building renovation, the role of electricty in the heating and cooling sector takes a crucial role in this scenario.

As mentioned above, this trend is present across all EU-MS. Deviations between Member States mainly occur due to the different structure and relevance of industry sectors, different renewable district heating potentials (mainly geothermal, industrial waste heat, biomass) and the share of remaining gases and liquids in the building sector. Overall, the relevance of electricity is also driven by electricity prices and in particular the level of taxation and grid fees.

Uncertainties on the one hand are caused by the uncertainty of future electricity prices and related taxation policies. On the other hand, achievable seasonal COPs are crucial for the total electricity demand and economic viability. In this respect, we consider the fact that building renovation on average leads to lower space heating supply temperatures required, with a corresponding effect on the SCOP of heat pumps.

District heating

The role of district heating in the decarbonisation pathway scenario strongly increases: in residential and tertiary buildings the share increases from about 12% in the base year to more than 24% in 2050, while in the whole heating and cooling sector, the share increases from 10% to 16%. The importance of district heating in the decarbonisation pathway scenario significantly differs between countries. This is driven by heat demand densities, policies (in particular zoning policies leading to high connection rates), availabilty of cheap renewable district heating technologies and the economic comparison to other, decentralised heat supply options. In particular, countries with currently high shares of district heating like the Scandinavian countries and Baltic countries keep and expand these high shares. But also more southern countries like Spain or Italy develop and expand the district heating sector.

Geothermal energy in the decarbonisation scenario turns out to be an important, cost-effective solution for renewable district heating in most countries, possibly providing 30-45% of thermal generation of DH. However, sensitivities have shown that large-scale heat pumps and (to a lesser extent) biomass can show an equal economic viability, mainly depending on price assumptions (e.g. electricity prices including taxes and fees). Thus, slight differences in policies or cost developments may lead to corresponding changes in the results. Industrial waste heat and the use of heat from municipal solid waste incineration should be increased as far as possible. Solar thermal energy could provide up to 10% of DH generation, depending on cost assumptions.

Long-term, seasonal thermal storage represents a key enabler of renewable district heating. Costs and barriers of different storage systems are still related to considerable uncertainty. Investments in thermal storage will also promote the low-cost integration of renewable heat potentials. The amount of these investments in our modelled scenarios is considered as moderate/conservative. Through higher uptake of low-cost thermal storage, district heating could gain even more relevance in the decarbonisation of space and water heating.

In the modelling, we explicitly considered the fact that building renovation on average leads to lower space heating supply temperatures required, with a corresponding effect on the possible lower supply temperature in district heating. Regarding the latter, we assumed a tendency towards fourth-generation district heating, allowing higher efficiencies and integration of low- oder medium-exergy heat sources. However, this temperature decrease requires coordinated actions on the building side as well as in the district heating grids.

H_2, e-fuels and other renewable gases and liquids

In the decarbonisation pathway scenario, hydrogen plays an important role in decarbonising industrial process heat in many countries, but not in all. Especially countries with large steel and chemical industries are likely to need huge quantities of hydrogen to decarbonise. On the other hand, countries with mainly less energy-intensive industries can better electrify. Overall, the hydrogen demand for H&C increases to about 380 TWh in the pathway scenario (plus potential demand for feedstocks in chemicals, which is outside the scope of this study). While the quantity is large, it still is substantially lower than the additional electricity demand in process heating.

For district heating, hydrogen boilers are only relevant for covering peak loads and thus cover only a very minor share of the energy use.

In the building sector, for some countries the full phase-out of gases and liquids turns out to be a considerable challenge. For these countries (e.g. BE, DE, NL) a considerable share of these fuels still remains in the mix of heating systems according to our modelling results. In our modelling approach, we were not able to depict in detail the spatial allocation of gas demand and the detailed gas grid decommissioning pathway. Thus, it remains an open question whether our model results might overestimate the share of gases for space and water heating in the scenario or whether there might remain some parts of the grid in operation, along which also buildings are supplied.

Solar energy

In the decarbonisation pathway scenario, solar energy plays a considerable role in particular in some MS for the space and hot water sector, mainly in decentralised heating systems. The share of solar energy for heating in residential and tertiary buildings increases to more than 11% in 2050. However, in some southern countries like CY, EL, IT, PT, ES solar energy covers shares of about 20%. Also in countries like DE, FR or DK significant solar shares are achieved. In order to understand this effect, it is worth noting that we consider both solar thermal collectors as well as the contribution of on-site PV for space and water heating. Thus, the increasing use of on-site PV will also increase the share of solar energy to the space and water heating sector.

In our modelling, we did not consider ambitious measures for shifting thermal loads and thus increasing the self-consumption of PV for heating and cooling. If implemented, this would increase the share of solar energy even further.

Solid biomass

In the base year, solid biomass by far holds the largest share in renewable heating and cooling. In line with the proposal for a revised Renewable Energy Directive (COM(2021) 557 final) to implement principles of cascadic use of biomass, reduce the use of round wood for energetic purposes and focus the use of biomass on high-exergetic uses, we restricted the use of biomass for space and water heating in the building sector. For district heating, it turned out that the economic viability of biomass in district heating mainly depends on the comparative costs and potentials of geothermal-based district heating and large-scale heat pumps. In industry, the pathway scenario shows a rather constant use of biomass in areas where it is used today: in countries with huge potentials and industries where biomass is a production residue like the pulp and paper production. There could be a higher use of biomass in many industrial applications, however, if electrification and hydrogen use are rolled out broadly, there is no need to use biomass, which is always more difficult to handle at an industrial site.

Overall, the uptake of biomass in the scenario was much below the technical potentials identifed in Chapter 2.

This leads to a declining role of biomass for H&C in the decarbonisation pathway scenario from almost 30% of energy use in the base year to about 20% in 2050.

7.5. Implications for 2030 targets

The modelling results show that the targets set in the Fit for 55 package are largely overfulfilled in the scenarios that achieve full decarbonisation in 2050. Table 37 summarises the level of compliance of the three scenarios for EU-27 . While the baseline scenario clearly fails to achieve the targets, the decarbonisation pathway scenario clearly overachieves the defined targets. Due to the short-term price elasticity effects on the demand, the price sensitivity scenario leads to slightly higher RES HC shares and related growth of renewables.

The targets proposed in Art 15a (for buildings) and Art 22a (for industry) of the revised Renewable Energy Directive refer to overall renewable energy and thus are not limited to heating and cooling. For the purpose and the scope of this project we calculate the contribution of heating and cooling to the total buildings' and industry's sector, according to the RES-HC shares method according to Art 7 of the Renewable Energy Directive, i.e. not accounting for electricity in the nominator and the denominator of the shares calculation. The calculation of renewable cooling follows the method described in the delegated regulation 2022/759[114]. These indicators are also provided by MS in Table 38 to Table 40 in the annex.

Table 37: Compliance of scenarios with different 2030 targets, EU-27

	Unit	Target according to proposed revision of RED	Baseline	Decarbo-nisation	Price sensitivity
RES-HC share (excl waste heat)	%		36%	48%	53%
RES-HC share (incl waste heat)	%		37%	49%	54%

[114] European Commission, 2021. Commission delegated regulation (EU) 2022/759 of 14.12.2021 amending Annex VII to Directive (EU) 2018/2001 as regards a methodology for calculating the amount of renewable energy used for cooling and district cooling.

	Unit	Target according to proposed revision of RED	Baseline	Decarbo-nisation	Price sensitivity
Art 15a - RES in buildings (*)	%	49%	43%	51%	56%
Art 22a - RES increase in industry (*)	ppt	1.1	0.72	2.18	2.64
Art 23 - RES-HC increase (excl waste HC)	ppt	1.1	1.03	2.04	2.44
Art 23 - RES-HC increase (incl waste HC)	ppt	1.5	1.06	2.07	2.50
Art 24 - RES-HC increase in DHC	ppt	2.1	1.13	1.79	3.64

(*) calculated only for the heating- and cooling-related share

The fact that the targets are exceeded in 2030 in the scenarios reaching full decarbonisation indicates that the proposed increase of ambition presented in the RePowerEU package is better aligned to the target of full decarbonisation than the Fit for 55 proposals, at least for the heating sector.

In addition, the transition pathway developed in the decarbonisation pathway scenario supports the objective of reducing natural gas demand and reducing import dependency.

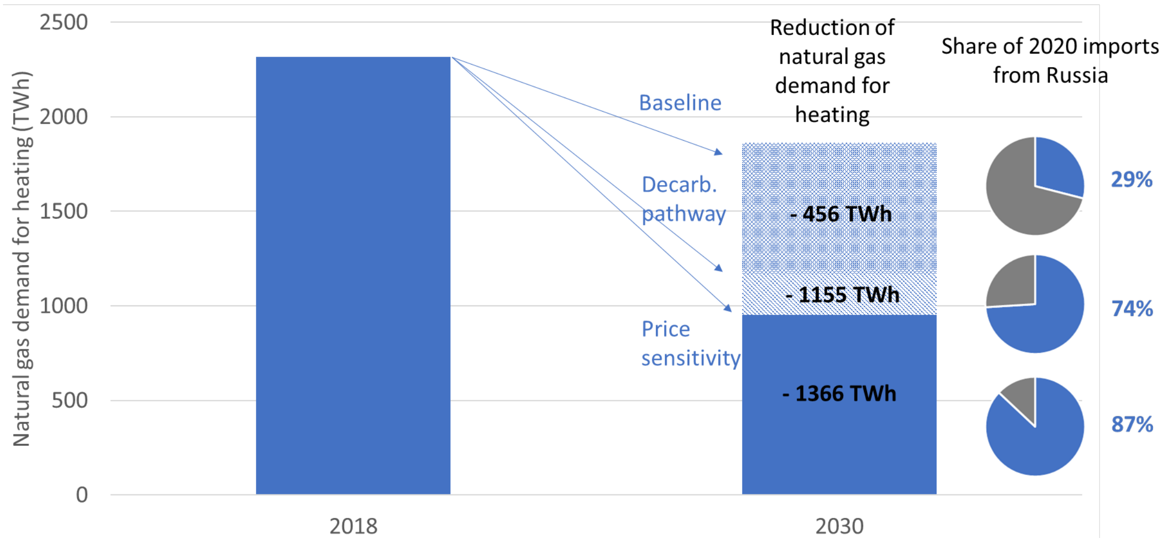


Figure 111: Reduction of gas demand in the scenarios (EU-27).

In 2030, natural gas demand in the heating sector is reduced by 1155 TWh in the decarbonisation pathway scenario as compared to a reduction by 456 TWh in the baseline scenario (1366 TWh in the price sensitivity scenario). This corresponds to 74% of the total natural gas imports in the EU in 2020 in the decarbonisation scenario (29% in the baseline, 87% in the price sensitivity scenario).

Annex

Annex A1: Renewable heating and cooling statistics

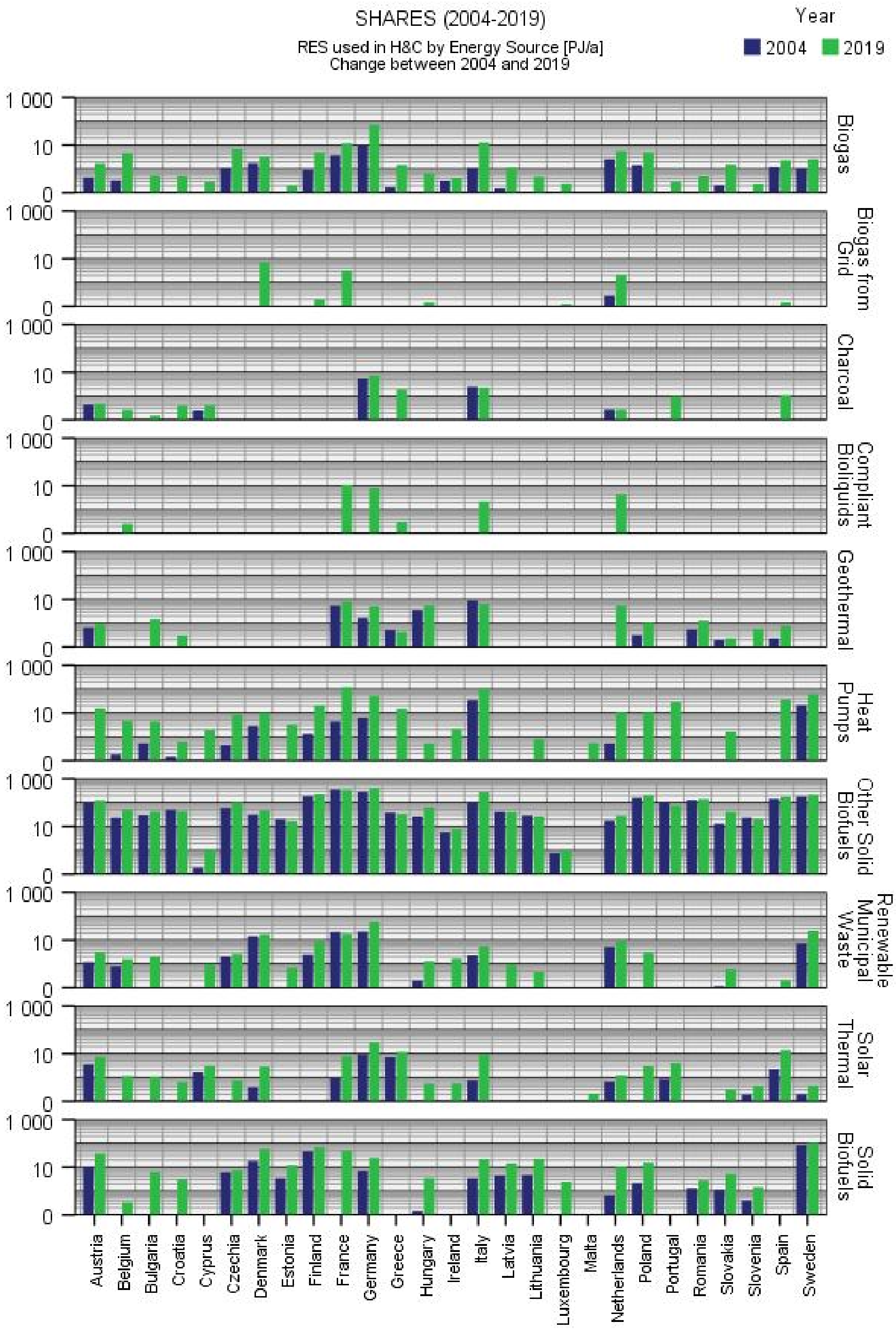


Figure 112: Change in Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for EU27 Member States, by energy source [PJ/a].

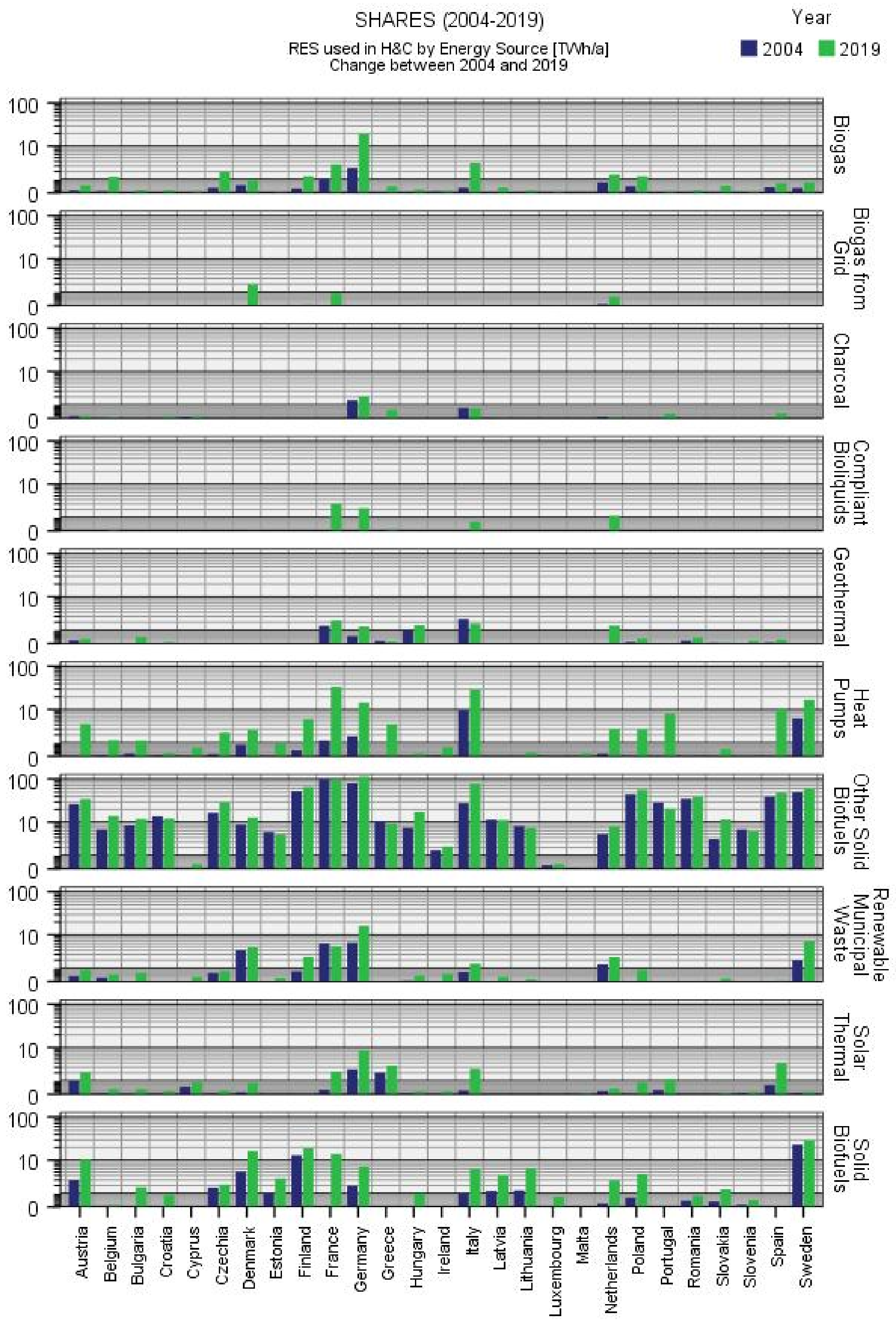


Figure 113: Change in Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling between 2004 and 2019 for EU27 Member States, by energy source [TWh/a].

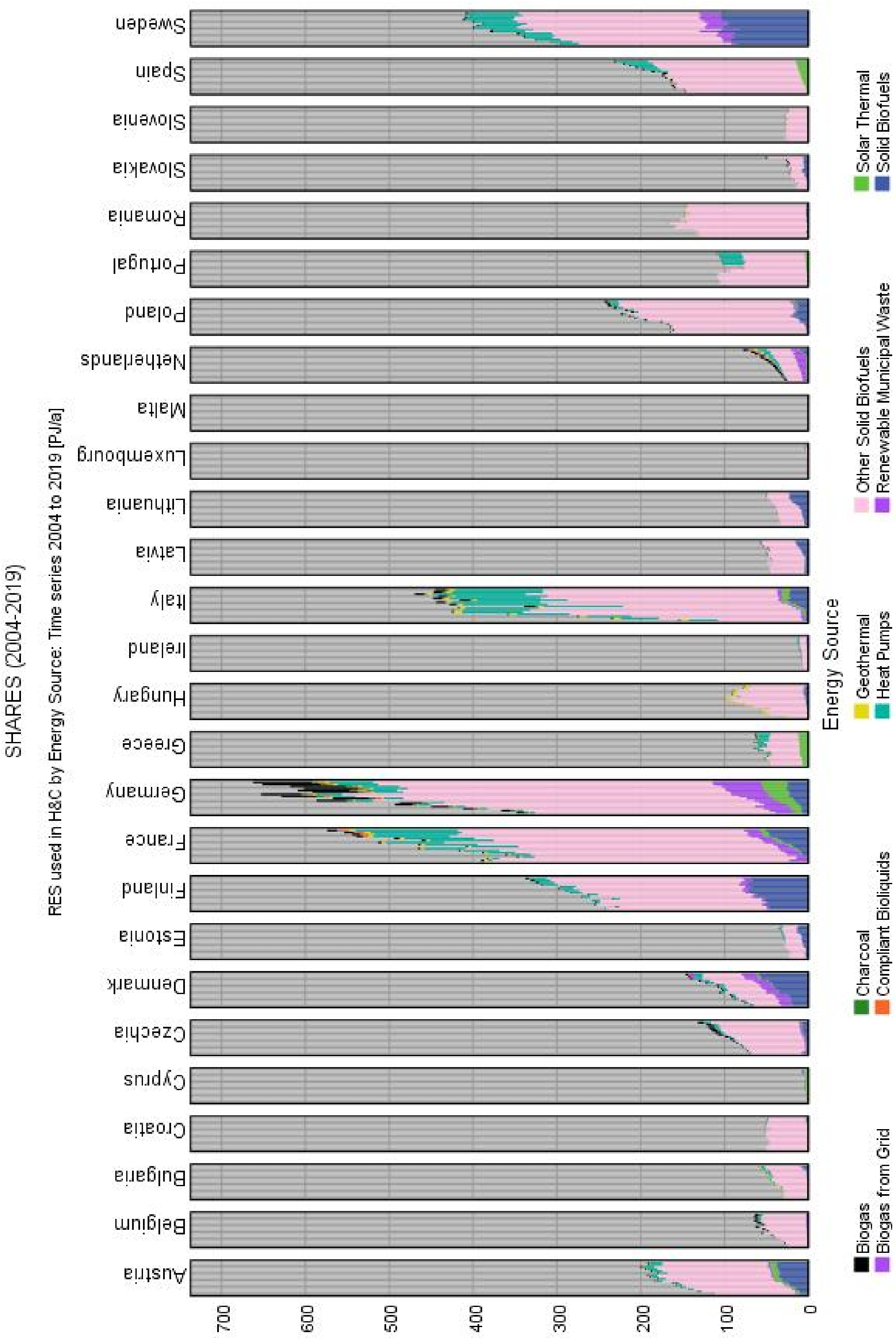


Figure 114: Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling from 2004 to 2019 for EU27 Member States, by energy source in time series [PJ/a].

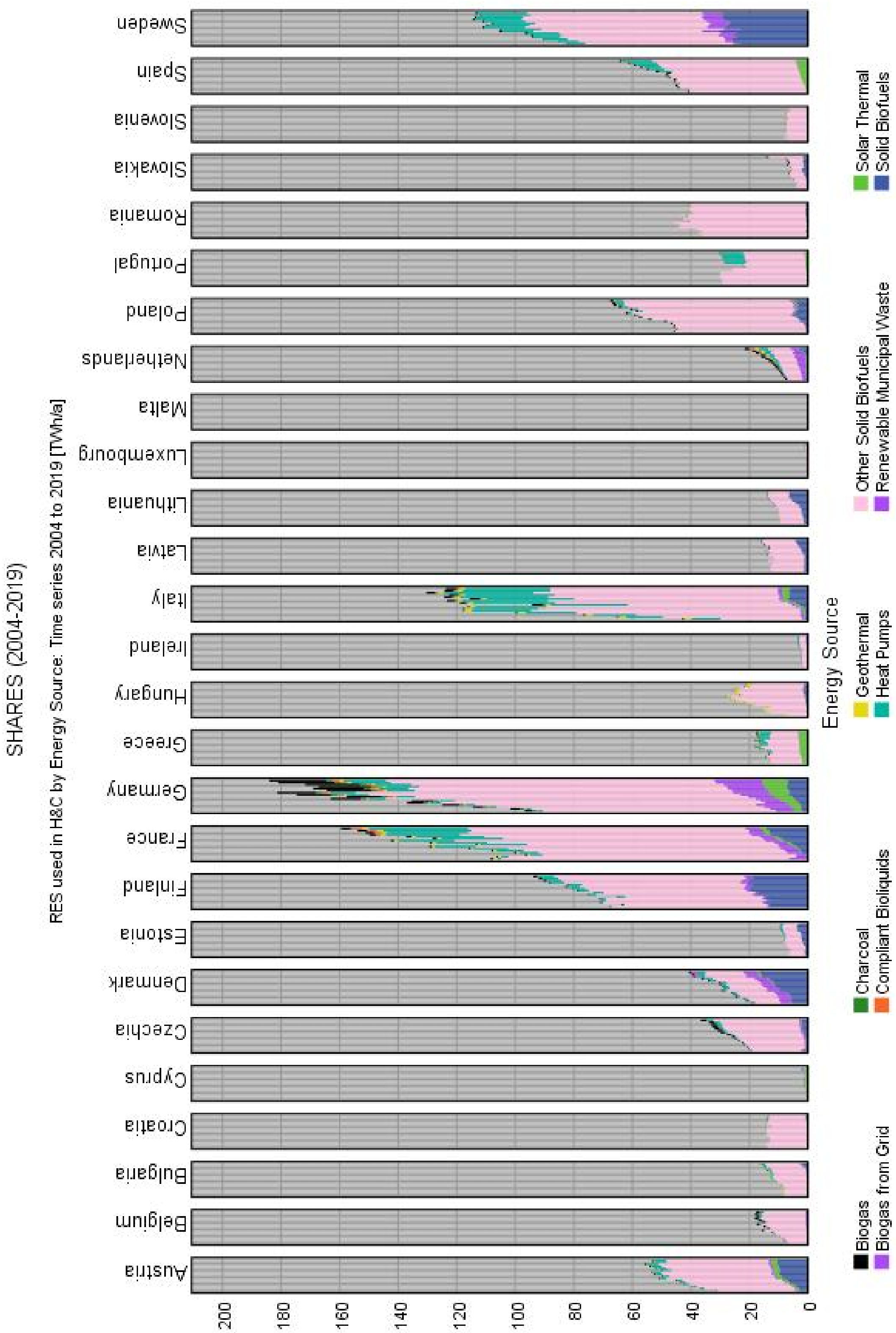


Figure 115: Gross Final Consumption of Energy from Renewable Sources for Heating and Cooling from 2004 to 2019 for EU27 Member States, by energy source in time series [TWh/a].

Annex C1: Additional modelling results

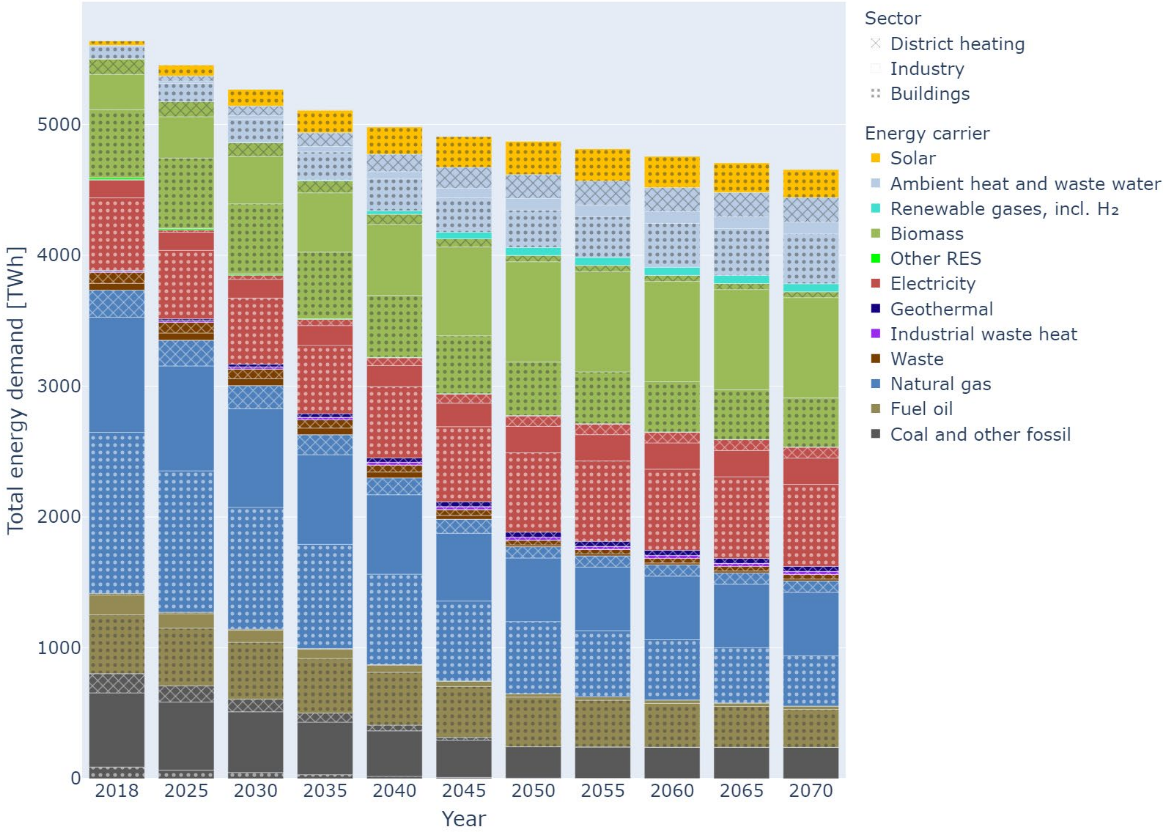


Figure 116: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, baseline scenario, EU-27, scenario period until 2070

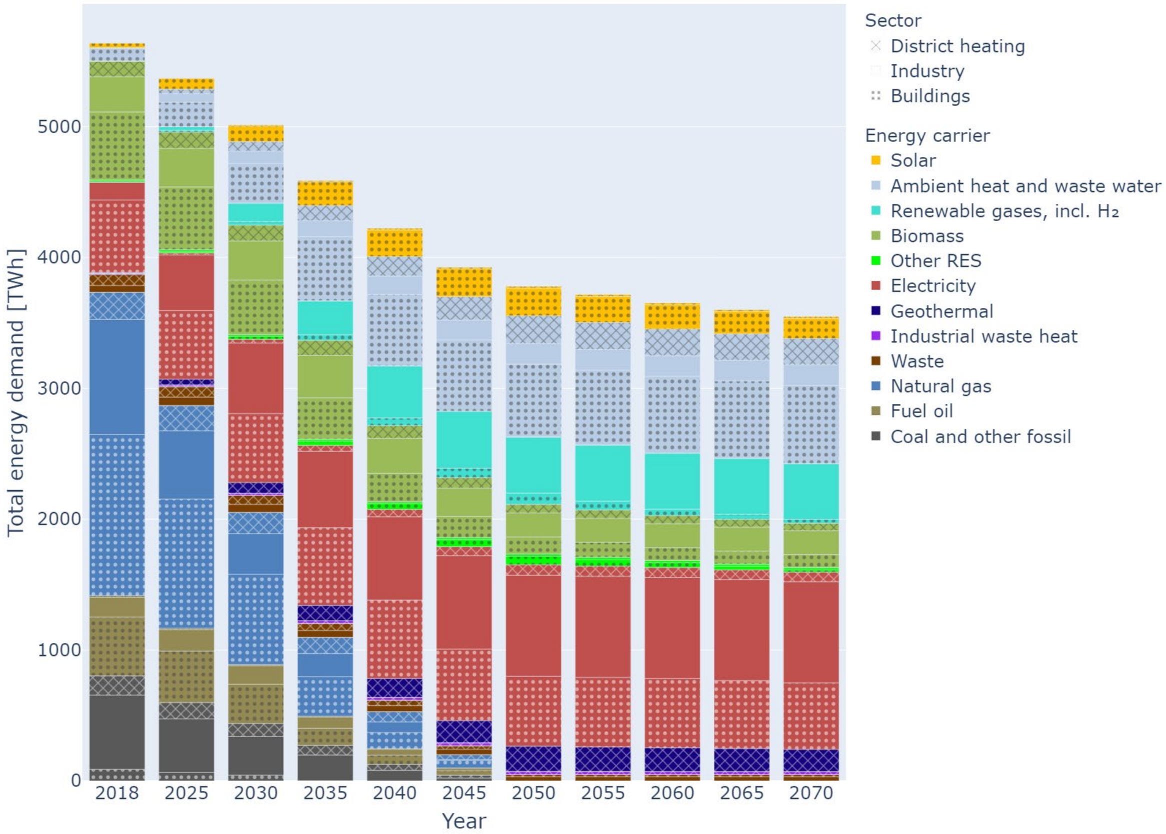


Figure 117: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, decarbonisation pathway scenario, EU-27

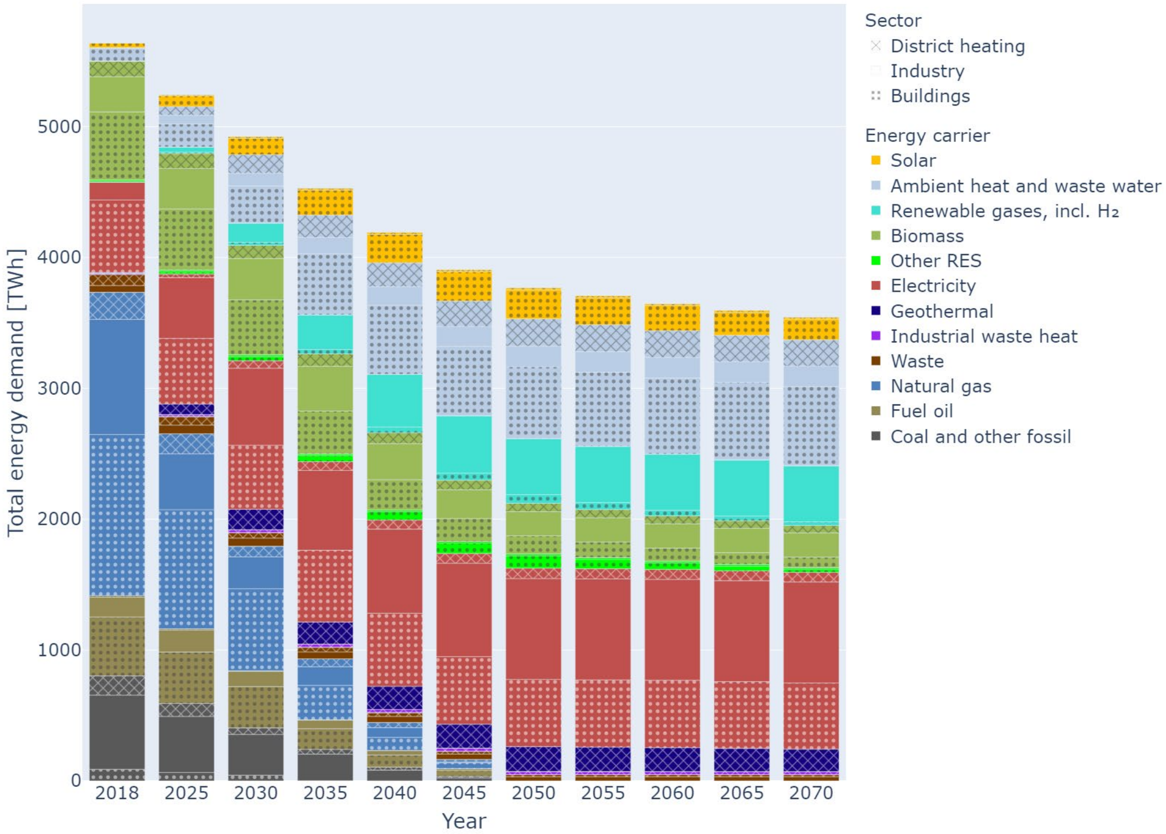


Figure 118: Energy use for heating and cooling by sectors (buildings, industry, district heating) and by energy carriers, price sensitivity scenario, EU-27

Table 38: RES-HC target achievement indicators by MS, baseline scenario

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
EU27	36%	37%	43%	1.03	1.06	0.72	1.13
AUT	42%	43%	55%	0.66	0.70	0.41	0.83
BEL	17%	17%	21%	0.57	0.57	0.23	1.09
BGR	46%	47%	67%	0.90	0.97	0.74	1.11
CYP	79%	79%	90%	2.17	2.17	-0.42	-
CZE	35%	36%	43%	1.02	1.13	1.01	1.54
DEU	24%	24%	29%	0.76	0.78	0.50	1.26

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
DNK	51%	54%	58%	0.42	0.55	1.03	0.57
EST	57%	59%	66%	0.47	0.60	0.98	0.88
ESP	45%	45%	60%	1.86	1.86	1.22	-
FIN	64%	64%	67%	0.57	0.60	0.41	0.75
FRA	40%	40%	46%	1.18	1.20	1.10	0.95
GRC	56%	57%	67%	1.53	1.54	0.90	2.23
HRV	48%	48%	60%	0.98	1.00	1.21	2.17
HUN	35%	36%	38%	1.22	1.28	1.60	1.52
IRL	18%	18%	13%	0.70	0.70	0.91	-
ITA	40%	40%	49%	1.35	1.36	0.71	1.41
LTU	53%	53%	61%	0.03	0.04	0.49	-0.46
LUX	29%	30%	39%	1.67	1.73	0.63	0.89
LVA	60%	61%	60%	-0.10	-0.01	-0.65	0.80
MLT	91%	91%	96%	1.10	1.10	0.63	-
NLD	20%	20%	25%	0.95	1.02	0.74	1.61
POL	35%	36%	40%	1.27	1.32	0.94	0.81
PRT	55%	56%	76%	0.79	0.80	0.19	2.25
ROU	35%	36%	48%	0.54	0.62	0.88	1.75
SWE	64%	68%	67%	0.28	0.39	-0.04	0.76
SVN	44%	45%	58%	0.73	0.76	0.98	1.14
SVK	33%	33%	44%	1.24	1.27	0.99	1.71

Table 39: RES-HC target achievement indicators by MS, decarbonisation pathway scenario

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
EU27	48%	49%	51%	2.04	2.07	2.18	1.79
AUT	50%	50%	57%	1.25	1.28	1.45	1.45
BEL	30%	30%	33%	1.67	1.68	1.36	2.22
BGR	54%	55%	67%	1.59	1.65	2.03	1.77
CYP	71%	71%	80%	1.53	1.53	1.34	-
CZE	44%	45%	50%	1.78	1.86	1.95	2.19
DEU	41%	41%	36%	2.20	2.21	3.32	2.11
DNK	65%	66%	69%	1.56	1.53	2.63	0.99
EST	62%	65%	69%	0.89	1.11	1.61	1.16
ESP	61%	61%	72%	3.26	3.26	2.48	-
FIN	70%	71%	69%	1.10	1.14	1.13	1.28
FRA	50%	51%	57%	2.05	2.07	1.45	0.95
GRC	64%	64%	72%	2.14	2.14	2.09	2.29
HRV	55%	56%	65%	1.54	1.68	1.92	2.71
HUN	47%	47%	50%	2.20	2.23	2.40	2.01
IRL	33%	33%	30%	1.89	1.89	1.70	-
ITA	47%	48%	53%	1.98	2.00	1.87	2.21
LTU	60%	64%	67%	0.69	0.99	1.29	0.96
LUX	37%	38%	41%	2.32	2.37	2.04	1.12
LVA	69%	70%	68%	0.69	0.74	0.46	1.46

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
MLT	92%	92%	97%	1.24	1.24	1.10	-
NLD	38%	38%	36%	2.48	2.51	2.79	1.74
POL	42%	44%	46%	1.86	1.96	1.61	2.25
PRT	67%	67%	81%	1.73	1.74	1.48	2.46
ROU	46%	46%	55%	1.45	1.49	2.05	2.64
SWE	70%	73%	71%	0.80	0.86	0.67	0.93
SVN	58%	59%	72%	1.91	1.92	2.00	2.06
SVK	45%	45%	53%	2.23	2.25	2.11	2.52

Table 40: RES-HC target achievement indicators by MS, price sensitivity scenario

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
EU27	53%	54%	56%	2.44	2.50	2.64	3.64
AUT	54%	55%	61%	1.62	1.68	1.80	2.91
BEL	33%	33%	34%	1.91	1.93	1.80	4.63
BGR	60%	62%	73%	2.07	2.20	2.44	3.67
CYP	72%	72%	80%	1.62	1.62	1.66	-
CZE	51%	53%	57%	2.35	2.50	2.44	4.73
DEU	46%	46%	40%	2.60	2.62	3.76	4.23

	Total RES-HC excl. waste heat - RES share [%]	Total RES-HC incl. waste heat - RES share [%]	Buildings RES-HC share [%]	Total RES-HC excl. waste heat share increase [ppt/yr]	Total RES-HC incl. waste heat - share increase [ppt/yr]	Industry RES-HC share increase [ppt/yr]	District heating RES-HC incl. waste heat share increase [ppt/yr]
DNK	71%	72%	76%	2.11	2.05	2.80	1.97
EST	67%	73%	74%	1.29	1.76	2.04	2.61
ESP	63%	63%	72%	3.39	3.40	2.82	-
FIN	76%	77%	79%	1.57	1.66	1.36	2.84
FRA	55%	55%	60%	2.41	2.45	2.12	2.03
GRC	66%	66%	74%	2.34	2.35	2.36	5.02
HRV	59%	62%	68%	1.88	2.19	2.58	5.47
HUN	53%	54%	55%	2.72	2.80	3.14	4.17
IRL	35%	35%	30%	2.04	2.05	2.13	-
ITA	54%	54%	58%	2.51	2.54	2.76	4.53
LTU	63%	71%	69%	0.94	1.58	1.67	2.03
LUX	42%	43%	45%	2.67	2.76	2.35	2.44
LVA	76%	77%	77%	1.29	1.38	0.80	2.94
MLT	92%	92%	97%	1.25	1.25	1.13	-
NLD	42%	43%	39%	2.84	2.91	3.34	3.78
POL	49%	51%	53%	2.38	2.60	1.98	4.74
PRT	70%	70%	82%	2.03	2.04	1.96	5.14
ROU	52%	53%	62%	2.00	2.08	2.51	5.39
SWE	74%	78%	77%	1.13	1.22	0.78	1.99
SVN	63%	64%	76%	2.31	2.34	2.55	4.28
SVK	49%	49%	60%	2.57	2.62	2.33	5.04

Annex C2: Input data for scenario development

Table 41: Emission factors for electricity (kg CO_2/MWh)

		Baseline		Decarbonisation pathway	
Country	2020	2030	2050	2030	2050
AT	82	24	34	27	0
BE	161	196	196	54	0
BG	410	377	163	137	0
CY	621	285	156	207	0
CZ	437	434	219	146	0
DE	311	228	92	104	0
DK	109	13	24	36	0
EE	775	429	97	258	0
ES	156	39	20	52	0
FI	69	160	128	23	0
FR	51	152	78	17	0
GR	479	164	67	160	0
HR	134	72	24	45	0
HU	216	235	189	72	0
IE	279	92	58	93	0
IT	213	133	66	71	0
LT	45	95	51	15	0
LU	59	15	96	20	0
LV	107	83	62	36	0
MT	379	345	326	126	0
NL	328	119	139	109	0
PL	710	485	198	237	0

		Baseline		Decarbonisation pathway	
Country	**2020**	**2030**	**2050**	**2030**	**2050**
PT	198	20	17	66	0
RO	300	223	104	100	0
SE	9	66	53	3	0
SI	218	296	186	73	0
SK	102	213	176	34	0

Sources: own calculations based on https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-chart_2; access 28 July 2022, PRIMES reference scenario 2020; Results of the Enertile model from the project ENER-2019/481, anchor-scenario.

Annex C3: Methods and assumptions for modelling of pathways and measures

In the following section the applied methods and models are described for the different steps. Further details on the models can be found in the literature sources linked.

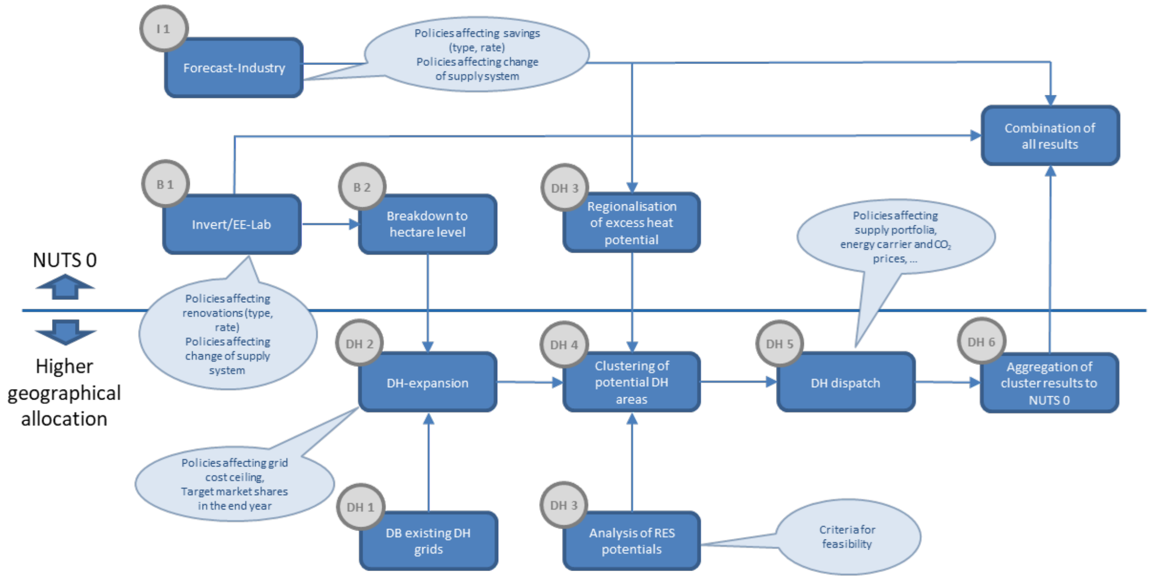


Figure 119: Steps and geographical detail in the modelling framework

<u>Modelling of the building stock (B1 – B2)</u>

The modelling of the building stock includes the following two steps:

(1) Scenarios developed with the model Invert (B1)

(2) Breakdown of the results to the hectare level (B2)

In the first step scenarios for the development of the building stock in the different countries are developed. In the second step the results of these scenarios are broken down to the hectare level to be used in the subsequent modelling of the district heating sector.

Calculation of scenarios for the development of the building stock (B1)

For the calculation of scenarios for the development of the building stock the model **Invert** is used. Invert is a bottom-up building stock model to simulate, optimise and/or analyse developments in buildings focusing on space heating, hot water generation and space cooling. It is based on a highly disaggregated description of the building stocks in the different countries of the EU (+ UK, Norway, Iceland, Switzerland) including type of building, age, state of renovation, existing heating systems, user structure as well as regional aspects such as availability of energy infrastructure as e.g. district heating or natural gas on a sub-country level.

With the **Invert/EE-Lab** variant of the model energy-related investment decisions in the building shell and the heat supply and distribution systems can be simulated via a combination of a discrete choice approach and technology diffusion theory. This makes it possible to study the influence of various side-conditions including policy measures on the decisions of the actors.

Policy measures implemented explicitly in the model include economic incentives (e.g. tax incentives, subsidies, energy taxation), regulatory approaches (e.g. building codes, RES-H obligations with different detailed policy setting versions, renovation obligation) as well as awareness raising measures (e.g. increase of awareness of certain policy measures for various agents). While the main calculation of the energy demand in Invert is based on a monthly approach, the model includes a module to assess the resulting load profiles on an hourly basis.

The Invert model has been developed and applied in national and international projects in the EU for more than 10 years, in many of them reflecting the entire EU building stocks[115].

In this study, the baseline (Task 6.1) and the decarbonisation pathways (Task 6.2) are calculated using the **Invert/EE-Lab** (as opposed to the Invert/Accounting or Invert/Opt model). Details on the settings used in the different scenario calculations are presented in the related chapters below.

The following tables provide more detailed information on modelling assumptions mentioned in the main part of the report.

[115] see: https://www.invert.at/projects.php

Table 42: Target requirements for the energy needs for space heating (kWh/(m²*yr))

	Small residential buildings (Volume-to-Surface ratio = 1.3)	Apartment building (Volume-to-Surface ratio = 3.0)	
AT	58	35	10% < Energy needs for space heating savings < 50%
BE	48	29	
BG	45	28	
CY	17	10	
CZ	56	34	
DE	53	32	
DK	55	34	
ES	35	21	
EE	67	41	
FI	82	50	
FR	44	27	
GR	32	19	
HR	42	26	
HU	48	29	
IE	50	30	
IT	37	22	
LT	63	38	
LU	51	31	
LV	65	40	
MT	13	8	
NL	48	29	
PL	57	35	

	Small residential buildings (Volume-to-Surface ratio = 1.3)	Apartment building (Volume-to-Surface ratio = 3.0)	
PT	26	16	
RO	51	31	
SK	54	33	
SV	49	30	
SE	79	48	

Table 43: Target renovation rates in residential buildings for the period 2012-2016 used to calibrate the Invert/EE-Lab model

	Annual refurbishment rate Residential buildings			
	Non-energy related (maintenance)	Deep (deeper than standard)	Standard refurbishment	Less ambitious than standard
	Calibration targets based on Ipsos (2019) and Invert component lifetimes			
EU28	1.14%	0.20%	0.53%	0.35%
Austria	0.66%	0.20%	0.82%	0.54%
Belgium	1.22%	0.20%	0.48%	0.32%
Bulgaria	1.08%	0.10%	0.62%	0.42%
Croatia	0.92%	0.10%	0.72%	0.48%
Cyprus	0.50%	0.40%	0.96%	0.64%
Czech Republic	0.84%	0.10%	0.77%	0.51%
Denmark	1.74%	0.00%	0.29%	0.19%
Estonia	1.56%	0.10%	0.34%	0.22%
Finland	1.98%	0.00%	0.14%	0.10%
France	1.22%	0.20%	0.48%	0.32%
Germany	1.40%	0.10%	0.43%	0.29%

	Annual refurbishment rate Residential buildings			
	Non-energy related (maintenance)	Deep (deeper than standard)	Standard refurbishment	Less ambitious than standard
Greece	1.14%	0.20%	0.53%	0.35%
Hungary	1.40%	0.10%	0.43%	0.29%
Ireland	1.64%	0.10%	0.29%	0.19%
Italy	0.72%	0.30%	0.72%	0.48%
Latvia	1.50%	0.00%	0.43%	0.29%
Lithuania	1.46%	0.20%	0.34%	0.22%
Luxembourg	1.80%	0.10%	0.19%	0.13%
Malta	1.64%	0.10%	0.29%	0.19%
Netherlands	1.48%	0.10%	0.38%	0.26%
Poland	1.02%	0.00%	0.72%	0.48%
Portugal	1.08%	0.10%	0.62%	0.42%
Romania	1.08%	0.10%	0.62%	0.42%
Slovakia	1.32%	0.10%	0.48%	0.32%
Slovenia	1.08%	0.10%	0.62%	0.42%
Spain	0.56%	0.30%	0.82%	0.54%
Sweden	1.56%	0.10%	0.34%	0.22%

Table 44: Target renovation rates in non-residential buildings for the period 2012-2016 used to calibrate the Invert/EE-Lab model

	Annual refurbishment rate Non-residential buildings			
	Non-energy related (maintenance)	Deep (deeper than standard)	Standard refurbishment	Less ambitious than standard
	Calibration targets based on Ipsos (2019) and Invert component lifetimes			
EU28	0.72%	0.24%	0.76%	0.50%
Austria	1.70%	0.16%	0.22%	0.14%
Belgium	0.55%	0.80%	0.84%	0.56%
Bulgaria	0.55%	0.48%	1.03%	0.69%
Croatia	1.40%	0.16%	0.40%	0.26%
Cyprus	0.55%	0.80%	0.84%	0.56%
Czech Republic	1.06%	0.32%	0.50%	0.34%
Denmark	1.34%	0.16%	0.43%	0.29%
Estonia	1.58%	0.16%	0.29%	0.19%
Finland	1.22%	0.16%	0.50%	0.34%
France	1.22%	0.16%	0.50%	0.34%
Germany	1.28%	0.16%	0.47%	0.31%
Greece	0.52%	0.32%	1.04%	0.70%
Hungary	0.98%	0.16%	0.65%	0.43%
Ireland	1.90%	0.08%	0.14%	0.10%
Italy	0.55%	0.48%	1.03%	0.69%
Latvia	1.20%	0.24%	0.47%	0.31%
Lithuania	1.70%	0.16%	0.22%	0.14%
Luxembourg	1.58%	0.16%	0.29%	0.19%
Malta	0.76%	0.32%	0.68%	0.46%

	Annual refurbishment rate Non-residential buildings			
	Non-energy related (maintenance)	Deep (deeper than standard)	Standard refurbishment	Less ambitious than standard
Netherlands	0.66%	0.24%	0.79%	0.53%
Poland	0.60%	0.24%	0.83%	0.55%
Portugal	0.55%	0.64%	0.94%	0.62%
Romania	0.76%	0.32%	0.68%	0.46%
Slovakia	0.55%	0.40%	1.08%	0.72%
Slovenia	1.08%	0.24%	0.54%	0.36%
Spain	0.54%	0.40%	1.04%	0.70%
Sweden	0.78%	0.24%	0.72%	0.48%

Techno-economic data of space cooling devices

The purchase and installation cost consist of the cost for all new installations that have to be installed in the future to cover the increasing demand together with installations to replace old systems at the end of their lifetime. The lifetime of each technology is provided in Table 45. In Table 47 the purchase and installation costs for single units depending on the technology are listed for the base year, 2030 and 2050. In order to calculate the amount of systems installed, the average capacity of each technology is provided in Table 46. Both, average capacity of each unit as well as the average full load hours of each technology are estimated not to change in the future. Average full load hours are different for each EU Member State. The values have been taken from Pezzutto et al (2021) (Table 20).

The fuel cost consist mainly of electricity cost as most technologies are powered electrically. However, for technologies which have waste heat as an energy input, the fuel cost are estimated to be 10€/MWh and do not change in the future. For technologies which use renewable heat as an energy input the fuel cost are estimated to be 70€/MWh. For technologies which are identified with an energy input of local renewable electricity, it was estimated that on average locally produced electricity will cover 30% of a cooling generator's total power need. Thus, even though technologies are marked with a local renewable energy input, they still rely on 70% of grid electricity. Therefore, the fuel cost for these technologies are calculated by taking 70% of the electricity retail price and 30% of the wholesale price as lost opportunity cost.

Table 45: Average lifetime of each technology

Technology	Average lifetime (years)
Movables + Window units	10
Small Split (<5 kW)	12
Big Split (>5 kW, inclusive ducted)	12
Variable refrigerant flow systems	15
Rooftop + Packaged	15
Chiller (air-to-water) < 400 kW	15
Chiller (air-to-water) > 400 kW	20
Chiller (water-to-water) < 400 kW	15
Chiller (water-to-water) > 400 kW	20

Table 46: Average capacity for each technology. GHE stands for ground heat exchanger

Cooling distribution system	Energy input	Cold source	average capacity [kW/unit]
Movables + Window units	Grid electricity	Air	2.5
Small Split (<5 kW)	Grid electricity	Air	3.5
Small Split (<5 kW)	Grid electricity	Water	3.5
Small Split (<5 kW)	Grid electricity	GHE	3.5
Small Split (<5 kW)	Grid electricity	Aquifer	3.5
Small Split (<5 kW)	Local renewable electricity	Air	3.5
Small Split (<5 kW)	Local renewable electricity	Water	3.5
Small Split (<5 kW)	Local renewable electricity	GHE	3.5
Small Split (<5 kW)	Local renewable electricity	Aquifer	3.5
Big Split (>5 kW, inclusive ducted)	Grid electricity	Air	7.5
Big Split (>5 kW, inclusive ducted)	Grid electricity	Water	7.5
Big Split (>5 kW, inclusive ducted)	Grid electricity	GHE	7.5
Big Split (>5 kW, inclusive ducted)	Grid electricity	Aquifer	7.5
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Air	7.5
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Water	7.5
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	GHE	7.5
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Aquifer	7.5
Variable refrigerant flow systems	Grid electricity	Air	25
Variable refrigerant flow systems	Grid electricity	Water	25
Variable refrigerant flow systems	Grid electricity	GHE	25
Variable refrigerant flow systems	Grid electricity	Aquifer	25
Variable refrigerant flow systems	Local renewable electricity	Air	25
Variable refrigerant flow systems	Local renewable electricity	Water	25
Variable refrigerant flow systems	Local renewable electricity	GHE	25
Variable refrigerant flow systems	Local renewable electricity	Aquifer	25
Rooftop + Packaged	Grid electricity	Air	65
Rooftop + Packaged	Grid electricity	Water	65
Rooftop + Packaged	Grid electricity	GHE	65

Cooling distribution system	Energy input	Cold source	average capacity [kW/unit]
Rooftop + Packaged	Grid electricity	Aquifer	65
Rooftop + Packaged	Local renewable electricity	Air	65
Rooftop + Packaged	Local renewable electricity	Water	65
Rooftop + Packaged	Local renewable electricity	GHE	65
Rooftop + Packaged	Local renewable electricity	Aquifer	65
Chiller (air-to-water) < 400 kW	Grid electricity	Air	80
Chiller (air-to-water) < 400 kW	Local renewable electricity	Air	80
Chiller (air-to-water) > 400 kW	Grid electricity	Air	616
Chiller (air-to-water) > 400 kW	Local renewable electricity	Air	616
Chiller (water-to-water) < 400 kW	Grid electricity	Air	114
Chiller (water-to-water) < 400 kW	Grid electricity	Water	114
Chiller (water-to-water) < 400 kW	Grid electricity	GHE	114
Chiller (water-to-water) < 400 kW	Grid electricity	Aquifer	114
Chiller (water-to-water) < 400 kW	Grid electricity	waste cold	114
Chiller (water-to-water) < 400 kW	Local renewable electricity	Air	114
Chiller (water-to-water) < 400 kW	Local renewable electricity	Water	114
Chiller (water-to-water) < 400 kW	Local renewable electricity	GHE	114
Chiller (water-to-water) < 400 kW	Local renewable electricity	Aquifer	114
Chiller (water-to-water) < 400 kW	Local renewable electricity	waste cold	114
Chiller (water-to-water) < 400 kW	renewable heat	Air	150
Chiller (water-to-water) < 400 kW	renewable heat	Water	150
Chiller (water-to-water) < 400 kW	renewable heat	GHE	150
Chiller (water-to-water) < 400 kW	renewable heat	Aquifer	150
Chiller (water-to-water) < 400 kW	renewable heat	waste cold	150
Chiller (water-to-water) < 400 kW	waste heat	Air	150
Chiller (water-to-water) < 400 kW	waste heat	Water	150
Chiller (water-to-water) < 400 kW	waste heat	GHE	150
Chiller (water-to-water) < 400 kW	waste heat	Aquifer	150
Chiller (water-to-water) < 400 kW	waste heat	waste cold	150

Cooling distribution system	Energy input	Cold source	average capacity [kW/unit]
Chiller (water-to-water) > 400 kW	Grid electricity	Air	755
Chiller (water-to-water) > 400 kW	Grid electricity	Water	755
Chiller (water-to-water) > 400 kW	Grid electricity	GHE	755
Chiller (water-to-water) > 400 kW	Grid electricity	Aquifer	755
Chiller (water-to-water) > 400 kW	Grid electricity	waste cold	755
Chiller (water-to-water) > 400 kW	Local renewable electricity	Air	755
Chiller (water-to-water) > 400 kW	Local renewable electricity	Water	755
Chiller (water-to-water) > 400 kW	Local renewable electricity	GHE	755
Chiller (water-to-water) > 400 kW	Local renewable electricity	Aquifer	755
Chiller (water-to-water) > 400 kW	Local renewable electricity	waste cold	755
Chiller (water-to-water) > 400 kW	renewable heat	Air	500
Chiller (water-to-water) > 400 kW	renewable heat	Water	500
Chiller (water-to-water) > 400 kW	renewable heat	GHE	500
Chiller (water-to-water) > 400 kW	renewable heat	Aquifer	500
Chiller (water-to-water) > 400 kW	renewable heat	waste cold	500
Chiller (water-to-water) > 400 kW	waste heat	Air	500
Chiller (water-to-water) > 400 kW	waste heat	Water	500
Chiller (water-to-water) > 400 kW	waste heat	GHE	500
Chiller (water-to-water) > 400 kW	waste heat	Aquifer	500
Chiller (water-to-water) > 400 kW	waste heat	waste cold	500

Table 47: Unit costs of the systems. GHE stands for ground heat exchanger

Cooling distribution system	Energy input	Cold source	2016 €/unit	2030 €/unit	2050 €/unit
Movables + Window units	Grid electricity	Air	340	362	415
Small Split (<5 kW)	Grid electricity	Air	1 051	1 421	2 097
Small Split (<5 kW)	Grid electricity	Water	1 051	14 421	2 097
Small Split (<5 kW)	Grid electricity	GHE	8 551	8 921	9 597
Small Split (<5 kW)	Grid electricity	Aquifer	10 051	10 421	11 097
Small Split (<5 kW)	Local renewable electricity	Air	1 051	1 421	2 097
Small Split (<5 kW)	Local renewable electricity	Water	1 051	1 421	2 097
Small Split (<5 kW)	Local renewable electricity	GHE	8 551	8 921	9 597
Small Split (<5 kW)	Local renewable electricity	Aquifer	10 051	10 421	11 097
Big Split (>5 kW, inclusive ducted)	Grid electricity	Air	1 692	1 875	2 168
Big Split (>5 kW, inclusive ducted)	Grid electricity	Water	1 692	1 875	2 168
Big Split (>5 kW, inclusive ducted)	Grid electricity	GHE	9 192	9 375	9 668
Big Split (>5 kW, inclusive ducted)	Grid electricity	Aquifer	10 692	10 875	11 168
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Air	1 692	1 875	2 168
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Water	1 692	1 875	2 168
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	GHE	9 192	9 375	9 668
Big Split (>5 kW, inclusive ducted)	Local renewable electricity	Aquifer	10 692	10 875	11 168
Variable refrigerant flow systems	Grid electricity	Air	19 720	21 950	23 975
Variable refrigerant flow systems	Grid electricity	Water	19 720	21 950	23 975
Variable refrigerant flow systems	Grid electricity	GHE	27 220	29 450	31 475

Cooling distribution system	Energy input	Cold source	2016 €/unit	2030 €/unit	2050 €/unit
Variable refrigerant flow systems	Grid electricity	Aquifer	28 720	30 950	32 975
Variable refrigerant flow systems	Local renewable electricity	Air	19 720	21 950	23 975
Variable refrigerant flow systems	Local renewable electricity	Water	19 720	21 950	23 975
Variable refrigerant flow systems	Local renewable electricity	GHE	27 220	29 450	31 475
Variable refrigerant flow systems	Local renewable electricity	Aquifer	28 720	30 950	32 975
Rooftop + Packaged	Grid electricity	Air	18 135	20 540	33 085
Rooftop + Packaged	Grid electricity	Water	18 135	20 540	33 085
Rooftop + Packaged	Grid electricity	GHE	40 635	43 040	55 585
Rooftop + Packaged	Grid electricity	Aquifer	45 135	47 540	60 085
Rooftop + Packaged	Local renewable electricity	Air	18 135	20 540	33 085
Rooftop + Packaged	Local renewable electricity	Water	18 135	20 540	33 085
Rooftop + Packaged	Local renewable electricity	GHE	40 635	43 040	55 585
Rooftop + Packaged	Local renewable electricity	Aquifer	45 135	47 540	60 085
Chiller (air-to-water) < 400 kW	Grid electricity	Air	20 768	23 200	26 960
Chiller (air-to-water) < 400 kW	Local renewable electricity	Air	20 768	23 200	26 960
Chiller (air-to-water) > 400 kW	Grid electricity	Air	111 370	133 056	156 464
Chiller (air-to-water) > 400 kW	Local renewable electricity	Air	111 370	133 056	156 464
Chiller (water-to-water) < 400 kW	Grid electricity	Air	1 676	20 406	21 090
Chiller (water-to-water) < 400 kW	Grid electricity	Water	1 676	20 406	21 090

Cooling distribution system	Energy input	Cold source	2016 €/unit	2030 €/unit	2050 €/unit
Chiller (water-to-water) < 400 kW	Grid electricity	GHE	46 676	65 406	66 090
Chiller (water-to-water) < 400 kW	Grid electricity	Aquifer	55 676	74 406	75 090
Chiller (water-to-water) < 400 kW	Grid electricity	waste cold	55 676	74 406	75 090
Chiller (water-to-water) < 400 kW	Local renewable electricity	Air	1 676	20 406	21 090
Chiller (water-to-water) < 400 kW	Local renewable electricity	Water	1 676	20 406	21 090
Chiller (water-to-water) < 400 kW	Local renewable electricity	GHE	46 676	65 406	66 090
Chiller (water-to-water) < 400 kW	Local renewable electricity	Aquifer	55 676	74 406	75 090
Chiller (water-to-water) < 400 kW	Local renewable electricity	waste cold	55 676	74 406	75 090
Chiller (water-to-water) < 400 kW	renewable heat	Air	59 308	59 308	59 308
Chiller (water-to-water) < 400 kW	renewable heat	Water	59 308	59 308	59 308
Chiller (water-to-water) < 400 kW	renewable heat	GHE	115 558	115 558	115 558
Chiller (water-to-water) < 400 kW	renewable heat	Aquifer	126 808	126 808	126 808
Chiller (water-to-water) < 400 kW	renewable heat	waste cold	126 808	126 808	126 808
Chiller (water-to-water) < 400 kW	waste heat	Air	59 308	59 308	59 308
Chiller (water-to-water) < 400 kW	waste heat	Water	59 308	59 308	59 308
Chiller (water-to-water) < 400 kW	waste heat	GHE	115 558	115 558	115 558
Chiller (water-to-water) < 400 kW	waste heat	Aquifer	126 808	126 808	126 808
Chiller (water-to-water) < 400 kW	waste heat	waste cold	126 808	126 808	126 808
Chiller (water-to-water) > 400 kW	Grid electricity	Air	88 033	96 640	133 635
Chiller (water-to-water) > 400 kW	Grid electricity	Water	88 033	96 640	133 635
Chiller (water-to-water) > 400 kW	Grid electricity	GHE	373 033	381 640	418 635
Chiller (water-to-water) > 400 kW	Grid electricity	Aquifer	430 033	438 640	475 635

Cooling distribution system	Energy input	Cold source	2016 €/unit	2030 €/unit	2050 €/unit
Chiller (water-to-water) > 400 kW	Grid electricity	waste cold	430 033	438 640	475 635
Chiller (water-to-water) > 400 kW	Local renewable electricity	Air	88 033	96 640	133 635
Chiller (water-to-water) > 400 kW	Local renewable electricity	Water	88 033	96 640	133 635
Chiller (water-to-water) > 400 kW	Local renewable electricity	GHE	373 033	381 640	418 635
Chiller (water-to-water) > 400 kW	Local renewable electricity	Aquifer	430 033	438 640	475 635
Chiller (water-to-water) > 400 kW	Local renewable electricity	waste cold	430 033	438 640	475 635
Chiller (water-to-water) > 400 kW	renewable heat	Air	85 000	85 000	85 000
Chiller (water-to-water) > 400 kW	renewable heat	Water	85 000	85 000	85 000
Chiller (water-to-water) > 400 kW	renewable heat	GHE	235 000	235 000	235 000
Chiller (water-to-water) > 400 kW	renewable heat	Aquifer	265 000	265 000	265 000
Chiller (water-to-water) > 400 kW	renewable heat	waste cold	265 000	265 000	265 000
Chiller (water-to-water) > 400 kW	waste heat	Air	85 000	85 000	85 000
Chiller (water-to-water) > 400 kW	waste heat	Water	85 000	85 000	85 000
Chiller (water-to-water) > 400 kW	waste heat	GHE	235 000	235 000	235 000
Chiller (water-to-water) > 400 kW	waste heat	Aquifer	265 000	265 000	265 000
Chiller (water-to-water) > 400 kW	waste heat	waste cold	265 000	265 000	265 000

Comparison of the baseline scenario with Primes reference 2020 scenario, space heating and hot water in buildings, EU-27

While the share of solid and liquid energy carriers decreases, the share of renewable energy sources increases. Compared to the Primes Ref 2020 (draft) scenario, the baseline scenario foresees a stronger reduction of natural gas but additional liquid fossil energy carriers. At the same time, the baseline scenario results in a significantly lower electricity consumption but higher other renewable energy carriers. This increase is mostly driven by the ambient and geothermal energy utilised by decentralised heat pumps as well as solar energy, either electricity form on-site PV systems used to provide heat or solar thermal collectors.

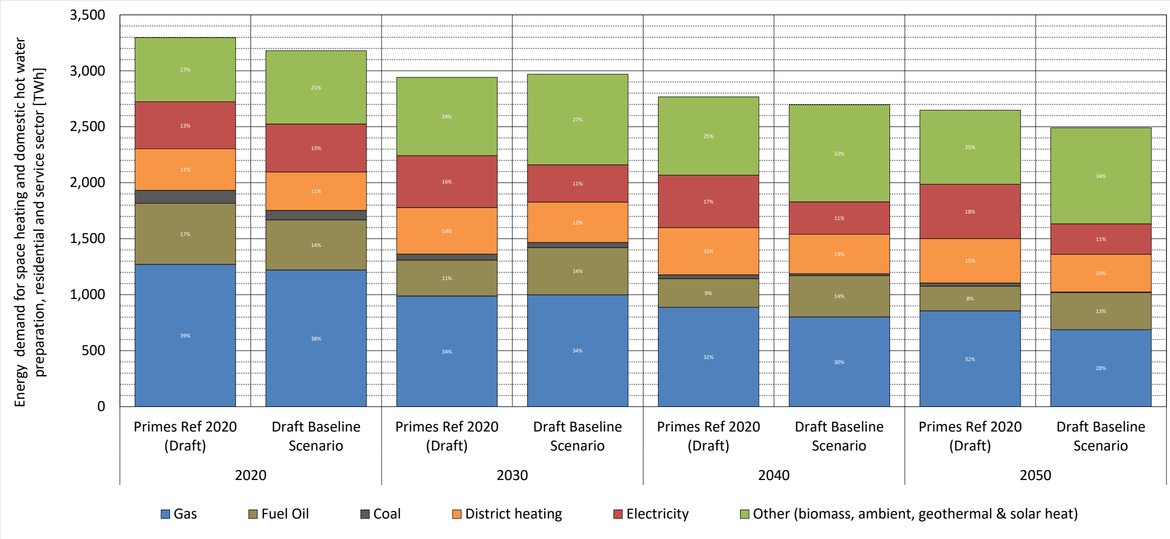


Figure 120: Development of the final energy demand in the Primes Ref 2020 (draft) scenario and the draft baseline scenario for the EU-27 until 2050.

The development of the final energy demand on a country level delivers a more diverse image. The fossil energy decreases in the baseline scenario in all (but Denmark) countries. With respect to the energy consumption, we see a range of -35% to +5% between 2020 and 2050 (Figure 120).

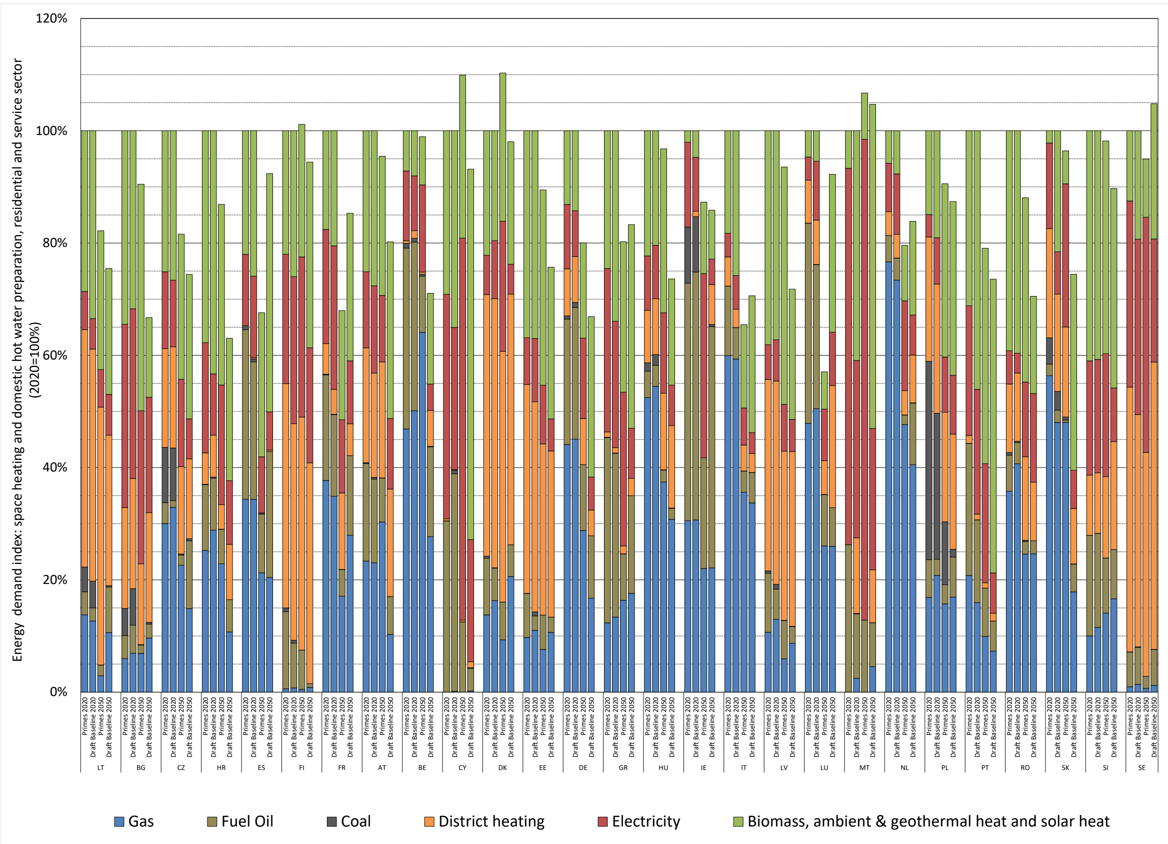


Figure 121: Comparison of the final energy demand in the Primes Reference Scenario and the draft baseline scenario for 2020 and 2050 on the level of MS.

Besides the calibration of the renovation activities based on country data for the period 2012-2016, the building construction activities are the most dominant driver of the future energy consumption. This is illustrated for five different countries (see table below), namely Sweden und Luxembourg, which show an increasing or only minor reduction of the energy consumption until 2050, France with a moderate reduction of about 15% and Italy and Bulgaria with a reduction of 30-35%, compared to 2020.

Table 48: Assumptions for the development of the heated floor area in five selected countries

	LUX	SWE	BGR	FRA	ITA
Residential sector					
Primes, increase households	55.2%	30.4%	-13.2%	10.5%	-1.5%
Baseline, increase heated floor area	58.9%	36.5%	-12.5%	11.2%	-0.8%
Baseline, increase households	66.2%	27.8%	-13.3%	6.0%	1.6%
Service sector					
Primes, increase sectoral value added	214.8%	204.6%	153.4%	168.0%	128.8%
Primes, increase area if elasticity = 0.35	30.7%	28.5%	16.2%	19.9%	9.3%
Baseline, increase heated floor area *	28.4%	31.7%	22.6%	18.8%	10.1%

** We model the increase in heated floor area in the service sector as a function of the increase in sectoral value added using an elasticity of 0.35, except for former Eastern European countries, for which an elasticity of 0.4 has been chosen, due to the present lower share of service sector buildings.*

<u>Breakdown of the Invert results to the hectare level (B2)</u>

The model Invert calculates and provides results for the building stocks at the national level, on the one hand for the start year of calculations, on the other hand for the final year as well as for different defined intermediate years. These national-level results are broken down to the hectare level in the following way: first, the results for the start year are broken down to NUTS3 level and subsequently to the hectare level. In a second step the changes between the start year and future years of the calculation are analysed and corresponding adjustments are applied to the hectare level data of the start year.

For breaking down the national-level Invert data to the NUTS3 level, statistical data for population, building stock characteristics (number of buildings and dwellings, floor area, shares per construction period) and value added per sector as well as Heating Degree Days (HDDs) are used. In the subsequent allocation of the NUTS3 data to the hectare level, several datasets and indicators at a higher geographical resolution are used. This includes population data layers on 1 km², on 250x250m level and on LAU2/LAU1 level, Corine land use data, the European Settlement Map, estimated GDP at LAU2 level, Global Human Settlement maps from different years and the Open Street Map dataset for buildings at

LAU2 level. Applying these datasets to the results of the Invert model at NUTS3 level results in gross floor area density and heat demand density maps at hectare level. These data distinguish between residential and non-residential buildings in three different construction periods: before 1977, between 1977 and 1990 and after 1990. A detailed description of the approach can be found in Müller et al. 2019[116].

For adjusting the hectare level data reflecting the start year of the calculation, the calculated scenarios are analysed regarding the developments of residential and non-residential buildings in the three construction periods mentioned before including demolition and new construction. This includes the changes in floor area and the changes in heat demand per floor area. Furthermore, the projected developments of population density at hectare level according to the JRC are applied. In places where buildings are demolished these are replaced by new buildings. Additional newly built gross floor area due to an increase of overall gross floor area in the region is placed at different locations: part of it is added on top of existing buildings, part of it is placed between existing buildings, and part of it is placed in locations where currently no buildings exist.

Modelling of the industry sector (I1)

Scenarios for the decarbonisation of the industry sector are calculated with the **FORECAST** model developed and run by Fraunhofer ISI. It is designed to support strategic decisions. Its main objective is to develop scenarios for the long-term development of energy demand and greenhouse gas emissions for the industry, services and household sectors of entire countries. The industry sector module of FORECAST considers a broad range of mitigation options combined with a high level of technological detail. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways and speed. The model further aims to integrate policies and considers changes in the socio-economic framework.

FORECAST considers the following mitigation options: energy efficiency (incremental and radical change), fuel switching (to renewable and low-carbon energy carriers), carbon capture and storage (CCS), circular economy and recycling, material efficiency and substitution down the value chain. The model is designed to cover the entire industry sector including major energy-intensive processes with a high level of detail, but also many less energy-intensive sub-sectors and applications. The complete simulation is conducted on the level of individual sub-sectors like e.g. iron and steel. The scope of the model is defined by the energy balances and focuses on final energy, but also includes useful energy.

The structure of FORECAST reflects the heterogeneity and data availability in the industry sector. Energy-intensive processes are considered explicitly, while other technologies and energy-using equipment are considered in the form of cross-cutting technologies modelled similarly across all sub-sectors. Core asset of the model is the EU-wide technology database that has been improved, maintained and extended for more than 10 years via individual research projects (e.g. SET-Nav[117], HotMaps[118], Heat Roadmap Europe[119],

---

[116] https://doi.org/10.3390/en12244789

[117] http://www.set-nav.eu/

[118] https://www.isi.fraunhofer.de/de/competence-center/energietechnologien-energiesysteme/projekte/318787_hotmaps.html

[119] http://www.heatroadmap.eu/deliverables.php

Industrial Innovation - Pathways to deep decarbonisation of industry[120], Mapping EU Heat Supply[121]).More details on the settings in the model used for calculating the baseline as well as the decarbonisation pathways for the different EU Member States are presented in the respective chapters below.

Modelling of the district heating (DH) sector (DH1 – DH6)

The approach for modelling scenarios in the district heating (DH) sector applies the following 6 consecutive steps:

1. Estimation of current market shares of DH in the different countries (DH1)
2. Calculation of potential future DH areas (DH2)
3. Derivation of generation potentials (waste heat and RES) for the identified DH areas (DH3)
4. Clustering of potential DH areas by size and RES potentials into DH types (DH4)
5. Calculation of supply dispatch to DH systems in the different DH types (DH5)
6. Compilation of results for DH types to country level (NUTS0) (DH6)

A description of the approaches followed in the different steps is provided in the following.

Estimation of current market shares of district heating (DH) in the different countries (DH1)

The first step in the calculation of scenarios of potential developments of DH in the EU is to understand the current share of the heat demand that is supplied by DH in different locations across Europe. This share, further on called current market share of DH, is estimated by combining data on location of and heat sold in existing DH systems from the HUDHC[122] database, data of heat demand on hectare level estimated within the Heat Roadmap Europe 4 (HRE4) project and shapes of urban areas created in the sEEnergies project. The data on heat sold in existing DH systems is spatially joined with the urban areas identified in the sEEnergies project, same is done for the estimated heat demand within the HRE4 project. The values of sold heat from the HUDHC database reflect different years for different existing DH systems. These values are recalculated to reflect the same year as the heat demand data from the HRE4 project using yearly HDD at NUTS3 level.

With the described approach an estimate of the current market share of DH in 2221 urban areas within EU27+UK with at least one recorded existing DH system has been elaborated. For the different countries between 1 and 387 urban areas with DH systems were found. The current market shares of DH differ remarkably between the different urban areas and the different countries ranging from below 5% to above 100%. Latter can be explained by potentially missing demand data like industrial heat demand as well as data uncertainty and potential double counting. However, with the approach it was possible to estimate an average current market share of DH in areas with DH systems for each of the countries using the weighted average of the different market shares in the different urban areas.

[120] https://www.isi.fraunhofer.de/de/competence-center/energietechnologien-energiesysteme/projekte/pathways.html

[121] https://www.isi.fraunhofer.de/de/competence-center/energiepolitik-energiemaerkte/projekte/mapping-heating_331945.html

[122] Halmstad University District Heating and Cooling (HUDHC) database

These national average values are further on used in the next step of calculating potential future district heating areas (DH2).

Calculation of potential future district heating (DH) areas (DH2)

After the estimation of current market shares of DH in urban areas with an existing DH grid, those areas are identified that are potentially suitable for DH in the future. For this a calculation module (CM) developed within the Hotmaps project[123] is used, the CM DH potential – economic assessment[124]. Working on hectare level the module identifies coherent areas that meet a given threshold of average heat distribution costs of all hectare elements within the coherent area. Heat distribution costs are hereby calculated as annualised investment costs for the grid infrastructure divided by the heat delivered over the considered period in EUR/MWh. Main inputs to the model are heat demand density and gross floor area density maps for the start as well as for the final year of the analysis period. These maps are generated based on the calculations in the Invert model at national level (B1) and their breakdown to the hectare level (B2). For calculating the annualised heat distribution costs in each hectare element the CM DH potential – economic assessment builds on the concept of the effective width developed by Persson et al. using the latest data update. The heat demand in each hectare element together with the share of DH on the overall heat supply (market share) is used to estimate the average diameters of the distribution as well as service pipes; these diameters together with the plot ratio (gross floor area per hectare) are used to calculate the absolute investment costs for network infrastructure. Developments of the DH market share as well as the heat demand density from the start year to the final year of the analysis are taken into account linearly for each hectare element.

For the different scenarios calculated in the project different input data are used in the module. All scenario related input data is described in the respective chapters.

Derivation of generation potentials (waste heat and RES) in the identified DH areas (DH3)

In this step, the aim is mapping generation potentials to the identified DH areas in the previous step. This is needed to enable the clustering of the DH areas into DH types, including their respective RES potentials as well as waste heat potentials.

It should be noted that solar thermal and biomass potentials (in the baseline scenario) were not mapped to the DH areas. It is assumed, that the solar thermal generation is not limited by spatial availability and thus by technical potential, but by economic potential. The economic potential will be analysed in step DH5 for each DH type identified in step DH4, considering the annual irradiation. Roundwood biomass potentials and wood chips are treated similarly, as it is assumed they could be transported. Hence, for each country, a biomass share is defined that does not exceed 50% of current biomass use in the baseline scenario. The potentials considered in this analysis are technical potentials with regional disaggregation. Furthermore, the temporal availability was considered by typical full load hours from existing projects and expert guesses. To some extent however, the derived technical potentials take into account typical sizes of projects (e.g. river heat pumps). The

[123] https://www.hotmaps-project.eu/

[124] https://wiki.hotmaps.eu/en/CM-District-heating-potential-economic-assessment

technical potentials are limited by the assumption of maximum distances from the DH areas to the generation potential where connection pipes need to be built. This assumption is based on average energy amounts of the individual generation potentials. Thus, the potentials derived do not reflect the total technical potential.

Geothermal energy is available at different temperature levels at different depths. The technical geothermal supply potential is defined as the potential that can be extracted technically from the underground. Principally, a geothermal plant includes one injection and one extraction borehole. The extraction borehole pumps water to the surface that stores the heat energy from the underground. The geothermal plant extracts the energy, depending on the temperature, e.g. with a steam process, organic rankine cycle or with a heat pump. After that, the cooled fluid is injected back to the underground with a second borehole, typically about 1 km away. There are two different possibilities to extract the heat with deep geothermal plants: hydrothermal and petrothermal. Hydrothermal plants use hot water basins within depths of typical 2000 - 4000m and extract the thermal water. Most of existing plants are hydrothermal, as they have higher flow rates and thus economic advantages. However, it is necessary to map the underground to locate these hydrothermal resources by test drillings (exploration risks). Petrothermal projects do not rely on hot water reservoirs underground, but extract the heat from the solid rock by injecting water that is heated up by the hot rock. In general, this potential is available almost everywhere, but the flow rates and maximum power is generally lower and so far only a few economically viable petrothermal projects have been realised[125]. Even though hydrothermal reservoir maps are published, they cover only selected regions. One exception is the GeoDH (Geothermal District Heating) project, which published hydrothermal potential areas by indicating layers of "aquiferes" and "other potential areas" for 14 EU member states, which is used here. It should be noted, that no hydrothermal potentials are assigned to the remaining member states, even though they could have potentials.

Estimating the geothermal potential depends mostly on the temperature variation in the underground in different depths. In the Atlas of Geothermal Resources in Europe, maps are available for temperature gradients in 1000m and 2000m depth. The temperature data of the underground is extracted as a raster file with the resolution of 1000m x 1000m in task 1. Each cell has stored the temperature of the underground at the depth of 2000m. As petrothermal projects are typically deeper due to higher temperatures, the depth of 2000m up to 3000m is considered here. The average temperature gradient is 30K/1000m, therefore 15K were added to the temperatures in the raster data to have an average value for this analysed underground layer. Excluded were regions with national parks, mountains and elevation higher than 500m, as well as water areas. Potential hydrothermal areas are clipped to the temperature layer, so the temperatures for the water is assumed are assumed to be equal to the underground temperature distribution. Hence, the greatest difference of petrothermal and hydrothermal potential is the assumed flow rate. To calculate the available geothermal power P, typical flow rates and the temperature of the underground are used, based on the publication of Umweltbundesamt, 2020:

$$P = Q \cdot \rho \cdot c \cdot (T_1 - T_2)$$

[125] Umweltbundesamt 2020: Kommunaler Klimaschutz durch Verbesserung der Effizienz in der Fernwärmeversorgung mittels Nutzung von Niedertemperaturwärmequellen am Beispiel tiefengeothermischer Ressourcen: Abschlussbericht, 2020.

with T_1 as the temperature in the underground in the depth between 2000m and 3000m, and T_2 as the temperature of the injected water. As the volumetric flow rate is assumed, the density of the water is needed. Furthermore, the heat capacity of the water is assumed:

$Q = 0.0194\, m^3/s$ for petrothermal projects, $Q = 0.06\, m^3/s$ for hydrothermal projects

$\rho = 1000\, kg/m^3$,

$c = 4000\, l/kg \cdot K$,

$T_2 = 70\,°C$ (in the baseline scenario), 50°C (in the policy scenario).

The injection temperature highly depends on the system design, future temperature levels in the district heating systems and technological progress as injection temperatures below 60°C can lead to scaling in the heat exchanger or pipes. The minimum temperature of the underground is assumed to be at least 15K higher than the injection temperature, in order to ensure a sufficient spread of injection and extraction water. Therefore, areas with lower temperatures than the threshold values of 85°C and 65°C were excluded for the reference and, respectively, the policy scenario. Furthermore, a risk factor of 40% (baseline) and 75% (pathway scenario) for hydrothermal and 50% for petrothermal projects (pathway scenario) is included, as not all boreholes will show the sufficient flow rate. The potential in MW is calculated for each raster pixel of the map, with a maximum distance of 25 km to the DH area. This potential should reflect the maximum heat that can be extracted by one project. However, the minimum distance between projects and therefore the borehole pairs (injection and extraction) needs to be considered. The area needed per borehole pair is 6.93km², so the potential per raster pixel is adapted. As a last step, the annual energy from the underground is estimated by assuming 3000 up to 4000 full load hours. In the reference scenario, no petrothermal potentials are included in the mapping, assuming that no policies will be in place to support the higher investment costs.

To determine available industrial waste heat in 2050, the transformation of industry in terms of production volumes and innovative processes from the report "Scenario analyses and pathways to deep decarbonisation"[126] is taken into account, reflecting a 95% CO_2 reduction. Industrial waste heat potentials consider the transformation of industrial processes to a climate-neutral economy and thus calculate the waste heat available in 2050. This assumption reduces the available potentials as on the one hand, energy efficiency potentials are exploited, and on the other hand, reduced production volumes are projected due to material efficiency. Furthermore, in the case of electrified furnaces or hydrogen-based steel making, the process efficiency is higher than the conventional process based on fossil fuels. The locations of industrial sites are assumed to remain where they are today, and the ISI Industrial Database, published in the Pan European Thermal Atlas 5 (peta 5), is used. The methodology to estimate waste heat potentials based on production is introduced in the publication of Manz et al., 2021[127]. For this study, the values were adapted to include carbon-neutral processes like hydrogen-based steelmaking and petrochemical products. The flow temperature of DH systems influences the energy that is available at industrial sites. Hence, it can be varied from 95°C to 55°C, depending on scenario. The maximum distance is assumed to be 40 km, with prioritising DH areas with higher demand.

---

[126] ICF, Fraunhofer ISI, Industrial Innovation: Pathways to deep decarbonisation of Industry: Part 2: Scenario analysis and pathways to deep decarbonisation. A report submitted to the European Commission, DG Climate Action, 2019.

[127] P. Manz, K. Kermeli, U. Persson, M. Neuwirth, T. Fleiter, W. Crijns-Graus, Decarbonizing District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites?, Sustainability 13 (2021) 1439. https://doi.org/10.3390/su13031439.

The locations of wastewater treatment plants are taken from Hotmaps, where the plants are published with the maximum energy that is available in the wastewater. In the Pan European Thermal Atlas 5, taken from ReUseHeat[128], data on waste heat from wastewater treatment plants with similar locations is also published, but without Switzerland and Norway. For this study, the locations and power were taken from Hotmaps, with typical full load hours of 4421 derived with the values from ReUseHeat, and a maximum distance to DH of 2 km.

The potential heat from waste incineration (waste to energy) was calculated in the project Heat Roadmap Europe 4[129] and published in the Pan European Thermal Atlas 5 (peta 5) as shapefile. These data were taken and multplied with a factor of 0.63, inidcating the heat utilization efficiency in CHP plants. The maximum distance for waste incineration plants to DH areas is assumed to be 50 km, with prioritizing DH areas with higher demand.

Heat from rivers and other water sources like lakes can be an interesting heat source for heat pumps. Studies[130] come to the conclusion, that there is a vast potential to be exploited, even though temperatures in winter are quite low (average 2°C - 8°C). The input data for river location and monthly average flow rates were taken from Copernicus Climate Change Service Information. River locations were filtered out that show less than 20 m³/s as an average winter flow rate. Additionally, smaller rivers have often not sufficient temperatures in winter. The rivers and lakes were grouped into areas that have great potentials, with flow rates above 100 m³/s, areas that have medium flow rates between 100 and 50 m³/s and areas with small potentials between 50 and 20 m³/s. From this, typical projects and studies[131] were taken to define mean values for typical power (30 MW for small, 80 MW for medium, and 150 MW for higher flow rates) that river heat pumps can generate. With assumed full load hours of 2000 for smaller projects (lower flow rates have generally lower temperatures) and 3000 for bigger projects the average potentials for river heat pumps are generated. The maximum distance to DH areas is 5 km and minimum distance between two extraction points at the river is 10 km.

In the following table, the potentials to supply DH from renewable and waste heat sources are listed, aggregated for EU-27. The supply potential is the total technical potential from the resources in all countries within a certain distance to DH Areas, calculated and estimated with the assumptions explained above. The demand potential is reduced by spatially available demand in a certain distance for different scenarios. Additionally, please note that the total supply potential for rivers and lakes could be higher, as no detailed analysis regarding the minimum distance between two extraction points was conducted. The wastewater treatment plants show a high demand potential compared to the supply potential, i.e. most of the treatment plants are close to human settlements, that are dense enough to be suitable for DH.

---

[128] U. Persson, H. Averfalk, Accessible urban waste heat: Deliverable D1.4 ReUseHeat. Recovery of Urban Excess Heat (2018).

[129] U. Persson, B. Möller, E. Wiechers, Methodologies and assumptions used in the mapping: Deliverable 2.3: A final report outlining the methodology and assumptions used in the mapping. Heat Roadmap Europe 2050, A low-carbon heating and cooling strategy (2017).

[130] UK Department of Energy & Climate Change, National Heat Map: Water source heat map layer (2015).

A. Lyden, Viability of river source heat pumps for district heating. Master's Thesis, 2015

A. Gaudard, M. Schmid, A. Wüest, Thermische Nutzung von Seen und Flüssen: Potenzial der Schweizer Oberflächengewässer, AQUA & GAS N°2 (2018) 26-33.

[131] A. Lyden, Viability of river source heat pumps for district heating. Master's Thesis, 2015.

Austrian Institute of Technology (AIT): Techno - ökonomische Analyse der Integration von flusswassergespeisten Großwärmepumpen in FW-Netzen, 2015.

Table 49: Technical supply and demand potentials for utilisation in DH in EU-27

Potential	Unit	Supply potential - baseline scenario	Demand potential - baseline scenario	Supply potential – decarbonisation pathway scenario	Demand potential – decarbonisation pathway scenario
DH demand	TWh	419.96	419.96	694.32	694.32
Geothermal (hydrothermal)	TWh	216.77	42.76	1344.07	249.01
Geothermal (petrothermal)	TWh	--	--	717.56	62.28
Wastewater treatment plants & heat pump	TWh	157.81	114.44	293.32	216.44
Waste incineration plants	TWh	85.95	67.73	97.137	87.21
Industrial waste heat)	TWh	16.88	13.90	31.96	26.90
Water resources (rivers, lakes) & heat pump	TWh	274.44	68.44	698.93	108.08
Total (EU-27)	TWh	751.850	307.26	3917.44	749.97

Clustering of potential DH areas by size and RES potentials into DH types (DH4)

In the next step DH types are derived, for which subsequently the dispatch of heat supply is calculated with the Hotmaps DH dispatch model (DH5). The DH types represent DH areas with similar RES and waste heat potentials. Up to five different DH types are derived using a clustering approach.

The input figures for the clustering are:

- Geothermal heat potential (expressed in coverage of demand in %)
- Heat potential from waste incineration (expressed in coverage of demand in %)
- Heat potential from wastewater treatment plants (expressed in coverage of demand in %)
- Industrial waste heat potential (expressed in coverage of demand in %)
- River and lake heat potential (expressed in coverage of demand in %)

In order to minimize the effect of different orders of magnitudes (especially between demand and coverage), the figures are scaled with a min-max scaler, resulting in figures between 0 and 1.

With the scaled data, a hierarchical agglomerative clustering is computed. A hierarchical clustering algorithm calculates the distance or dissimilarity between all elements and stepwise combines two elements with the lowest dissimilarity to a cluster. This formed cluster is then used again in the next iteration. The clustering algorithm can use various schemes differing in the dissimilarity calculation between the original elements and formed clusters. The Euclidean distance and wards minimum variance method (similar to Triebs et al. 2021[132]) are used in this study.

The Euclidean distance between the two figures $p = (p_1,\dots,p_n)$ and $q = (q_1,\dots,q_n)$ is calculated as following:

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}$$

The wards minimum variance is computed as follows:

$$d(u,v) = \sqrt{\frac{|v| + |s|}{T} \cdot d(v,s)^2 + \frac{|v| + |t|}{T} \cdot d(v,s)^2 - \frac{|v|}{T} \cdot d(v,s)^2}$$

Thereby, u is the newly joined cluster consisting of the clusters s and t. The value v is an unused cluster and $T = |v| + |s| + |t|$. The operator $|\ \ |$ calculates the cardinality of its argument.

As a sensitivity, we also conduct a k-means clustering using Euclidean distances and compare the results. In k-means clustering, clusters are represented by a central vector. When the number of clusters is fixed to k, k-means clustering gives a formal definition as an optimization problem: find the k cluster centers and assign the objects to the nearest cluster center, such that the squared distances from the cluster are minimized.

Exemplary DH types are presented in the following table, which were determined in a methodology test run, for 2248 (coherent) DH areas in the considered countries (in 2050), using hierarchical agglomerative clustering with Euclidean distance and wards minimum variance method.

[132] Triebs et al. (2021): Landscape of district heating systems in Germany – Status quo and categorization, in Energy Conversion and Management, https://doi.org/10.1016/j.ecmx.2020.100068

Table 50: Exemplary DH types

DH type	#	Average DH demand [GWh]	Average geothermal coverage [%]	Average waste-water treatment coverage [%]	Average waste to energy coverage [%]	Average waste heat coverage [%]	Average rivers-to-energy coverage [%]	Average biomass coverage [%]
1	204	76	5%	25%	0%	9%	95%	21%
2	341	647	11%	21%	2%	1%	6%	15%
3	825	75	97%	57%	2%	3%	1%	11%
4	164	246	83%	70%	88%	19%	46%	15%
5	715	61	95%	57%	1%	12%	91%	11%

From a qualitative perspective, the exemplary DH types can be described as follows:

- DH type 1 represents smaller networks with low geothermal, medium wastewater treatment, low waste to energy, low industrial waste heat, medium biomass but high rivers to energy potentials for coverage of the demand.
- DH type 2 represents bigger networks with low geothermal, medium wastewater treatment, low waste to energy, low industrial waste heat, low rivers to energy and also low biomass potentials for coverage of the demand.
- DH type 3 represents smaller networks with high geothermal, high to medium wastewater treatment, low waste to energy, low industrial waste heat, low rivers to energy and low biomass potentials for coverage of the demand.
- DH type 4 represents medium networks with high geothermal, high wastewater treatment, high waste to energy, low to medium industrial waste heat, medium rivers to energy and low biomass potentials for coverage of the demand.
- DH type 5 represents smaller networks with high geothermal, high wastewater treatment, low waste to energy, low industrial waste heat, low biomass but high rivers to energy potentials for coverage of the demand.

The dispatch of heat supply to the DH systems of the identified types is calculated for each country mainly due to differences in economic input data. Hence, for each country up to 5 DH types are calculated in the Hotmaps DH dispatch model (DH5). For these calculations average values of heat demand and coverage potentials (per country) for each DH type will be used. The fowlloing figure shows the DH types per country as well as the total number of (coherent) DHC areas. It can be seen that not all 5 DH types are present in each country. In Poland, for example, only three different types are represented.

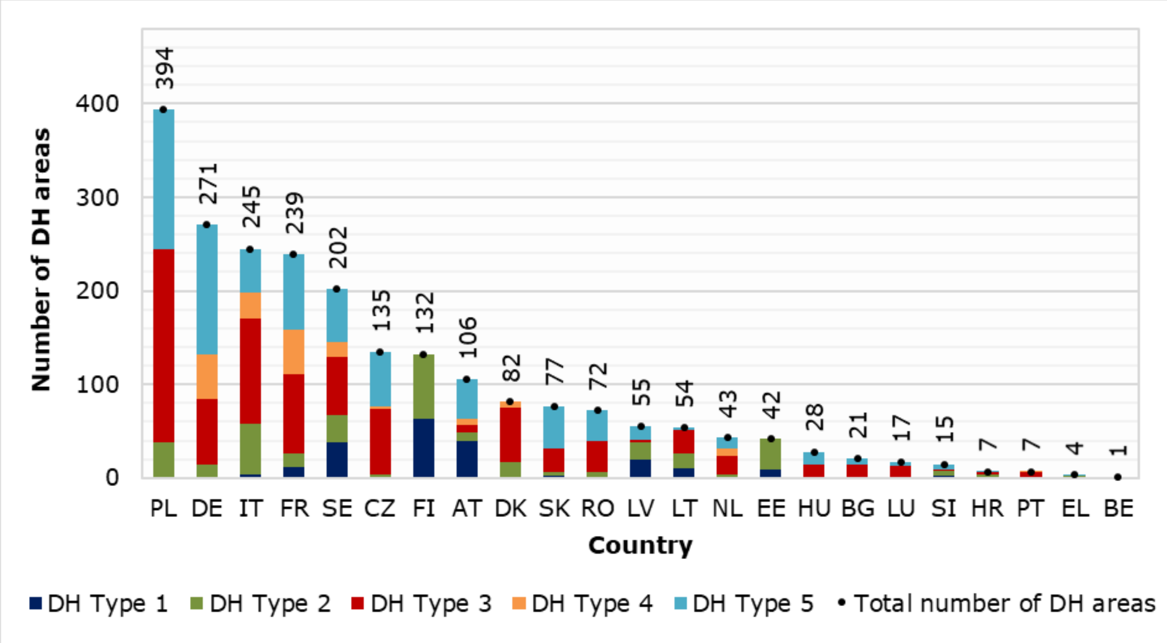


Figure 122: Exemplary DH types in the different countries

Calculation of supply dispatch to DH systems in the different DH types (DH5)

For each of the DH types in each of the countries identified in the previous step (DH4) the supply of the heat from different available sources is derived with the calculation module (CM) DH supply dispatch[133] initially developed in the Hotmaps project[134]. The module calculates the cost-minimal operation of a portfolio of heat supply technologies in a defined DH system for each hour of the year. Main inputs to the module are various hourly profiles: for the heat demand and temperature level in the network, for the potential heat supply and temperature levels from different sources, and for energy carrier prices. Furthermore, cost (investment, O&M, ramping) and efficiency parameters for each technology are important input. The module considers the relation between the COP of heat pumps and the changes in the temperature levels of heat sources and the flow temperature of the DH system. The module also considers different heat storage options from short term daily to medium term monthly as well as seasonal storage. The calculation yields the costs of heat supply, the share of energy carriers used and the implied CO_2 emissions. Despite the optimisation of the dispatch of different supply technologies, the module can also be used to optimize the capacities of installed heat supply technologies to cover the defined heat demand in the network. In this analysis a mixed approach is used: part of the capacities in the DH systems are defined by the modelling team, part of it is optimised by the module.

As the annual heat demand and profiles of temperature and irradiation are dependent on the location, they are weighted. Input are profiles that apply for each single DH area considered in a certain cluster of one country. These are then weighted by the DH demand and the population of these regions where the DH areas are located. One profile per cluster and country for the heat load and renewables is the result and an input for the dispatch model.

---

[133] https://wiki.hotmaps.eu/en/CM-District-heating-supply-dispatch

[134] https://www.hotmaps-project.eu/

For the different scenarios calculated in the project different input data are used in the module. All scenario related input data is described in the respective chapters.

Compilation of results for DH types to country level (NUTS0) (DH6)

In this final step of modelling the DH sector the results from different intermediate steps are aggregated to the country level (NUTS0). The results from the DH supply dispatch (DH5) for each of the DH types identified in (DH4) are aggregated as follows: absolute values reflecting a typical DH system type like energy carrier demand, yearly costs and emissions are multiplied by the number of coherent areas per system type and summarised for all existing DH types. This yields the total energy carrier demand, yearly costs and emissions for DH supply in the country. For calculating average heat supply costs the total yearly costs per country are divided by the total heat supplied by DH in the country. As an example, the fowlloing table shows the number of DH areas per DH type in Austria (from the test run). In Austria, 39 DH areas are of the DH type 1, 10 areas correspond to the DH type 2 and so on. Therefore, in order to aggregate the result for Austria, the dispatch results for each DH type are multiplied with the corresponding number of areas (i.e. 39, 10, etc.).

Table 51: Exemplary number of DH areas per DH type in Austria

Cluster, i.e. DH types	Number of DH areas
1	39
2	10
3	8
4	6
5	43

For deriving the total costs of DH network infrastructure (distribution and service pipes) the results of the CM DH potential – economic assessment (DH2) are aggregated to country level. To do so, the yearly investment costs of each identified DH area is summed up according to DH type as well as to the country totals.

Annex C4: The building stock model Invert

Invert is a bottom-up model to analyse space heating, hot water generation and space cooling in the building stock. It is designed to quantitatively evaluate the effects of different framework conditions on total energy demand, energy carrier and technology mix, CO_2 emissions and costs. Such framework conditions include price scenarios for energy carriers, cost scenarios for technologies and efficiency measures, different settings of economic and regulatory incentives, consumer behaviour, climate change and resource potential restrictions.

Bottom-up representation of the building stocks

Invert is based on a highly disaggregated description of the building stocks in the different analysis regions. This includes the type of a building, age, state of renovation, existing heating systems, user structure as well as regional aspects such as availability of energy infrastructure for gas or district heating. In the analyses usually, both residential and tertiary buildings, are covered.

Application at different geographical levels

Invert is used at various geographical levels: a) at the national level, either at single country level, multi-country level, or entire EU-27 (+ Norway, Iceland, Switzerland and UK), b) at the regional level such as e.g. federal states in Germany or Austria, or c) at local level for analysing building stocks at city level.

Database of technologies and efficiency measures

The model uses an extended database of technologies and efficiency measures containing their technical and economic characteristics. On the one hand this integrates currently applied and potential future technologies for the supply of space heating, hot water and space cooling, including on-site solar thermal and PV generation as well as the heat distribution systems in the building. On the other hand a large set of options for building shell refurbishment and heat recovery systems is considered for decreasing energy needs in the buildings.

Calculation of energy needs and demand

In the “Energy module” of Invert the energy needs, final energy demand and delivered energy for space heating, hot water generation and space cooling are calculated. The module applies a quasi-steady state monthly energy balance approach according to EN13790. Furthermore, these standard calculations are adjusted to take into account the observed differences between calculated and measured energy demand using a disaggregated service factor approach.

Determination of investment timing

Based on age and lifetime distributions of buildings and their different components like shell elements and installed technologies, the timing of investment decisions in the building stock is determined in the “Service lifetime module”. This includes building demolition, new construction, refurbishment activities and supply system change.

Three different model types

For calculating scenarios of potential future states of the building stocks three different modules can be applied, each representing a different model type:

- **Invert/EE-Lab** applies a combination of a discrete choice approach and technology diffusion theory to simulate energy-related investment decisions in the buildings over a defined analysis period.
- **Invert/Opt** uses an optimisation approach to identify the least-cost combination of investment decisions in all buildings of an analysis area under given conditions and constraints until a defined future year.
- **Invert/Accounting** is designed to quantify the effects of exogenously defined settings in a defined future year e.g. related to renovation rates or supply system shares.

The following Figure 123 shows the structure of the Invert model in the applied EE-Lab version mode of the tool.

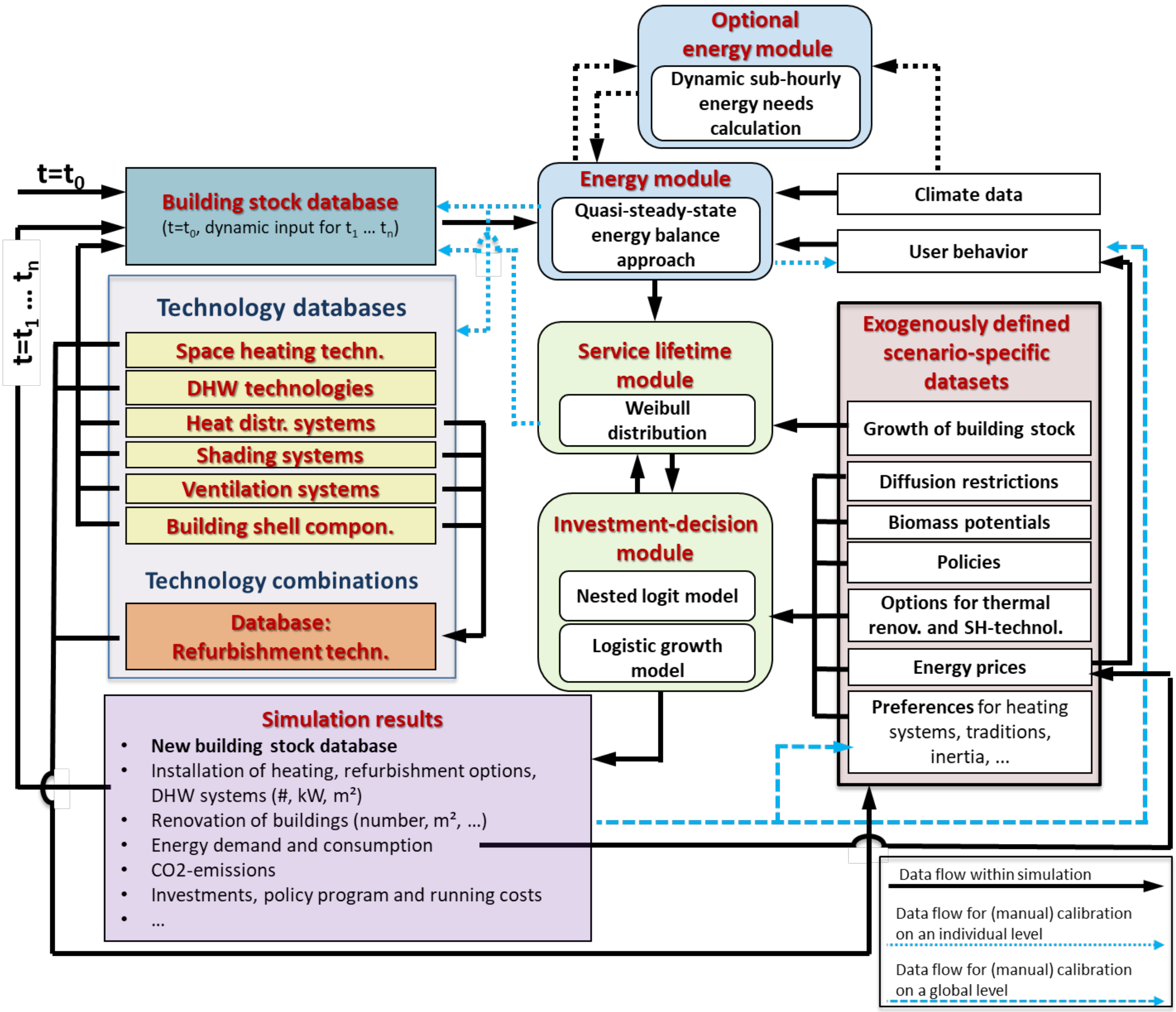


Figure 123: Overview of the structure of Invert when applying the EE-Lab version

Basic approach of the EE-Lab (simulation) version

Invert/EE-Lab simulates energy-related investment decisions in the building stocks. This version is particularly used for studying the effects of economic and regulatory incentives on the decisions of different agents (i.e. owner types) in case an investment decision is due for a specific building segment. It hereby takes into account the inhomogeneous structure of decision-makers in the building sector. The core of the EE-Lab version is a myopic, multinomial logit approach, which optimizes the objectives of agents under imperfect information conditions and by that represents the decision makers. It applies a nested logit approach to calculate market shares of heating systems and energy efficiency measures depending on building and investor type. The following equation depicts the market share calculation as logit-model. A detailed representation of the decision algorithm is given by Müller (2015) and Steinbach (2016).

The model enables the definition of different owner types as instances of predefined investor classes: owner occupier, private landlords, community of owners (joint-ownership), and housing association. The structure is motivated by the different perspectives regarding building-related investments. For instance, energy cost savings are only relevant for those owners who occupy the building. The corresponding variable relevant to landlords is a refinancing of energy savings measures through additional rental income (investor-tenant dilemma).

Owner types are differentiated by their investment decision behavior and the perception of the environment, the former is captured by investor-specific weights of economic and non-economic attributes of alternatives. The perception-relevant variables – information awareness, energy price calculation, risk aversion – influence the attribute values.

Standard outputs

Standard outputs from the Invert model on an annual basis are:

- Installation of heating and hot water systems by energy carrier and technology (number of buildings, number of dwellings supplied)
- Refurbishment measures by level of refurbishment (number of buildings, number of dwellings)
- Total delivered energy by energy carriers and building categories (GWh)
- Total energy needs by building categories (GWh)
- Policy programme costs, e.g. support volume for investment subsidies (M€)
- Total investment (M€)

Because of the importance of the heat pumps in our model results, the following section presents the implementation of the annual efficiency of heat pumps along with key assumptions on the heat supply temperature in buildings, which has a significant influence on the performance of heat pumps.

Modelling the annual efficiency of heat pumps in the Invert model

In the Invert model, the annual average efficiency is not defined by a single parameter but is modelled as a function of the average heat supply temperature of heat distribution system in buildings and in the case of the air-source heat pumps on the average monthly ambient air temperature. Based on the system boundaries according to JAZ4 definition (see Figure 124), we assume that heat pumps deliver their seasonal coefficient of performance if the heat is distributed at a supply line temperature level of 35 °C (for hydronic heating systems).

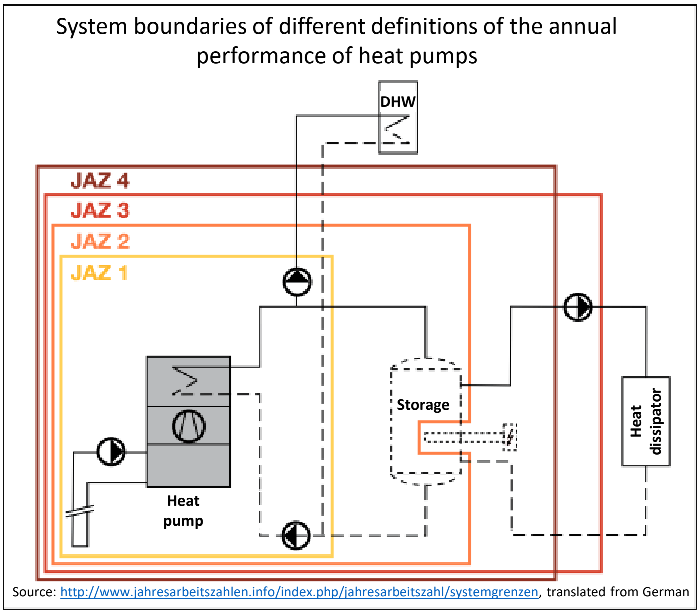


Figure 124: System boundaries of different definitions for the annual efficiency of heat pumps

If the supply line temperature is higher than 35 °C, the efficiency decreases linearly by 35% for air-sourced and 25% for brine-water based heat pumps if the annual weighed average supply line temperature increases to 55 °C. Above the temperature level, the efficiency drops non-linearly using an elasticity of 1.2 (Figure 125).

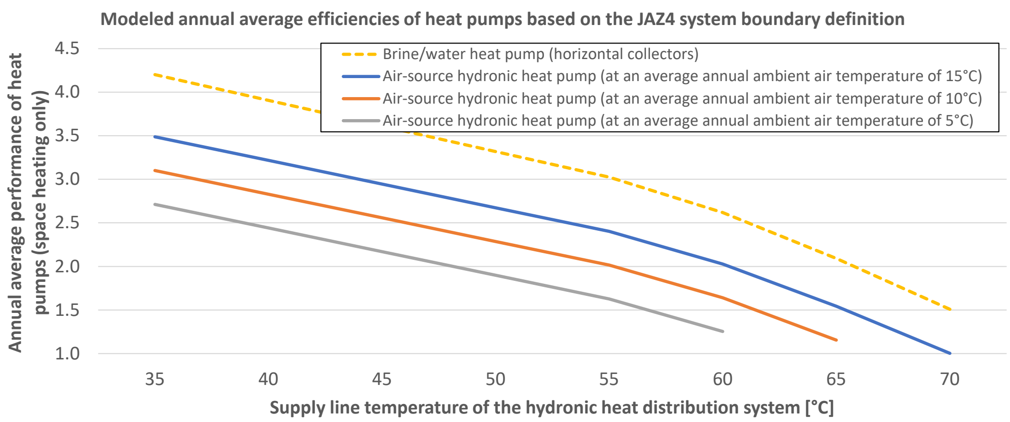


Figure 125: Implemented annual efficiencies of heat pumps

Regarding the heat distribution system and their average annual supply line temperature, we assume that older buildings use heating systems, which were designed for higher temperature levels, and that the design temperature dropped if buildings were constructed since the 1970ies. Based on our assumptions, buildings constructed before 1970 are equipped (if a building or apartment central heat distribution system is installed), with a distribution system that is designed to deliver the design heat load of the building at the winter design temperature conditions at a temperature level of 70-90°C, which leads to an average supply line temperature of about 58-70°C. For buildings constructed between 1970 and 2000, a design temperature of 55-60°C (leading to an average annual temperature of about 48-52°C) has been chosen. For more recent buildings, we assumed an average design temperature of 40-50°C (annual average temperature of 38-47°C). In addition, we defined a lower limit for the supply line temperature depending on the specific energy needs for space heating. Here consider that the average supply line temperature can fall below 40°C only if the annual energy needs for space heating are less than 70 kWh/m² and must be above 50°C, if the energy needs exceed 130 kWh/m²[135].

If a building gets refurbished within the simulation, the Invert model estimates a new, reduced average supply temperature that would be sufficient to heat the building since the heat load of the building has been reduced by energy efficiency measures, while the heat dissipator area (radiator area) did not (according to our assumptions). To estimate the effect, we implemented a simplified calculation procedure for the concept of logarithmic excess temperature (see Müller, 2015) along with the assumption, that buildings utilize 80% of the possible temperature decrease.

History and further information

The Invert model originally has been developed by TU Wien – Energy Economics Group (EEG) in the frame of the Altener project Invert (Investing in RES&RUE technologies: models for saving public money) between 2003 and 2005. In 2010 the model has undergone a major reprogramming process and since then focuses on a bottom-up representation and analysis of building stocks and related heating and cooling demand and supply. Since then the model is jointly applied and developed by TU Wien / EEG and e-think energy research. In more than 50 projects since 2010 the model has been applied to different locations and research questions across Europe. Steadily the model and the database has been and is further extended to cover new locations and research questions.

Based on the specific needs of projects and clients, other and more detailed types of evaluations and further model extensions can be performed.

More information about the Invert model family and contact to the development and consulting team can be found at www.invert.at

Reference

Müller, A., 2015. Energy Demand Assessment for Space Conditioning and Domestic Hot Water: A Case Study for the Austrian Building Stock (PhD-Thesis). Technische Universität Wien.

Steinbach, J. (2016): Modellbasierte Untersuchung von Politikinstrumenten zur Förderung erneuerbarer Energien und Energieeffizienz im Gebäudebereich. Fraunhofer Verlag. ISBN 978-3-8396-0987-3

[135] We implemented the following equations for the lower limit of the heat supply line temperature:
$T_{supply,\ lower\_limit}$ = min(60°C, max(0, en_{sh} – 50)/10 * 20°C + 35°C), where en_{sh} denotes the annual energy needs for space heating per square meter of heated gross floor area in [kWh/m²].

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

– at the following standard number: +32 22999696, or

– by email via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from: https://op.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: http://eur-lex.europa.eu

Open data from the EU

The EU Open Data Portal (http://data.europa.eu/euodp/en) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

Publications Office
of the European Union