ENER/C1/2018-494 – Renewable Space Heating under the Revised Renewable Energy Directive

Final report

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Glossary

DH	District heating
DHW	Domestic hot water
HDD	Heating degree days
LCC	Life Cycle Costs
LCOH	Levelised costs of heat
NECP	National Energy and Climate Plan
NPV	Net present value
REC	Renewable energy community
RED II	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources
SH	Space heating
SFH	Single family house
MFH	Multi-family house
TYNDP	Ten Year Network Development Plan
NTC	Net transfer capacity
CCS	Carbon capture and storage
CHP	combined heat and power

1. Executive Summary

Space and water heating accounts for almost one third of the European final energy consumption. Thus, the sector needs special attention in the decarbonisation process. This study aims to provide a better information basis for policy design targeting decarbonisation of the space and water heating sector. This involves collecting data and information on the status-quo of the space and water heating sector in the EU with regard to energy consumption, energy carriers, technologies and the regulatory framework. Furthermore, alternative decarbonisation pathways are modelled to better understand the long-term perspectives and related costs. Finally, recommendations for policy design were developed and discussed with relevant stakeholders from EU and the Member States. The study focuses on heat consumption in buildings and covers space heating and the supply of sanitary hot water.

Space and water heating in the EU: Consumption and technology data

As a first step, final, useful and primary energy balances for space and water heating are calculated for 31 EU and non-EU countries for the year 2017. In the EU-28, final energy for space and water heating accounts for about 47% of the total final energy demand across the sectors households, industry, and commercial & public services. Among these sectors, households are the largest consumer of final energy for space and water heating purposes (67%), followed by commercial & public services (26%) and the industry (7%).

The overall fuel mix for space and water heating in the EU-27 is dominated by natural gas (43%), biomass (16%), and fuel oil (15%). With about 62%, fossil fuels account for the major share of final energy supply in the EU-27. Emerging energy carriers such as ambient heat (heat pumps), solar thermal and geothermal energy can be seen as niche options, with a total share of approximately 3.6% in final energy demand for space and water heating. Taking explicit account of the fuel mix for electricity and district heating, the renewable share of the EU-27's primary energy fuel mix is estimated at 23%, giving rise to several recommendations for courses of action.

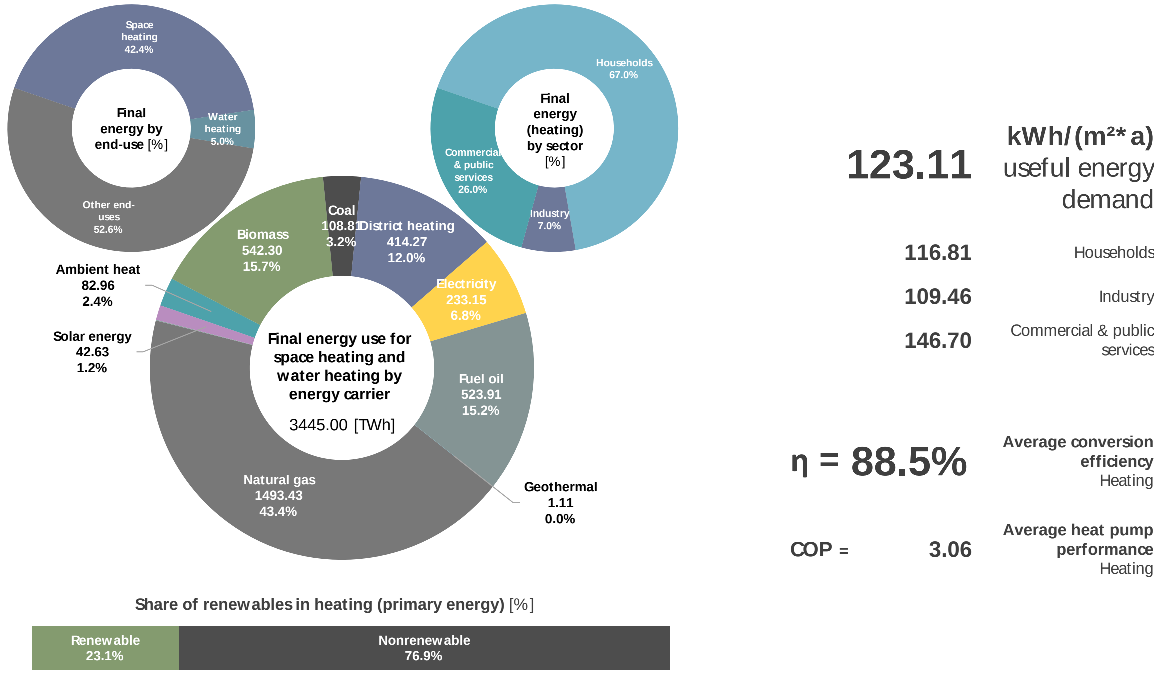

Figure 1: Energy demand for space and water heating in the EU-27 in 2017.

The end-use balances for space and water heating developed in this task provide a substantial complement to Eurostat's energy balances. Adding the dimensions of sub-sectors (e.g. single- and multi-family homes for the households sector), end-uses (space heating, water heating, other end-uses) and technologies (e.g. different heat pump types) allows for a comprehensive overview of energy use for heating in the 31 European countries considered.

As second task, the study provides an overview of all the relevant current and emerging space and water heating technologies in buildings and their technological development trends. This includes all relevant fossil-based and renewable heating technologies including renewable electricity, e-fuels and hydrogen H2. The overview provides technical characteristics, stock figures, development trends and estimates on the costs of heat supply for each individual Member State and reported in structured Excel data sheets.

Finally, these data on space heating energy balances and technologies have been summarized and presented in the format of country fact sheets for all individual EU member states including the EU-27 aggregate. The summary country files include information on the energy consumption for space and water heating, the technology distribution, building structure as well as the regulatory framework in place.

Decarbonisation scenarios for space and water heating

Based on the data elaborated above, we developed a baseline scenario and a series of technology-focused decarbonisation scenarios of the sector until 2050: A direct RES-H scenario (focusing on individual heat pumps, biomass boilers and solar), an electrification scenario, one scenario focusing on e-fuels and another one on hydrogen and finally a district heating scenario. Subsequently, we carried out a comparative assessment and derived a "best-case" scenario. For this purpose, we applied three models: the building stock model Invert, the energy system optimization model Enertile and the Hotmaps district heating model. The model results allow comparing the scenarios with regard to additional costs, GHG reduction, energy demands and energy savings.

The overall logic of the scenario development is to define boundaries for the relevance of certain energy carriers in supplying space and water heating to buildings, including constraints regarding their potential. Within these constraints, an algorithm identifies the cost-minimal constellation of the use of energy carriers and technologies in different parts of the building stock and the cost-optimal renovation levels. This leads to scenarios, which are not considered as extreme scenarios but rather realistic implementations of pathways, with each of the scenarios showing a mix of systems, energy carriers reflecting also the suitability in different parts of the building stock as well as climatic and regional constellations.

Overall, it turns out that e-fuels and hydrogen are very close to the minimum boundaries defined. This is an indication that these energy carriers are more costly than other systems. For heat pumps, it rather depends on the type of building whether an efficient use of heat pump is deemed economic. In general, the model has the tendency to move towards the upper limit of the boundary and heat pumps gain major shares in all scenarios. Biomass heating systems tend to be economically viable under the considered modelling and scenario assumptions towards climate neutrality. Here, the biomass potential restrictions and the underlying assumptions regarding more relevant use of biomass potentials in other end-use sectors are the main constraints limiting a further deployment of biomass-based heating. The economic viability of district heating in the model varies between countries. Due to the fact that district heating use was limited to areas with high heat demand densities and corresponding low heat distribution costs, district heating tends to be selected by the optimisation algorithm within the set constraints.

Following main insights can be derived from the modelling. First, if measures and the overall system are optimised (as assumed in our modelling approach) the costs, in particular for the scenarios hydrogen, direct RES, district heating and e-fuels do not deliver a clear criteria for a decision. More relevant are the barriers and policy implications for the decision for one or the other pathway. Second, some measures can be regarded as no-regret options as they are identical for all scenarios: a high level of building renovation, a high diffusion of heat pumps and district heating in suitable areas. Moreover, even in the H2 and e-gas scenario parts of the gas grid would need to be decommissioned, because there would be more economic decarbonisation solutions. Third, the best case scenario – resulting in the lowest cost – is close to the electrification scenario, however, with slightly higher penetration of solar heat and district heating.

A policy maker can thus pursue the no-regret measures rapidly (valid for all scenarios) and the measures specific to the best-case or electrification scenario. Nevertheless, she must also take into account other relevant drivers and barriers to policy implementation for the pathways that go beyond system cost-optimization aspects treated in the modelling.

Feasibility and framework conditions

In order to make the decarbonisation scenarios happen in reality, a multitude of barriers have to be addressed through a coherent set of policy measures. Thus, the final part of the study analyses the barriers and technological, economic and regulatory framework conditions required in order to facilitate the transition towards the respective target systems studied above.

The methodological approach for deriving recommendations for the technological, economic and regulatory framework conditions includes the following four steps: (1) Analysis of the barriers for the deployment of the different space heating options, (2) analysis of policy instruments available to overcome the barriers identified in the first step, (3) definition of policy sets for different country clusters and transformation pathways and (4) recommendations for policies at EU, national and local level. Moreover, the role of renewable energy communities for heating was analysed.

From the analysis of barriers, the following conclusions are derived:

- Each of the decarbonisation options is facing a heterogeneous set of barriers. This requires a mix of policies to support the transformation.
- **Economic barriers** for the decarbonisation of heating in buildings results mainly from the investment in energy efficiency and renewable energy technologies as well as the operation costs. High investment costs as compared to fossil heating equipment act as a barrier for all of the considered technology pathways, including the investments by building owners in end-use equipment as well as infrastructure investments (e.g. district heating grids). Economic barriers during the use-phase are predominant particularly for the electrification pathway (low prices for fossil fuels as compared to electricity) as well as for the hydrogen and e-fuels pathways.
- **Barriers related to technology maturity** occur where the required decarbonisation technologies are not fully developed. Such barriers are particularly pronounced in the (green) hydrogen and e-fuels pathways, where large-scale production, distribution and storage is currently limited to pilot projects. Across all pathways, technology maturity is a barrier for the deployment of new retrofit approaches based on serial renovation supporting a cost-efficient and fast deployment of energy efficiency in buildings. Furthermore, the lack of digital solutions to support the deployment is a barrier for several decarbonisation technologies: For heat pumps, a lack of digital technologies to support the use of flexibility options and demand side management as well as to continuously control the efficient operation are needed for large-scale deployment. Likewise, for district heating the transition to highly efficient systems based on renewable energy requires digital technologies.

- Barriers related to **market maturity (including technology, fuel and installer markets)** are particularly pronounced in the H_2 and e-fuels scenarios, where no markets exist so far. However, market maturity also acts as a barrier in the electrification pathway, as in most EU MS heat pumps currently have a low market share. In district heating, the lack of market maturity for large-scale renewable heat production poses a barrier in most EU MS.
- The **impact on the electricity system** is a barrier in all decarbonisation pathways relying on heat production that involves electricity consumption. This includes decentralised heat pumps, large-scale heat pumps for district heating as well as hydrogen and e-fuels. At the same time, these technologies provide also benefits in form of flexibility options for the electricity system.
- **Resource availability** is a key barrier in most pathways and covers the availability of the energy carriers (particularly strong barrier for biomass and hydrogen and e-fuels), the availability of heat sources (particularly pronounced for geothermal installations as well as water-source heat pumps) and the availability of space (particularly strong barrier for large-scale solar thermal as well as RES-E installations).
- **Regulatory barriers and licensing** are particularly pronounced for technologies with currently low deployment, where codes and standards as well as licencing procedures have not yet been developed (particularly for hydrogen). Regulatory barriers are also relevant for the deployment of ground-source heat pumps as well as the use of the soil or aquifers for heat storage. For district heating, regulatory barriers include the planning and licensing for heat production facilities as well as third-party access to heating grids.
- **The suitability of the building stock** poses a barrier for the deployment of most renewable heating technologies: For heat pumps as well as for RES-based district heating, an efficient deployment requires low-temperature heating systems. For solar thermal installations, rooftops may be unsuitable for the installation. For hydrogen and e-fuels, due to the high costs of the energy carriers, their application in non-efficient buildings leads to high costs.
- **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
- **Hydrogen for heating** faces key barriers: Firstly, from the economic perspective, using hydrogen for individual space heating would require extensive investments in hydrogen distribution grids. Secondly, it is highly uncertain if green hydrogen will be available for heating in buildings and if so in what quantities and at what price. Thirdly, hydrogen as a decarbonisation option faces the risk of lock-in if investments in infrastructure and end-use appliances are undertaken despite the large uncertainties. For these reasons, we conclude that priority should be given to the other decarbonisation options for heating in buildings.

The most effective way of aligning investments in building components and heating systems to the objective of decarbonisation is by establishing a **strong regulatory framework** to restrict the use of technologies that are not consistent with the objective.

In order to address the economic barriers, **economic policy instruments** facilitate an affordable transition and provide a level playing field for renewable technologies. Key economic instruments include subsidies and preferential loans for investments in renewable heating technologies as well as energy and carbon pricing.

To support market and technological maturity and to address regulatory barriers, a set of **supporting complementary policies** is needed to support the transition. This includes R&D support measures, market transformation measures such as collective procurement programmes, capacity building and training for installers, capacity building to support planning skills in local administrations.

As the transformation of the heating sector has impacts on the use of key infrastructures (district heating, gas grid and electricity grid), approaches for **heat planning and citizen involvement** are needed to coordinate the expansion, modernisation and decommissioning of such infrastructures.

2. Introduction

This study aims to provide a better information basis for policy design targeting decarbonisation of the space heating sector. This involves collecting data and information on the status-quo of the space heating sector in the EU with regard to energy consumption, energy carriers, technologies and the regulatory framework. Furthermore, alternative decarbonisation pathways are modelled to better understand the long-term perspectives and costs of different decarbonisation technology paths in different climatic and geographical settings in Europe. Finally, recommendations for policy design are developed and discussed with relevant stakeholders from EU and the Member States. The study focuses on heat consumption in buildings and covers space heating and the supply of sanitary hot water.

More specifically, and according to the tender specifications, the objectives of the study are listed and described in the following. More details regarding the exact scope, type of output and methodology are provided for each work package and each task in Chapter 2, 3 and 4.

- **Establish current consumption for space heating in buildings (residential, tertiary, industrial).**

  Task 1 develops a comprehensive profiling of final and primary energy demand for space and water heating for a given year (not earlier than 2017). This includes an end-use energy balance for space and water heating, which is accompanied by additional information like peak demands and daily profiles in hourly resolution. More specifically, the end-use space heating energy balance will be a consistent data set that allows comparability across countries.

- **Overview space heating and renewable space heating technologies and establish costs of heating by fossils (current mainstream fossil heating technologies), by renewable space heating technologies, by e-fuels and H2 and by electricity covering levelized cost of heating (LCOH), lifecycle costs and primary energy efficiency.**

  Task 2 provides an overview of the current and emerging space and water heating technologies in buildings and their technological development trends. This covers all relevant fossil-based and renewable heating technologies including renewable electricity, e-fuels and hydrogen H2. The overview will provide technical characteristics, stock figures, development trends and estimates on the costs of heat supply, which will be reported in a standard format in individual data sheets.

- **Describe the space heat sector in the individual EU Member States, and provide a comparative summary of the EU space heat sector.**

  In Task 3 we develop summaries (country files) for the status-quo of space and water heating in all EU member states plus Norway, Switzerland and Iceland plus the EU28 aggregate. The summary country files will be country specific and include information on the energy consumption for space and water heating, the technology distribution, building structure as well as the regulatory frame in place.

- **Establish model-based scenarios of the space heating and water heating sector up to 2050 allowing an assessment of these scenarios in terms of costs, investment needs, infrastructure requirements, primary energy use, benefits regarding GHG reduction and energy savings.**

- The starting point was the establishment of a baseline (Task 4) for modelling of heat supply as a basis of comparative analysis of space heating and its supply options. This was followed by a series of technology-focused decarbonisation scenarios for the cases of:
  - Direct renewable heating sources (Task 5)

- Renewable electricity (Task 6)
- E-fuels (gaseous and liquids) and H2 (Task 7)
- District heating as an enabling instrument to deliver renewable energy sources and other decarbonised supply options for heating (Task 8)

For these decarbonisation scenarios, the cost-effective balance between thermal insulation and renewable supply was identified and considered in the modelling.

- **Compare the different technology-focused decarbonisation scenarios for renewable heat supply options with the baseline and with each other and develop a best-case (optimal) scenario.**

  Task 9 provided this comparison on a quantitative basis regarding total system costs and other techno-economic parameters. In addition, a qualitative discussion of several aspects will be added that needs to be taken into account to derive sound recommendations. Followed by this comparison, we will develop a best-case scenario combining the lessons learnt and insights of most attractive and feasible ways of decarbonisation of different parts of the building stock in different European geographies.

- **Define feasibility conditions for deploying renewable and decarbonised heating supply in buildings covering changes in heating equipment (technical building systems for heating), changes in building shell; changes in decarbonised fuel/sources supply chains; energy infrastructures (electricity, gas, alternative fuels, district heating) and facilitating regulatory framework relating to the supply chain of heating fuels/energy sources, building regulations; supply chain of equipment, (urban/municipal), spatial planning and other urban/municipality regulation.**

  In Task 10 we analysed the barriers and technological, economic and regulatory framework conditions required in order to facilitate the transition towards the respective target systems studied in the scenarios in WP2. It provides recommendations regarding the actions that must be taken and the enabling conditions required to achieve the long-term goals.

- **Define regulatory conditions for energy communities for renewable heat.**

  In view of the upcoming transposition of the requirements of Article 22 of the RED II into national law in the EU Member States, the aim of Task 11 is to analyse the role of renewable energy communities (RECs) in the area of renewable and decarbonised heating and assess the necessary enabling conditions.

- **Organise a stakeholder consultation workshop.**

  The aim of Task 12.1 stakeholder workshop is to consult relevant stakeholders about the results of WP1 and WP2 to secure high quality of the deliveries. The stakeholders will be provided with the draft documents enabling also to provide written comments.

- **Present the work, the deliverables and results in meetings, including with Member States and in regional renewable energy cooperation fora.**

  The aim of Task 12.2 is to inform the Member States representatives including the regional energy cooperation groupings about the results, both for consulting them using the input for the editing the final deliveries and for discussing implementation at Member State and regional level.

The report consists of following parts:

Chapter 3 describes the results of WP1. As a key element of this chapter, energy consumption balances for space heating and hot water are shown (Task1). For task 2 on technologies, the data structure of a technology catalogue for reporting the data collected and processed has been developed in Excel and data including LCC and LCOH are reported for all technology clusters (combinations of technologies and energy carriers). Country fact-sheets have been elaborated and are provided as additional files. Chapter 4 includes the description of the framework conditions, the scenario specifications and the method to develop the baseline and technology focus decarbonisation scenarios in WP2 on the modelling of scenarios. Model results are presented for the technology focus scenarios (direct-RES, electrification, e-fuels, H2 and district heating) as well as for the baseline and the best-case scenario. Chapter 5 provides an analysis of barriers and related policy packages. A proposed country clustering for Task 10 is provided and the methodological approach. The results of the analysis of renewable energy communities for heat (Task 11) are described in the annex.

3. Space heating in the EU: Consumption and technologies

3.1. Establish energy consumption for space and water heating for EU

3.1.1. Objective

The objective of this part of the study is the development of a comprehensive profiling of energy demand for space and water heating in 31 European countries for 2017. The quantification of the final, useful and primary energy demand in the sectors residential, services and industry are covered by this task. The result is a consistent data set that allows comparability across countries and can be broken down to the following dimensions (see also Figure 2):

- Sectors and sub-sectors
- End-uses
- Technologies
- Primary and final energy carriers

The provided end-use balance in the end of this task has been set up on country level including the EU-27 by Member States and United Kingdom, Norway, Switzerland and Iceland. The developed energy balances are compatible with to the Eurostat final and primary energy balances, i.e. the energy demand as provided by Eurostat by energy carrier, country and sector have been linked in a consistent way to the bottom-up calculated energy demand for space heating and hot water. However, by including end-uses and technologies, it goes substantially beyond what is currently available from Eurostat.

The data set also includes hourly and seasonal profiles of space heating and hot water demand provided at country level. Based on the profiles, peak and low demands can be calculated for individual countries or end-uses.

In quantification of the energy demand in the technology level, Task 1 builds partly on the input from chapter 3.2. The results of this task will be then used as the input for the scenario modelling. This task also aims at assessing the available energy statistics and data sources and identifying the gaps. Recommendations are made to improve the data collection.

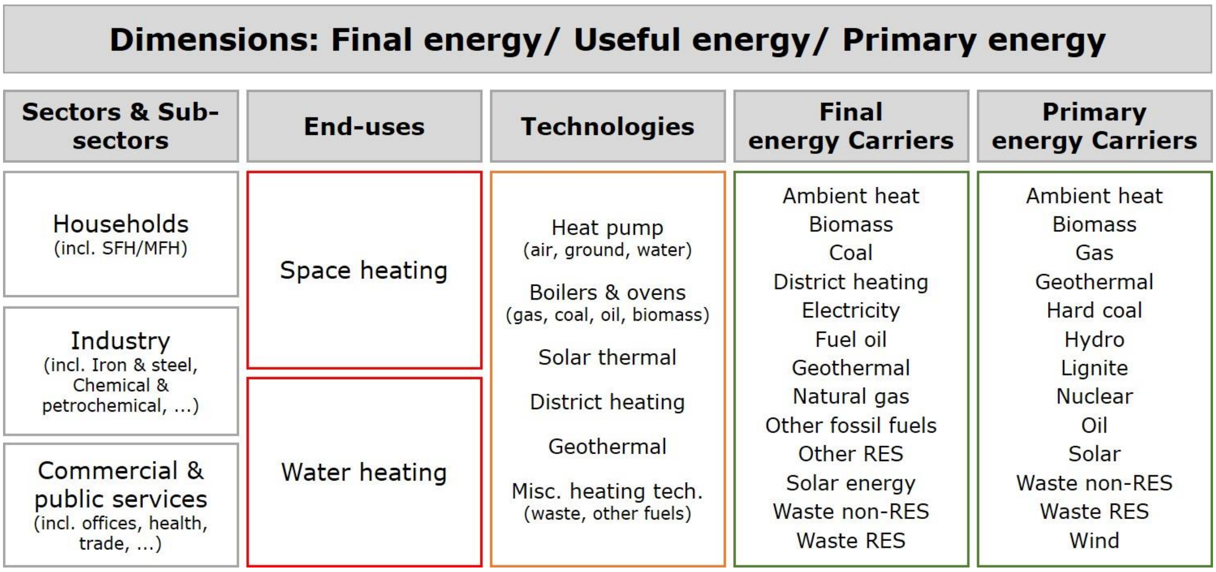

Figure 2: Scope of energy balances developed.

The following section describes the methodology for the calculation of the end-use balances.

3.1.2. Methodology: Calculation of heating energy balances

3.1.2.1. Definitions

This section outlines the main definitions used for the calculation of end-use balances.

Useful, final, primary energy

In terms of the energy conversion chain, as illustrated in Figure 3 the following descriptions on the conversion of energy carriers are applied.

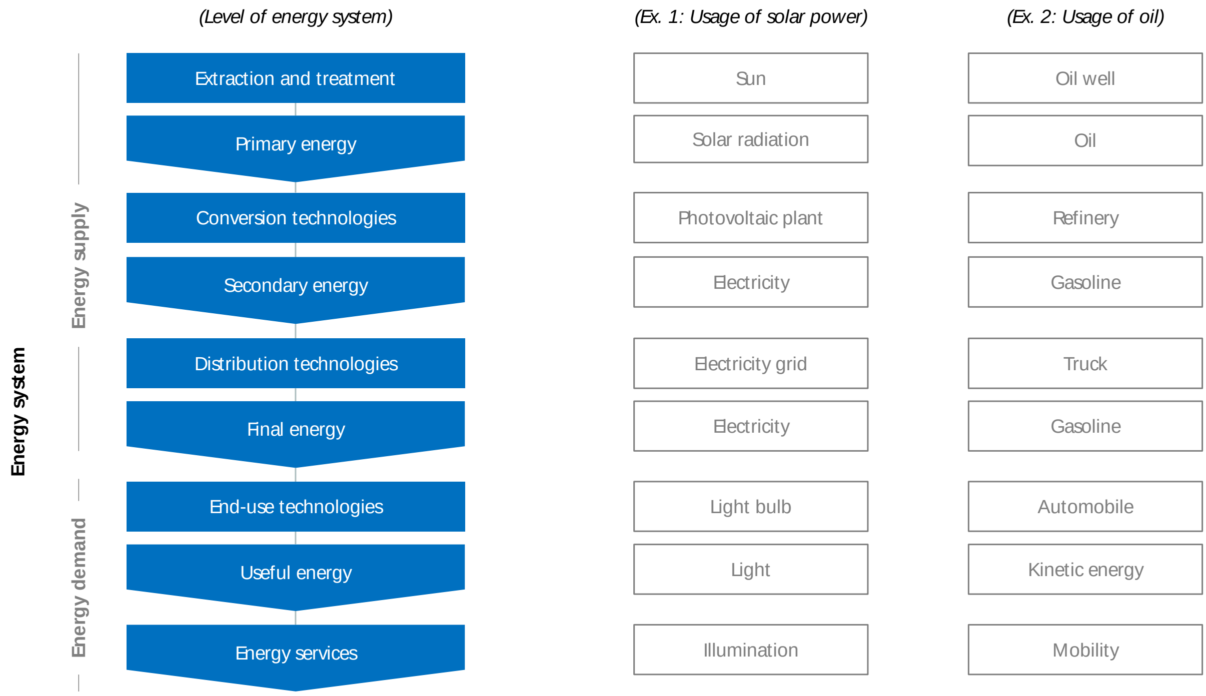

Figure 3: Schematic chart of energy carrier conversion with two illustrative examples. Ex. 1: a PV plant converting solar radiation into electricity; Ex. 2: crude oil being converted into gasoline to power an automobile. Source: (Blok and Nieuwlaar 2016)

The supply sector involves indigenous extraction as well as imports and exports of primary energy carriers, such as coal, natural gas and crude oil – adding up to **primary energy demand**. Further conversion of these energy carriers is needed to make them suitable for specific applications. Such conversion processes include power plants, that convert fossil fuels to electricity, and refineries that convert crude oil to petroleum products. The result of these conversion processes is then referred to as **secondary energy**, of which electricity, heat and gasoline are of major importance for the system. Following transport, storage and distribution, **final energy** is provided to the end user. Here, on the demand side of the energy system, further conversion into **useful energy** may be needed, for example converting fuel to heat in a boiler. In its ultimate form, this energy can provide a certain **service** or function for the user, such as lighting, transportation or room temperature adjustment.

Energy carriers and technologies

A consistent definition of energy carriers is essential for calibrating the developed end use balances to the official EUROSTAT energy balances. EUROSTAT itself uses a range of 63 different energy carriers, ranging from fossil fuels and renewable energy sources to electricity and heat as secondary energy carriers. For the sake of legibility, as shown

Table 1, this study merges the 63 EUROSTAT energy carriers into a) 13 **final energy carriers** (applied at the end use level in the demand sectors), as well as b) 13 **primary energy carriers** (applied to differentiate the generation mix of electricity and district heat). These definitions correspond to established reports on the topic of end use energy balances at the EU level (Fleiter et al. 2016).

Table 1: Overview of final and primary energy carriers used in this study.

Category	Energy carriers included	
Final energy carriers	▪ Ambient heat ▪ Biomass ▪ Coal ▪ District heating ▪ Electricity ▪ Fuel oil ▪ Geothermal	▪ Natural gas ▪ Other fossil fuels ▪ Other RES ▪ Solar energy ▪ Waste non-RES ▪ Waste RES
Primary energy carriers	▪ Ambient heat ▪ Biomass ▪ Gas ▪ Geothermal ▪ Hard coal ▪ Hydro ▪ Lignite	▪ Nuclear ▪ Oil ▪ Solar ▪ Waste non-RES ▪ Waste RES ▪ Wind

Note that each EUROSTAT energy carrier is discretely allocated to one *final energy carrier* and one *primary energy carrier* to ensure that aggregating the latter will again result in the official Eurostat values for final energy demand at a country level. Table 34 in Chapter 7.1 provides the detailed allocation of EUROSTAT energy carriers to the final and primary energy carriers used in this study. In addition, energy carriers are labelled either as renewa*ble* or *nonrenewable*. For electricity and district heating as final energy carriers, the renewable share is calculated based on the primary energy mix (Section 3.1.2.3).

Concerning the definition of energy carriers, particular attention needs to be paid to renewable energy carriers that are collected onsite and that are not commercially traded – particularly ambient heat, geothermal energy, and solar thermal energy. Commission Regulation (EU) 2017/2010 on energy statistics provides distinct definitions in this regard:[1]

- **Ambient heat (heat pumps)** (Code: RA6000) does not only comprise the ambient heat captured by air source heat pumps, but also by ground source and other heat pumps, defined in the Regulation as "heat energy at a useful temperature level extracted (captured) by means of heat pumps that need electricity or other auxiliary energy to function. This heat energy can be stored in the ambient air, beneath the surface of solid earth or in surface water."
- **Geothermal energy** (Code: RA200) – which might be mistaken for the ambient heat captured by ground source heat pumps – is explicitly defined as "energy available as heat emitted from within the earth's crust, usually in the form of hot water or steam; excluding ambient heat captured by ground source heat pumps."
- **Solar thermal** (Code: RA410) only includes solar thermal and excludes solar photovoltaic installations (which are reported in the transformation section of the energy balances). Solar thermal is defined as "heat from solar radiation (sunlight) exploited for useful energy purposes. By the way of example, this includes solar thermal-electric plants and active systems for the production of sanitary hot water or for space heating of buildings." This definition applies to the final energy carriers

[1] Note that these definitions are not fully consistent with the ones laid down in Commission Regulation (EU) 2018/2001 (Renewable Energy Directive, RED II). RED II defines *ambient energy* more generally as "naturally occurring thermal energy and energy accumulated in the environment with constrained boundaries, which can be stored in the ambient air, excluding in exhaust air, or in surface or sewage water"; *geothermal energy* is defined as "energy stored in the form of heat beneath the surface of solid earth" (Art. 2). The delimitation of different heat pump types is thus not as distinct as in the Regulation on energy statistics. Overall, we assume and that countries reporting to Eurostat do so based on the Regulation on energy statistics ((EU) 2017/2010) and the definitions set therein.

introduced above. Note however that the primary energy carrier *solar* does include solar photovoltaics, as these energy carriers reflect the primary energy input for the generation of electricity and district heat as secondary energy carriers.

A major added value of the calculated end-use balances compared to the default Eurostat energy balances is the consideration of particular technologies per end-use (e.g. air source electric heat pump for space heating). Table 2 lists the heating technologies considered in the end-use balances developed. Heat pumps are accounted for both in terms of their electricity use, as well as the ambient heat captured.

Table 2: Definition of technologies considered in the end-use balances.

Final energy carrier	Heating technologies
Ambient heat	- Heat pump (air-to-air) - Heat pump (air-to-water) - Heat pump (ground-to-water) - Heat pump (average)[a]
Biomass	- Biomass oven/boiler
Coal	- Coal oven/boiler
District heating	- District heating substation
Electricity	- Heat pump (air-to-air) - Heat pump (air-to-water) - Heat pump (ground-to-water) - Heat pump (average)[a] - Direct electric heating
Fuel oil	- Oil boiler
Geothermal	- Geothermal installation
Natural gas	- Gas boiler (average)[a] - Gas boiler (condensing) - Gas boiler (non-condensing) - Heat pump (average)[a]
Other fossil fuels	- Generic fossil boiler/oven
Other RES	- Generic RES boiler/oven
Solar energy	- Solar thermal collector
Waste non-RES	- Generic waste boiler/oven
Waste RES	- Generic waste boiler/oven

[a] *Industry sector only*

Note that this overall selection of technologies is primarily driven by the availability of technology data, most notably stocks per country and sector, as well as typical/average conversion efficiencies. In particular, technology data is missing for gas-driven heat pumps, gas micro-CHP and fuel cells, which thus could not be included in the technology split, except for the industry sector (see Task 2 in Section 2.2).

Sectors

In terms of sectors, we build upon the Eurostat division into households, industry and commercial & public services. Each of these sectors is subdivided into different sub-sectors (Table 3).

Table 3: Division of sectors and sub-sectors applied in the end-use balances.

Sector	Sub-sectors	Eurostat allocation
Households	- Single-family homes - Multi-family homes	
Industry	- Chemical industry	▪ Chemical & petrochemical
	- Engineering and other metal	▪ Transport equipment ▪ Machinery
	- Food, drink and tobacco	▪ Food, beverages & tobacco
	- Iron and steel	▪ Iron & steel
	- Non-ferrous metals	▪ Non-ferrous metals
	- Non-metallic mineral products	▪ Non-metallic minerals
	- Other non-classified	▪ Mining & quarrying ▪ Wood & wood products ▪ Construction ▪ Textile & leather ▪ Not elsewhere specified (industry)
	- Paper and printing	▪ Paper, pulp & printing
Commercial & public services	- Education - Health - Hotels and restaurants - Offices - Trade - Other non-residential buildings	

The households sector is subdivided into single-family homes (1-2 dwellings per building) and multi-family homes (3+ dwellings per building). By default, this subdivision is not included in Eurostat energy balances, but can be calculated via the respective useful energy demand for these different building types (see Section 3.1.2.4). Following Eurostat conventions, the industry sector is subdivided into different economic sub-sectors. Here, a minor aggregation of 13 Eurostat sub-sectors into 8 aggregated sub-sectors is made. Similar to the households sector, the commercial & public services sector is sub-divided based on calculations, yielding a total of 6 sub-sectors.

3.1.2.2. Main data sources

In calculation of the energy balances in this study several national and EU sources and statistics have been used. They differ in terms of the countries that they cover and the details of the available data. In order to provide a consistent set of results, a structured set of required data has been defined for the calculations across the three sectors including the following:

- Energy balances
- Framework data
- Climate data
- Technology data

Energy balances: Eurostat energy balances are the main source in this category. The available figures on primary and final energy carriers in the energy balances are used as the reference for calibrations of the calculated energy demand in different sectors. Energy balances for all countries in this study are available in Eurostat database (Eurostat 2020b). Except for Switzerland for which a simplified energy balance is available (FSO 2020).

Framework data: Depending on the sector, this category includes data on number of the dwellings/ units, type of the buildings, floor area, etc. The main consulted sources are Building stock observatory (BSO) (European Commission 2020b), ODYSSEE (Odyssee 2020) and Hotmaps (Pezzutto et al. 2018).

Climate data: To consider climate data in the calculations, indicators such as heating degree days (HDD) and outside temperature are needed. They are available mainly in ODYSSEE database (Odyssee 2020), TABULA database (Loga et al. 2013), Eurostat (Eurostat 2020a).

Technology data: To break the calculated energy balances down to the technology level, data on the type and number of technologies in each country is required. The input data for this category relies mainly on the Task 2 results of this study.

The databases mentioned above are the main consulted sources for data collection. When necessary other national sources and studies have been used to fill in the data gaps and other data categories have been added. This will be explained in detail and for each sector in Section 3.1.2.4.

3.1.2.3. Cross-sectoral approaches

This section describes methodological approaches that are applied across sectors and subsectors. These approaches concern primary energy factors, the supply mix of power and district heating, as well as hourly heat demand profiles.

Primary energy factors

Primary energy factors (PEF) indicate the amount of primary energy needed to deliver a unit of energy for final consumption. The higher a primary energy factor, the higher are the losses occurring throughout the conversion chain of a given energy carrier. Calculating the primary energy demand for space heating and water heating thus requires the definition of PEF for the 13 final energy carriers defined (Section 3.1.2.1). In order to ensure compliance with Eurostat energy balances, the PEF are derived directly from these energy balances for each country and final energy carrier. The approach for calculating the PEF differs for (i) electricity and district heating, and (ii) all other RES-H energy carriers.

With regard to (i) electricity and district heating, the methodological challenge is to properly account for the combined generation of these energy carriers in CHP plants. While Eurostat energy balances provide the transformation output for electricity and derived heat (Eurostat codes *GEP and GHP*), the transformation input (electricity and heat generation) is only given in an aggregated manner for each energy carrier (Code *TI_E*). Put differently, the transformation input for CHP plants needs to be properly allocated to the generation of electricity and derived heat (district heat) to calculate the respective PEFs. A common method for this is the allocation based on the energy content of the two products (also referred to as the IEA method). However, the problem with this approach is that the energy content does not properly reflect the quality and usefulness of the energy carriers. Instead, the exergy content method is selected (Blok and Nieuwlaar 2016) which is also prescribed in the Renewable Energy Directive (EU 2018/2001) (Annex VI). In this approach, the transformation input to electricity and derived heat is allocated on the basis of their exergy value. The exergy/energy ratio can be called the quality factor β. For electricity, this ratio is 1. For heat flows, the value ranges between 0.1 for hot water and 0.4 for steam. According to the Directive, a β value of 0.3546 is prescribed for excess heat that is used for heating of buildings, i.e. district heating. The PEF energy factors for electricity PEF_E and heat PEF_H for a country i are then calculated according to **Equation (1)**:

Primary energy factor for electricity (1)

$$PEF_{E,i} = \left(\frac{TO_{E,i}}{TO_{E,i} + \beta * TO_{H,i}}\right) * TI_i * \frac{1}{TO_{E,i}}$$

Primary energy factor for district heating

$$PEF_{H,i} = \left(\frac{\beta * TO_{H,i}}{TO_{E,i} + \beta * TO_{H,i}}\right) * TI_i * \frac{1}{TO_{H,i}}$$

Key:

Variables		**Unit**	**Indices**	
PEF	= Primary energy factor	[-]	E	= Electricity
TO	= Transformation output	[TWh]	H	= Heat
β	= Exergy/energy ratio heat	[-]	i	= Country
TI	= Transformation input	[TWh]		

PEFs are also defined for the remaining final energy carriers (e.g. natural gas). Again, the PEFs are derived from Eurostat energy balances for each country. However, this requires a different approach in order to only account for the direct use of the energy carriers, i.e. excluding the use in power plants as well as non-energy uses. This approach requires country-specific data on total energy supply, transformation input, transformation output, final consumption for non-energy use, and statistical differences. For each country i and energy carrier j the PEF is calculated as follows (**Equation 2**):

Primary energy factor for remaining energy carriers (2)

$$PEF_{j,i} = \frac{TES_{j.i} - TI_{j,i} + TO_{j,i} - FCN_{j,i} - S_{j.i}}{FCE_{j,i}}$$

Key:

Variables		**Unit**	**Indi-ces**	
PEF	= Primary energy factor	[-]	j	= Energy carrier
TES	= Total energy supply	[TWh]	i	= Country
TI	= Transformation input	[TWh]		
TO	= Transformation output	[TWh]		
FCN	= Final consumption non-energy use	[TWh]		
S	= Statistical differences	[TWh]		
FCE	= Final consumption energy use	[TWh]		

Overall applying Equations 1 and 2 yields a set of 13 PEFs per country, i.e. one discrete value per final energy carrier. The calculated PEFs are given in Section 3.1.3.1.

Electricity and district heating supply mix

The primary energy factors (PEF) introduced above indicate how much primary energy is needed to deliver a unit of energy for final consumption. Hence, PEFs are discrete numbers that do not account for the mix of primary energy carriers needed to provide a given final energy carrier. This is particularly relevant for the generation of electricity and district heat, with the average mix of both commodities being composed of multiple primary energy inputs (e.g. natural gas, biomass, wind power, etc.). Determining the primary energy mix for these two commodities is essential for determining an array of auxiliary indicators associated with space and water heating, most notably the RES share of electricity and district heating.

However, determining the primary energy mix for power and district heating supply is complicated by the fact that Eurostat energy balances by default only provide the *gross generation* by fuel for power (Eurostat code *GEP*) and heat (Eurostat code *GHP*). For examining the primary energy mix of the two commodities, gross generation is an inappropriate indicator as it gives the generation measured at the output of the main generators, i.e. after conversion losses. It thus does not appropriately reflect the relatively low conversion efficiencies of thermal power plants and cogeneration plants compared to renewable generators and the aggregate impact on emissions and other indicators.

In order to make the primary energy mix for the generation of electricity and district heat visible, again the exergy method – used for the calculation of PEFs (see above) – is used in a slightly modified way. Again, the challenge is to account for multi-output processes in CHP plants, i.e. allocating primary energy inputs (e.g. natural gas) to the outputs *electricity* and *heat*. **Equation (3)** shows the calculation of primary energy inputs for electricity and district heat per country and fuel.

Primary energy input for electricity (3)

$$P_{i,j,E} = \left(\frac{GEP_{i,j}}{GEP_{i,j} + \beta * GHP_{i,j}} \right) * TI_{i,j}$$

Primary energy input for district heat

$$P_{i,j,H} = \left(\frac{\beta * GHP_{i,j}}{GEP_{i,j} + \beta * GHP_{i,j}} \right) * TI_{i,j}$$

Key:

Variables		**Unit**	**Indices**	
P	= Primary energy input	[TWh]	i	= Country
GEP	= Gross electricity production	[TWh]	j	= Primary energy carrier
GHP	= Gross heat production	[TWh]	E	= Electricity
β	= Exergy/energy ratio heat	[-]	H	= Heat
TI	= Transformation input	[TWh]		

Based on these formulas, Figure 4 provides exemplary output charts for the primary energy factors and primary energy mix of electricity for Austria in the year 2017.

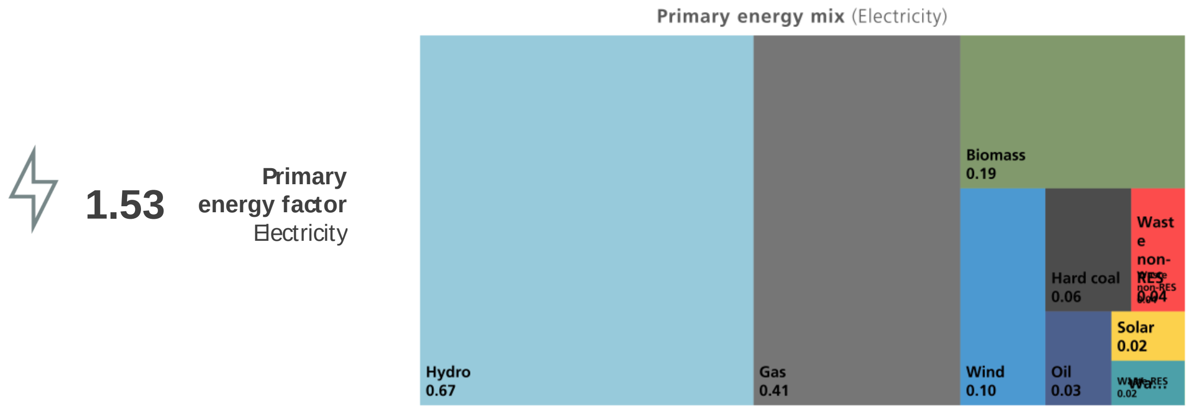

Figure 4: Calculation of primary energy factors and primary energy mix for electricity and district heating. Exemplary data for Austria in 2017.

While the primary energy factor indicates how much primary energy is needed per unit of final energy, the treemap charts in the middle illustrate how much of each primary energy carrier is needed to supply this one unit of final energy. For example, for the given case of Austria in 2017, consuming 1 kWh of electricity in the demand sectors (final energy demand) requires 0.67 kWh of hydro energy, 0.41 kWh of gas, 0.19 kWh of biomass, etc. – adding up to a total of 1.53.

Note that these are single average values for the entire year 2017, which do not reflect short-term variations in power demand and the corresponding power supply mix. A more detailed representation of these variations require advanced model-based data to determine the marginal generation units a country a region utilises to cover different load levels (e.g. natural gas power plants for peak demand) (Esser and Sensfuss 2016). The values presented here principally aim to provide a transparent and comprehensible account of primary energy use associated with final energy demand for electricity and district heating.

Renewable energy share in heating

Based on the primary energy factors and the primary energy mix associated with this final energy mix, the renewable share of space and water heating in the countries and across the three sectors can be calculated. In general, various metrics exist concerning the RES share of heating and associated energy uses. Eurostat's SHARES database uses three metrics relevant in this context ():

(i) **Electricity (RES-E)**: Gross final consumption of electricity from renewable sources divided by gross final consumption of electricity. Hydropower, wind power and other technologies are subject to normalisation rules. Value in 2017 is 31.09% for the EU-27.

(ii) **Heating & cooling (RES-H&C)**: Gross final consumption of energy from renewable sources for heating and cooling divided by gross final consumption of energy for heating and cooling. Includes all demand sectors other than transport. Numerator excludes electricity, heat and bioliquids. Denominator excludes electricity. Value in 2017 is 20.95% for the EU-27.

(iii) **Overall RES share (RES)**: Gross final consumption of energy from renewable sources divided by gross final consumption of energy. Comprises electricity, heating and cooling and transport. Subject to statistical transfers and adjustments for aviation. Value in 2017 is 18.47% for EU-27.

Equation (4) provides the RES share metric adopted in this report:

Renewable energy share of space and water heating (4)

$$RES_H = \frac{\sum_{i,j}(E_{H,i,j} * PEF_{i,j} * RES_{i,j})}{\sum_{i,j}(E_{H,i,j} * PEF_{i,j})}$$

Key:

Variables		**Unit**	**Indices**	
RES	= Renewable energy share	[%]	i	= Country
E	= Final energy demand	[TWh]	j	= Final energy carrier
PEF	= Primary energy factor	[-]	E	= Space and water heating
			H	= Space and water heating

It differs from the metrics above in several ways. First, in terms of end-uses, it covers only space and water heating in the sectors households, commercial & public services, and industry. Second, in terms of energy carriers, it comprises not only fuels and renewable energy carriers, but also electricity and district heating in a unified metric. Third, it measures the RES share in primary energy, not in final energy terms, thus taking into account all conversion losses from primary energy to secondary and eventually final energy. Altogether, the RES share will be provided at the level of countries, sectors, and sub-sectors.

The following section describes the calculation of hourly load profiles for space and water heating.

Hourly load profiles

The method to calculate hourly profiles for space heating and hot water is following the approach laid out in the Hotmaps project, which aimed to calculate an EU-wide open data set for heating and cooling profiles (see Pezzutto et al. 2018). The method distinguishes space heating and hot water in residential and commercial and public services sectors. Regarding the industry sector the energy need is not separated for the space heating and hot water and the profiles are generated for the subsectors with the highest heating energy demand. Calculating the need for space heating is mainly considering the outside temperature while the energy need for hot water is mainly behaviour dependent. Exemplary, the approach is explained for residential space heating as illustrated in Figure 5.

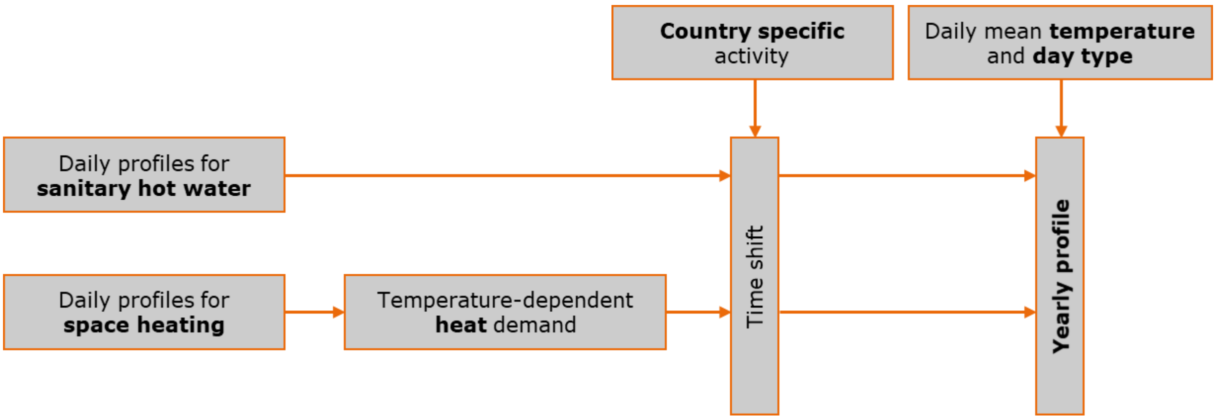

Figure 5: Approach for the calculation of hourly profiles for residential space heating and hot water demand by country (Pezzutto et al. 2018).

The generic profiles provide the energy demand for the hours of each day during the year. In order to generate the hourly demand profiles first the structure of the year 2017, meaning the order of the days, is determined. In the next step, combining the hour of the day, temperature and demand from the generic profile, a unitless load value will be attributed to each hour of the year. Finally these values will be scaled according to the actual annual total demand. Depending on each sector and profile (space heating or hot water) other factors will be considered. For calculation of hot water demand the seasonal influence and the day type are also considered. The days of the year are categorized as weekdays, Saturday (or day before a holiday) and Sunday (or a holiday). As for the season, summer, winter and the transition are recognized. Therefore in this case after structuring the year day type and season for each day of the year will be determined and these will be then also considered when attributing the load values of each hour.[2] Figure 6 illustrates an exemplary daily and seasonal profile for Austria in 2017.

[2] For a comprehensive explanation of the generic profiles see https://gitlab.com/hotmaps/load_profile

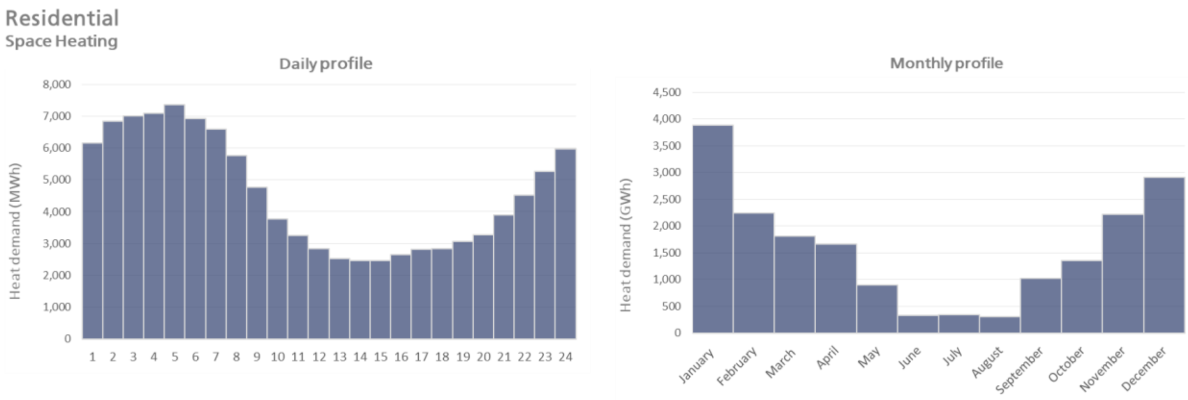

Figure 6: Hourly and monthly loads for space heating in residential sector. Exemplary data for a winter day in Austria (figure on the left) and for total year 2017 (figure on the right).

3.1.2.4. Sectoral approaches

The general approach to derive complete and consistent end-use energy balances for space heating and hot water consists of five steps:

1. **Bottom-up calculation of the useful heat demand in buildings** with same method for all countries based on a consistent quantity structure, taking input data like building stock, population and specific energy indicators into account.
2. The **bottom-up calculation of final energy consumption** by energy carrier is based on the calculated heat demand and adds information on the distribution and use of technologies as well as their conversion efficiencies.
3. The **calibration to Eurostat** energy balances for final energy on the level of countries, energy carriers and sectors ensures that the resulting energy balance is compatible with Eurostat. In case of large deviations, step 1 and 2 are repeated. In case of small deviations, the results are scaled to Eurostat, also taking into account the potential demand of other end-uses like cooking.
4. **Calculation of primary energy demand** based on the final energy demand multiplied by primary energy factors on energy carrier and country level. The resulting primary energy consumption e.g. allows to make the share of wind and solar electricity visible in the energy carrier mix for space heating and hot water generation.

In the following, a more detailed description of these steps is provided for each of the demand sectors considered (households, industry, commercial & public services).

(i) Households

In line with the objectives defined in Section 3.1.1, the end-use balances for households sector are calculated at the following levels: sub-sectors; end-uses (space heating, water heating); technologies; final energy carriers; primary energy carriers. In terms of sub-sectors, a distinction between single-family homes (SFH, buildings with 1-2 dwellings) and multi-family homes (MFH, buildings with 3+ dwellings) is made. Calculating the end-use balances for households is based on a combination of two approaches (Fleiter et al. 2016):

- **Energy service (ESV) approach:** The useful energy demand for space and water heating is calculated at the level of energy services, i.e. in the case of space heating the required indoor temperature subject to boundary conditions (thermal losses and gains); in the case of water heating the amount and temperature of warm water. For both end-uses, useful energy is expressed as a specific value of kWh per square meter and year [kWh/(m²*a)]. These specific values are multiplied with the total surface area of a given sub-sector to yield total useful energy demand, and divided by a technology's conversion efficiency to yield final energy demand.

- **Final energy demand (FED) approach:** Useful energy demand is derived from final energy demand for a given energy carrier by multiplying with the conversion efficiency of the devices generating the useful energy (e.g. gas boiler). The calculated total useful energy demand can then be split by sector and end-use.

In general, the advantage of the FED approach lies in its convergence with the target values provided by Eurostat's energy balances. For example, knowing that the final energy demand for natural gas in country X is 10 TWh, this value can be easily converted into useful energy demand by multiplying with the average conversion efficiency of all gas boilers and other natural gas-based heating devices installed. In turn, the FED requires complete reference data for each country and energy carrier, which is not always given (see further below). The ESV approach is very effective for filling such data gaps, based on dedicated calculations on useful energy demand and technology stocks. In addition, it is essential for providing a split by end-use and sub-sector, which the FED cannot provide by default. Overall, ESV and FED are complementary, rather than alternative approaches for calculating end-use balances. Figure 7 provides a flowchart of the procedure for the calculation of end-use balances for the households sector.

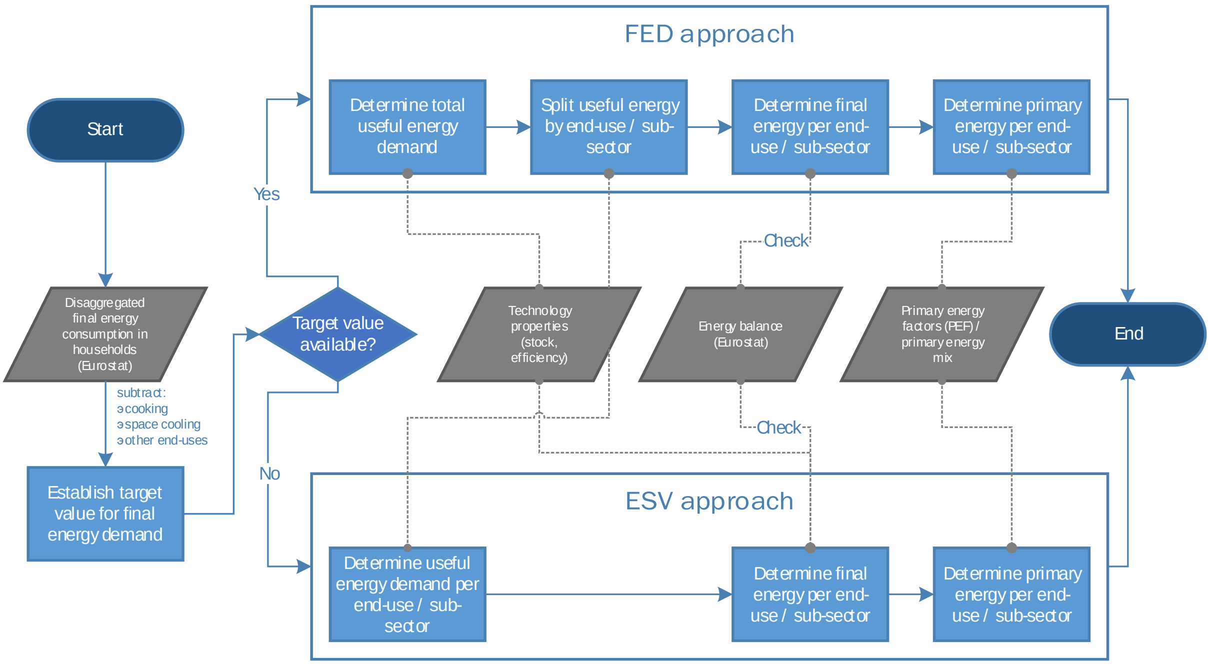

Figure 7: Procedure for calculation of end-use balances for the households sector.

At the beginning, for each country and final energy carrier (see definitions in Section 3.1.2.1), a calibration **target value** is calculated. This target value is based on the Eurostat energy balances as well as Eurostat's disaggregated final energy consumption in households.[3] The latter reports final energy demand by end-use (space heating, water heating, space cooling, lighting and appliances, cooking, other end-uses) and energy carrier. As the energy balances calculated in this Work Package only account for space heating and water heating, we subtract certain end-uses from the Eurostat energy balance values to yield a

[3] Based on Commission Regulation (EU) 431/2014, Member States are required to collect and to provide data on energy consumption in households by type of end-use. Voluntary reporting began in 2010 and became mandatory with the year 2015. For the year 2017, the dataset provides a nearly complete end-use balances for households, with the exception of Cyprus and the non-EU countries Iceland and Switzerland.

target value per energy carrier and country. This is only done for the end-uses *cooking*, *space cooling*, and *other end-uses,* given their marginal shares in overall final energy demand. The disaggregated values for *lighting & appliances* – which exclusively concern the energy carrier *electricity* – are not subtracted to account for the relatively high uncertainty associated with these values. Instead, the electricity need for space and water heating is calculated in a bottom-up fashion (ESV approach).

Next, a check is carried to evaluate whether **target values are available** per country and energy carrier. This essentially concerns ambient heat for heat pumps as a renewable energy carrier that is not commercially traded. While Regulation (EU) 2017/2010 requires Member States and other European countries to collect such data starting at reference year 2017, seven countries do not report ambient heat for the households sector.[4] Besides data gaps for ambient heat, a target value also cannot easily be established for direct electric heating. Electricity is the energy that is used most widely used across end-uses. Besides space and water heating, it is used for cooking, space cooling, and – most notably – the end-use of lighting & appliances. As noted above, cooking and space cooling are subtracted from the demand listed in the Eurostat energy balance to yield a target value. Lighting & appliances are not subtracted because of the uncertainty associated with this end-use. The final energy demand for direct electric heating is thus calculated based on the ESV approach – i.e. based on useful energy demand and technology properties (stocks, conversion efficiency). Overall, if an appropriate target value (greater than 0 TWh) can be established, then the calculation primarily follows the FED approach. Otherwise, the ESV approach is applied.

Table 4 lists for each final energy carrier which of the two approaches is applied to estimate useful energy demand for space and water heating.

[4] In fact, zeros are reported, suggesting that no heat pumps and solar thermal installations are used in these countries. This however contradicts with the technology data collected in Task 2, which do indicate respective technology stocks for the given countries.

Table 4: Approach used for calculation of useful energy demand for different final energy carriers in the households sector.

Final energy carrier	FED approach	ESV approach
Ambient heat	✓	(✓) (data gaps)
Biomass	✓	-
Coal	✓	-
District heating	✓	-
Electricity	-	✓
Fuel oil	✓	-
Geothermal	✓	-
Natural gas	✓	-
Other fossil fuels	✓	-
Other RES	✓	-
Solar energy	✓	-
Waste non-RES	✓	-
Waste RES	✓	-

In practice, the **ESV approach** is based on the calculation of useful energy demand for the end-uses space heating and water heating as well as per country and sub-sector (i.e. building type: single-family or multi-family houses). For space heating, we refer to the TABULA Reference Calculation procedure, which calculates the energy need per m² of a given building by applying the seasonal method according to EN ISO 13790 (Loga et al. 2013). Following the method, external boundary conditions (air temperature, solar radiation) are defined for each country. Standard values are used for the utilization conditions (room temperature, air exchange rate, internal heat sources) and for solar radiation reduction factors through windows (shading). With regards to thermal transfer coefficients (U-values) we build upon data from the Hotmaps project that provides these values at the level of countries, age classes (construction period), and building types (single-family, multi-family) of residential buildings. The steps for calculating useful energy demand for space heating are outlined in the following.

The **overall useful energy demand for space heating** Q_H for a country i, a building type j, and a building age class k is calculated according to Equation (5).

$$Q_{H,i,j,k} = Q_{HT,i,j,k} - \eta_{GN,i,j,k} * Q_{GN,i,j,k} \tag{5}$$

Variables		Unit	Indices	
Q_H	= useful energy demand for space heating	[kWh/a]	i	= country
Q_{HT}	= total heat transfer	[kWh/a]	j	= building type
η_{GN}	= gain utilization factor	[kWh/a]	k	= building age class
Q_{GN}	= total heat gains	[kWh/a]		

The **total heat transfer** Q_{HT} is given by Equation (6):

$$Q_{HT,i,j,k} = 0.024\frac{kh}{d} * HDD_i * F_{i,j,k} * \left(H_{TR,i,j,k} + H_{Vi,j,k}\right) \tag{6}$$

Variables		Unit	Indices	
Q_{HT}	= total heat transfer	[kWh/a]	i	= country
HDD	= heating degree days	[Kd/a]	j	= building type
F	= correction factor for non-uniform heating, taking into account systematic deviations of the set-point temperature and the actual temperature	[-]	k	= building age class
H_{TR}	= overall heat transfer coefficient by transmission, determined in accordance with Equation (7)	[W/K]		
H_V	= total heat transfer by ventilation, determined in accordance with equation (8)	[W/K]		

The **overall heat transfer coefficient by transmission** H_{TR} is calculated according to Equation (7):

$$H_{TR,i,j,k} = \left(\sum_{i,j,k,l} A_{i,j,k,l} * U_{i,j,k,l} * F_{i,j,k,l}\right) + \left(\sum_{i,j,k,l} A_{i,j,k,l}\right) * 0.05\frac{W}{m^2K} \tag{7}$$

Variables		Unit	Indices	
H_{TR}	= overall heat transfer coefficient by transmission	[W/K]	i	= country
A	= area of envelope element	[m²]	j	= building type
U	= thermal conductivity (U-value) of envelope element	[W/m²K)]	k	= building age class
F	= reduction factor of envelope element	[-]	l	= envelope element

The **overall heat transfer coefficient by ventilation** H_V is calculated as given by Equation (8):

$$H_{V,i,j,k} = c_{air} * n_{air} * A_{ref,i,j,k} * h \quad (8)$$

Variables		Unit	Indices
H_{TR}	= overall heat transfer coefficient by transmission	[W/K]	i = country
c_{air}	= Specific heat capacity of air, standard value 0.34 Wh/(m³K)	[Wh/(m³K)]	j = building type
n_{air}	= average air change rate	[1/h]	k = building age class
A_{ref}	= reference area of building	[m²]	
h	= reference room height, standard value 2.50 m	[m]	

The **total heat gains** Q_{GN} are calculated as follows (Equation (9)):

$$Q_{GN,i,j,k} = Q_{INT,i,j,k} + Q_{SOL,i,j,k} \quad (9)$$

Variables		Unit	Indices
Q_{GN}	= total heat gains	[kWh/a]	i = country
Q_{INT}	= internal heat gains	[kWh/a]	j = building type
Q_{SOL}	= solar gains	[kWh/a]	k = building age class

The **internal heat gains** Q_{INT} are calculated as given by Equation (10):

$$Q_{INT,i,j,k} = 0.024\frac{kh}{d} * \varphi_j * d_i * A_{ref,i,j,k} \quad (10)$$

Variables		Unit	Indices
Q_{INT}	= internal heat gains	[kWh/a]	i = country
φ	= thermal output of internal heat sources	[W/m²]	j = building type
d	= length of the heating season	[d/a]	k = building age class
A_{ref}	= reference area of building	[m²]	

The **solar heat load** Q_{SOL} is calculated as given by Equation (11):

$$Q_{SOL i,j,k} = \sum_{i,j,k,m} \left(F_{SH} * F_F * F_W * g * A_{W,i,j,k,m} * I_{SOL,i,m}\right) \quad (11)$$

Variables		Unit	Indices	
Q_{INT}	= internal heat gains	[kWh/a]	i	= country
F_{SH}	= reduction factor external shading, standard value 0.6	[-]	j	= building type
F_F	= reduction factor for frame, standard value 0.7	[-]	k	= building age class
F_W	= reduction factor for radiation non-perpendicular to the glazing, standard value 0.9	[-]	m	= window orientation
g	= total solar energy transmittance for radiation perpendicular to the glazing	[-]		
A_W	= area of window	[m^2]		
I_{SOL}	= average global irradiation	[kWh/(m^{2}a)]		

Overall, this calculation procedure yields the useful energy demand for space heating [kWh/(m²a)] per country, building type (single-family/multi-family homes), and building age class. **Useful energy demand for water heating** is calculated on a per-m² basis. The TABULA Reference Calculation procedure suggests uniform values of 10.0 kWh/(m²*a) for single-family buildings and 15.0 kWh/(m²*a) for multi-family buildings across all EU countries. In the next step of the ESV approach, the specific useful energy demand for space heating and water heating is multiplied with share (stock) and conversion efficiency of the respective heating and hot water technologies. Primary energy demand is calculated based on the calculated primary energy factors (PEF) introduced in Section 3.1.2.3.

In contrast to the ESV approach, the **FED approach** starts with the target value for a given energy carrier and country. It then converts the final energy demand into useful energy demand by multiplying with the weighted average conversion efficiency of the heating technology stock. This useful energy demand is split into end-uses (space heating, water heating) as well as sub-sectors (single-family homes, multi-family homes) according to the shares in useful energy demand from the ESV approach. Next, final energy demand is reassembled at the level of countries, sub-sectors, energy carriers and technologies. Finally, final energy demand is multiplied with primary energy factors to yield primary energy demand.

Overall, the combination of the ESV and FED approaches provides complete household end-use balances for space and water heating for each EU Member State (plus Iceland, Norway and Switzerland). Note that these approaches feature certain shortcomings. The FED approach relies on Eurostat's energy balances, which primarily focus on commercially traded energy carriers. Energy carriers that are collected onsite – especially ambient heat, but also solar thermal and geothermal energy – are not yet completely captured by all Member States. While Regulation (EU) 2017/2010 requires Member States and other European countries to collect such data starting at reference year 2017, some data gaps remain. The ESV approach is based on a norm- and standard-based calculation of useful energy demand. These calculated values can only provide an approximation of actually measured consumption in real buildings. Due to the lack of data and information about real utilization conditions (e.g. indoor temperatures, air exchange rates) and the exact thermal properties of existing buildings (construction elements, supply systems) these values cannot exactly correspond to realistic levels, even for the average of building types. In consequence, there are deviations of the calculated energy use from the typical level of measured consumption.

(ii) Industry

In the industry sector, the end-use energy balances are calculated applying the **FORE-CAST-Industry** model. The model was developed by Fraunhofer ISI as a tool that can be used 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.

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 iron and steel. The scope of the model is defined by the energy balances and focuses on final energy. It includes useful energy as a derived value based on the deployed technologies and their efficiencies. The structure of FORECAST also 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. Accordingly, the model is divided into sub-models.

The following figure shows the structure of FORECAST. Six sub-models are distinguished: macro, energy-intensive processes, space heating and cooling, electric motors and lighting, furnaces, and steam and hot water. Add-ons are also defined that can be applied after the calculation of the core model. Different approaches to simulate technology change are used in the various sub-models. These range from exogenous assumptions, diffusion curves to vintage stock models and discrete choice simulation.

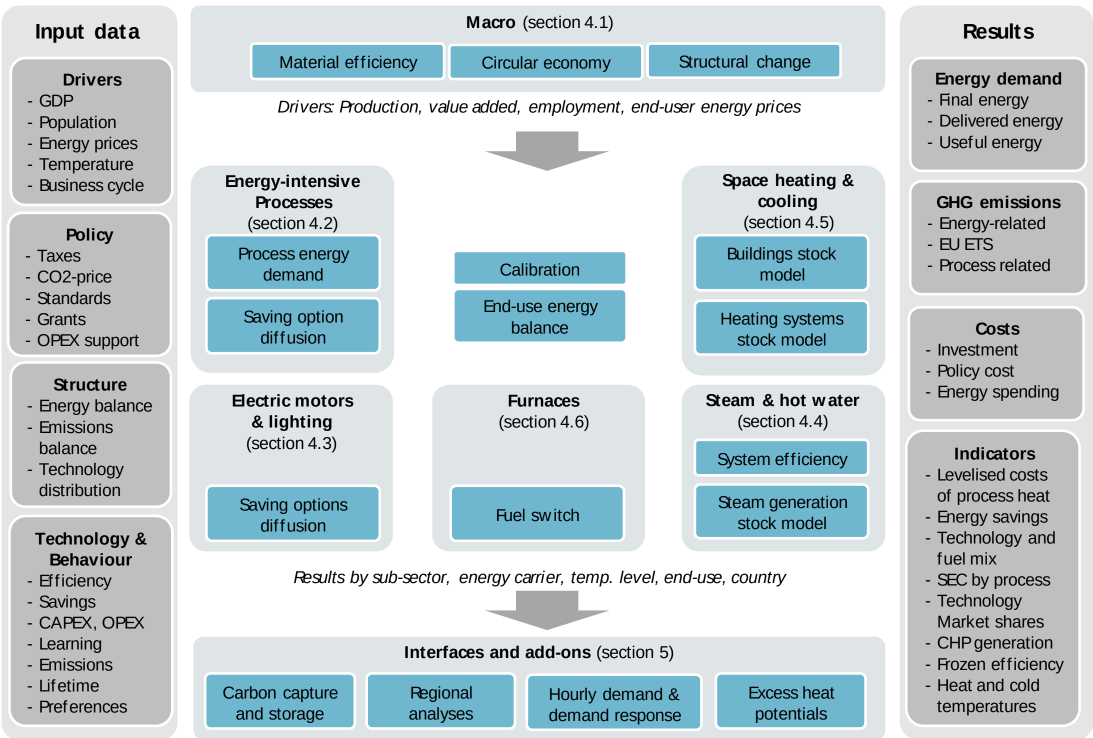

Figure 8: Overview of the FORECAST model: Input data, methods and sub-models (Fleiter et al. 2018).

FORECAST Industry uses techno-economic data to add information to energy statistics, in this case the Eurostat energy balance. It uses data on individual production processes (e.g. specific energy demand, temperature levels of heat demand, energy carrier mix …) to generate a bottom-up structure of industrial energy demand. This structure allows to allocate the use of technologies like boilers, heat pumps, combined heat and power generation and others. In addition to a bottom-up calculation of the space heat demand based on employees, floor area and detailed generation technologies, the integrated relation to other heat uses (process heat as steam and furnaces) and non-heat applications allows FORECAST Industry to generate a consistent picture of the current energy use.

In addition to conformity with the base statistics, FORECAST is thus able to generate plausible estimates of otherwise not existing or not available data points. In this project, FORECAST Industry was used to create a detailed breakdown of space heat use in the EU27 (plus UK, Norway, Switzerland and Iceland) in 2017. The results include the dimensions country, industrial subsector, energy carrier and a differentiation of space heat and hot water use, both for final end useful energy.

Input data comprise the main drivers, policy parameters, structural information and a huge set of technology parameters including behavioural assumptions. Most of these input parameters are long-term drivers of energy demand and GHG emissions, but business cycles and temperature (heating degree days) are included as well since these can affect energy demand in a one-year timeframe.

The model requires a broad set of input data, which combines a variety of data sources. Energy balances, employment, value added, and energy prices are calibrated to the most recent EUROSTAT statistics whenever possible. The calculation of heating energy needs in the industry sector is mainly based on the number of employees, the occupied floor area per employee (m^2) and the specific energy consumption per m^2.

Industrial production on country and process level (e.g. electric steel production in Italy) is a major input. It is collected and annually updated via a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.).

Technology data (costs, efficiencies, age distribution etc.) are mostly not available from public data sources but need to be collected from literature or estimated via discussion with industry representatives.

For a more detailed description of the approach to calculate end-use balances for industry, we refer to Rehfeldt et al. (2018) and for a more comprehensive description of the FORECAST model we refer to Fleiter et al. (2018).

(iii) Commercial & public services

For the calculation of end-use energy balances in the commercial & public services sector, the model **FORECAST-Tertiary** is applied. These calculations are largely based on earlier work summarized in (Fleiter et al. 2016).

FORECAST Tertiary uses the final energy balances provided by Eurostat as the main dataset for modelling which is complemented by other data sources in case of data gaps. The model calculates the final and useful energy consumption on the level of the sub sectors, end-uses and the energy carriers. Figure 9 shows an overview of the model structure, including the input and output data.

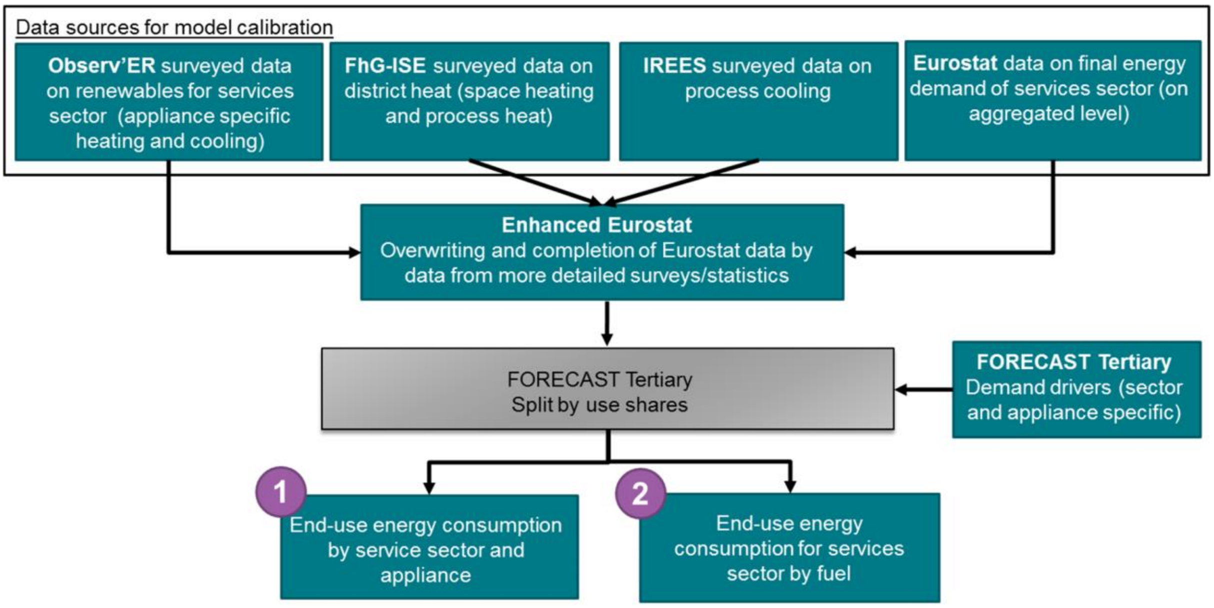

Figure 9: Overview of the FORECAST model (Fleiter et al. 2016).

In calculating the energy demand, the model follows a bottom-up methodology, using the global and specific energy service drivers and specific energy consumption indicators as input. The model attributes energy service drivers to each end-use and calculates the energy demand by multiplying the quantity of a given energy service driver by the specific energy demand of each unit of this energy service driver. The end-uses space and water heating are mainly related to the floor area and number of employees as the energy drivers. Number of employees in the commercial & public sector is calculated using the population data and GDP per capita. The result is then divided among the subsectors, applying specific regression models, and providing the number of employees in each subsector. Next, this sub sectoral data is used to calculate the floor area in each subsector by multiplying the sub sectoral number of employees by a specific floor area.

3.1.3. Results: Description of heating energy balances

This section presents the calculated results of the comprehensive profiling of energy demand for space and water heating in 31 European countries for the year 2017. First, Section 3.1.3.1 shows results that are relevant across sectors – aggregating the three demand sectors into one and referring to primary energy factors and the primary energy mix for electricity and district heating. Subsequently, Section 3.1.3.1 provides results for each demand sector (households, industry, commercial & public services). In both sections, for the sake of legibility, results are given for the 27 EU Member States as an aggregate region. The comprehensive results for each of the 27 Member States, as well as Iceland, Norway and Switzerland are provided as MS *Excel* spreadsheets in a single file. This file features:

- **Dashboard:** Key information for single countries or regions is provided in a user-friendly dashboard, highlighting framework conditions (e.g. of dwellings), the energy carrier split for space heating and water heating, as well as miscellaneous performance indicators (e.g. specific energy need per m^2).
- **Data tables:** Comprehensive data on useful energy demand, final energy demand and primary energy demand per country, sub sector, energy carrier and technology is provided as Excel data tables. By using the filter function in Excel, this allows for a detailed and complete appraisal of energy use for space heating and water heating in single countries or regions.

3.1.3.1. Cross-sectoral results

Complementing the comprehensive datasets in the MS *Excel* worksheets, this section presents key results for the EU-27 as an aggregate region, i.e. the summed data of its 27 single Member States. Figure 10 provides a general profile of energy demand for space heating and water heating in the EU for the calculated year 2017. These charts cover the three sectors households, industry, and commercial & public services. The top left chart shows that space heating and water heating in these three sectors account for 47.4% of total final energy demand across all end-uses in the EU-27. According to the top right chart, among the three sectors, households contribute most to heating demand (space/water heating), while the industry sector only has a minor share. As the centre chart illustrates, the energy carrier mix for space and water heating (final energy) is dominated by natural gas (43.4%), followed by biomass (15.7%) and fuel oil (15.2%). Based on the primary energy factors and the primary energy mix associated with this final energy mix (see also Section 3.1.3.1), the renewable share of space and water heating in the EU-27 in 2017 and across the three sectors amounts to 23.1%.

The indicators on the right provide auxiliary information. The useful energy demand for space and water heating (kilowatt-hours of useful energy per square meter and year) indicates the overall thermal quality of the building stock, along with the warm water usage behaviour. While an average building in the EU-27 has a specific useful energy demand of 123.11 kWh/(m²*a), the building stock in the industry and households sectors are slightly more efficient than in the commercial & public services sector. The indicators on the bottom right indicate the overall conversion efficiency (useful energy per final energy) of the three demand sectors for space and water heating. Average conversion efficiency amounts to 88.5%, i.e. on average the conversion of final into useful energy for space and water heating purposes is subject to losses of 11.5%. With particular regard to heat pumps, the average coefficient of performance (COP) indicates that an average heat pump can generate 3.06 kilowatt-hours of useful energy from one kilowatt-hour of external power (most commonly: electricity).

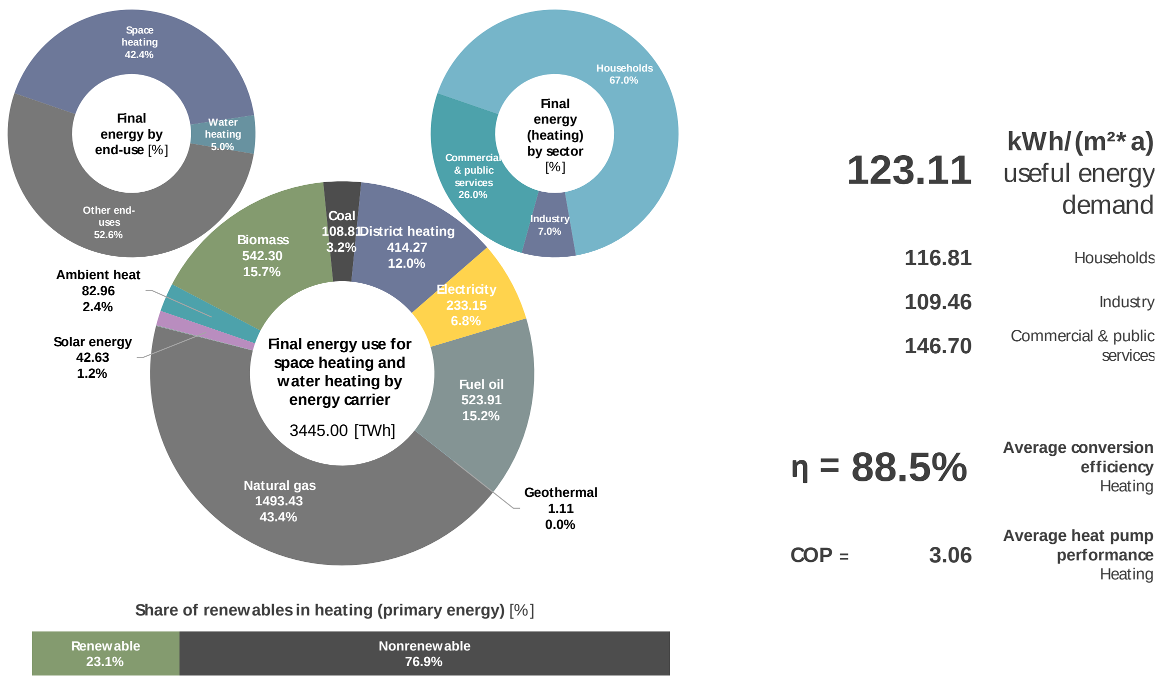

Figure 10: Energy demand for space and water heating in the EU-27 in 2017.

Figure 11 shows the calculated primary energy factors (PEF) and primary energy mix for electricity and district heating in the EU-27 in the year 2017 – based on the methodology described in Section 3.1.2.3. The PEF for electricity is 2.22, meaning that, on average, one kWh of electricity used in the demand sectors requires 2.22 kWh of primary energy input in thermal power plants, CHP plants, and other power generators. The treemap charts illustrate the composition of the primary energy mix. On average, one kWh of electricity in the EU-27 requires 0.78 kWh of nuclear energy, 0.37 kWh of gas (mostly natural gas, but also to a minor extent recovered gases from industry processes, see Table 34), 0.28 kWh of hard coal, and 0.79 kWh of other primary energy carriers – adding up to a total of 2.22. Based on these numbers, the average EU-27's electricity mix, used across all sectors and end-uses, has a renewable share of 19.1% in primary energy use in 2017.[5] Note that this value is lower than the RES share of 32.2% in gross electricity generation, i.e. after conversion losses.

The PEF for district heating is estimated at 0.79, meaning that one kWh of district heat for final use in the demand sectors requires 0.79 kWh of primary energy input. The value below zero reflects the predominant generation of district heat in combined heat and power (CHP) plants instead of a separate production of electricity and heat in power plants and heat-only boilers. The EU-27's average district heating mix is dominated by natural gas (0.25), biomass (0.17) and hard coal (0.16), with waste (RES and non-RES), lignite and oil providing complementary inputs. Overall, the district heating mix has a renewable share of 31.6% in primary energy use in 2017.

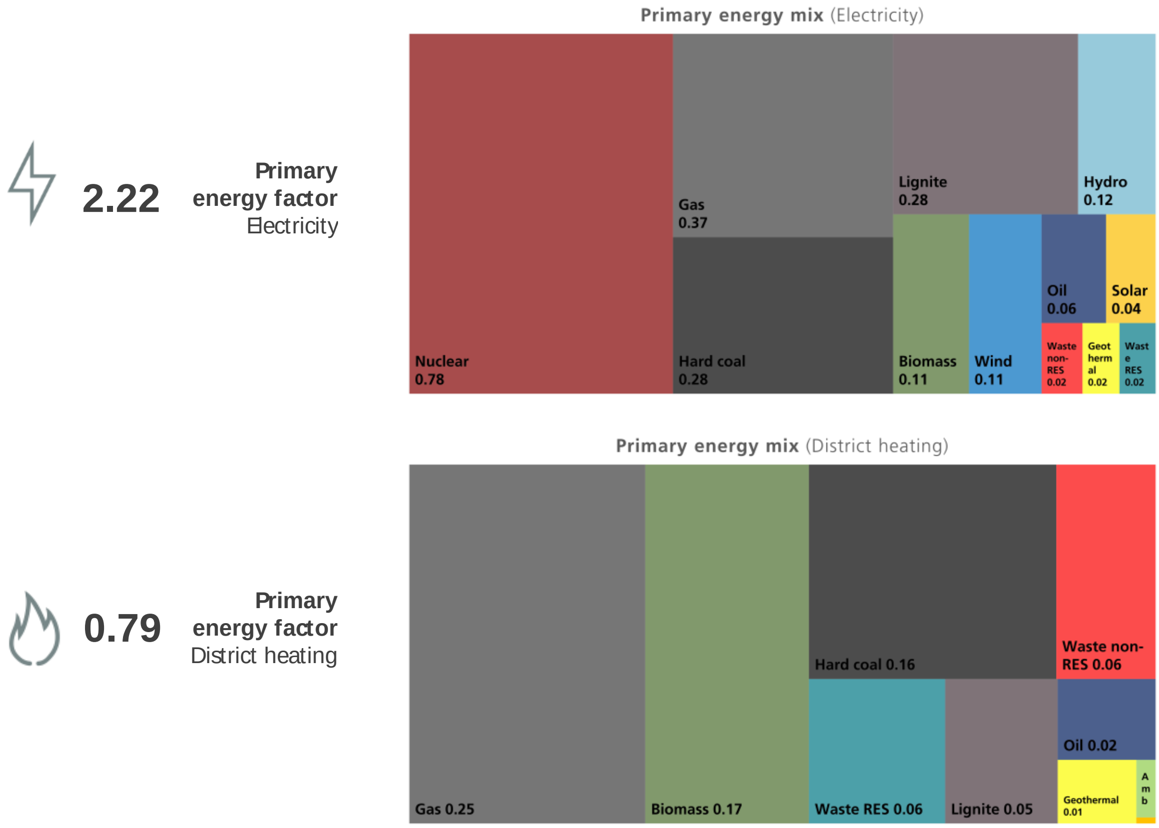

Figure 11: Primary energy factors and primary energy mix of electricity and district heating in the EU-27 in 2017.

[5] Note that this share refers to transformation input, thus reflecting the amount of primary energy needed before conversion to generate electricity and district heat. The RES share can also be reported in terms of final energy or gross/net electricity generation, i.e. after conversion. The latter leads to a greater RES share as the conversion losses in non-renewable generators are not taken into account.

Figure 12 illustrates the medium-term developments for the two commodities' primary energy factors (PEFs) and renewable mix from 2012 until 2017 in the EU-27. The PEF of electricity has improved from 2.32 in 2012 to 2.22 in 2017, reflecting a minor improvement in the primary energy needed to generate a unit of electricity for final use. Along with the ongoing deployment of renewable power generators, the renewable share has increased from 15.6% in 2012 to 19.1% in 2017. District heating has also experienced a greater efficiency in primary energy supply. While the average kWh of district heat in 2012 required 0.82 kWh of primary energy input, this value is now at 0.79. In parallel, the renewable share of district heat has increased from 24.2% to 31.6%.

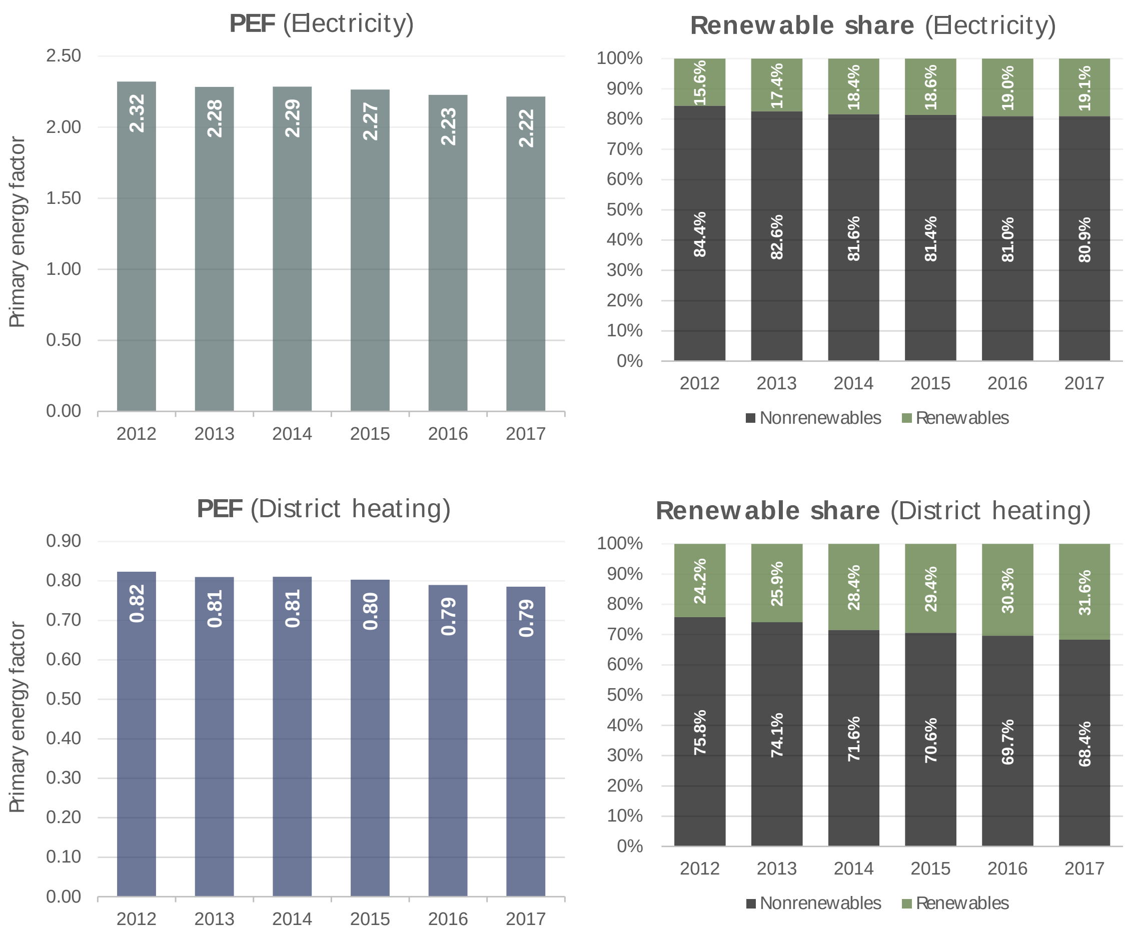

Figure 12: EU-27 primary energy factors (PEF) and renewable share (primary energy) for electricity and district heating (2012–2017).

Figure 13 shows the development of PEFs for natural gas, fuel oil, coal, and biomass from 2012 until 2017. All four energy carriers are subject to losses occurring throughout their conversion and transportation chain. Natural gas and fuel oil both have a PEF of 1.07 in 2017, indicating the each unit of final energy consumed requires about 7% of additional primary energy input that are lost through conversion losses (especially refineries for fuel oil) and distribution losses. Coal and biomass are close to PEFs of 1.0, indicating only minor conversion losses before being used in the demand sectors.

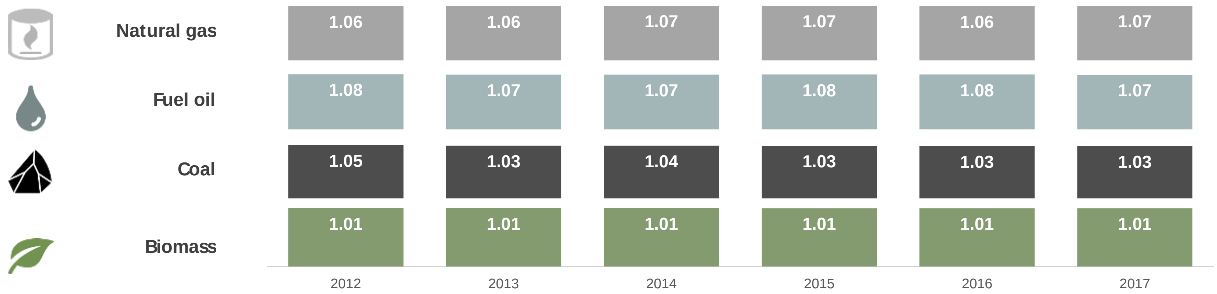

Figure 13: EU-27 primary energy factors for natural gas, fuel oil, coal, biomass (2012–2017).

After having established general findings for the EU-27, the following section reports on more detailed data in the households, industry, and commercial & public services sectors.

3.1.3.2. Sectoral results

In the following, key results are presented for the EU-27 and the sectors considered – households, industry, and commercial & public services. Figure 14 provides an overview of energy demand for space and water heating in the EU-27's **households sector** in 2017. Overall, space heating and water account for 79.1% of the sector's final energy demand. Energy for space and water heating is predominantly used in single-family houses with 1 to 2 dwellings (72.2%), while multi-family houses with 3 or more dwellings have a share of 27.8%. The overall fuel mix (final energy) for space and water heating is dominated by natural gas (38.0%, 876.5 TWh), biomass (20.9%, 482.2 TWh), and fuel oil (14.1%, 325.2 TWh). Ambient heat and solar energy as emerging energy carriers in the households sector make up 3.4% (76.9 TWh) of final energy demand for space and water heating. The 185 TWh of electricity are primarily used for direct electric heating (radiators, night storage heating, instantaneous water heaters, etc.) (85.7%) while electric heat pumps altogether require 14.3% of electricity use for heating (data not illustrated in charts). Overall, the renewable share of the households sector's primary energy mix for space and water heating is approximately 27.5%. The EU-27's residential building stock is characterized by single-family buildings with relatively poor thermal performance (136.43 kWh/(m²*a)) while, on average, multi-family buildings consume about 85 kilowatt-hours per square meter and year for providing space and water heating. The average conversion efficiency of all space and water heating technologies is estimated at 88.5%, i.e. losses of 11.5% occurring in the conversion from final into useful energy. Heat pumps have an average coefficient of performance (COP) of 3.23, indicating that one kilowatt-hour of external power (electricity, natural gas) can generate about 3.23 kilowatt-hours of useful energy for space and water heating.

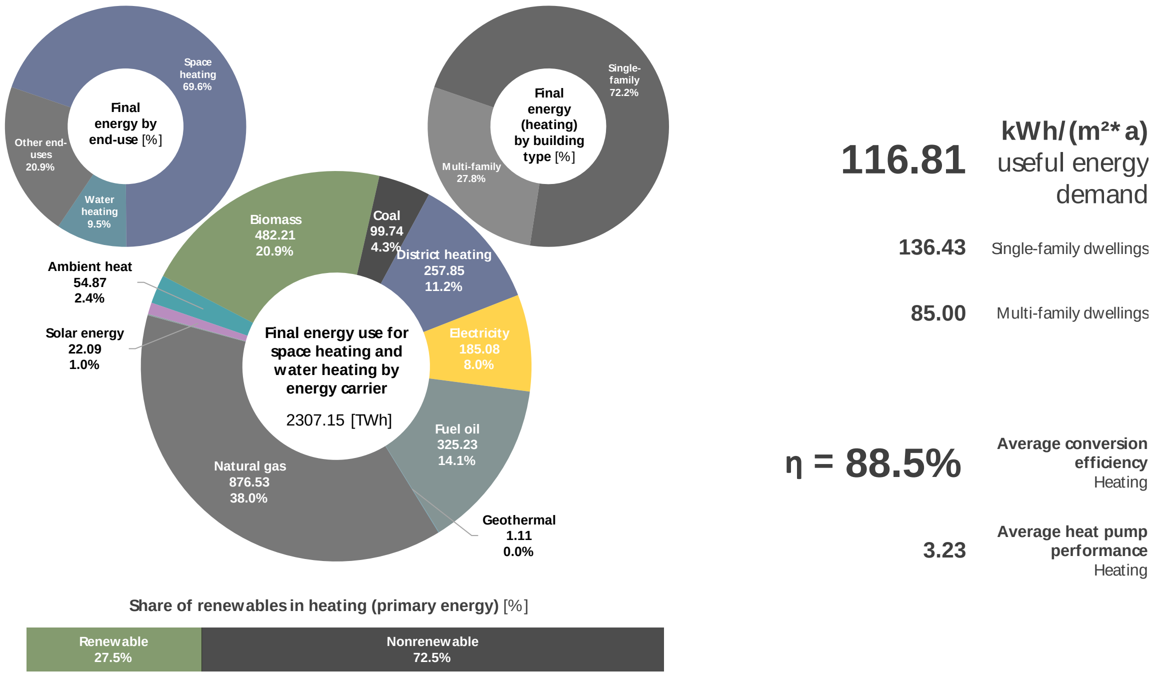

Figure 14: Energy demand for space and water heating in the households sector in the EU-27 in 2017.

Figure 15 illustrates the general characteristics of energy demand for space and water heating in the EU-27's **industry sector** in the year 2017. In general, space heating and water heating are of only minor significance for the industry sector. The two end-uses only account for approximately 8.7% of the sector's total final energy demand, with the remaining 91.3% subsuming process heating and cooling, mechanical energy, lighting, electrical appliances and other end-uses. The top right charts illustrates the three industry sub-sectors with the highest demand for space and water heating. The *engineering and other metal* sector requires about 32.6% of the sector's total final energy demand for heating, followed by *other non-classified* (including construction, textile industry, and other sub-sectors) (20.9%), and the *food, drink and tobacco* sector (20.9%). The overall fuel mix for space and water heating is largely dominated by natural gas (70.9%, 172.0 TWh), district heating (14.5%, 35.1 TWh) and fuel oil (11.8%, 26.6 TWh). Ambient heat (heat pumps) and solar thermal installations together practically play no role for space and water heating (0.1%, 0.29 TWh) in the industry sector. Overall, the industry sector's for space and water heating is almost entirely based on non-renewable fuels, with renewables having a share of only 4.6% in the primary energy demand for these end-uses. The specific useful energy demand for space and water heating in industry facilities is about 109.5 kilowatt-hours per square meter and year, with slight variations across the different sub-sectors. Overall conversion efficiency is estimated at 74.8%, i.e. losses of 25.2% occurring in the conversion of final into useful energy for space and water heating. The average heat pump performance (COP) is estimated at 3.29.

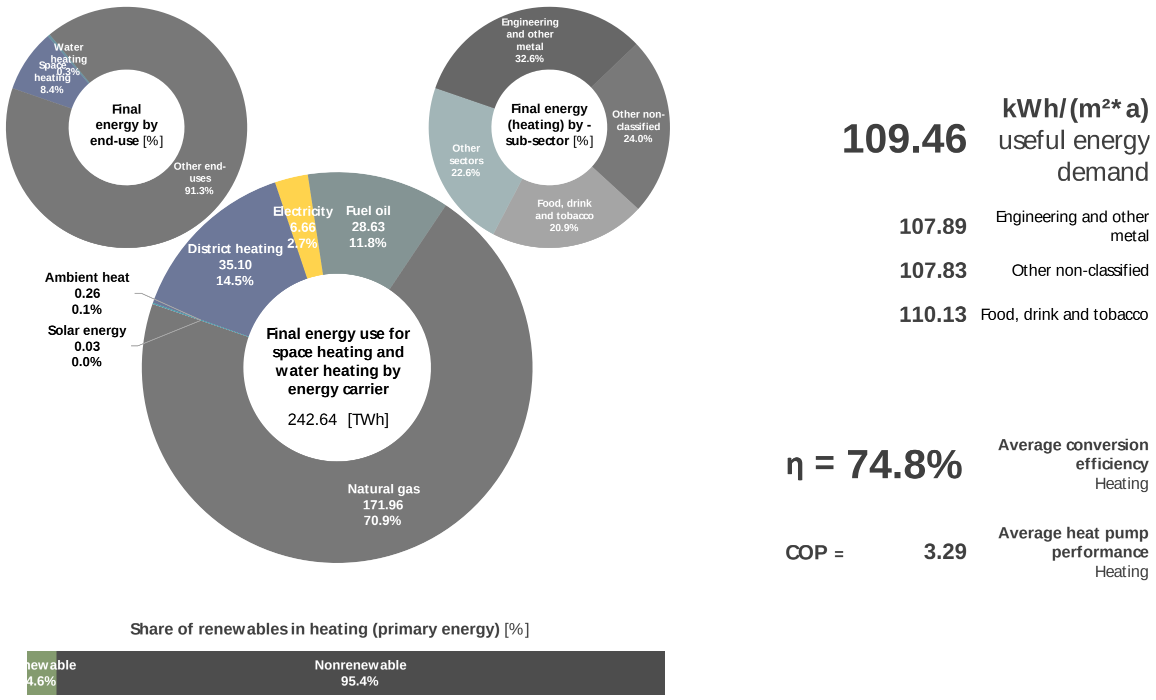

Figure 15: Energy demand for space and water heating in the industry sector in the EU-27 in 2017.

Finally, Figure 16 presents an overview of energy demand for space and water heating in the EU-27's **commercial & public services sector** in the year 2017. Altogether, space and water heating make up about 51.9% of the sector's total final energy demand. The sub-sector with the largest space and water heating demand is *other non-residential buildings* (33.3%) which is an aggregate for all sub-sectors not explicitly listed in Section 3.1.2.1. The sectors *trade* and *education* together account for about 37.4% of total demand for space and water heating. The commercial & public services sector's final energy demand for space and water heating is led by natural gas (49.7%, 444.9 TWh), fuel oil (19.0%, 170.1 TWh) and district heating (13.6%, 121.3 TWh). Ambient heat (heat pumps) and solar thermal installations together account for about 5.4% (48.3 TWh) of final energy demand for space and water heating. Electricity-driven space and water heating is composed of direct electric heating (67.4%, 27.9 TWh) and electric heat pumps (32.6%, 13.5 TWh) (data not shown in charts). The overall renewable share in the commercial & public services sector's fuel mix for space and water heating is estimated at 17.2%. Average building performance (useful energy demand for space and water heating) is approximately 146.70 kilowatt-hours per square meter and year, with the education sector being slightly more efficient than the trade sector. Average conversion efficiency of all heating technologies is about 92.2%. The average COP of heat pumps is estimated at 3.06.

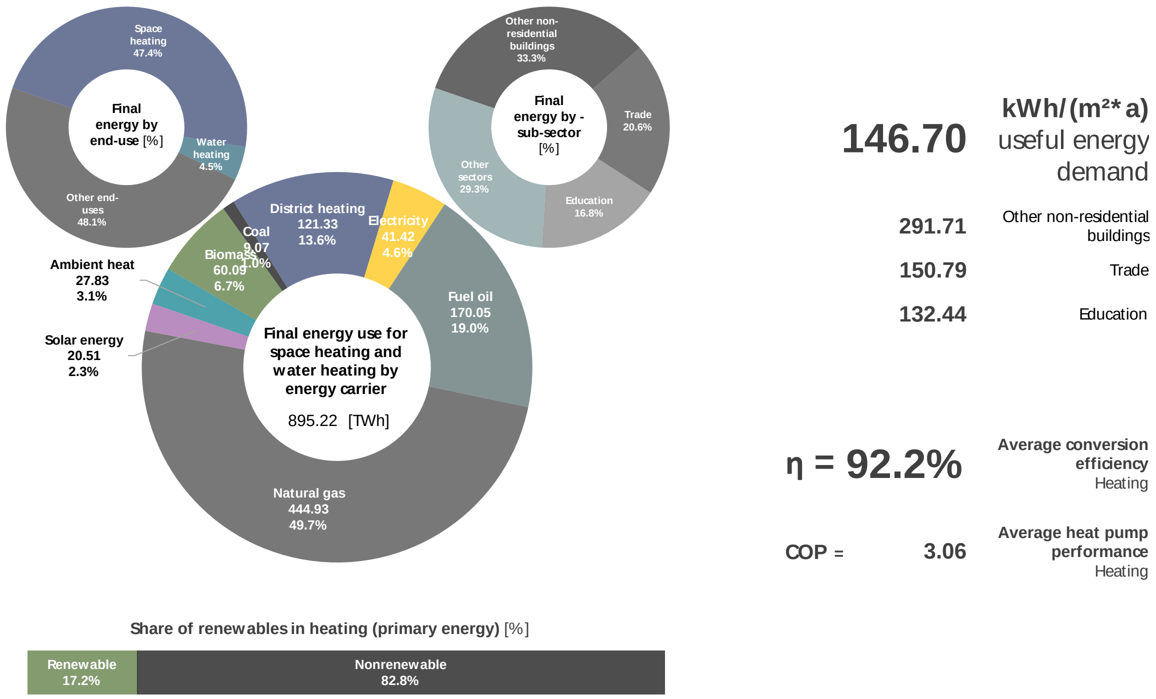

Figure 16: Energy demand for space and water heating in the commercial & public services sector in the EU-27 in 2017.

Overall, these data suggest that space and water heating are of major significance for the EU-27's energy demand in the households and commercial & public services sectors, with lower relevance for the industry sector. The following section provides general conclusions on the analyses in Task 1.

3.1.4. Conclusion and recommendations

3.1.4.1. Significance of space heating and water heating

In Task 1, final, useful and primary energy balances for space and water heating are calculated for 31 EU and non-EU countries in the year 2017. As an exemplary case, the Member States of the EU-27 were analysed in detail as an overall aggregate region. This analysis reveals that final energy for space and water heating accounts for 47.4% of the total final energy demand across the sectors households, industry, and commercial & public services. Among these sectors, households are the largest consumer of final energy for space and water heating purposes (67.0%), followed by commercial & public services (26.0%) and the industry (7.0%).

The overall fuel mix for space and water heating in the EU-27 is dominated by natural gas, biomass, and fuel oil (74.3% of final energy demand for heating). Emerging energy carriers such as ambient heat (heat pumps), solar thermal and geothermal energy can be seen as niche options, with a total share of approximately 3.6% in final energy demand for space and water heating. Taking explicit account of the fuel mix for electricity and district heating, the renewable share of the EU-27's primary energy fuel mix is estimated at 23.1%, giving rise to several recommendations for courses of action (Section 3.1.4.1). More detailed findings at a single country level can be derived from the MS Excel spreadsheets accompanying this document.

3.1.4.2. Quality of results

The quantitative data presented in this Task 1 was prepared based on established modelling approaches as well as a comprehensive set of input data. Both of these aspects are subject to limitations and provide potential for future improvements. Moreover, they lead to deviations between the end-use energy balances calculated for the country sheets in the frame of this study, as well as those created by individual Member Studies in dedicated studies.

While a detailed assessment of methods for end-use balances and an overview of approaches used by individual member states is provided in Fleiter et al. (2016), we summarize key fields for future improvement in the following.

With regard to the quantitative approaches applied, the following limitations need to be taken into account:

- Establishing the useful energy demand for space and water heating in the demand sectors is largely based on norm- and standard-based calculations. For each subsector/building type, this implies various input data and assumptions on external boundary conditions (air temperature, solar radiation), utilization conditions (room temperature, air exchange rate, internal heat sources), average thermal transfer coefficients (U-values), and other parameters. Combining the calculations on useful energy demand with the detailed technology data yields final energy demand. Again, these technology data are subject to uncertainties with regard to stock, distribution across building types and age classes, average efficiencies, and more. Altogether, the calculated values for energy demand can only provide an approximation of actually measured consumption in real buildings. Due to the lack of data and information about real utilization conditions (e.g. indoor temperatures, air exchange rates) and the exact thermal properties of existing buildings (construction elements, supply systems) these values cannot exactly correspond to real-life levels. In consequence, there are deviations of the calculated energy use from the target values for final energy demand per energy carrier established in the Eurostat energy balances.[6]

- The primary energy factors and split of primary energy sources for electricity and district heating should be understood as average yearly values that do not adequately represent short-term variations in demand and in the corresponding supply mix. The method applied and the data generated generally provide a transparent and comprehensive supplement to the default data available from Eurostat. However, a more detailed approach would need to take into account how different marginal generation units serve different load levels, resulting in dynamic instead of static primary energy factors and mixes for different technologies and points in time. Such an approach requires advanced model-based data that was beyond the scope of this task. The data generated nonetheless provide a reasonable image of the primary energy implications for the use of electricity and district heating in the demand sectors.

The input data used in this analysis is subject to the following shortcomings:

- Eurostat's energy balances for single countries were used as a principal reference for the development of the end-use balances. While in the general these data are highly versatile for established energy carriers, they feature particular gaps and ambiguities regarding energy carriers that are collected onsite and that are not commercially traded (in particular, ambient heat, solar energy, geothermal energy). In terms of gaps and data availability, Regulation (EU) 2017/2010 requires Member States and other European countries to collect consumption data for these non-

[6] For each country and energy carrier, these deviations are provided in the MS Excel Spreadsheets accompanying this report – see the columns 'Eurostat energy balance check' under the *EndUseBalance* sheets. Taking the example of the Commercial & public services sector, the EU-27 as a country aggregate, and district heating as an energy carrier, the calculations for space and water heating yield a total of 116.04 TWh, while the target value established in the Eurostat energy balance is 106.71 TWh (Difference of 9.33 TWh or 8.7%).

commercially-traded energy carriers starting at reference year 2017. Yet, for the given year, detailed sectoral data was not comprehensively reported by all countries. For example, seven of the countries analyzed do not report demand data for ambient heat (heat pumps) in the households sector. Member States should be encouraged to collect and report these data to ensure adequate conclusions to be drawn from them. Besides availability, Eurostat's conventions for data collection are subject to minor ambiguities. Again concerning ambient heat and geothermal energy, there are slight contractions between Regulation (EU) 2017/2010 on energy statistics and Regulation (EU) 2018/2001 (Renewable Energy Directive) regarding the accounting of ground-source heat pumps (see Section 3.1.2.1). This analysis assumed that Eurostat data is collected under precedence of the Regulation on energy statistics. Prospective amendments or recasts of the two legislations should ensure improved consistency in the definitions they include to avoid misinterpretations from the side of countries collecting data.

- An analysis of the available data at the national and EU level identifies the inconsistencies in the availability and depth of detail for different countries. Available data sources and statistics mainly cover the EU countries, resulting in the gaps in data for non-EU countries. Moreover, when the missing data from one database is addressed in another source, in most of the cases the method used or the details available vary in the two data sources, constraining the application of a consistent calculation method for all the studied areas. An example of this case is the end-use balances available in Eurostat vs. ODYSSEE database. The inconsistencies were especially observed regarding the building stock data, comparing the three main available sources namely BSO, ODYSSEE and Hotmaps database. For instance, in the household sector in BSO the available data follows, in general, a homogenous trend until 2016; however, there is a sudden and noticeable break in the data between 2016 and 2017 in all countries, which is not explainable due to the relatively long technical lifetime (typically 30 years or more) (Commission 2012) of a building in the building stock. In the ODYSSEE database, data is not provided for all the countries, therefore this database could not be used as the main source in this project. The Hotmaps database includes data for all the countries, building types and age classes. However, there are some uncertainties in data calculation (e.g. total number of dwellings vs. total floor area) and we identified a need to better describe and clarify some of the indicators. The observations revealed that each of the data sources has some issues and none of them provides the complete dataset needed for this project. Therefore, we combined several sources to derive one complete data set. Considering the homogenous trend and the completeness until 2016 in BSO, this dataset is considered as the main data source and the data for 2017 is calculated then by extrapolating the available data from 2012 to 2016. When necessary other data sources are consulted used to fill the gaps in data (especially for the non EU countries) and to generate a homogenous dataset.

The above-mentioned data gaps and inconsistencies apply to other sectors as well as other input data. To build a stronger data foundation for calculation of the energy balances, further empirically studies should be carried out to fill in the existing data gaps and to complement the input data. This especially concerns the industry and commercial & public sectors. Further, the existing data in various sources should be harmonized and prepared to be used in the calculations and models. It is recommended to develop a methodology to be used by all the countries however, since the energy pattern varies in each country the country specific situations are to be considered when developing the methodologies for the improvement of data for the individual countries.

In conclusion, the end-use balances for space and water heating developed in this task provide a substantial complement to Eurostat's default energy balances. Adding the dimensions of sub-sectors (e.g. single- and multi-family homes for the households sector), end-uses (space heating, water heating, other end-uses) and technologies (e.g. different heat pump types) allows for a comprehensive overview of energy use for heating in the 31 European countries considered. Taking account of the abovementioned limitations, the following section provides overall policy recommendations with regard to heating energy use in Europe.

3.1.4.3. Recommendations

The detailed findings from this task support the following recommendations.

First, comparing households, industry, and commercial & public services, space and water heating have a different significance with regard to overall sectoral final energy demand and thus should be prioritized differently. While space and water heating account for about 79.1% of final energy demand in the households sector and 56.8% in the commercial & public services sector, this share is only approximately 8.7% in the industry sector. Regulatory and policy efforts dedicated to reducing the energy demand for space and water heating and to increasing the share of renewable energy sources should thus have a particular focus on the first two sectors and develop custom strategies for the decision-makers and actors involved.

Second, particularly for the industry sector this suggests that strategies need to look beyond space and water heating and consider other end-uses not explicitly considered in this analysis, i.e. process heating, mechanical energy, space and process cooling, lighting, electrical appliances, etc. Dedicated research should be carried out to quantify the shares of these single end-uses in overall final energy demand for each sector to identify key priorities and to develop custom strategies.

Finally, the calculated renewable share of 23.1% for space and water heating in the EU-27 suggests several courses of action to comply with a climate-neutral building stock by 2050. (i) In line with the European Commission's guiding principle of 'Energy Efficiency First' (Regulation (EU) 2018/1999) as well as the provisions set out in the Energy Performance in Buildings Directive (Directive (EU) 2018/844), the end-uses of space and water heating hold substantial cost-effective energy efficiency potentials that need to be unlocked. In particular, enhancing the thermal performance of buildings reduces useful energy demand and thus the amount of fuels and electricity needed in terms of final and primary energy. (ii) Following the direction of the Renewable Energy Directive (Directive (EU) 2018/2001), Member States will need to increase the share of renewable energy they use for heating. The analysis in this task reveals that ambient heat, solar thermal energy and other renewable energy carriers so far only play a minor role for space and water heating in the EU-27 – compared to the dominance of natural gas, fuel oil and other fossil fuels. (iii) Given the considerable and potentially increasing share of electricity and district heating as derived energy carriers in overall heating demand, policy efforts will need to continue to increase the share of renewable energy carriers for these commodities.

In conclusion, this task provided a comprehensive quantitative profiling of energy demand for space and water heating in 31 European countries for the year 2017. The subsequent tasks in Work Package 1 describe the role of individual heating technologies (Task 2) and provide an overall description of heat supply in individual European countries (Task 3).

3.2. Comparative overview of renewable space and water heating technologies

3.2.1. Objective

The objective of this part of the study is to provide an overview of all the relevant current and emerging space and water heating technologies in buildings and their technological development trends. This includes all relevant fossil-based and renewable heating technologies including renewable electricity, e-fuels and hydrogen H2. The overview provides technical characteristics, stock figures, development trends and estimates on the costs of heat supply for each individual Member State and reported in structured Excel data sheets. The information and data feed into modelling scenarios (chapter 4) and the country reports (chapter 3.3). The overview is based on processed data from a variety of sources including data collected from industry associations.

3.2.2. Method

Figure 17 provides an overview of the methodology, which will be detailed in the following.

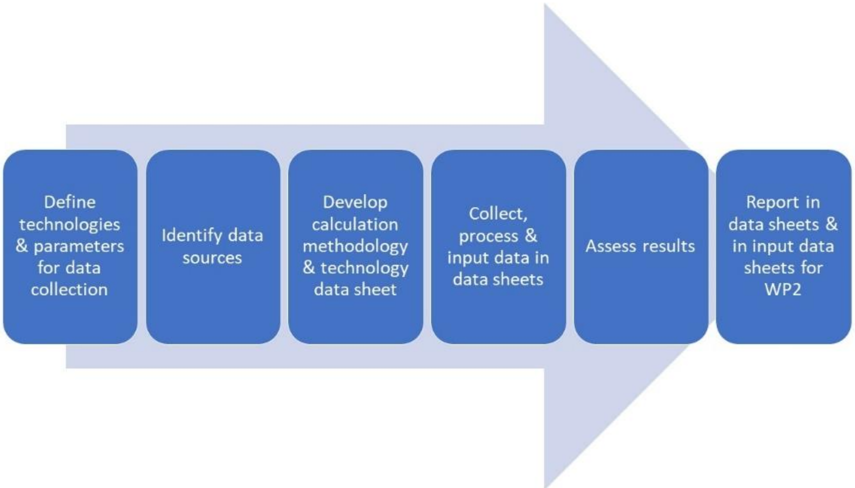

Figure 17: Overall illustration of the methodology.

3.2.2.1. Define technologies & parameters for data collection

The technologies are defined through five overall technology clusters:

- Individual heat pumps (space and combination heaters, air-to-air, air-to-water, ventilation (for heat recovery)), thermal solar and direct electric heaters
- Individual boilers (space and combination heaters) and micro CHP
- Individual dedicated domestic hot water heaters (electric, solar, oil, gas and heat pumps)
- District heating plants heat pumps, geothermal and solar heating
- District heating plants heat only boilers and CHPs

And through the relevant energy carriers for each technology:

- Natural gas
- Biogas
- Synthetic natural gas
- Liquid petrol gas
- Gasoil
- Biooil

- Heavy fuel oil
- Coal
- Wood chips
- Wood pellets
- Wood logs
- Solar
- Electricity
- Hydrogen
- Ambient heat
- Geothermal energy
- Ventilation air
- Sea water
- Waste heat

And distributed on sizes:

- Heat capacity (output):
  - Individual boiler and micro CHP: <25 kW, 25-50 kW, 51-250 kW, >250 kW
  - Heat pump:<20 kW, >20 kW
  - District heating: <5 MW, 5-10 MW, 10-50 MW, >= 50 MW

The heat pumps can be used for larger needs as well e.g. for building blocks, where several heat pumps can be connected.

Hybrid systems such as combination of an electric heat pump and a gas boiler have not explicitly been covered because e-gases and hydrogen turned out to be energy carriers with high running cost. A key challenge is to have a low level of gas consumption and still need to operate the gas grid with high costs.

For each combination of technology and energy carrier, and distributed by size, the following parameters are defined:

Technical data:

- Heat capacity (output) average, kW (for individual), MW (for DH)
- Thermal efficiency, annual average, %
  - Heat pump: SCOP for heating system temperature 35 / 55 ºC
  - District heating: Total, thermal and electric efficiency
- Heat pump: Climate zone
- Electric efficiency (micro CHP), annual average, %
- Auxiliary electricity consumption, Wh/kWh (for individual), kW/MW (for DH)
- District heating: Availability, %
- District heating: Construction time, years
- Technical lifetime, years

Financial data:

- Specific investment, k€/unit (for individual), M€/MW (for DH), distinguished by the same categories of sizes as above; hereof
  - equipment, %
  - installation, %
- Fixed O&M, €/unit/year (for individual), k€/MW/year (for DH)
- Variable O&M excl. auxiliary electricity consumption, €/kWh

As mentioned above, the technologies have been divided into five technology clusters since the relevant parameters and format for the technical and financial data differ between the technologies.

Data on the heating system stock:

- Stock, units
- Stock, installed thermal capacity (size), MW_{th}
- Stock DH: Installed thermal capacity or total capacity MW_{th}
- Data for:
  - Total
  - Age distribution:
    - 1st half of lifetime
    - 2nd half of lifetime
    - Older than lifetime

Data have been provided for EU27 and United Kingdom, Norway, Switzerland and Iceland for most recent year, and if several years are available (2016-2019), data will be compared and adjusted in order that data will be compared for the same year. Furthermore, for the technical and financial parameters, data will be forecasted to 2030 and 2050.

Please notice that there is a huge variety of technologies and systems on the market. Due to this large variety, not each and every technology could be collected data for and be considered in details for this study. In particular, this also includes hybrid solutions.

Identify data sources

The following data sources have been identified as providing the best data quality based on the resources available and therefore been selected for the study:

- Danish technology catalogue for individual heating technologies with performance data and financial data for 2015 and with forecasts for 2020, 2030 and 2050 (Danish Energy Agency 2016) for individual heating and micro CHP installations Danish technology catalogue for electricity and district heating generation with performance data and financial data for district heating and CHP plants for 2015 and with forecasts for 2020, 2030 and 2050 (Danish Energy Agency and Energinet 2016). The data in the catalogue are based on Danish and European sources.
- Danish technology catalogue for industrial process heating with performance data and financial data for large boilers for 2020 with forecasts for 2030, 2040 and 2050 (Danish Energy Agency and Energinet 2020)

- The Danish “Heat pump list", Danish Energy Agency, accessed April 2020 (Danish Energy Agency’s List of Heat Pumps; 2020)[7]
- Nordsyn study on air-to-water heat pumps in humid Nordic climate, Nordic Council of Ministers 2019
- Sales, stock, performance and price data for space heating boilers and water heaters from review study of ecodesign and energy labelling for space heating boilers and combination heaters, review study of ecodesign and energy labelling for water heaters and tanks (VHK 2020) and ecodesign review study on Local Space Heaters (VM 2019). The most recent updated data at the time of the study have been used.
- “Efficiency of Heat Pumps in Real Operating Conditions – Results of three Monitoring Campaigns in Germany”, Group Heat Pumps. Fraunhofer-Institute for Solar Energy Systems ISE, REHVA Journal – September 2014
- Internet research on online vendors of heat pumps, April 2020.
- ”Guidelines for large heat pump projects in district heating”, Denmark
- Sales and stock data for individual heat pumps for space heating and DHW is primarily based on data on new sales for heat pumps from European Heat Pumps Market and Statistic Report 2019, (EHPA - European Heat Pump Association).
- Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables). Work package 2: Assessment of the technologies for the year 2012. Final report, September 2016 for establishing stock and qualifying technology data.
- Data for costs have been compared with cost data in the database for Invert model, Technische Universität Wien, 2020
- For solar heating data and methods from Global Solar Atlas (Solargis on behalf of the World Bank Group), Technical_note_solar_thermal_capacity (Simssolar UK), and Solar Thermal world Org have been included.
- Stock data for district heating CHP plants are based on data from PLATTS database 2020.

DH stock data are additionally based on:

- IEA SHC - Solar Heat Worldwide 2018
- EurObserv’ER – Solar Thermal and CSP barometer 2018
- Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems, Aalborg University, Andrei David, Brian Vad Mathiesen, Helge Averfalk, Sven Werner and Henrik Lund

Develop calculation methodology and technology data sheet

Data are provided for a large amount of combinations of energy technologies, energy carriers and sizes for 31 countries. None of the sources have data for all countries and for all combinations. Furthermore, massive amount of data is required (>300,000 data points) to cover all parameters for all technologies for all countries. Within the scope of this study, it is unfeasible to carry out a primary data collection. Instead a different methodology has been developed.

[7] The list is managed by the Danish Energy Agency and is a kind of a Danish TOP TEN. To be on the list the heat pumps must be tested by an independent laboratory.

The chosen methodology for the technical and financial data is to provide a dataset for one country (referred to as the baseline country) for which many data were available and then scale the relevant parameters from the baseline country to all countries based on established scaling factors taking into account relative price differences between the countries, climate zone, efficiency level, expected domestic hot water (DHW) share of total heating delivered, typical size of units etc. Not all factors are used for all technology clusters. This is considered to be a quite precise way of reaching comparable country level data, when extensive and detailed data collection in each country is not possible. A few input data have been verified with national specific data, where possible. Furthermore, the resulting calculated LCOH data have been compared with other available data. See further in this section.

For the stock data, the starting point for individual technologies has been sales and stock data for different years and different countries available from different sources. The scaling takes into account the historical pattern in sales development, the economic/social and historical characteristic of the countries, the population, the climate etc. Stock data district heating technologies data is for the CHP from the PLATT data base, for the other DH technologies data for 2012 been scaled to 2018 looking at the changes in the countries, energy consumption and energy carrier distribution, furthermore data from scientific papers and IEA have been used for qualifying the data. The estimation of the stock is done different for the different technology clusters, because different data have been available.

The technology data sheets have been developed for input data, calculations and output data. See the model structure in Figure 18.

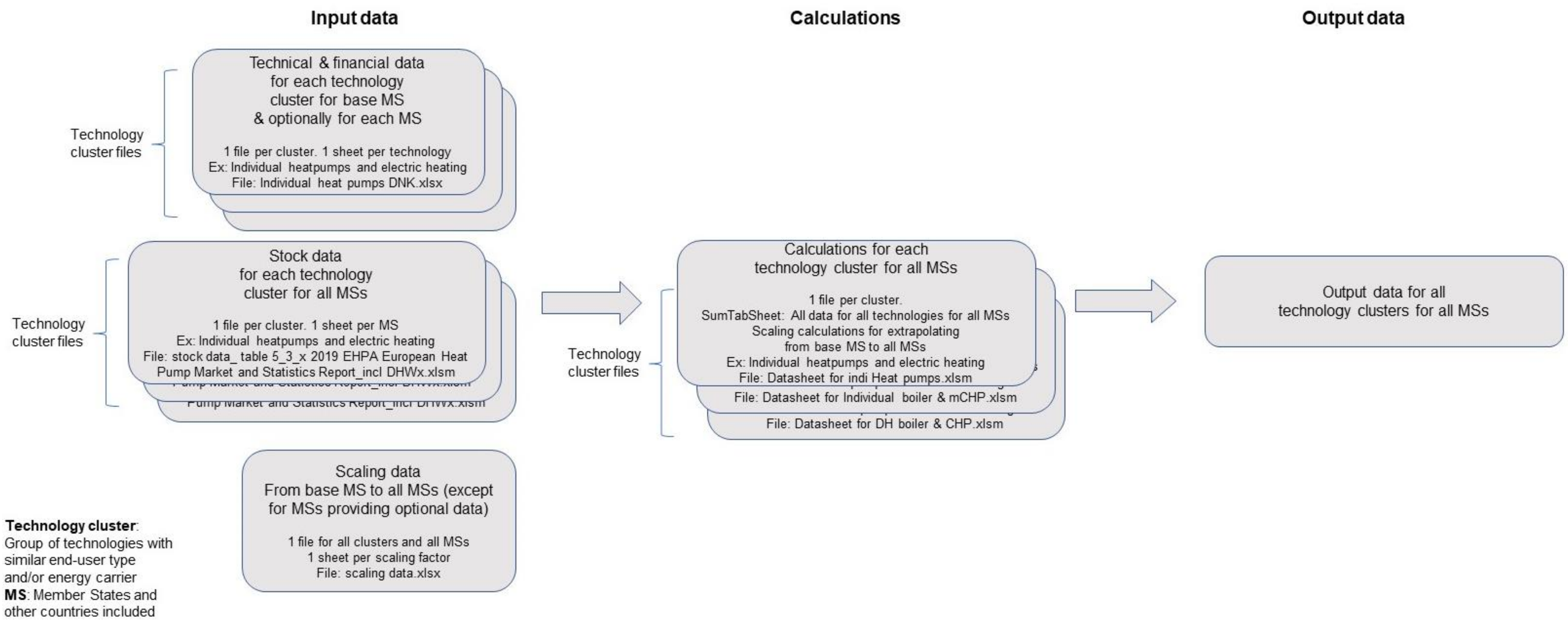

Figure 18: Model structure for technology data and indication of exemplary data files.

For the input data and calculations, each technology cluster is covered in one Excel workbook. In this file, each country is represented by a specific input sheet listing all the technologies for that cluster and all associated parameters. Additional, sheets containing scaling and metadata are included. In these files the calculations from the baseline country to all the other countries are made. The technical and financial part of the input sheets will be empty for all countries except for the baseline country. The reason for including these empty input sheets for all countries is to keep open the possibility of inserting figures for a specific country in case the model will be used for this purpose. The output data for all countries is found in one large matrix output. All these Excel files are delivered as supplementary material.

An example of the table for input data for the energy cluster individual heat pumps and electric heating is shown in Table 5.

Table 5: Input data for the energy cluster individual heat pumps and electric heating.

Name of technology	Air-to-water	Electric heat pump						
Energy carrier	eletricity							
Country	Denmark							
Climate zones	Average							
Energy/technical data	**Unit**	**source/not**	**2017**		**2030**		**2050**	
Heat **capacity** (output)			**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**
Heat **capacity** (output) average	kW							
Thermal **efficiency**, annual average(SCOP), average climate zone, heat.sys.temp 35 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), average climate zone,heat.sys.temp 55 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), warmer climate zone, heat.sys.temp 35 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), warmer climate zone, heat.sys.temp 55 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), colder climate zone, heat.sys.temp 35 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), colder climate zone, heat.sys.temp 55 C, Low %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), average climate zone, heat.sys.temp 35 C, High %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), average climate zone, heat.sys.temp 55 C, High %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), warmer climate zone, heat.sys.temp 35 C, High %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), warmer climate zone, heat.sys.temp 35 C, High %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), colder climate zone, heat.sys.temp 35 C, High %DHW	SCOP							
Thermal **efficiency**, annual average(SCOP), colder climate zone, heat.sys.temp 35 C, High %DHW	SCOP							
Auxiliary Electricity consumption	Wh/kWh							
Technical lifetime	Years							
Financial data								
Specific investment	k€/unit							
- hereof equipment	%							
- hereof installation	%							
Fixed O&M	€/unit /year							
Variable O&M excl. auxiliary electricity consumption	€/MWh							

Stock 2017, individual heat pumps (stock 2018 for HP)											
Air-to-water			**Total**	**Total**		**Older than technical lifetime**		**2nd half of technical lifetime**		**1st half of technical lifetime**	
Heat capacity (output) Heat pumps	kW_{th}		**All sizes**	**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**
Stock, Installed thermal capacity	MW_{th}										
Stock, units	units										

SCOP for the Space heaters part of the combination heater and for the DHW part of the combination heater			**2017**		**2020**		**2030**	
			<20 kW	**>20 kW**	**<20 kW**	**>20 kW**	**<20 kW**	**>20 kW**
Thermal **efficiency**, annual average(SCOP), average climate zone, heat. sys.temp 35 C, **space heating part**	SCOP							
Thermal **efficiency**, annual average(SCOP), average climate zone, heat. sys.temp 55 C, **space heating part**	SCOP							
Thermal **efficiency**, annual average(SCOP), average climate zone, **DHW part**	SCOP							

The structure of the output data matrix is shown in the separate Excel data file (Output data heat technologies.xlsx).

A methodological document details for each technology cluster how the technical and financial data and the stock data have been collected and adapted. This document has been provided as a supplementary document.

Life Cycle Cost (LCC) and Levelised Cost of Heating (LCOH) are calculated for all countries, all technologies and all energy carrier combinations (where relevant) installed in 2020. LCC and LCOH are reported as averages of all capacity ranges for the particular combinations of country, technology and energy carrier.

The following additional data have been assumed and used for the calculations:

- Average annual full load hours
- Average SCOP/efficiency levels for each MS based on the technical data

- Energy input prices from various sources (PRIMES, other Commission data, Eurostat, Acer Market Monitoring and separate studies). See details in the supplementary document on energy input prices
- Discount rate: 4% (as prescribed by the European Commission)

LCC is calculated as NPV (Net Present Value) of investment + NPV of annual O&M + NPV of annual costs of fuel/electricity consumption in lifetime. For CHP the income for the sale of the electricity produced have been subtracted at wholesale price (spot marked price).

LCC and LCOH have been calculated with two different prices. The one using price data are without VAT and excise duties. The other using price data are with VAT and excise duties for individual technologies and price data are with excise duties for DH technologies.

Annual costs of fuel/electricity consumption are calculated as heat capacity output multiplied with annual full load hours divided by SCOP/efficiency multiplied by fuel / electricity unit costs for the particular year.

LCOH is calculated as LCC divided by (sum of annual heat capacity output multiplied by annual full load hours discounted to present time).

2020 energy prices have been used for all years.

The calculations are naturally not without uncertainties; main uncertainties and deviations include:

- Energy input prices. This holds for all energy carriers but especially for emerging energy carriers such as e-gases and hydrogen, however, these will be further assessed in the modelling in WP2.
- Cost of technologies, which are based on an updated basis of current prices, however, there are always variations of technologies and their functionalities as well as market distortions which have an impact on the technology prices. Furthermore, in the tables below LCC and LCOH are reported as averages of all capacity ranges for the particular combinations of country, technology and energy carrier, as mentioned above, whereas in the detailed data sheets there are distinctions of these cost data.
- Assumptions on usages, i.e. the amount of annual full load hours and how these are distributed on various load levels over the year.

Costs of related energy infrastructure in particular district heating and electricity networks will be provided as part of the WP2 modelling.

The resulting LCOH figures have been compared with other LCOH figures reported in literature. Conclusion is that the LCOH figures are only comparable within reasonable uncertainty limits and deviations occurring in practice.

Collect, process and input data in data sheets

While collecting data from the sources presented previously and processing them, technical data are assessed for country characteristics e.g. climate. Data are split according to the size categories & age distribution.

Assess results

The results are assessed as part of the quality control e.g. comparison of figures for same parameter for different but comparable technologies is carried out.

Report in data sheets and in input data sheets for WP2

Data for each country and each combination of energy technology and energy carrier are reported in one large matrix for each technology cluster, totally approximately 5000 data lines. This matrix is also input data sheet for the scenario modelling in WP2.

3.2.3. Results

3.2.3.1. Excel data sheets

All the results are provided in the following supplementary Excel data sheets:

- An output data file containing all the reported technology and financial data and stock data for all countries as described previously
- 5 technology cluster data files, each covering 1 technology cluster, with all the input data, calculations and output data

3.2.3.2. Methodological document

A methodological document has been prepared presenting details and assumptions of the analyses. This is provided as a supplementary document.

3.2.3.3. Levelised cost of heating (LCOH)

The levelised cost of heating has been calculated for each country and combination of technology and energy carrier. See the methodology behind it in section “Define technologies & parameters for data collection”.

Below we present on an exemplary basis the results of one country, France, through 1 illustrative chart and 5 tables. France has been selected as an example partly due to the size, partly due to having all three climate zones within one country (cold climate zone, average climate zone and warm climate zone).

This set of 5 tables are available for all 31 countries in the LCOH analyses. All LCOH data are reported as averages of all capacity ranges for the particular combinations of country, technology and energy carrier.

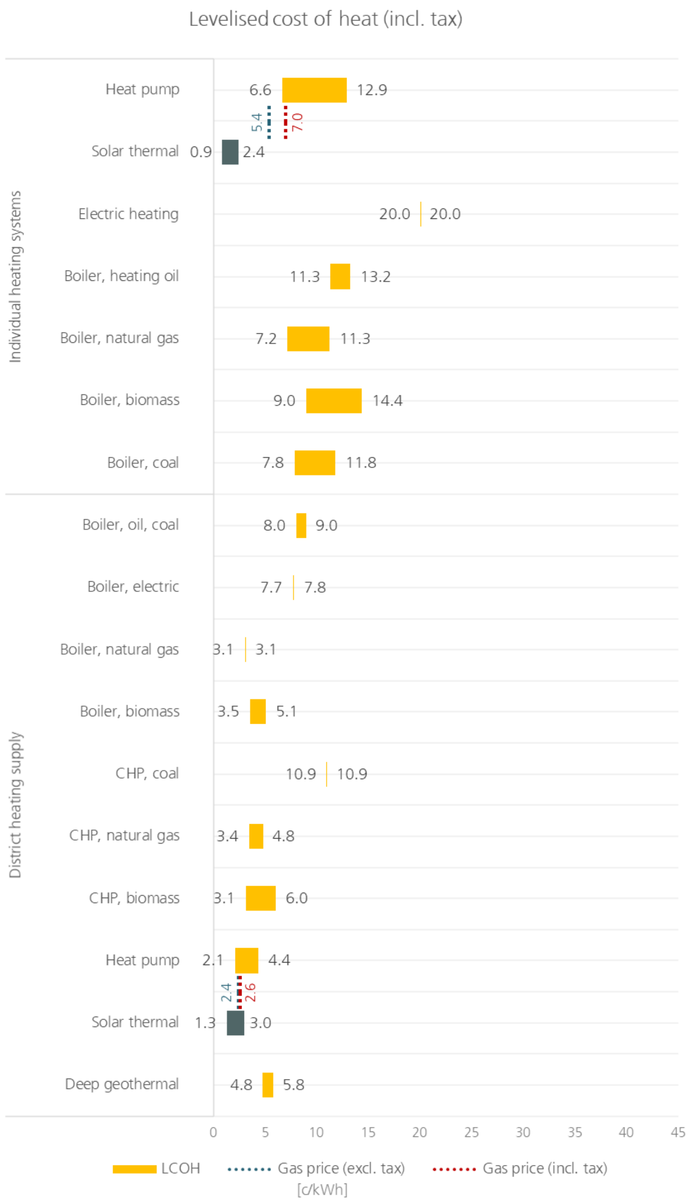

Figure 19: Illustrative chart of LCOH (Levelised Cost of Heat, incl. tax) for all the technology clusters for France. LCOH charts for all countries are available in the country fact sheets.

Table 6: Cluster 1 - Heat pumps and thermal solar heating for district heating, France.

LCOH & costs elements	Unit	Air source DH heat pump	Geothermal, Heat Pump, medio temp	Geothermal, Heat Pump, high temp	Sea Water Source DH Heat Pump	Solar Heating	Waste Heat Source DH Heat Pump
LCOH, cold climate zone	€c/kWh	3.3	5.2	4.7	3.4	2.7	2.1
LCOH, average climate zone	€c/kWh	2.9	5.2	4.7	2.9	2.2	2.1
LCOH, warm climate zone	€c/kWh	2.5	5.2	4.7	2.5	1.4	2.1
Specific investment	M€/MW	0.7	1.9	1.9	0.6	2.6	0.6
Fixed O&M	k€/MW/year	1.8	15.7	15.6	3.5	0.6	1.8
Variable O&M incl. auxiliary electricity consumption	€/MWh	1.4	3.8	3.0	1.6	0.0	1.4
Energy carrier price	€/MWh	63.5	63.5	63.5	63.5	0.0	63.5

Abbreviations used in the table:

- Air source DH heat pump: Electric compression heat pump using outdoor air as heat source
- Waste Heat Source DH Heat Pump: Electric compression heat pump using waste heat from e.g. industrial processes as heat source
- Sea Water Source DH Heat Pump: Electric compression heat pump using sea water as heat source
- Solar Heating: Thermal solar system without separate storage
- Geothermal, HP medio temp: Electric compression heat pump using geothermal heat as heat source
- Geothermal, HP high temp: Combination of direct heat exchange and an electric compression heat pump using geothermal heat as heat source

Table 7: Cluster 2 - Boilers and combined heat and power plants for district heating, France.

LCOH & costs elements	Unit	Boiler, Coal	Boiler, Gas	Boiler, Oil	Boiler, Wood Chip	Boiler, Wood Pellet	CHP CCGT, BP, gas	CHP CCGT, Ext, gas	CHP Gas Turbine, gas	CHP Steam Turbine, coal	DH Electric Boiler	Gas-motor, natural gas	Wood Chip CHP	Wood Pellet CHP
LCOH, all climate zones	€c/kWh	5.7	2.5	7.7	3.4	4.3	2.8	2.3	2.4	6.2	6.6	2.8	3.5	4.8
Specific investment	M€/MW	0.48	0.04	0.04	0.54	0.56	1.22	0.35	0.56	0.35	0.08	0.78	1.14	1.22
Fixed O&M	k€/MW/year	32	1	2	31	26	28	12	16	7	943	8	45	48
Variable O&M incl. auxiliary electricity consumption	€/MWh	1.0	0.9	0.8	1.1	0.5	3.8	1.7	3.5	0.6	0.4	4.5	1.3	0.7
Energy carrier price	€/MWh	39	24	72	21	29	24	24	24	39	64	24	21	29

Abbreviations used in the table:

- Boiler, Coal: Boiler/"heat only" plant burning coal
- Boiler, Gas: Boiler/"heat only" plant burning natural gas
- Boiler, Oil: Boiler/"heat only" plant burning gas oil
- Boiler Wood Chip: Boiler/"heat only" plant burning wood chips on a grate as the base assumption
- Boiler, Wood Pellets: Boiler/"heat only" plant burning wood pellets on a grate as the base assumption
- CHP CCGT, BP, gas: Gas turbine, combined cycle, back pressure, burning natural gas
- CHP CCGT, Ext, gas: Gas turbine, combined cycle, extraction plant, burning natural gas
- CHP Gas Turbine, gas: Gas turbine burning natural gas
- CHP Steam Turbine, coal: Pulverized coal fired, supercritical steam process, extraction plant burning coal
- DH Electric Boiler: Electric boiler
- Gas-motor, Natural Gas: Spark ignition engine burning natural gas
- Wood Chip CHP: Combined heat and power plant burning wood chips. The boiler in the plant is a circulating fluid bed boiler (CFB) producing steam to be used in a subsequent back-pressure or an extraction steam turbine.
- Wood Pellet CHP: Combined heat and power plant burning wood pellets. The boiler in the plant is a circulating fluid bed boiler (CFB) producing steam to be used in a subsequent back-pressure an extraction steam turbine.

Table 8: Cluster 3 – Boilers and mCHP for individual heating, France.

LCOH & costs elements	Unit	Biomass boilers, auto stoking	Biomass boilers, manual stoking	Coal boilers	DH substa-tion, direct	DH substa-tion, indirect	Gas heat pump, absorp-tion	LT-PEMFC mCHP, hydro-gen	LT-PEMFC mCHP, natural gas	Natural gas or bio, conden-sing	Natural gas or bio, not conden-sing	Oil-fired boiler, bio-conden-sing	Oil-fired boiler, gas-conden-sing	Oil-fired boiler, bio non-conden-sing	Oil-fired boiler, gas non-conden-sing	SOFC mCHP	Wood stove combin-ed	Wood stove space heating only
LCOH, all climate zones	€c/kWh	8.6	12.2	6.4	4.3	4.5	7.0	104.7	52.5	6.6	7.6	13.4	9.6	13.9	10.1	137.2	9.5	9.5
Specific investment	k€/kW	0.4	0.0	0.2	0.1	0.1	0.2	1.7	1.4	0.1	0.4	0.3	0.2	0.3	0.2	3.7	0.1	0.1
Fixed O&M	€/kW/year	17.7	3.2	4.0	1.5	1.6	2.4	220.3	148.1	7.1	6.4	6.2	6.6	5.6	5.9	413.0	3.6	6.4
Variable O&M incl. auxiliary electricity consumption	€/MWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.3	7.8	13.7	7.0	0.0	0.0	0.0
Energy carrier price	€/MWh	51.7	51.7	39.3	40.0	40.0	53.9	120.0	53.9	53.9	53.9	93.5	71.9	93.5	71.9	53.9	46.6	46.6

Abbreviations used in the table:

- Biomass boilers, auto stoking: Non-condensing boiler automatic stoking burning wood pellets
- Biomass boilers, manual stoking: Non-condensing boiler manual stoking burning wood pellets
- Coal boilers: Non-condensing boiler automatic stoking burning coal
- DH substation, indirect: In direct district heating substation including heat exchangers for space heating and for domestic hot water. Please notice that the energy carrier price (district heating delivered to the building) varies substantially depending on the technology and district heating system, see also Table 6 and 7. The energy carrier price in the table has been used as exemplary case.
- DH substation, direct: Direct district heating substation including heat exchangers for domestic hot water heating but not for space heating. Please see the comment for DH substation, indirect regarding energy carrier price.
- Gas heat pump, absorption: Gas absorption heat pumps “thermally driven heat pumps” using gas both as source of heat to be upgraded and as energy source to drive the heat pump process.
- LT-PEMFC mCHP, hydrogen: Low Temperature PEM Fuel Cells in micro Combined Heat and Power plant burning hydrogen, delivering less than 0.5% of the space heating and app. 1 % of domestic hot water. Please notice that the energy carrier price (hydrogen) is very uncertain. It has been based on Table 16.
- LT-PEMFC mCHP, natural gas: Low Temperature PEM Fuel Cells in micro Combined Heat and Power plant burning natural gas, delivering less than 0.5% of the space heating and app. 1 % of domestic hot water
- Natural gas or bio, condensing: Condensing boiler burning natural gas or biogas
- Natural gas or bio, not condensing: Non-condensing boiler burning natural gas or biogas
- Oil-fired boiler, gas-condensing: Condensing boiler pressure atomisation burner burning gas-oil
- Oil-fired boiler, bio-condensing: Condensing boiler pressure atomisation burner burning bio-oil
- Oil-fired boiler, gas-non-condensing: Non-condensing boiler pressure atomisation burner burning gas-oil
- Oil-fired boiler, bio-non-condensing: Non-condensing boiler pressure atomisation burner burning bio-oil
- SOFC mCHP: Solid oxide fuel cell micro combined heat and power systems fuelled by natural gas or biogas, delivering less than 0.5% of the space heating and app.1 % of domestic hot water
- Wood stove combined: Wood stove with water tank burning wood logs, delivering app. 45% of the space heating app. 20 % of domestic hot water
- Wood stove space heating only: Wood stove without water tank burning wood logs, delivering app. 40% of the space heating

Table 9: Cluster 4 - Heat pumps, direct electric and thermal solar space and combination heaters for individual heating, France.

LCOH & costs elements	Unit	Air-to-air heat pump	Air-to-water heat pump	Electric heating	Ground-to-water heat pump	Solar Heating	Ventila-tion heat pump
LCOH, average climate zone, 35 C, low %DHW	€c/kWh	4.7	7.0	12.9	8.7	n.a	7.7
LCOH, average climate zone, 55 C, low %DHW	€c/kWh	4.7	7.6	12.9	9.3	n.a	8.4
LCOH, colder climate zone, 35 C, low %DHW	€c/kWh	5.1	7.5	12.9	8.8	n.a	8.1
LCOH, colder climate zone, 55 C, low %DHW	€c/kWh	5.2	8.2	12.9	9.5	n.a	9.1
LCOH, warm climate zone, 35 C, low %DHW	€c/kWh	4.2	6.5	12.9	8.3	n.a	7.0
LCOH, warm climate zone, 55 C, low %DHW	€c/kWh	4.3	7.1	12.9	9.0	n.a	7.8
LCOH, average climate zone, 35 C, high %DHW	€c/kWh	n.a	7.5	12.9	9.2	1.7	7.9
LCOH, average climate zone, 55 C, high %DHW	€c/kWh	n.a	7.9	12.9	9.7	1.7	8.4
LCOH, colder climate zone, 35 C, high %DHW	€c/kWh	n.a	7.9	12.9	9.4	1.9	8.4
LCOH, colder climate zone, 55 C, high %DHW	€c/kWh	n.a	8.6	12.9	10.0	1.9	9.1
LCOH, warm climate zone, 35 C, high %DHW	€c/kWh	n.a	6.8	12.9	8.8	1.2	7.3
LCOH, warm climate zone, 55 C, high %DHW	€c/kWh	n.a	7.4	12.9	9.4	1.2	7.8
Specific investment	k€/unit	4.6	13.8	0.3	23.0	10.2	5.1
Fixed O&M	€/unit/year	73	251	0	479	80	308
Variable O&M excl. auxiliary electricity consumption	€/MWh	0.0	0.2	0.0	0.2	0.0	0.0
Energy carrier price	€/MWh	119.0	119.0	119.0	119.0	0.0	119.0

Abbreviations used in the table above:

- Air-to-air heat pump: Electric compression heat pump drawing heat from the ambient air and supply heat locally through an air heat exchanger, only delivering space heating
- Air-to-water heat pump: Electric compression heat pump drawing heat from the ambient air and supply heat supply heat through a water-based distribution system

- Ground-to-water heat pump: Electric compression heat pump drawing heat from the ground (ambient heat) and supply heat supply heat through a water-based distribution system
- Solar heating: The cost of individual solar thermal is without storage solutions and for covering part of the domestic hot water demand.
- Ventilation heat pump: Electric compression heat pump drawing heat from the ventilation outlet air and supply heat through a water-based distribution system or to the air intake in the ventilation system, delivering app 80% of the space heating and 90% of domestic hot water
- Electric heating: Electric radiators mounted in each room or electric floor heating, only delivering space heating
- n.a.: Not available

Table 10: Cluster 5 - Water heaters for domestic hot water, France.

LCOH & costs elements	Unit	EIWH	ESWH	GIWH_con	GIWH_non_con	GSHP ground source	GSWH_con	GSWH_non_con	HPWH air	HPWH ventila-tion	SOL
LCOH, cold climate zone	€c/kWh	12.6	15.7	6.1	6.7	4.9	7.5	7.2	8.2	6.5	1.9
LCOH, average climate zone	€c/kWh	12.6	15.7	6.1	6.7	4.0	7.5	7.2	6.6	5.9	1.7
LCOH, warm climate zone	€c/kWh	12.6	15.7	6.1	6.7	3.5	7.5	7.2	5.7	5.6	1.2
Specific investment	k€/unit	0.7	1.3	1.3	1.0	3.9	2.1	1.7	2.6	2.9	10.2
Fixed O&M	€/unit/year	18.0	39.3	63.3	50.6	98.2	69.9	55.9	87.3	98.2	79.6
Variable O&M excl. auxiliary electricity consumption	€/MWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy carrier price	€/MWh	119.0	119.0	53.9	53.9	119.0	53.9	53.9	119.0	119.0	0.0

Abbreviations used in the table:

- EIWH: Electric resistance instantaneous water heaters
- GIWH_non_con: Gas-fired instantaneous non-condensing water heaters
- GIWH_con: Gas-fired instantaneous condensing water heaters
- ESWH: Electric resistance, storage types water heaters
- GSWH_non_con: Gas-fired storage water heaters non-condensing water heaters
- GSWH_con: Gas-fired storage water heaters condensing water heaters
- HPWH air: Air to water heat pump water heaters Electric compression HP drawing heat from the ambient air
- HPWH ventilation: Ventilation air heat pump water heaters, electric compression HP drawing heat from the ventilation outlet air
- GSHP ground source: Ground source heat pump water heaters, electric compression HP drawing heat from the ground (ambient heat)
- SOL: The cost of individual solar thermal is without storage solutions and for covering part of the domestic hot water demand.

3.3. Provide a Description of the heat supply sectors of individual EU Member States

3.3.1. Objective

The main objective of this part of the study is to develop summaries (country files) for the status-quo of space and water heating in all EU member states including the EU-27 aggregate. The summary country files are country specific and include information on the energy consumption for space and water heating, the technology distribution, building structure as well as the regulatory framework in place. The EU-27 aggregated fact sheet provides a condensed presentation including those figures and indicators where an aggregation is feasible and reasonable.

3.3.2. Structure

The information provided for each country is divided into three parts. The content and data sources for each part are explained in the following.

Part 1: Heat demand structure and energy use for heat supply

The information shown in this part is mainly based on the data collected or calculated in Task 1. For this part, the following key data is included in the country reports:

- **Building stock data:** including the total floor area of the buildings in each sector (Residential, Commercial & public services and Industry). For residential buildings the data is further detailed for the main building types (SFH and MFH), by number of dwellings and total floor area for each type. The age classification of residential buildings is also covered in this part. In summary, this data will provide an overview of the building structure, a central determinant of any heating and cooling transition. The main consulted sources are the Building Stock Observatory, the ODYSSEE database, and the Hotmaps project.
- **Climate data:** comparing the heating degree days (HDD) in the addressed country in comparison with the EU-27 average. Data is taken from Eurostat [nrg_chdd_a].
- **Overview of energy demand:** the FED for space and water heating in each sector as well as the total FED compared to other end uses is shown here. Further the share of each energy carrier in final and primary energy demand is illustrated. In total, this will provide an overview of the energy mix used to provide space heating. Several national and EU sources and statistics have been used to provide the framework data needed to calculate the energy balances. The main data sources include Eurostat [nrg_bal] and [nrg_chdd_a], the TABULA and ODYSSEE databases, the Hotmaps project and the Building Stock Observatory. Eurostat energy balances are the major input and framework for the data set.
- **Generation mix:** the primary fuel mix for electricity and district heating generation by quantities of the type of fuels. The Eurostat energy balances [nrg_bal] are the main primary data source for this part.
- **Space and water heating in the residential buildings sector:** covering the energy demand in the household sector including FED by end use, FED for space and water heating by energy carrier, specific final and primary energy demand by the main building types (SFH and MFH). Data sources are similar to the overview of energy demand and building stock data above.

Part 2: Technology stock

The input for this part is mainly the output data from Task 2. The heating technologies are categorized in “district heating supply” and “individual heating systems” and are shown in different graphs. The following key data is included in the country reports:

- **Technology mix:** illustrates the data on the heating equipment stock by installed capacities and the age of the technologies. The data are based primarily on the Danish Technology Catalogues and the economic parameters are scaled relative to the Danish prices for each country. The investment cost based on the catalogues is the overnight cost.
- **Levelised cost of heat:** compares the costs of heat generation for different heating technologies. The levelised cost of heat (LCOH) is calculated for each country, with and without taxes, and for different climate zones and required supply temperatures. The LCOH for district heating describes the cost of supply and does not contain distribution costs.

  The LCOH is calculated by adding up the discounted investment costs, fuel costs, auxiliary electric costs, O&M costs and dividing the total by the discounted heat production over the technology’s lifetime. Revenues from generated electricity are subtracted before dividing by the discounted heat production. The electricity spot price is used for combined heat and power plants (CHPs). The retail electricity price is used for individual technologies.
- **Stock of district heating technologies:** the stock of district heating technologies, excluding electricity generating technologies, is estimated based on the development in gross heat production (GHP) from 2012 to 2018. The stock from *Mapping and analyses of the current and future (2020 – 2030) heating/cooling fuel deployment (fossil/renewables)* is aggregated into the technology categories used in this analysis and scaled with the difference in GHP. The stock of geothermal, solar thermal, and heat pumps is based on recent reviews of large-scale installations.
- **Stock of individual technologies:** is based on sales data from ecodesign studies, market statistics, previous heating and cooling studies, and the FED from part 1. The heat pump stock is taken from the European Heat Pump Association’s 2019 annual report. The stock of non-solid oil and gas boilers is based on an ecodesign study for *Space and combination heaters* that provided recent stock numbers and sales data for the European Union. The stock of solid fuel boilers is largely based on the FED in the residential sector combined with climate zone-specific full-load hours and average capacities to determine the total installed capacity and the stock. To determine the distribution of the FED of biomass, the stock of individual biomass stoves from *Mapping and analyses of the current and future (2020 – 2030) heating/cooling fuel deployment (fossil/renewables)* was used to remove their share from the FED, and it is then assumed that the rest of the FED is covered by biomass boilers.

Part 3: Policies and historical trends

For this part, the following key data is included in the country reports:

- **Overview of Policies:** covering past and existing policies for heating, renewable heating and for the decarbonisation of heat, including regulatory (e.g. zoning), building regulation, fuel taxes and other fiscal and financial measures, such as carbon taxes, support measures, the distribution of regulatory and policy responsibilities at national, regional and local levels. The overview is based on literature review, desk research and the key databases shown in

- Table 11.
- **Historical trends:** following indicators are selected to show the historical developments of the heat sector. Data for this part is extracted from Eurostat.
    - RES-H shares in heating and cooling 2004-2017: They show the evolution of renewables in total heating and cooling energy demand. Note that by including process heating, this indicator goes beyond space heating. However, as space heating has the highest share in total heating, the trends give an important indication for space heating. Data is collected from Eurostat [nrg_ind_ren].
    - Energy carrier shares in household sector 2000-2017: The evolution of energy carrier shares in the household sector shows important structural shifts, like gaining market shares of natural gas or renewable energies. Note that also this indicator has a little broader scope than only space heating, as it also includes electricity consumption (mostly for non-heating end-uses) and gas use for stoves. However, space heating accounts for the major share of most energy carriers and results show robust trends for space heating. This indicator can also be used to explain changes observed in the above RES-H indicator. Eurostat [nrg_bal_c] is used as the data source.
    - Energy carrier shares in gross heat production of district heating 2000-2017. As district heating is mainly used for space heating, this indicator provides a good overview of structural changes in the upstream heat supply, ultimately affecting primary energy and embodied CO^2 emissions in space heating. The data source for this part is Eurostat [nrg_bal_peh].

Table 11: Selected data sources for the analysis of policies addressing heating, renewable heating and for the decarbonisation of heat in the EU Member States.

RES-Legal database[8]	The RES-Legal database provides information on the important legislation, the support schemes, grid issues and policies for energy from renewable sources covering all three energy sectors: electricity, heating & cooling and transport. The geographical scope is the EU 28 Member States, the EFTA Countries and the Members of the Energy Community.
MURE database[9]	MURE (Mesures d'Utilisation Rationnelle de l'Energie) provides information on energy efficiency policies and measures that have been carried out in the Member States of the European Union. It further covers measures addressing renewable energy in buildings.
The IEA/IRENA Global Renewable Energy Policies and Measures Database[10]	The IEA/IRENA Global Renewable Energy Policies and Measures Database provides information on policies and measures taken or planned to encourage the uptake of renewable energy in all IEA and IRENA Member countries and signatories.
The IEA Energy Efficiency Policies and Measures Database[11]	The Energy Efficiency Policies and Measures database provides information on policies and measures taken or planned to improve energy efficiency.
Comprehensive assessments of the potential for efficient heating and cooling[12]	The comprehensive assessments of the potential for efficient heating and cooling includes, among others, information on policies and strategies in the EU MS.
The National energy and climate plans (NECPs)[13]	The NECPs provide information on existing policies and strategies to address the decarbonisation of H&C

[8] http://www.res-legal.eu/home/

[9] http://www.measures-odyssee-mure.eu/

[10] https://www.iea.org/policiesandmeasures/renewableenergy/

[11] https://www.iea.org/policiesandmeasures/energyefficiency/

[12] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0826&from=EN

[13] https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en?redir=1

4. Decarbonisation Scenarios for Space and Water Heating

Under WP2, we developed a baseline scenario and a series of technology-focused decarbonisation scenarios of the sector until 2050. Subsequently, we carried out a comparative assessment and derived a "best-case" scenario.

We start with a short description of the methodological framework[14], before we document the scenario framework conditions as well as the scenario specifications. Finally, we explain results for the technology-focused scenarios and the best-case scenario in the form of an aggregated cross-scenario comparison, followed by some selected, more detailed exemplary sectoral results. More detailed cross country comparison can be found in the spreadsheet files provided for selected result parameters.[15]

4.1. Method, Models and Model interfaces

We apply three bottom-up models: Invert, Enertile and the Hotmaps district heating model. The building stock simulation model *Invert* provides demand for space heating and hot water (both individual and district heating), the mix of individual supply solutions and corresponding load profiles[16]. The model *Invert* is applied in two versions (see also description in chapter 3.1.2):

- *Invert/EE-Lab,* which is a simulation model, delivering pathways of the space heating and hot water sector under different framework conditions. It is applied for the baseline scenario (task 4).
- *Invert/Opt,* which is an optimization model, delivering cost-optimal combinations of heat supply and heat saving measures. It will be applied for the decarbonisation scenarios (task 5-9).

The load profile module within Invert/EE-Lab builds on the database of the model e-load (Boßmann 2015) and provides hourly profiles, by such representing the seasonal and daily variations of heat demand and related fuel or energy consumption.

The energy system optimisation model *Enertile* covers the link to the upstream supply sector (i.e. electricity, district heating, H2 and e-fuel supply) on an hourly basis. This will include analysing the implications on the electricity transmission grid as well as district heating, hydrogen, and e-fuel generation.

For8 district heating grid expansion the consortium builds on the *Hotmaps district heating model* (Fallahnejad et al. 2018)[17]. This model calculates the investment needs related to the expansion and development of district heating infrastructure and derives the optimal district heating size associated with different input data and restrictions. As the model calculates on a hectare-level resolution for all EU countries, it is able to capture very specific local situations with regard to heat demands. The spatial distribution of the heat demand uses the Hotmaps European heat density map on hectare level (Müller et al. 2019).

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[14] More details on the applied models and related assumptions are provided in the annex.

[15] The WP2 datafiles include results on final and primary energy demand for space and water heating by energy carrier and country as well as cot data (EU-27 by Member State).

[16] Load profiles are provided by making use of the database of the model e-load. (Boßmann 2015)

[17] Fallahnejad et al. 2018 For the online version see also: The Hotmaps Toolbox: https://www.hotmaps.hevs.ch/ and https://gitlab.com/hotmaps/heat

Regarding the gas-grid, previous analyses from the H2020 project SET-Nav (TU Wien, Fraunhofer ISI, Comillas 2019b, 2019a) have shown that in most decarbonisation scenarios it will be economical to dismantle parts of the gas grid. We base our analysis framework on these insights. For the scenarios in task 7 (e-fuels and H2) we carry out a rigorous literature review regarding costs and implications of corresponding distribution and transport infrastructure. In areas without gas grid, we explore the supply of e-fuels or H2 embedded in liquid fuels.

By combining these models, we are able to meaningfully, rationally and scientifically answer questions such as "How does heating system choice affect optimal renovation activities, costs, investment needs, primary energy use, GHG emissions as well as primary and final energy efficiency?".

4.1.1. Model overview and linkage

The interactions between Invert, the Hotmaps district heating model and Enertile are established and the models were already used in European and national projects[18]. The data exchange between Invert/EE-Lab and Enertile is documented in the annex; the Hotmaps district heating model has been developed with a direct interface to the Invert model, which has been applied in the Hotmaps project.

The model results allow to compare the scenarios with regard to additional costs, GHG reduction, energy savings as well as primary and final energy efficiency. Additionally, we can assess the impact of the additional demand for electricity, hydrogen, e-fuels and district heat on:

- necessary capacity expansion in the electricity sector
- necessary electricity transmission grid deployment
- investments in the electricity sector
- GHG-emissions from both buildings and electricity sectors

The following Figure 20 describes the model framework, interfaces and outputs. The numbers in the boxes indicate the order of steps in the modelling process. As explained above, the model Invert is used in two different versions in the baseline and in the decarbonisation focus scenarios.

[18] e.g. the H2020 project Set-Nav or the project „ Long-term energy scenario study for Germany"

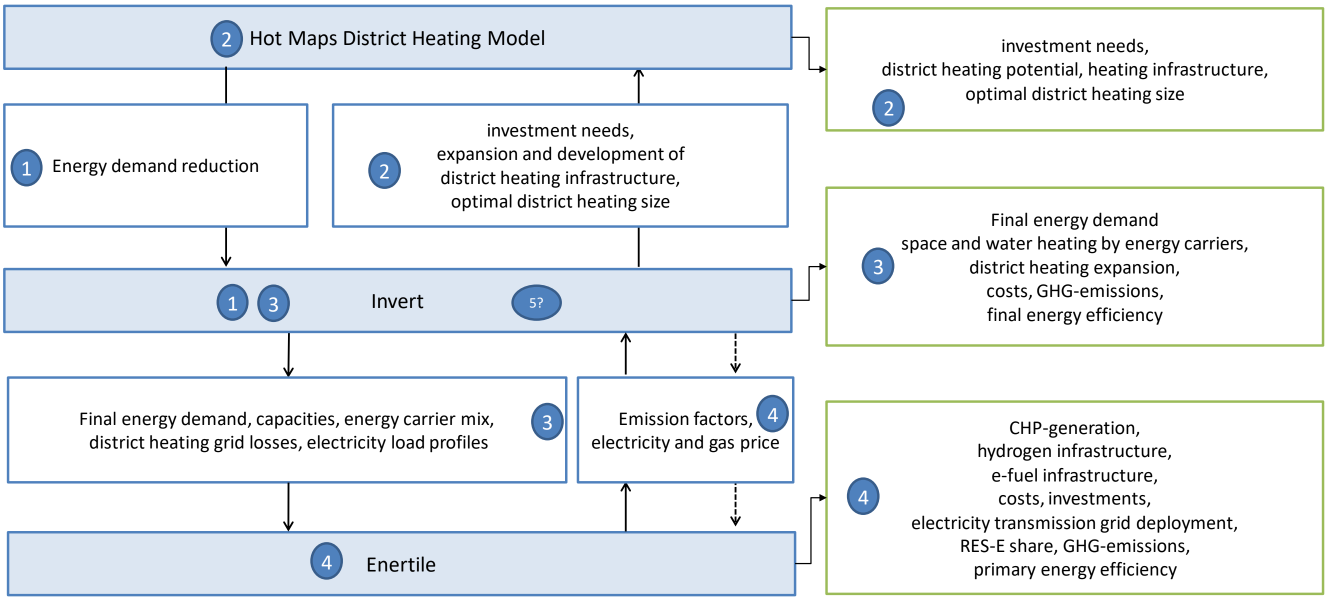


Figure 20: Model overview and interfaces.

A more detailed description of the models can be found in the Annex 7.2.

4.1.2. Indicators and presentation of key results

Finally, the outputs of the model chain described above are used to derive the following indicators as key results of the analysis:

- Costs:
    - Total system costs, including (and distinguished by) capital costs, operation and maintenance and variable energy costs. Costs are displayed as cumulative costs for the periods 2021-2030, 2021-2040 and 2021-2050.
    - Investment needs
- Required installed capacities by technologies and used energy carriers
- Primary, final and useful energy demand used by energy carrier, end-use and sector.
    - Primary and final energy efficiency
    - Useful, final and primary energy savings compared to the base year and compared to the baseline scenario
- GHG-emissions
    - GHG emission reduction compared to the base year and compared to the baseline scenario (only direct emissions).
- Seasonal and daily variations, in particular resulting peak loads during different seasons throughout the year.

Table 35 in the Annex indicates which model derives which of the indicators and in which sectoral split they are provided.

4.2. Framework conditions

In this section, we describe the general framework conditions for the scenario analysis. In order to allow a comparison between the decarbonisation scenarios, we define a consistent set of framework data. In the following paragraphs, the central assumptions for overall framework conditions are presented. These include general input data like fossil fuel prices, demand for electricity, hydrogen and e-fuels in other sectors (not including space heating and hot water applications), and electricity grid expansion.

4.2.1. General input data

In Enertile, the optimal portfolio of technologies to supply electricity, heat, hydrogen and e-fuel demand is determined. In this cost-optimization the **interest rate** largely influences the capital costs of the different technologies. In reality, the imputed interest rate of an investment depends on many different factors, including the risk assessment of investors and lenders. A very safe investment has lower risk premiums than a high-risk investment. However, the use of different interest rates for different technologies would greatly distort the comparison between individual technologies. The different return requirements would thus have a strong influence on the results of the models and would, for example, favour certain technology options over others in the optimisation process. In order to achieve fair competition among the technologies, a uniform interest rate of 2% is assumed for all technologies in the modelling of electricity, heat grid, hydrogen and e-fuels supply in Enertile and in the modelling of the building sector in Invert. The low interest rate of 2% is based on the assumption that the low interest rate in the euro area will continue for a longer period of time. The depreciation time for building renovation is set at 30 years, for heating systems at 20 years.

The level of **fuel prices** and their relative relationship to each other have a direct impact on the decisions of the models, making fuel prices one of the key input data of energy system modelling. Fossil fuel prices, which are given in Table 12, are based on the IEA sustainable development scenario of the WEO 2019 (World Energy Outlook 2019). Figure 21 shows assumed fossil fuel prices in this study based on the World Energy Outlook 2019 (solid lines) as well as fossil fuel price developments of the recently published Global Energy and Climate Outlook 2019 in a reference (thick dashes) and a 2°C (fine dashes) context. While assumed fossil fuel prices based on the sustainable development scenario of the World Energy Outlook 2019 remain stable or show a slight decrease until 2050, fossil fuel prices in the Global Energy and Climate Outlook 2019 remain stable or slightly increase for 2°C scenarios.

Table 12: Fossil fuel prices in this study based on WEO 2019 sustainable energy scenario.

Fuel price in €$_{2018}$/MWh	2018	2020	2025	2030	2035	2040	2045	2050
Crude oil	35.4	34.6	33.8	32.3	31.5	30.7	30.0	29.2
Natural gas	22.0	21.9	21.8	21.7	21.7	21.7	21.7	21.7
Steam coal	9.6	8.7	7.8	6.0	6.1	6.2	6.4	6.5

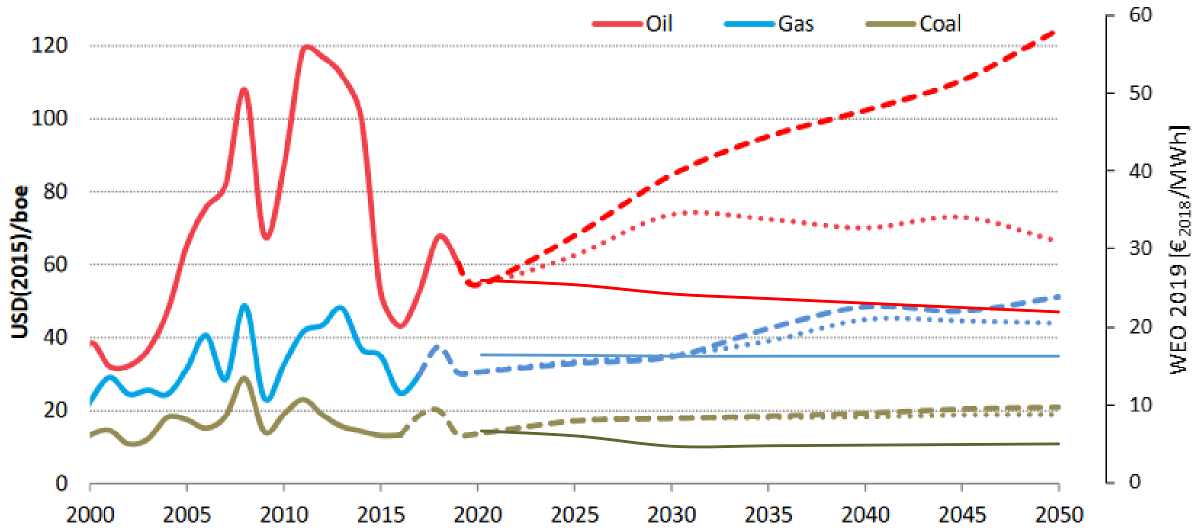


Figure 21: Fossil fuel prices in the Global Energy and Climate Outlook 2019 in USD[2015]/boe for Reference (thick dashes) and 2°C-Medium (fine dashes) scenarios and IEA sustainable development scenario of the World Energy Outlook 2019 (solid line [€$_{2018}$/MWh]).

Besides fossil fuel prices, prices for electricity and electricity-based fuel supply (green gases) and district heat supply are modelled endogenously in Enertile. Within this optimisation, a decreasing carbon budget is implemented to reflect the overall aim of reaching carbon neutrality by 2050 in all sectors.

4.2.2. Demand for electricity, hydrogen and e-fuels

The demand for district heating from buildings as well as the demand for electricity, hydrogen and e-fuels from heating applications is endogenously calculated by the model Invert for each scenario and used as input for Enertile. The development of electricity, hydrogen and e-fuels in other sectors needs to be assumed exogenously, as Enertile optimizes the supply for all sectors and captures inter-sectoral effects and competition for CO2-neutral energy carriers. As all sectors need to reach a carbon neutral energy supply by 2050, they compete for cheap low-carbon energy supply. While energy needs for space heating will be modelled in detail in the different scenarios, the energy needs for all other sectors are held constant between those scenarios to ensure comparability and interpretability of differences between the scenarios.

The following figures show the assumed energy demand from other sectors. The datasets are based on total numbers in 2050 for Europe according to the 1.5TECH scenario (European Commission). Unfortunately, the data publicly available from the 1.5TECH is limited to overall values for Europe in 2050. Thereby this leaves important data gaps for our scenario assessment as demand values before 2050 are missing and each European country is modelled separately in this study. Therefore, these gaps are filled by using other sources for the development before 2050 and the demand distribution between European countries. The national distribution and the development until 2050 is based on the SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b).

In the SET-Nav project, four different development paths for the strong decarbonisation of the European energy supply have been investigated. The "Diversification Pathway" is characterised by a comparatively high demand. Figure 22 shows the development of total electricity demand in other sectors and the electricity demand in 2050 per country. The total electricity demand for transport in 2050 (603 TWh) corresponds to the 1.5TECH scenario. The demand share of electric vehicles (76 %) and the demand development until 2050 is based on the SET-

Nav "Diversification Pathway". The other electricity demand share in the transport sector is attributed to trains, trolley trucks and trolley busses. The national distribution of the electricity demand in the transport sector is based on the distribution of demand in the "Diversification Pathway". The electricity demand from other sectors apart from heating and transport is directly taken from the "Diversification Pathway". Figure 23 shows the development of total hydrogen, e-gas and e-liquid demand in other sectors and the demand in 2050 per country. Again, the total demand values in 2050 correspond to the 1.5TECH scenario: 707 TWh hydrogen, 266 TWh e-gas and 473 TWh e-liquids. The development until 2050 and the national distribution of demand is based on the hydrogen demand in the "Diversification Pathway". Table 40 and Table 41 in section 7.4.2.1 show the assumed demand values from 2030 until 2050 per country.

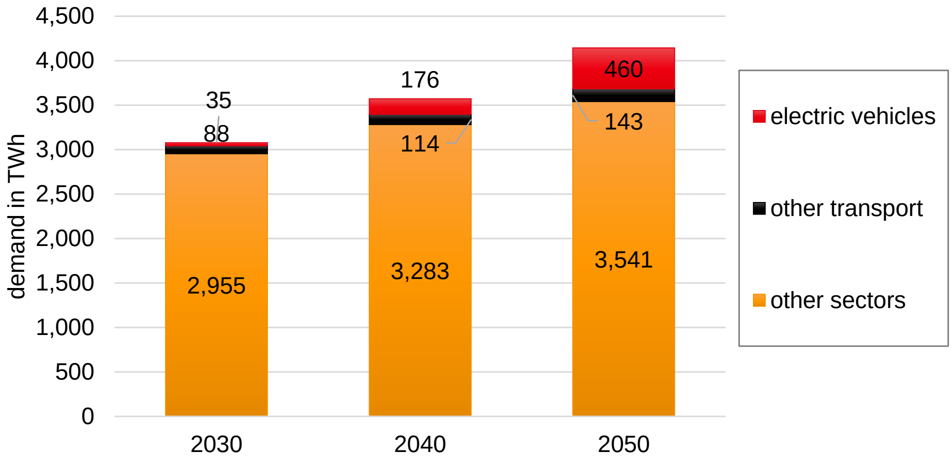


Figure 22: Development of electricity demand in other sectors (i.e. all sectors excluding space and water heating) from 2030 until 2050, EU-27 +UK, CH, NO (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

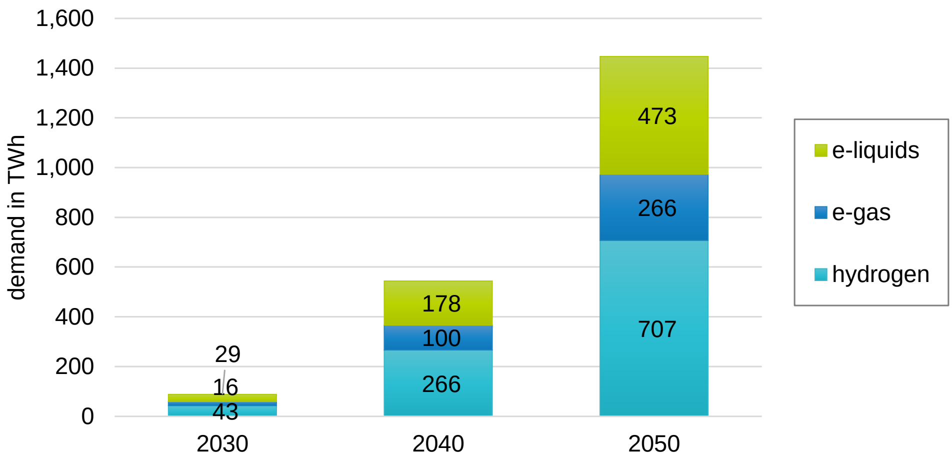


Figure 23: Development of hydrogen, e-gas and e-liquids demand in other sectors (i.e. all sectors excluding space and water heating) from 2030 until 2050, EU-27 +UK, CH, NO (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

4.2.3. Expansion of the electricity grid

The electricity transmission grid offers flexibility for the energy system by providing opportunities for inter-regional balancing, which is particularly important when the share of renewable energies in the system is high. Enertile models the transmission of electricity between different model regions using a model of net transfer capacities (NTCs). These transfer capacities limit the possible electricity exchange between model regions. In all scenarios we assume that the reference grid of 2027 from the current Ten Year Network Development Plan (TYNDP) of ENTSO-E is implemented as a minimum status for the transmission grid in 2030 (ENTSO-E 2018).The expansion of these initial transfer capacities is part of the optimization with Enertile taking into account required investments and occurring grid losses. A new TYNDP was recently published in autumn 2020, but the detailed data for cross border capacities of the reference grid have not yet been published. Therefore, the TYNDP 2020 cannot be used in this project. Details on allowed expansion is given in section 7.4.2.7.

4.2.4. Role of Carbon Capture and Storage (CCS)

In general there are two options to define the role of CCS in the scenarios reflecting slightly different levels of public acceptance:

1. CCS is not available for fossil fuel based electricity generation as CCS as well as CCU associated with biomass is reserved for negative emissions to reach carbon neutrality.
2. CCS is available for electricity generation at relatively high costs, but will not play a major role in the transformation sector.

Within this project, we favour the first option and consequently used this approach. This option is in line with results of the 1.5LIFE scenario, while the 1.5TECH scenario relies on CCS associated with biomass as well as fossil fuels.

4.2.5. Carbon budget for energy supply

There are two options to ensure that electricity and district heat supply is low-carbon in the short term and carbon-neutral in the long term. Either, a strongly increasing carbon price is assumed to ensure that renewables become increasingly competitive and in the end replace fossil power plants. Alternatively, a strongly decreasing carbon budget is assumed to achieve the same result. Within this optimisation a decreasing carbon budget is implemented to reflect the overall aim of reaching carbon neutrality by 2050 in all sectors. Using a carbon budget assures comparability between the different decarbonisation scenarios and therefore this approach is used in this project. The carbon budget includes all CO_2-emissions to the atmosphere from the electricity and district heat supply in Europe and serves as an upper bound. The assumed carbon budget for the scenarios and years are given in the table below. The value for 2030 considers the Commission's proposal to cut greenhouse gas emissions by at least 55% by 2030. All scenarios are ambitious decarbonisation scenarios aiming for climate-neutrality by 2050 and the budget is therefore drastically reduced to 5 Mt of CO_2 in 2050.

Table 13: Carbon budget for electricity and district heat supply and emission reduction compared to 1990 values (1500 Mt CO_2).

	2030		2040		2050	
All scenarios	**Mt CO_2**	**Reduction**	**Mt CO_2**	**Reduction**	**Mt CO_2**	**Reduction**

	675	55%	150	90%	5	100% (99.67%)

4.2.6. Climate and weather data

Since weather data and in particular temperature and heating degree days (HDD) are highly fluctuating from year to year, we used the long-term average of temperature data (1995-2015). Regarding expected climate change in particular regarding decrease of HDD, for the year 2050 we apply a linear regression of HDD data on member state level, because no resources for the work on climate scenarios was foreseen in this project. For the extrapolation until the year 2050 we assume an equally weighted average of constant HDDs (average 1995-2015) and this linear regression approach. Within Enertile long-term average solar radiation, wind speed as well as temperature data is used to assess costs and generation potentials for renewable electricity.

4.3. Scenario specification

Under WP2, we prepare a baseline scenario and several space heating decarbonisation scenarios until 2050. The baseline establishes a scenario with a representation of current policies in place. For this purpose, we assume that the clean energy package, including targets will be implemented in MSs, even if this currently is not yet the case. So, we assume the clean energy package as the "current policies" is in place and targets for 2030 will be achieved. The other space heating decarbonisation scenarios will focus on specific technology pathways.

We want to emphasize that none of these technology-focused scenarios specified in tasks 5-8 below are "pure" scenarios, focusing 100% on only one technology (or even group of technologies). In each scenario, all main technologies are represented, however with a different focus. The mix of technologies also considers the spatial/geographical differences and existing infrastructure between and within the considered countries.

We consider this as a special asset of the presented scenarios: they all represent pathways which – from the current perspective – might be considered as realistic in the sense that they respect certain country and technology specific barriers and constraints.

The geographical coverage of the scenarios is the EU-27 and its Member States, and UK, Norway, Switzerland and Iceland.

Table 14 shows an overview of the key scenario settings. Each cell in the table represents a certain assumption how the scenarios will be designed, either via exogenous determination of model parameters (e.g. limited biomass potentials under the electrification scenario) or via endogenous optimisation (e.g. determining the optimal efficiency levels for thermal efficiency improvement of buildings or the optimised scaling of heat pumps in the district heating sector). The quantitative implementation of these assumptions in the models is described below in this chapter and in the Annex 7.4.

The best case scenario (last column in Table 14) was defined after developing the technology focus scenarios and also considering the analysis of barriers (chapter 5). The insights from these analyses have been used to determine the settings of this scenario. The overall considerations for the design of the best case scenario are that the costs of the scenarios are not sufficiently different to allow a purely cost-based decision. Rather, barriers, uncertainties and policy implications should be considered as important additional decision criteria. According to the analysis in chapter 5, the scenario with the highest uncertainties and barriers is the H2 scenario. In particular, this refers also to the need for H2 import. Having said that, the H2 scenario is not the cheapest scenario. Thus, the study team proposes to exclude H2 in the best-case scenario[19]. Due to the fact that existing district heating infrastructure at least in many cases remains a relevant capital stock, we assume that this infrastructure remains at least partly in place. The other technology options are optimized without strong restrictions.

Table 14: Overview of key scenario settings.

<table>
<tr><th></th><th></th><th>Baseline</th><th>Direct RES-H</th><th>Electrification</th><th>e-fuels</th><th>H2</th><th>District heating</th><th>Best-Case</th></tr>
<tr><th></th><th></th><th>Task 4</th><th>Task 5</th><th>Task 6</th><th>Task 7.1</th><th>Task 7.2</th><th>Task 8</th><th>Task 9</th></tr>
<tr><td rowspan="7">Buildings (*)</td><td>Efficiency of building envelope</td><td>Baseline policies</td><td colspan="6">Optimised</td></tr>
<tr><td>Biomass</td><td>Baseline assumptions</td><td>upper boundary: high; lower boundary: none; full resource potentials</td><td colspan="3">upper boundary: moderate; lower boundary: none; moderate resource potentials</td><td>upper boundary: low; lower boundary: none; low resource potentials (**)</td><td>upper boundary: moderate; lower boundary: none; between moderate and low resource potentials</td></tr>
<tr><td>Solar thermal</td><td rowspan="3">Baseline policies</td><td>upper boundary: high; lower boundary: none</td><td colspan="3">upper boundary: low; lower boundary: none</td><td>upper boundary: high; lower boundary: none</td><td>upper boundary: moderate; lower boundary: none</td></tr>
<tr><td>Direct electric heating</td><td rowspan="2">upper boundary: moderate; lower boundary: none</td><td rowspan="2">upper boundary: high; lower boundary: high</td><td colspan="3" rowspan="2">upper boundary: moderate; lower boundary: none</td><td rowspan="2">upper boundary: high; lower boundary: low</td></tr>
<tr><td>Heat pumps</td></tr>
<tr><td>Gas based heating systems</td><td>Baseline policies</td><td colspan="2">upper boundary: moderate; lower boundary: none</td><td>upper boundary: high; lower boundary: high</td><td>upper boundary: high; lower boundary: high</td><td>upper boundary: moderate; lower boundary: none</td><td>upper boundary: low; lower boundary: none</td></tr>
<tr><td>Liquid fuel heating systems</td><td>Baseline policies</td><td colspan="2">upper boundary: low; lower boundary: none</td><td>upper boundary: high; lower boundary: moderate</td><td colspan="3">upper boundary: low; lower boundary: none</td></tr>
</table>

[19] This assumption is confirmed by the publication Deloitte Finance et al (2021), which sees only a very limited role of hydrogen in buildings in future scenarios, while very high hydrogen demand is proposed in industry and transport.

		Baseline	Direct RES-H	Electrification	e-fuels	H2	District heating	Best-Case
		Task 4	Task 5	Task 6	Task 7.1	Task 7.2	Task 8	Task 9
District heating	Expansion potential of grid	Baseline policies	upper boundary: moderate; lower boundary: none				upper boundary: high; lower boundary: high	upper boundary: high; lower boundary: none
	Biomass	Baseline assumptions	optimised under moderate reduction of resource potentials	optimised under strong reduction of resource potentials	optimised under moderate reduction of resource potentials		optimised under reduction of resource potentials (**)	optimised under moderate reduction of resource potentials
	Solar thermal		strong increase	small increase	moderate increase		strong increase	moderate increase
	Deep geothermal		strong increase	small increase	moderate increase		strong increase	moderate increase
	Heat pumps	Optimised						
	Direct electric heating							
	Hydrogen	No deployment	Optimised					
	E-fuels							
Power sector	Electricity demand in other sectors	exogenously determined (in line with 1.5TECH scenario)						
	Biomass	Limited deployment						
	Other direct RES	Optimised						
Electricity Transmission	Cross-border inter-connectors	2030 TYNDP + optimal expansion						
H2 generation	Hydrogen demand in other sectors	exogenously determined (in line with 1.5TECH scenario)						
	Import	At high prices						
E-fuels generation	E-fuels demand in other sectors	exogenously determined (in line with 1.5TECH scenario)						
	Import	At very high prices						

(*) In the building sector, the mix of all measures (building envelope and heating systems) is optimised under minimisation of life cycle costs. The table indicates the constraints (upper and lower boundary) for this optimisation, as share of the heated floor area in the total building stock which can (or needs to) be covered by a certain technology. In addition, for biomass systems, an overall resource constraint is applied.
(**) In the district heating scenario, we assume a higher biomass allocation for district heating and a lower allocation of

		Baseline	Direct RES-H	Electrifi-cation	e-fuels	H2	District heating	Best-Case
		Task 4	Task 5	Task 6	Task 7.1	Task 7.2	Task 8	Task 9

individual biomass heating, compared to the other scenarios. The settings are defined in a way to result in total in a similar biomass constraint as in the direct RES-H scenario.

4.3.1. Buildings

Efficiency of the building envelope

The model Invert/Opt for each building type identifies packages of measures for improving the building envelope and for installing heating and hot water systems with the lowest life cycle costs. Thus, the level of efficiency improvement at the building envelope is optimised under consideration of the choice of heating systems. The optimisation algorithm considers certain constraints regarding the share of buildings which are more difficult or very unlikely of being renovated, e.g. due to heritage protection.

More detailed information can be found in the Annex, section 7.4.1.

Individual heat supply

As described above, the share of different heating systems installed in the building stock by 2050 is being optimised subject to a minimisation of life cycle costs. Thus, the installation of heating systems and the resulting mix of energy carriers is a result of this optimisation algorithm under certain constraints. These constraints are defined as share of the total building floor area in a certain country which can be supplied by a certain heating system. The model can consider both upper and lower boundaries of the use of technologies. Depending on the scenario setting, either upper or lower boundaries are used or both. Each of these boundaries are defined specifically for each Member State. The detailed approach and the concrete values are described in chapter 7.4.1.

In the following, we describe the overall logic of setting these constraints and specific additional considerations by energy carrier and technology, respectively.

Biomass heating

In addition to the constraints of the heated floor area, as described above, biomass resource potentials are restricted in a way to avoid an increasing use of biomass for heating compared to the base year. While these biomass potential constraints are identical for the scenarios Direct RES-H, Electrification, e-fuels and H2, for the district heating scenario, these biomass potentials – allocated for individual heating – is further reduced to allow a correspondingly higher use for district heating[20]. For the same reason, the upper boundary of biomass use in the building stock is lowest in the district heating scenario, moderate for the scenarios Electrification, e-fuels and H2 and high for the direct RES-H scenario.

No lower boundary constraints are applied.

Solar thermal

[20] The generation mix of district heating, including biomass, is modelled according to the assumptions described in Table 14. Results are described in chapter 4.4.3.

The upper boundary constraints for solar thermal systems are set high for the Direct RES-H and district heating scenarios, whereas in the other scenarios these constraints are set to a moderate level. It needs to be considered, that for all scenarios we assumed that no decentral solar thermal systems are applied in buildings connected to district heating.

No lower boundary constraint is applied.

Direct electric heating

Direct electric heating is following purely cost-optimal considerations, without any upper or lower constraints. The logic is that we consider direct individual electric heating also in the electrification scenario not as an efficient option as a main heating and hot water system. Still, we do not exclude it and keep it as a technology option in the model.

Heat pumps

For heat pumps, upper and lower boundary constraints are set to a high level in the electrification scenario, whereas the remaining scenarios assume a moderate upper boundary and no lower boundary.

Gas heating systems

For gas boilers, upper and lower boundary constraints are set to a high level in the H2 and e-fuel scenario, whereas the remaining scenarios assume a moderate upper boundary and no lower boundary. The composition of gas in the gas grid is described in

Table 15 – with the corresponding implications regarding gas wholesale and retail prices.

Liquid fuel heating systems

For heating systems using liquid fuels, we apply high upper and moderate lower boundary constraints in the e-fuel scenario, whereas the remaining scenarios assume a low upper boundary and no lower boundary.

4.3.2. District heating

Expansion of grid

District heating potentials are being determined based on heat densities and already existing infrastructure. The exploitation of these potentials is optimized under the same type of constraints as for the individual heating systems in terms of the maximum or minimum share of total building floor area to be supplied by the systems. We set moderate upper boundary and no lower boundary for all scenarios except for the district heating scenario. For the latter one, we applied high upper and lower boundaries.

District heat generation

Enertile models district heat supply with different technology options, for which capacity expansion and hourly operation is optimized. Nevertheless, for the direct use of renewables like biomass, solar thermal and geothermal additional exogenous assumptions determine or limit the actual deployment.

As the potentially available **biomass** is rather scarce and more urgently needed for decarbonisation in other sectors like industry and transport, we assume the use of biomass for district heat supply is generally declining until 2050. The available biomass is implemented as an upper bound in the optimization in Enertile. Below this limit, the actual usage of biomass in district heating is optimised. The limit of available biomass for district heat differs in the scenarios and is assessed on the basis of current use (100 % corresponds to today's use). As the baseline scenario is less ambitious concerning emission reductions and efficiency improvement, the available biomass for district heating is only slightly reduced to 80 % in 2050. In all other scenarios, we assume that less biomass is available for district heat supply. In the direct RES-H, e-fuels and hydrogen as well as the best case scenarios, the available biomass for district heating is reduced to a limit of 50 % in 2050. In the electrification scenario, even less biomass is available and the limit is strongly reduced to 25 % in 2050. In the district heating scenario, slightly more biomass is available for district heat supply and the limit is reduced to 60 % in 2050.

The use of **solar thermal and deep geothermal** for district heat supply is marked with local constraints regarding resource and land availability. For ambitious decarbonisation scenarios, their deployment is necessary to achieve emission reduction targets and is therefore supported with additional assumptions and restrictions in the optimization. In the baseline scenario, we assume the following constant developments. Solar thermal for district heating is not widely deployed in Europe, apart from Denmark, which already uses solar thermal nowadays. For Denmark, the current solar thermal production remains constant until 2050. For deep geothermal, in the baseline scenario countries currently using geothermal energy for heat production are using this energy source until 2050. There is no further deployment and the production remains constant until 2050. In all other scenarios, these technologies are increasingly deployed until 2050, however the assumptions on the increase differ between scenarios. We assume solar thermal is deployed in all countries until 2050 and covers certain shares of district heat demand. As district heat demand varies between scenarios these shares lead to different overall heat production in absolute terms. In the direct-RES-H and district heating scenarios, the share of solar thermal is strongly increasing and rising to 15 % in 2050. In the electrification scenario, the share of solar thermal is slightly increasing and rising to 5 % in 2050. In the e-fuels and hydrogen scenario, the share of solar thermal is moderately increasing and rising to 10 % in 2050. For deep geothermal, we assume that countries currently using geothermal energy for heat production will further deploy this energy source until 2050. In the direct-RES-H and district heating scenarios, geothermal production is strongly increasing and reaches 15 times today's production in 2050. In the electrification scenario, geothermal production is slightly increasing and reaches 5 times today's production in 2050. In the e-fuels and hydrogen scenario, geothermal production is moderately increasing and reaches 10 times today's production in 2050. The total share of deep geothermal energy is limited to a maximum of 30 % of heat demand.

The deployment of large **heat pumps, direct electric heating, hydrogen and e-fuels** is optimised in Enertile and no further restrictions are applied. Enertile optimizes the supply for all sectors and captures inter-sectoral effects and competition for CO_2-neutral energy carriers. As all sectors need to reach a carbon neutral energy supply by 2050, they compete for cheap low-carbon energy supply via electricity, hydrogen and e-fuels. Therefore, we use no additional restrictions for hydrogen and e-fuels in district heat supply. This approach enables that the use of these fuels for district heat is completely price-driven and without distortion. In the baseline scenario, hydrogen and e-fuels are not deployed for district heating purposes.

4.3.3. Power sector

The **demand** for electricity in other sectors (i.e. all sectors excluding space and water heating) is exogenously determined and held constant in all scenarios. Demand from other sectors is based on assumptions in line with the 1.5 TECH scenario.

Comparable to the deployment of **biomass** for district heat supply, we assume a reduction of biomass deployment for electricity supply (100 % corresponds to today's use). In all scenarios, the available biomass resource potentials for electricity is reduced to 50 % in 2050. However, the resulting role of biomass in the electricity generation in the year 2050 is negligible.

The electricity generation mix and the capacity expansion of other direct RES like solar and wind energy are optimised in Enertile.

4.3.4. Electricity transmission: Cross-border interconnectors

Enertile models the transmission of electricity between different model regions using a model of net transfer capacities (NTCs). These transfer capacities limit the possible electricity exchange between model regions. In this study, Europe including all current 27 member states of the EU plus Norway, Switzerland, and the United Kingdom is covered. Consequently, each country represents one model region. We assume that the reference grid of 2027 from the latest 2018 Ten Year Network Development Plan (TYNDP) of ENTSO-E is implemented as a minimum status for the transmission grid in 2030. The expansion of these initial cross border interconnector capacities is part of the optimization with Enertile taking into account required investments and occurring grid losses.

4.3.5. Hydrogen and e-fuels generation

The **demand** for hydrogen and e-fuels in other sectors (i.e. all sectors excluding space and water heating) is exogenously determined and held constant in all scenarios. Demand from other sectors is based on assumptions in line with the 1.5 TECH scenario (see Annex section 7.4.3.

These electricity-based fuels can either be produced with renewable electricity within the EU or be **imported** from countries with very good potentials for renewable electricity generation outside the EU (typically the MENA region). In all scenarios, import of hydrogen and e-fuels is generally allowed but at high prices to prioritise production in the EU. Generally, the import prices for e-fuels are higher than the hydrogen import prices.

Demand from heating applications in buildings

The demand for hydrogen and e-gas from heating applications from INVERT is derived as part of the total gas demand using assumptions on shares for the addition of hydrogen or synthetic methane in the gas network. These shares vary in the scenarios according to the technology focus and scenario specifications. The same applies for e-fuels as part of the total heating oil demand.

In the baseline scenario, no additional demand for hydrogen or e-fuels from buildings is assumed. In the hydrogen scenario, the focus is on hydrogen and e-fuels are minimally deployed. We assume that in 2050 90 % of the energy demand for gas comes from hydrogen. Further 5 % of the energy demand for gas comes from e-gas. Comparably, e-liquids have a share of 5 % in the total energy demand for heating oil. In the e-fuels scenario, the focus is on e-fuels and hydrogen is minimally deployed. We assume that in 2050 90 % of the energy demand for gas comes from e-gas and 90 % of the energy demand for heating oil comes from e-liquid. Hydrogen has a share of 5 % in the total energy demand for gas.

In the other decarbonisation scenarios, hydrogen and e-fuels are partly deployed. We assume that in 2050 hydrogen and e-gas each cover 10 % of the energy demand for gas. Comparably, e-liquids have a share of 10 % in the total energy demand for heating oil.

For the years 2030 and 2040, we assume that energy shares of hydrogen and e-gas increase in the same relation as demand for hydrogen and e-gas from other sectors. The following tables shows the assumed shares of energy demand from gas covered with hydrogen and e-gas and the assumed shares of energy demand from heating oil covered with e-liquid. Remaining shares are assumed to be covered by biogas or biooil. Thus, the biogas and biooil potentials assumed to be available for the space and water heating sector (according to Table 39) also determine an upper boundary for the use of gas and oil.

Table 15: Assumed shares of gas and liquids covered with hydrogen and e-fuels.

Scenario (down) / Fuel (right)	Hydrogen			e-gas			e-liquid		
	Share on gaseous heating fuels						Share on liquid heating fuels		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Baseline	0%	0%	0%	0%	0%	0%	0%	0%	0%
Hydrogen	5%	34%	90%	0%	2%	5%	0%	2%	5%
E-fuels	0%	2%	5%	5%	34%	90%	5%	34%	90%
Direct RES-H / Electrification / District Heating	1%	4%	10%	1%	4%	10%	1%	4%	10%

4.4. Scenario results

This chapter presents scenario results for the sectors space heating and hot water[21] and the upstream supply sector (i.e. supply of electricity, district heating, e-fuels and H2). The first section (4.4.1) shows an aggregated comparative scenario overview for the key indicators listed in chapter 4.1.2. Subsequently, we present exemplary more detailed sectoral results for the building sector, the upstream supply sector and grid infrastructure.

4.4.1. Comparative scenario overview

The following Figure 24: shows final energy demand for space and water heating by energy carrier in residential and tertiary buildings. While final energy demand in the baseline scenario reduces from more than 3100 TWh/yr (267 Mtoe/yr) in 2017 by about 40% until 2050, the different decarbonisation scenarios show higher energy savings in the range of 47%. This results from energy savings due to the retrofitting of the building envelope and shift to more efficient heating systems. Counting delivered energy only (i.e. subtracting solar, ambient and geothermal energy), the reduction accounts to more than 70% in the electrification scenario. However, final energy demand in the sense of the renewable energy directive, also for counting RES-HC shares, needs to include solar, ambient and geothermal energy as well. The Annex (Figure 75 and Figure 77) includes also results for the different building categories.

The results show the correlation of electricity demand and ambient heat and geothermal, which makes clear that electrification happens through the use of heat pumps and not through direct electric resistance heaters.

For the understanding of the scenario results, it should be kept in mind that for each scenario boundaries for energy carriers in the analysed sector were defined. Within these constraints,

[21] Process heating, space cooling and process cooling is not in the scope of this project.

the model identifies the cost-minimal constellations. This leads to scenarios with a mix of systems in all scenarios, i.e. not to extreme scenarios. Thus, the scenarios consider and reflect the suitability of technologies in different buildings as well climatic and regional constellations. Overall, the results show that e-fuels and H2 need to be pushed into the model.[22] Heat pumps tend to be used towards the upper limit of the constraint, although of course also depending on the specific characteristics of each building type. Biomass heating systems tend to be economically viable. However, biomass potentials restrict their use. The economic viability of district heating differs between regions. Since district heating was limited to areas with high heat densities and thus lower costs, in these areas district heating is mostly economical and thus applied in the scenarios. Highest renovation activities occur in buildings with H2 and e-fuels, due to the high variable costs of these energy carriers.

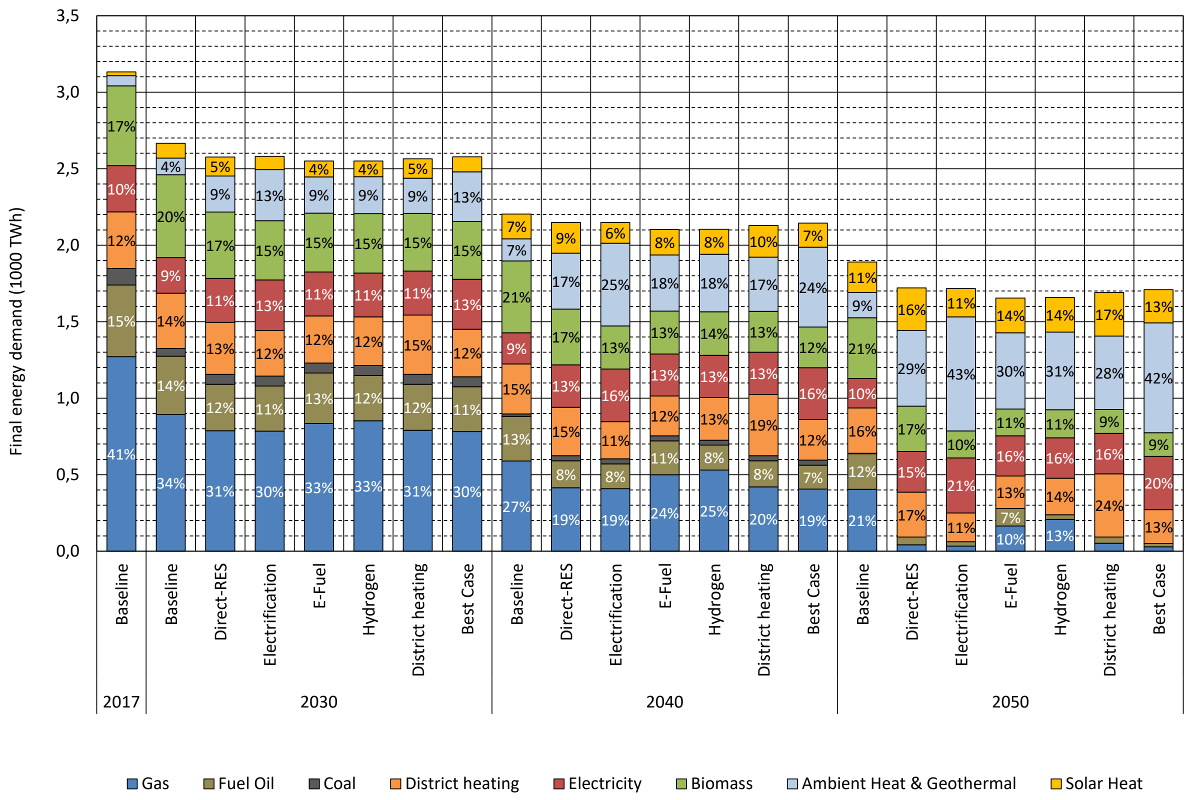


Figure 24: Final energy demand for space and water heating by energy carriers in residential and tertiary buildings, EU-27, 2017, 2030 and 2050 across scenarios.

The main part of the energy savings is due to improvement of the building envelope (by building renovation on the one hand and more efficient new buildings and demolition of old buildings on the other hand). Thus, in the decarbonisation scenarios, the share of space heating reduces from 83% in the base year to about 73% in 2050. Still, the scenarios also show a slight decline

[22] The fact that the model tries to minimise the use of these energy carriers becomes even clearer when comparing the results in terms of final energy demand with the results in terms of heated floor area as shown in chapter 3.4.2. While significant shares of the heated floor area are covered by e-fuels and H2 in the corresponding scenarios, these systems are applied in buildings with very efficient building envelope and they are combined with solar heating. This leads to much lower shares of final energy demand of these energy carriers compared to their share of heated floor area.

in the final energy demand for hot water due to the increased conversion efficiency (Figure 25).[23]

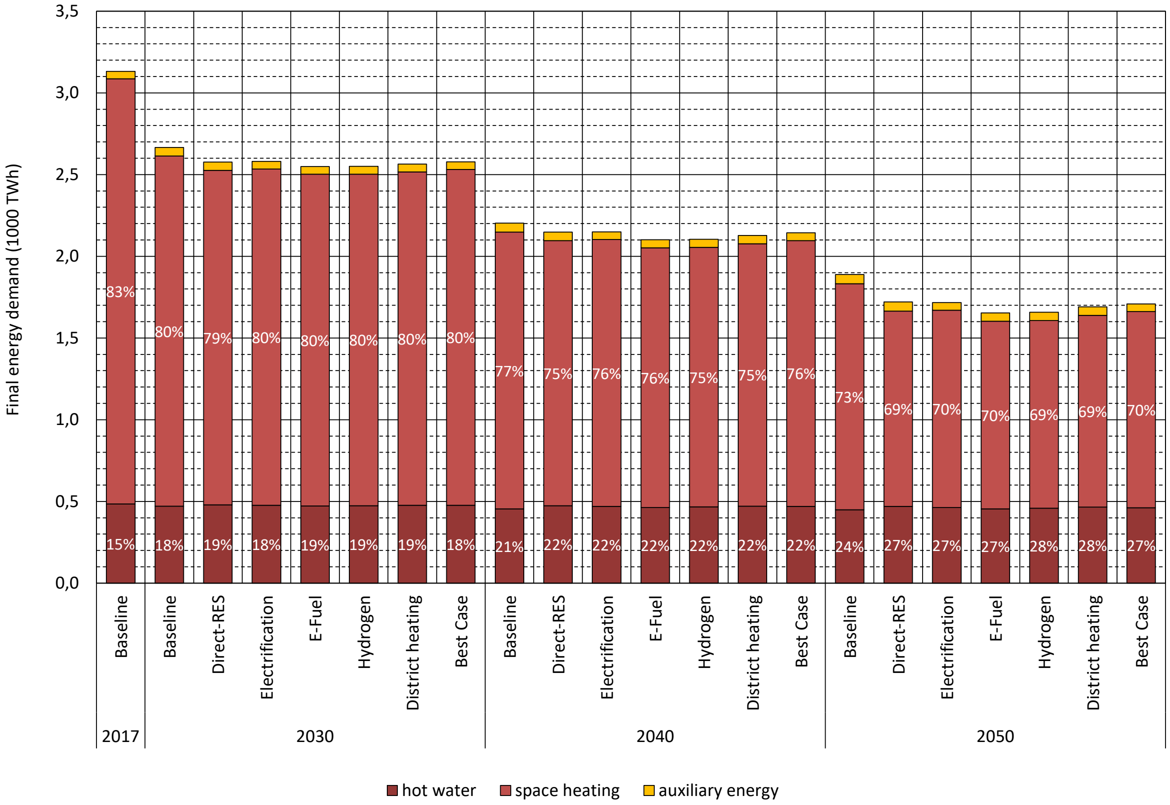


Figure 25: Final energy demand for space and water heating by energy end-uses, EU-27, 2017, 2030 and 2050 across scenarios.

Even the electrification scenario leads only to a moderate increase in total final electricity demand of about 17% for the sector (see Figure 26)[24]. The main reason is that in the base year we see a high share of direct electric heaters (more than 70% of electricity consumption in the sector). By replacing these systems gradually through other heating systems leaves room to increase the number of heat pumps significantly, covering a much larger share of the heated floor area with a similar overall electricity consumption. Only the electrification scenario leads to an increase in electricity consumption in absolute terms compared to the demand in 2017. However, although this is true for the aggregate of EU-27, there are significant differences between countries[25]. In some countries like PL, NL or IT the electrification scenario leads to a quite significant increase of electricity consumption, whereas this is not the case e.g. for FR, with a high share of direct electric heaters in the base year.

[23] The share of heated floor area supplied by different energy carriers differs from the share of energy carriers on final energy demand. This can be seen in Figure 33.

[24] We emphasize that in the context of this figure we are only referring to *final* electricity demand, i.e. electricity directly used in buildings for space and water heating. Electricity consumption for the generation of e-fuels and hydrogen is covered below in the context of primary energy consumption (Figure 28).

[25] Country results can be obtained from the scenario result files.

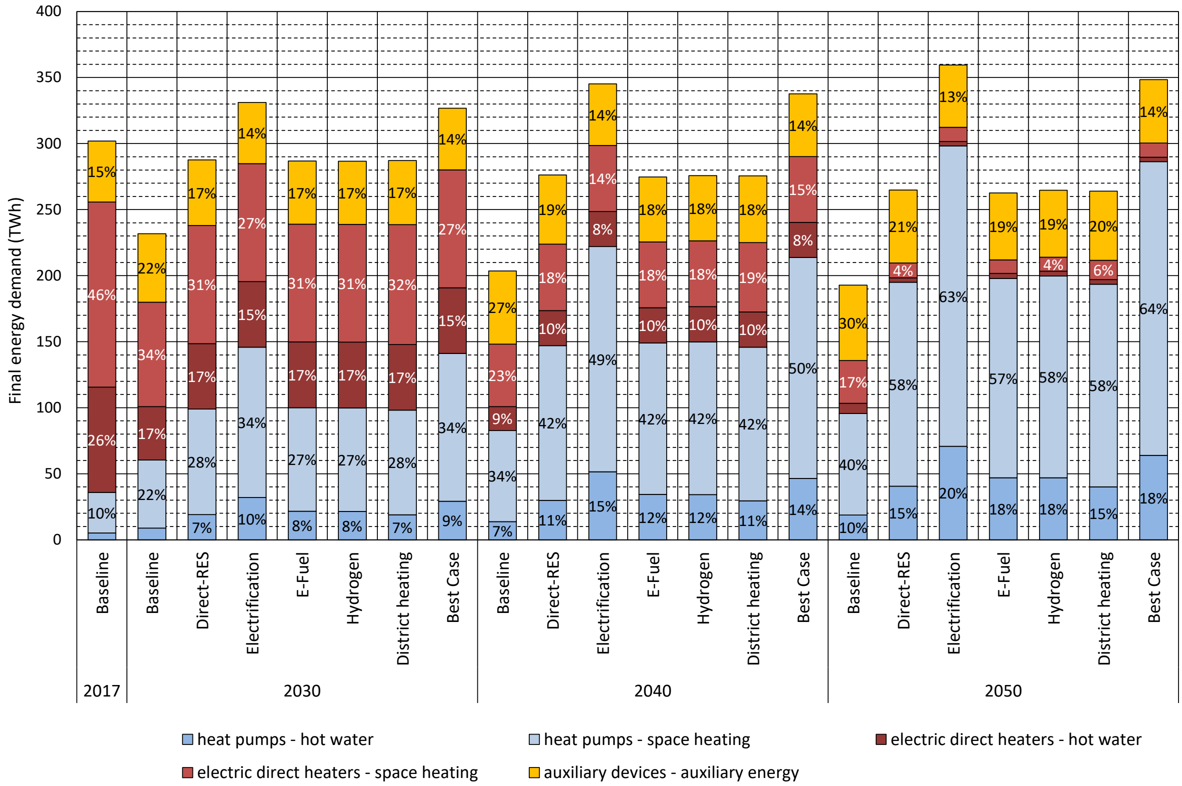


Figure 26: Final electricity demand for space and water heating by technology and end-use groups, EU-27, 2017, 2030 and 2050 across scenarios.

For the indication of primary energy savings, we distinguish the use of primary energy in individual heating systems, like fossil fuels, biomass or solar thermal on the one hand and the use of primary energy in the upstream supply sector. The latter is defined as the sum of all generation and supply of electricity, district heating, hydrogen, e-gases and e-liquids to the space heating and hot water end use sector.

We include fossil and renewable primary energy, i.e. also renewable energy carriers like solar thermal and ambient and geothermal heat is counted as primary energy demand.

The primary energy demand is presented in two alternative ways. First, primary energy demand of the space and water heating sector only (Figure 27). For this purpose, simplifications need to be done regarding the primary energy factors of the energy carriers electricity, H2 and e-fuels, which are not only used for space and water heating but also for other end-uses. Thus, the detailed primary energy carrier mix cannot be indicated in this figure. Rather, we indicate the whole primary energy demand (PE) e.g. for electricity generation. While this is a shortcoming, the primary energy demand for space and hot water heating can be shown in absolute terms.

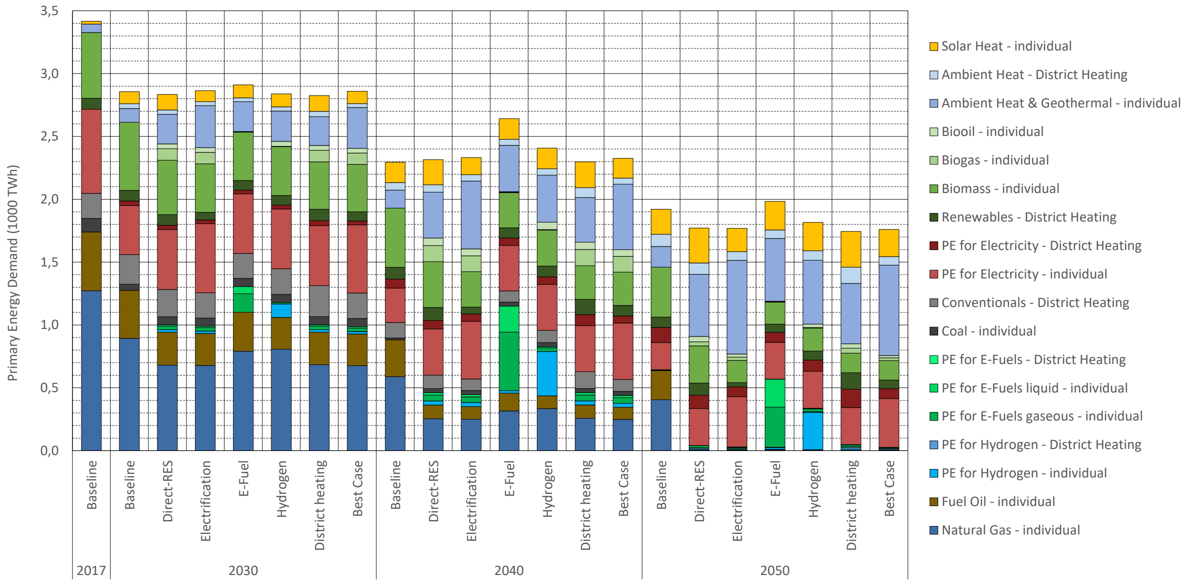


Figure 27: Primary energy demand compared to the baseline scenario by energy carrier and technology, EU-27, 2017, 2030, 2040 and 2050 across scenarios (space and water heating).

As a second figure, the whole modelled energy system, including the whole upstream supply sector and demand in other sectors is shown as difference to the baseline scenario (see Figure 28 and explanations below). A key objective of this analysis was to consider the implications of a change in H2, e-fuels, district heating or e-fuels demand in the overall upstream supply sector. For this purpose, also the demand for these energy carriers in other sectors like industry or transport needed to be covered. In order to ensure comparability between scenarios, the demand in the sectors outside the space and water heating sector were kept identical, also in the baseline scenario. Thus, by showing the primary energy savings of the different target scenarios compared to the baseline scenario (see Figure 28), we can derive insights regarding the overall impact of the changes in the space and water heating sector on the overall energy system (see Figure 28).

Including all indicated primary energy carriers, by 2050 the highest savings – compared to the baseline scenario - occur in the electrification scenario with about 104 TWh (9 Mtoe) net annual primary energy savings, followed by the direct RES and district heating scenario with 81 TWh (6.9 Mtoe) and 80 TWh (6.8 Mtoe) savings and the H2 scenario with about 53 TWh (4.5 Mtoe). The e-fuel scenario results in an increase of primary energy demand of 82 TWh (7 Mtoe).

The highest savings – occurring in all scenarios in almost the same magnitude – are those of gas and oil applied directly in individual heating systems.

All scenarios result in primary energy savings of biomass used in individual heating systems. First, this is the result of enforced building renovation compared to the baseline scenario. Second, all scenarios except the direct RES scenario assume a lower focus on individual biomass heating systems compared to the baseline scenario. Thus, the biomass primary energy savings for direct use in individual heating systems is the lowest in the direct RES scenario. Also, the energy use of biomass in the upstream supply sector, i.e. for electricity and district heat generation reduces in all scenarios[26]. The differences between the scenarios are driven through the relevance of district heating and thus the use of biomass in district heating. Hence,

[26] Total use of biomass for electricity generation in 2050 is very low and mainly through CHP. Biomass based electricity generation without the use of heat is negligible in the scenario results.

the biomass related primary energy savings in the upstream supply sector is lowest in the district heating scenario.

The use of solar heat compared to the baseline scenario slightly decreases in the electrification scenario. All other scenarios result in an increase of solar heat.

The most visible increase over all scenarios is ambient and geothermal heat used by individual heat pumps. According to the strong increase of this technology in the electrification scenario, the additional use of ambient and geothermal heat compared to the baseline scenario by 2050 is about twice as high as in most of the other scenarios. Only in the Best Case scenario similar amounts of ambient and geothermal heat are used.

In the modelling high import prices for e-fuels and hydrogen of 130 €/MWh and 80 €/MWh respectively in the year 2050 are assumed (see chapters 4.3.5 and 7.4.2.6). Despite these high import price assumptions, in all scenarios at least a smaller amount of these energy carriers are imported to the EU. In the e-fuels and H2 scenarios, a significant share of these energy carriers are imported in the years 2040 and 2050, while the share of these energy carriers that are generated in the EU is rather small. Figure 28 shows the primary energy demand required for the production of these energy carriers outside EU, mainly in the MENA region. Due to the higher share of oil demand by 2040 in the e-fuels scenario, these imports are mainly e-fuels. With decreasing share of oil and the phase out of fossil gas and oil by 2050, this shifts towards mostly hydrogen imports by 2050.

The significant reliance on imported e-fuels and hydrogen may seem questionable in the light of the European Union's ambition of achieving climate neutrality mostly by resources from its own territory. The fact that the optimisation algorithm of the Enertile model chose the import option reflects that the costs of the e-fuels and hydrogen scenario would increase when producing these energy carriers within the EU-27. This will need to be carefully considered in deriving conclusions and comparing the scenarios.

The additional electricity demand for space heating in all target scenarios (compared to the baseline scenario) is mainly covered through increased onshore wind and – in particular in the e-fuels and hydrogen scenario – also through PV.[27]

Moreover, Figure 28 shows that the increased (renewable) district heating demand in the district heating scenario is provided through biomass, large scale solar thermal as well as ambient and geothermal heat.

The total primary energy demand is shown in the Annex (Figure 80).

[27] For further details regarding the power generation mix please refer to chapter 3.4.3.2.

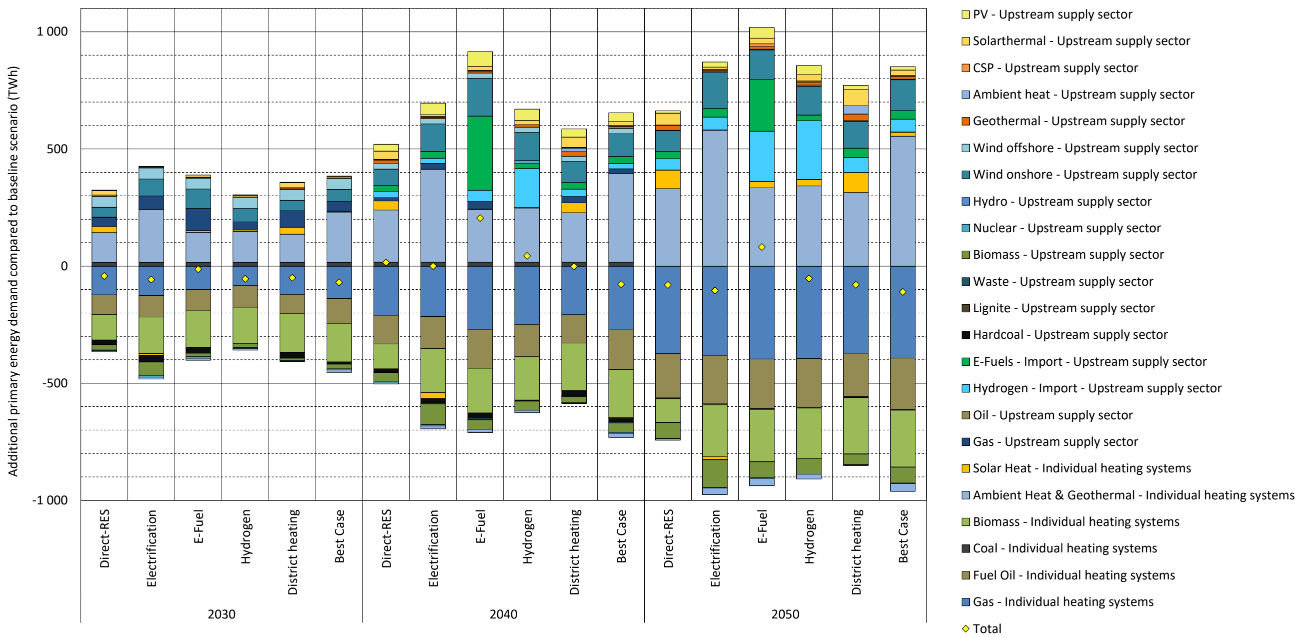


Figure 28: Additional primary energy demand compared to the baseline scenario by energy carrier and technology, EU-27, 2030, 2040 and 2050 across scenarios (space and water heating and total upstream supply sector).

GHG-emissions by 2050 decline in all target scenarios (Figure 29) and are very close to climate neutrality. Remaining emissions and the related differences between the scenarios are negligible and mainly due to accounting reasons for different energy carriers. Overall, GHG-emissions in all target scenarios are below 2% of the emissions in the base year.

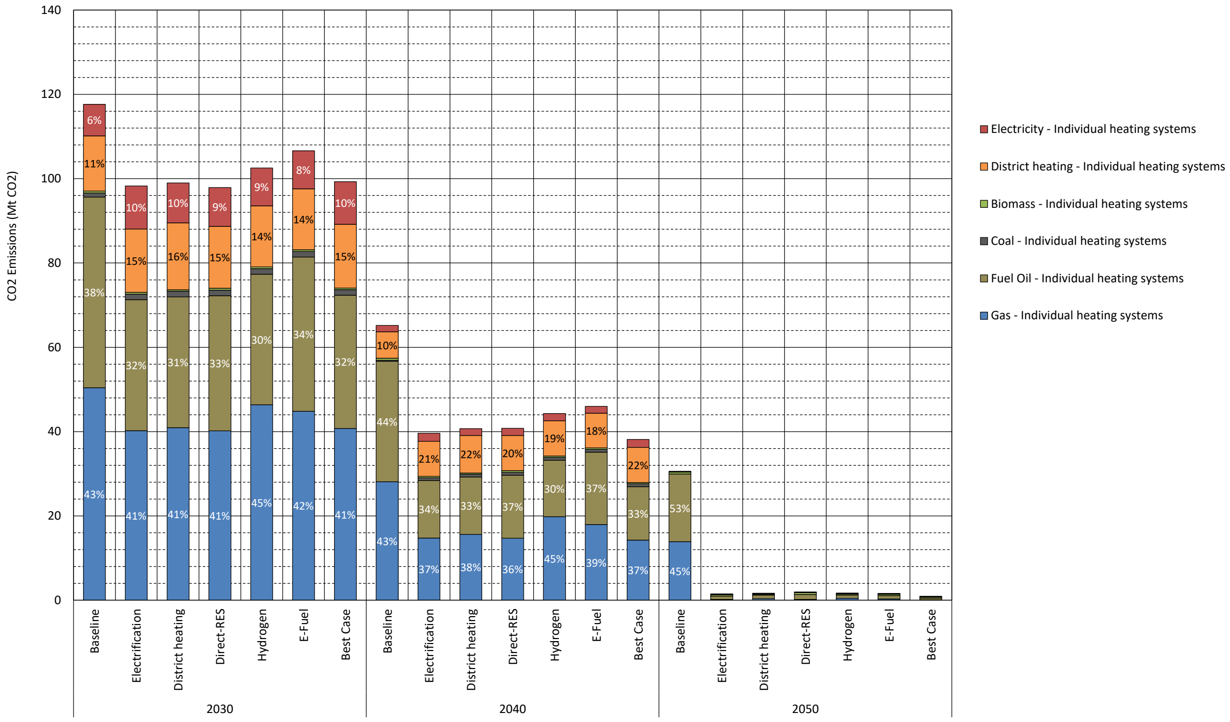


Figure 29: GHG-emissions by energy carrier and technology, EU-27, 2030, 2040 and 2050 across scenarios for space and water heating.[28]

Figure 30 shows total system costs, divided in the main categories of capital costs and running costs both in the building sector and in the upstream supply sector.

All scenarios show a strong gradual reduction of running costs of individual heating systems. This is the highest single cost component (as cost savings compared to the baseline scenario). This is triggered on the one hand by building renovation and resulting reduction in energy demand. On the other hand, in particular for the case of gas and oil, due the replacement of natural gas by H2 and e-gases, costs are shifted from the building sector to the upstream supply sector. While the costs of generating H2 and e-gases are accounted in the upstream supply sector, the costs e.g. for biogas fed into the gas grid is still accounted in the building sector, the same way as fossil fuels are (in the years before 2050). Thus, under the category variable energy costs of individual heating systems we show all cost components which have to be covered by end-users and which are not already covered in the upstream supply sector (i.e. generation costs of electricity, district heating, H2 and e-fuels). This also includes costs for retail services and distribution of energy carriers.[29] Taxes are considered as transfer payments and thus are excluded.[30]

[28] GHG-emissions including the full upstream supply sector are shown in the Annex in Figure 79.

[29] Distribution grid costs are discussed in more detail in chapter 4.4.4.2.

[30] An argument for excluding taxes from the considerations is that they constitute transfer payments between different actors in the society but do not represent costs. On the other hand, taxes, in particular on energy carriers also represent a form of internalizing external costs occurring over their supply chain. Such external costs do not necessarily occur only for the case of fossil fuels, but might also be relevant for renewable energy technologies, e.g. regarding land-use, change in the landscape or use of materials, whose prices do not fully reflect their costs (including external costs). While for some cost categories like energy prices, excluding taxes could be done quite easily, for other cost categories this is not that straightforward. The installation of RES-H technologies and even more of building retrofitting measures usually requires a considerable amount of labor costs, which again include a high share of income tax or social insurance. The latter ones again constitute to some extent transfer payments. However, it would have been clearly beyond the scope of the project to identify the share of these transfer payments in detail. Thus, in order to avoid a distortion by excluding only energy taxes but still keeping income taxes as part of costs for e.g. installing a heat

For a better understanding of this cost component, running costs are displayed in Figure 32.

The e-fuel scenario and the district heating scenario leads to the highest overall costs. Regarding the e-fuel scenario, the reduction in running costs for individual heating systems are to a large extent compensated by the costs of importing e-fuels, H2 as well as the capital costs for electricity generation. For the district heating scenario, there are uncertainties regarding the capital costs for district heating grids (see discussion below).

The electrification scenario leads to the overall lowest costs. The considerable investments in capital costs of electricity generation are overcompensated through a strong reduction of running costs on individual heating systems. Electricity grid costs according to our analysis do not outweigh this effect (see chapter 4.4.4.1).

In between are the scenarios H2 and direct RES, with very similar costs. A considerable uncertainty results from the assumed import price for hydrogen of 80 €/MWh in the hydrogen scenario. An increase of this import price by 50% (or assuming that the generation of H2 within the EU-27 would lead to a corresponding additional costs) would mean that the H2 scenario would show the highest costs, followed by the e-fuel scenario.

pump, for the building stock modelling all taxes except value added tax are included. The costs indicated in the cost figure exclude energy taxes.

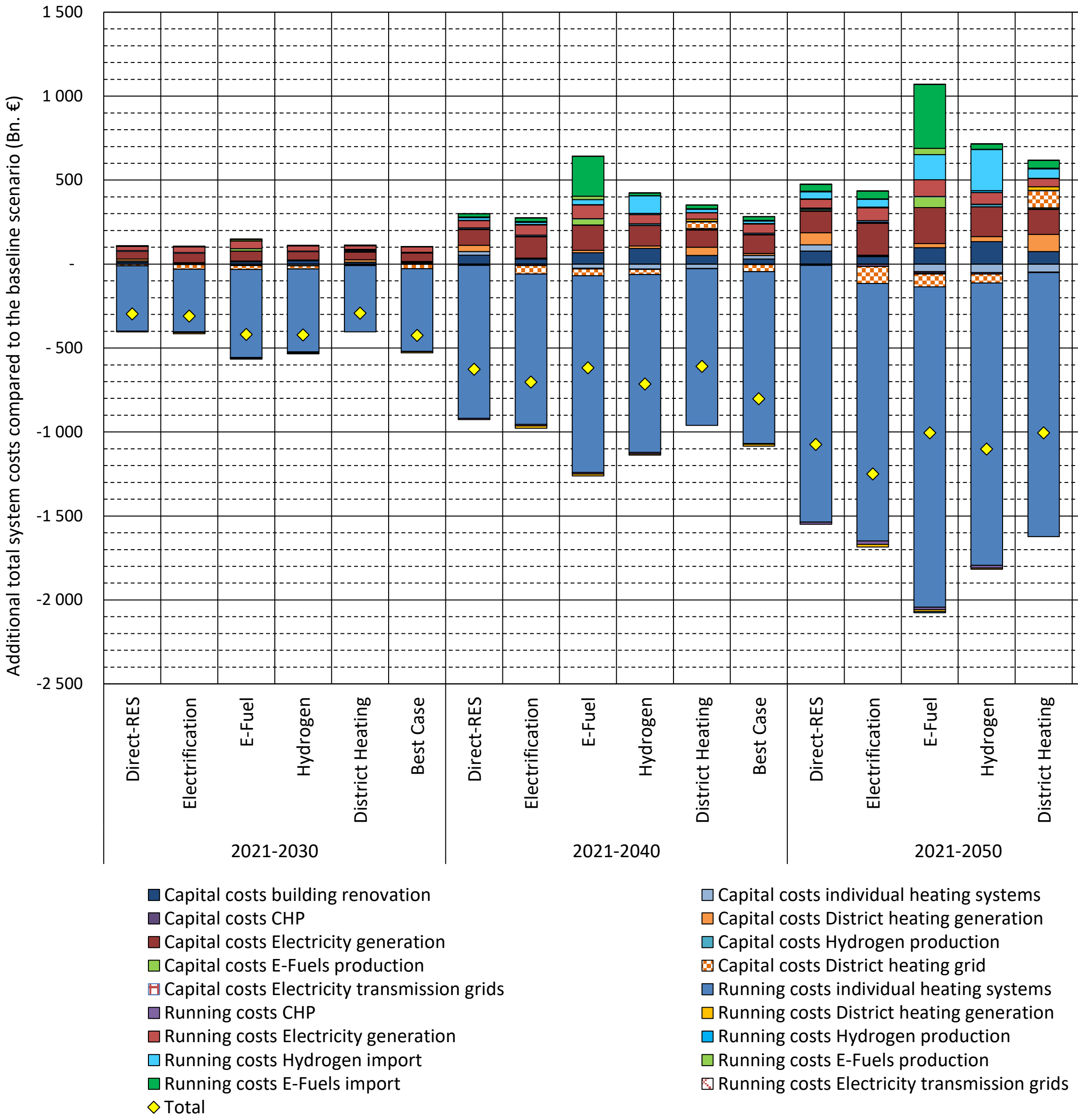


Figure 30: Additional total system costs compared to the baseline scenario, EU-27, cumulated 2021-2030, 2021-2040 and 2021-2050, space and water heating including total upstream supply sector.[31]

The following figures (Figure 31 and Figure 32) show the total system costs in a more detailed split of capital costs and running costs.

Compared to the baseline scenario the main additional capital costs occur for building renovation and heat pumps, e-fuel production (for the e-fuel scenario), district heating generation and grid costs (mainly in the district heating scenario) and in all scenarios for electricity generation (wind onshore, offshore and PV). Lower capital costs – compared to the baseline scenario – occur for gas and liquid based heating systems (less significantly for the e-fuels and hydrogen scenario), for biomass heating systems, partly for solar thermal systems (less pronounced in the direct RES and the district heating scenario) and for district heating grids (only for electrification, e-fuels, hydrogen and best-case scenarios).

[31] A graph for total costs is shown in the Annex in Figure 82.

In particular in the electrification scenario, the highest cost component are the capital costs for heat pumps, being partly compensated by lower investments in gas and oil based heating systems, solar thermal and biomass. Moreover, significant investments occur in additional wind onshore capacities, in particular in the electricity based scenarios (electrification, e-fuels, H2).

Renovation investments are highest in the H2 and e-fuel scenario. Here, it needs to be considered that the costs for building renovation assume that anyway, maintenance of the retrofitted building component needs to take place. The costs indicate only the additional costs for improving the energy performance. E.g. the scaffold costs are not included, because we assume that this is anyway required for maintenance work on the building. The renovation rates underlying the shown results, which are resulting from the model runs can be found in Figure 36.

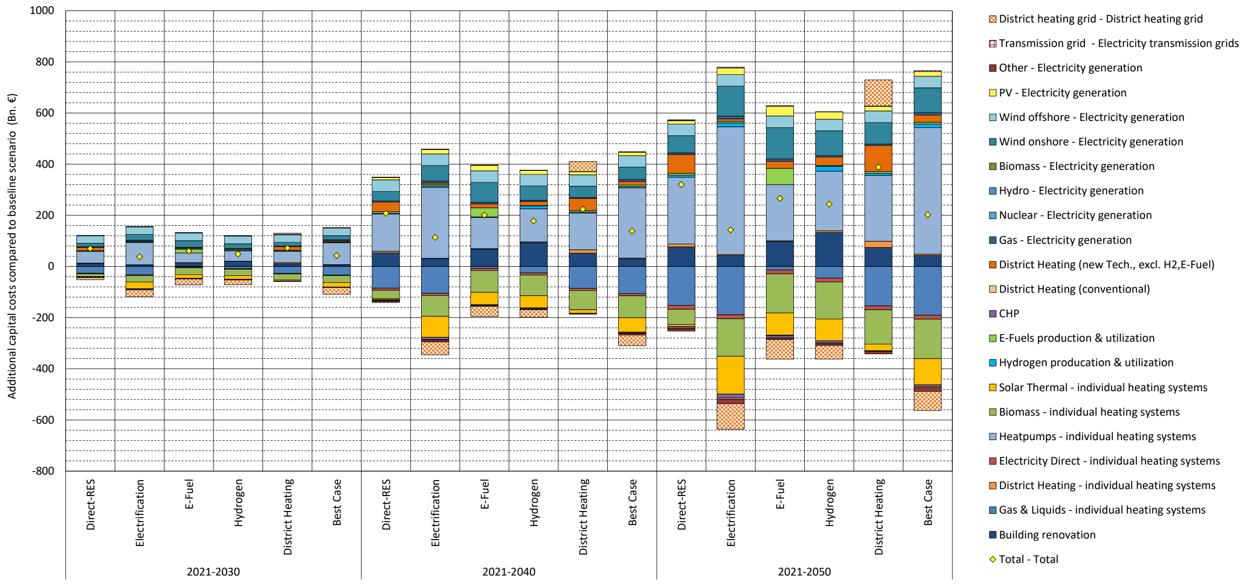


Figure 31: Additional capital costs compared to the baseline scenario, EU-27, cumulated 2021-2030, 2021-2040 and 2021-2050, space and water heating including total upstream supply sector.

For the assessment of district heating grid costs significant uncertainties exist. They mainly refer to local conditions, which could not completely be covered in the scope of this study. Also, the current situation of district heating grids and required re-investments are a source of uncertainties. Moreover, the question whether major grid expansion is required or just densification of an existing grid is possible in order to connect a larger number of buildings affects the costs of district heating grids. When comparing district heating grid costs between the scenarios it should be considered that the baseline scenario is not an optimized scenario. Thus, the results indicate that through an optimized allocation of district heating capital costs can be reduced while still connecting a larger number of buildings[32].

While all scenarios lead to higher capital costs compared to the baseline scenario (Figure 31), running costs are significantly lower in all scenarios (Figure 32). Higher running costs than in the baseline scenario occur due to hydrogen and e-fuels generation and imports (mainly in the e-fuel and hydrogen scenario), for electricity based heating systems and operation of renewable electricity generation. On the other hand, the scenarios result in lower running costs for

[32] The share of heated floor are covered by each energy carrier and thus also connected to district heating is sown in Figure 33.

gas and liquid fuels (excluding the generation and import of e-fuels and hydrogen) and for biomass fuels in individual heating systems.

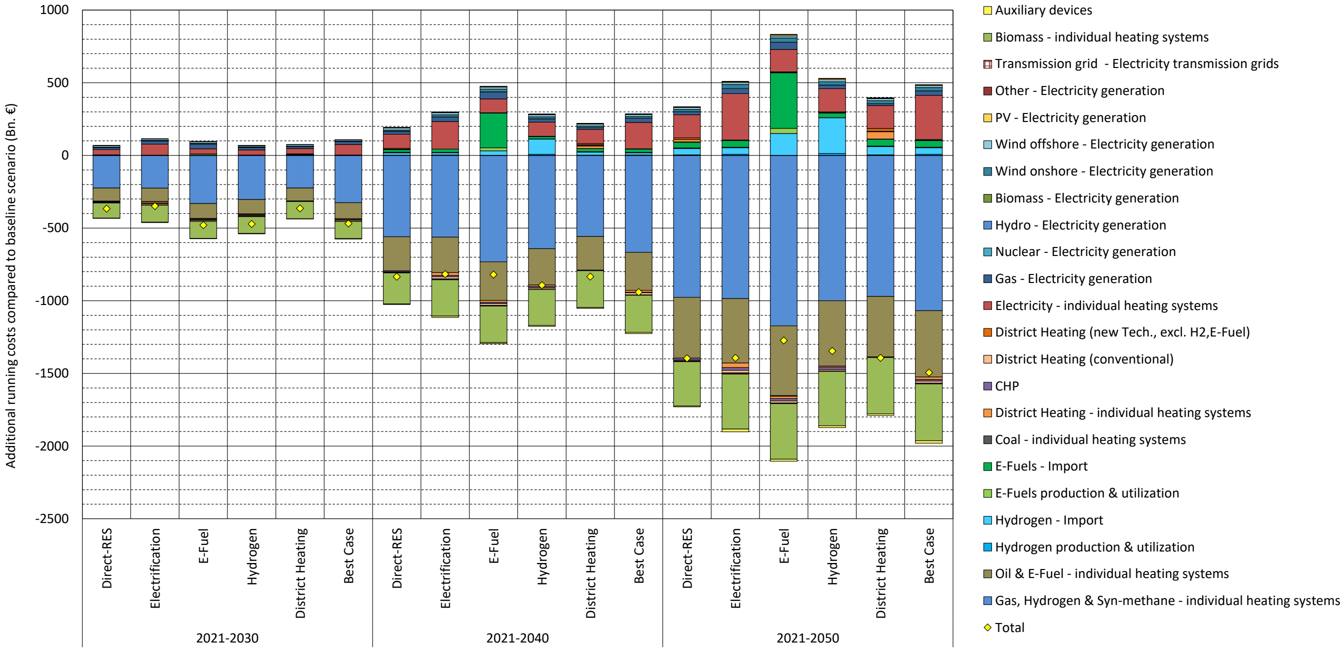


Figure 32: Additional running costs compared to the baseline scenario, EU-27, cumulated 2021-2030, 2021-2040 and 2021-2050, space and water heating including total upstream supply sector.

4.4.2. Detailed results on the demand side and decentral supply

In the following chapter, selected detailed results of the building stock modelling, in particular the utilization of roof area for solar technologies and the development of specific useful energy demand for space heating due to building retrofitting.

Heated floor area by energy carrier

While Figure 24: shows the final energy demand by energy carrier, it is not clear which share of the building stock and of the heated floor area is supplied by which energy carrier. This is depicted in Figure 33. Due to the different level of variable energy costs of the heating systems, the incentive to carry out deep renovation and install solar energy varies. In particular, this is visible for the case of the e-fuels and the H2 scenario. The model implements minimum restrictions for the supplied floor area by energy carrier in each Member State. While this restriction needs to be fulfilled, the algorithm minimises the use of these energy carriers through higher use of solar energy and building renovation (or to put it the other way round, these energy carriers are used in buildings with the lowest energy demand). Thus, the share of final energy demand on these energy carriers is lower than the actually supplied heated floor area.

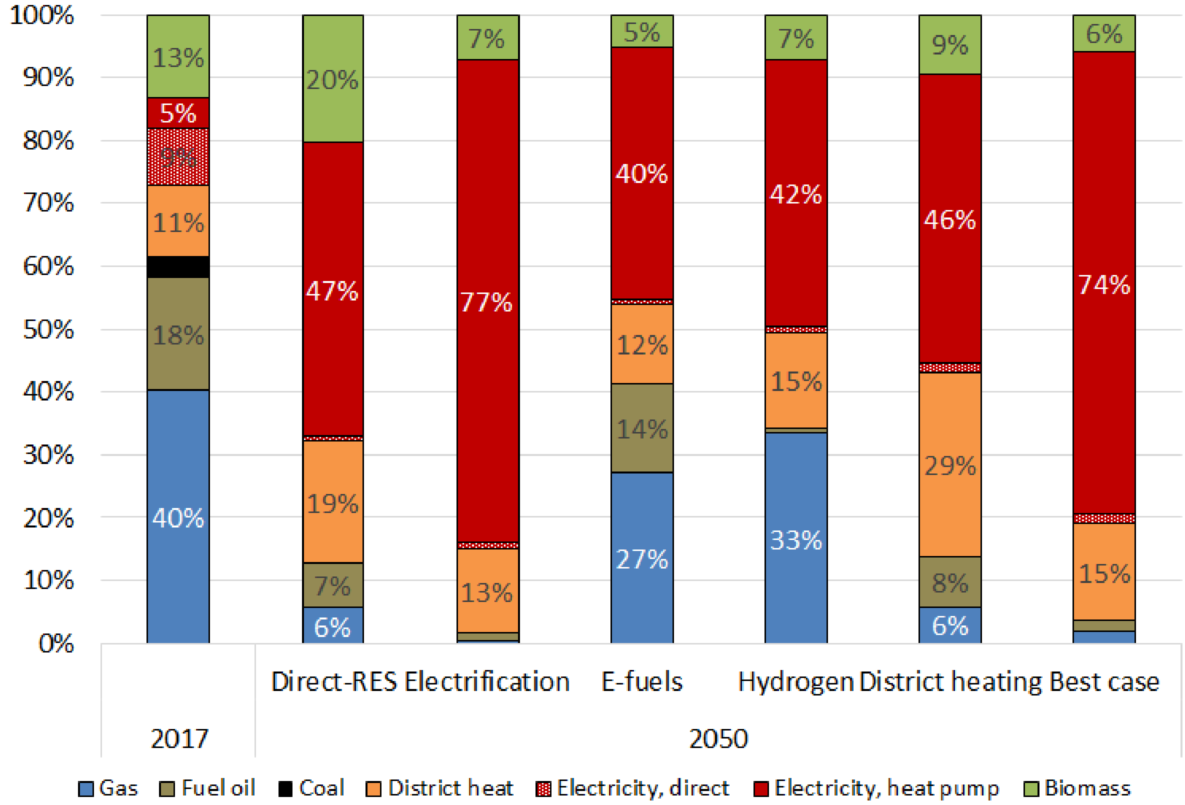


Figure 33: Share of heated area by energy carrier, EU-27, 2017 and 2050, space and water heating.

Utilization of roof area for solar technologies

While the model Enertile covers solar contribution to district heating, the Invert/Opt model covers the use of solar energy for decentral applications. The latter is described in more detail below. The Invert/Opt model allows the utilization of the roof for technologies harvesting solar energy, namely solar thermal collectors and PV. In the model, the upper limit for these technologies is restricted by the available roof area that can be used by these technologies. The restrictions are as follows: First, it is considered that only a certain share of buildings can use solar thermal collectors or PV. For buildings in central Europe the share of buildings that can install solar thermal collectors is set to 50%, while PV can be installed on 65% of the buildings. We further increased these shares for countries located in the south of Europe (e.g.: 65%/75%: Croatia; 65%/80%: Italy; 75%/90%: Spain, Portugal; 80%/100%: Greece, Malta and Cyprus) and decreased the share in northern countries such as Finland (40%/55%), Sweden, Baltic States, Iceland and Norway. This should reflect the barriers for the use of solar energy which are not reflected in the costs and the solar radiation. The cost differences arising from different building geometries and in particular the ratio between the achievable solar yield and the demand of the building during different seasons is explicitly covered in the modelling approach. A second restriction considers that only a certain share of the roof[33] of an individual building can be used for solar technologies. Our default assumption here is 40%, in case a building uses solar thermal collectors and PV, this limit is increased to 60%. In the case of solar thermal collectors, we assume that they can be used in buildings with central heating systems only (and they cannot be used if the building is heated by district heating).

[33] In our case, we consider the roof as the horizontal projection of the roof excluding overhangs. Thus, the considered roof area is equal to the building footprint.

With respect to the size of the technologies, we allow PV systems that cover either 40% or 80% of the roof area that can be used for solar technologies, where the optimisation algorithm selects the system which is more economic for the corresponding building type. This means that if PV is installed, either 40%x40%=16% or 80%x40%= 32% of the roof area is used for PV. In case of solar thermal collectors, the size of collectors is defined in relation to the domestic hot water demand. Again, two types are offered. The smaller one is intended to provide mainly domestic hot water, while the larger also provides heat for space heating. For central European countries, the size of the smaller system is set to be 6m² per apartment, while the larger is 15m². If the available, suitable roof area is not sufficient, the model scales down the size of the solar thermal system automatically. For southern European countries the sizes of the systems are reduced, to consider the higher solar energy gains.

The utilization of the roof area for selected countries is depicted in Figure 34. The y-axis indicates the roof-share of individual buildings that are covered with solar technologies, the x-axis depicts the share of buildings. For example, the total considered roof area in Germany amounts to 2920 km². According to Invert-model results, in the e-fuels scenario, 148 km² of solar thermal collectors and 643 km² of PV are installed on building roofs by 2050. In the electrification scenario, the model installs slightly more PV and less solar thermal collectors. From the figures, it can be seen that the model basically installs as much PV as possible, while it does not exploit the full roof potential for solar thermal collectors.

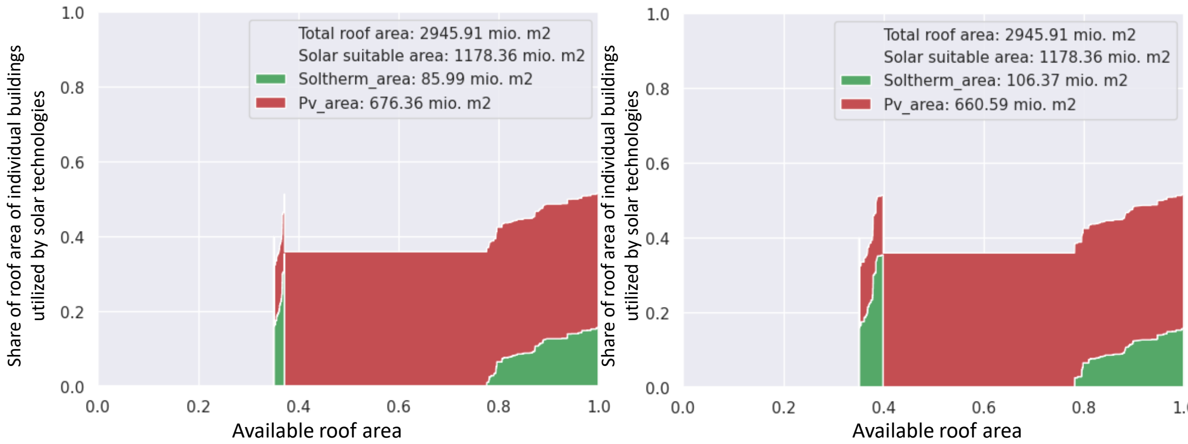


Figure 34: Utilization of roof area for solar thermal collectors (green) and PV (red) in Germany in the electrification scenario (left) and the e-fuels scenario (right).[34]

A similar picture is given for Malta (left) and Finland (right) in Figure 35. In Malta, almost the full PV potential is used (except for the 5% share of roofs on the left side that install larger solar thermal collectors). Solar thermal collectors are also installed by virtually every building that is allowed to install the technology, however much smaller systems are chosen in the model run. The same holds for Finland: PV is fully exploited while only small solar thermal systems are installed by the model.

[34] The buildings in the graph are sorted in a way that first buildings without PV and solar thermal are shown, second the buildings with higher share of solar thermal than PV and third buildings with higher share of PV than solar thermal.

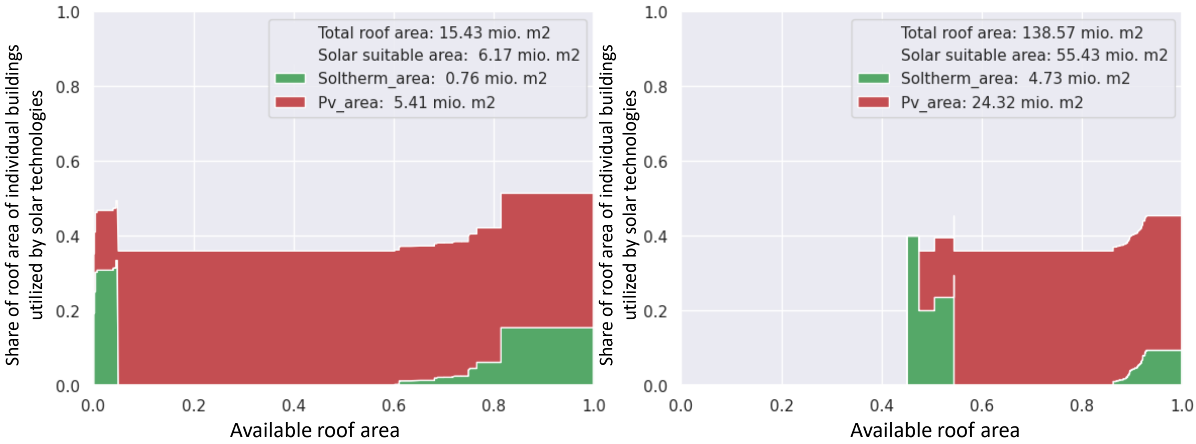


Figure 35: Utilization of roof area for solar thermal collectors (green) and PV (red) in Malta (left) and Finland (right) in the e-fuels scenario.[34]

Energy needs for space heating and renovation activities

In the Invert model, the energy needs (useful energy demand) are determined by the building shell, its geometry and energy related properties (e.g. u-values) of its components (ceiling, floor, façade and windows, and heat recovery systems), the climate (monthly temperatures, solar radiation) and the utilization of the building (e.g. permanently occupied residential building). While we consider that a certain share of old buildings are demolished over time in the model, we assume that the utilization of the building does not change and the geometry remains as it is for the entire considered period. Therefore, the energy needs of a given building are determined by its initial demand, the probability (share) that it is demolished, the probability (share) that it has been refurbished and the energy savings that have been achieved due to the refurbishment. Whether or not (or the probability/share of) a building needs to be refurbished in the simulation period is determined by the age of the building components façade and windows.

If, however, the components reach their end of lifetime (described by Weibull-distributed survival rates) the model decides based on a utility function if the installed components are replaced by a new component with the same energetic properties or if energy efficiency measures (thermal renovation) are carried out. I.e. the rate of exchange of building shell components is calculated endogenously by the model in dependence of the age of the components of the buildings in the stock and the simulation period. Figure 36 shows the upper limits for the average annual refurbishment rates assuming that all building shell components changes include thermal renovation.

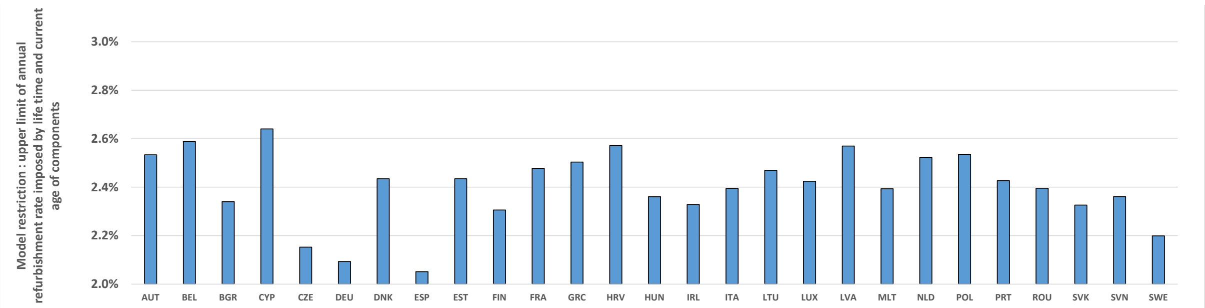


Figure 36: Model restriction for the average annual upper limit thermal renovation imposed by remaining life time of existing components.

The share of the thermal renovation activities on the total refurbishment activities (thermal renovation + maintenance) is shown in Figure 37. It reveals that about half of the countries choose the maximum share of thermal renovation activities as defined by the exogenously defined restriction. Without consideration of this restriction, the model (based on the cost and performance assumptions) would tend to a higher share of thermal renovation and a lower share of maintenance work. The latter would not impact the energy performance of buildings.

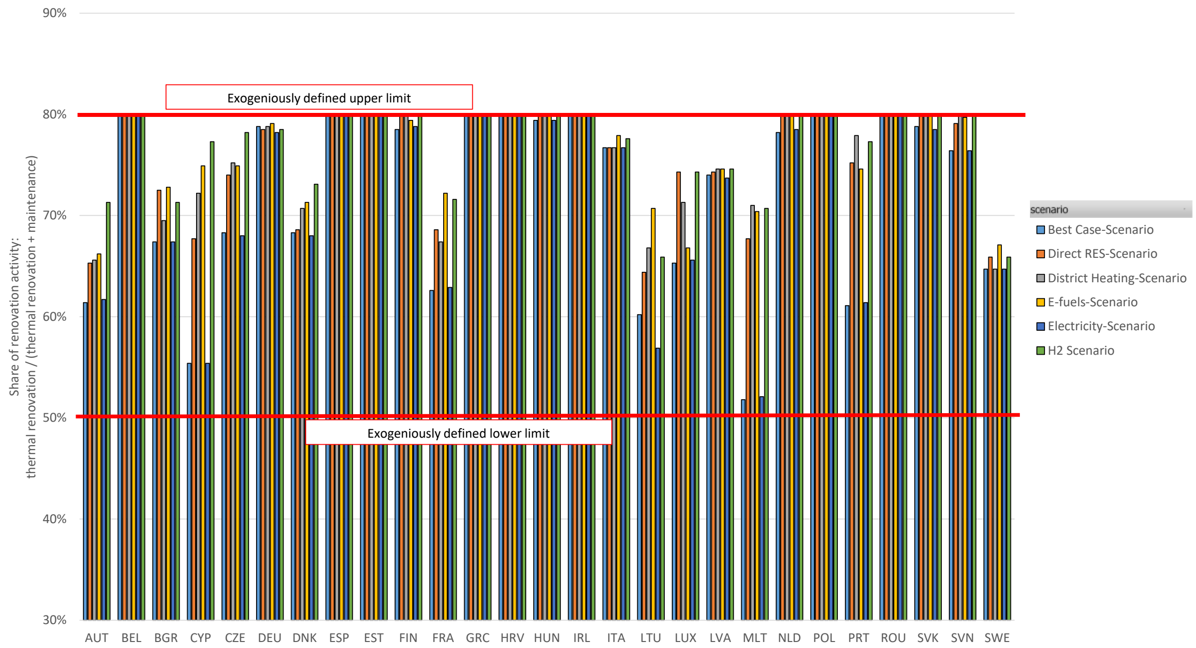


Figure 37: Share of thermal renovation activities on total refurbishment activities.

The resulting annual renovation rates are shown in Figure 38. The depicted renovation rate is calculated as the total area of buildings that undergo a thermal renovation within the period 2020 – 2050 dived by the total area of buildings in 2020.

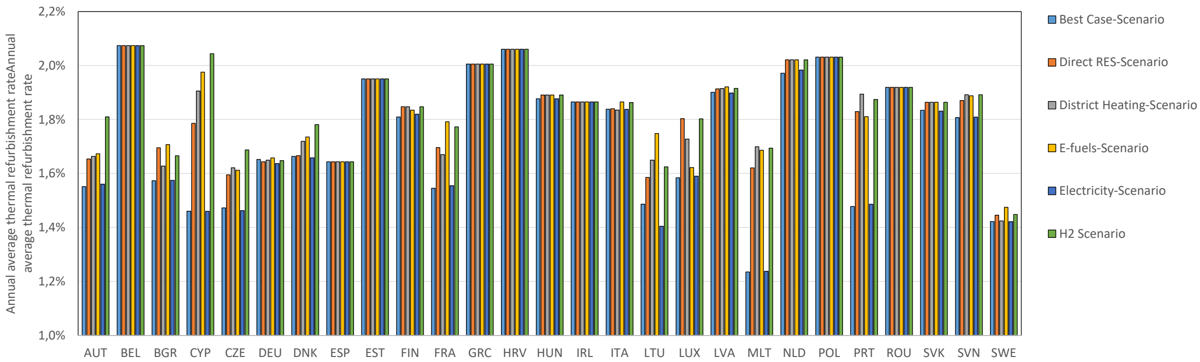


Figure 38: Annual thermal renovation rate.

4.4.3. Detailed results on energy supply

In the following sections, the detailed results on energy supply will be given, analysed and compared.

4.4.3.1. Electricity demand

Figure 39 shows the results of the development of total electricity demand in the different scenarios until 2050 originating from the EU 27. The electricity demand can be categorized in four demand groups. First, the electricity demand that is identical in all scenarios and has the largest share in total demand. This comprises the electricity demand from other sectors including transport, which is described in Section 4.2.2 and 7.4.2.1, and the electricity demand for air conditioning, which is based on the SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b). The second group comprises the electricity demand from different decentral heating applications as modelled by INVERT: electric direct heaters, electric heat pumps and auxiliary devices for heating, according to the results presented above (chapter 4.4.1). The third group is the endogenously optimized electricity demand for electric district heating within Enertile. This category includes centrally installed electric heaters and large heat pumps for district heat supply. Furthermore, the electricity demand incurred for hydrogen and e-gas production, which strongly depends on the demand for these fuels. Part of this demand is induced by the space heating and hot water sector, the other part is consumed in other end-use sectors. The effect of H2 and e-fuels imports and the corresponding supply and demand balance is described in chapter 4.4.3.4. The corresponding electricity demand for their production outside of the EU 27 is not reflected here.

The total electricity demand increases similarly until 2050 in all scenarios. The highest demand corresponds to the Electrification scenario with 6,008 TWh (517 Mtoe). The lowest demand can be observed for the Direct-RES with 5,942 TWh (511 Mtoe). The production level of hydrogen and e-fuels plays an important role in all the scenarios. In this respect, the e-fuels scenario shows a difference compared to the other scenarios, as the hydrogen production is decreased by ~182TWh (16 Mtoe). The demand is covered by the e-fuels production which exhibits an increase of 252 TWh (22 Mtoe). The larger part of the demand is covered by imported e-fuel from outside Europe. Further details are described in section 4.4.3.4. The share of electricity demand for heating applications, both decentral and central, increases from around 10-17% of total electricity demand in 2030 to 36-38% in 2050 due to the higher electricity demand for heat pumps as well as the hydrogen and e-fuels production.

In the best-case scenario, electricity demand for heat pumps is three times as high as the one of the baseline scenario, with 287.8 TWh (25 Mtoe) vs 94 TWh (8Mtoe), and the highest among the rest with the exception of the electrification scenario (301.7 TWh, 26 Mtoe). The demand for electric direct heaters and DH electric heaters are the lowest among the scenarios with a demand of 15.7 TWh (1.3 Mtoe) and 8.7 TWh (0.75 Mtoe) respectively. The share of hydrogen and e-fuels production varies just slightly in comparison with the focus scenarios, with the exception of the e-fuel scenario.

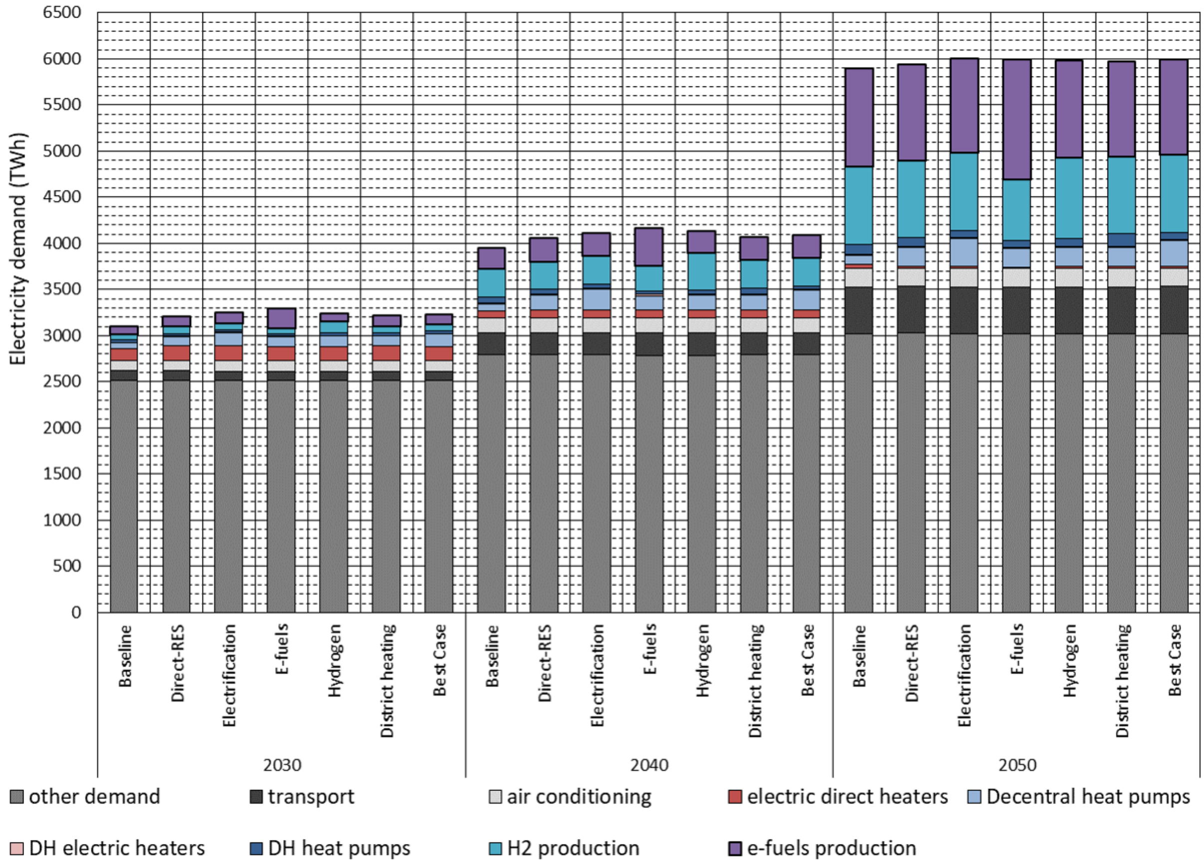


Figure 39: Development of total electricity demand in the different scenarios from 2030 until 2050 in the EU-27.

4.4.3.2. Electricity generation and capacity

Figure 38 and 39 show the results of the development of electricity generation and installed capacities in the different scenarios until 2050 in the EU 27. Total electricity generation is always slightly higher than electricity demand as shown in Figure 39 due to curtailment of renewable electricity generation and losses due to transmission and storage of electricity.

In all focus scenarios, conventional electricity generation disappears and nuclear energy declines until 2050. Fossil fuels are completely replaced with renewable electricity generation. Only in the baseline scenario, a small share of gas remains in the electricity mix. This is because of the different carbon budgets available for energy supply (compare Section 3.2.5). Wind onshore is the most important technology for electricity supply in 2050, followed by PV and wind offshore. Photovoltaic production in 2050 is mainly utility scale (94%) with a small part of it being installed on rooftops as decentralized option. A small additional extension of battery storage capacities is necessary to balance supply and demand with high shares of fluctuating renewable electricity generation. The small quantity of batteries is due to the fact that the grid extension is not restricted, leading to a scenario where the model prefers to import electricity produced elsewhere rather than install batteries locally. The E-fuel scenario has the largest battery storage with 16 TWh. The electrification and best case scenarios having the lowest values, 1.9 and 3 TWh respectively. The use of biomass for generation of electricity in CHPs is reduced for all scenarios until 2050. The lowest use is for the electrification scenario with 13 TWh and the highest is for the hydrogen scenario with 31 TWh. Only conversion of hydrogen to electricity is used to some extent in 2050. Even if these fuels can be used as long-term electricity storage, the complete conversion chain from electricity to hydrogen or e-gas and back to electricity is accompanied with high efficiency losses and thus applied only to a minor extent.

The best-case scenario in terms of electricity generation and demand is close to all the other technology focus scenarios.

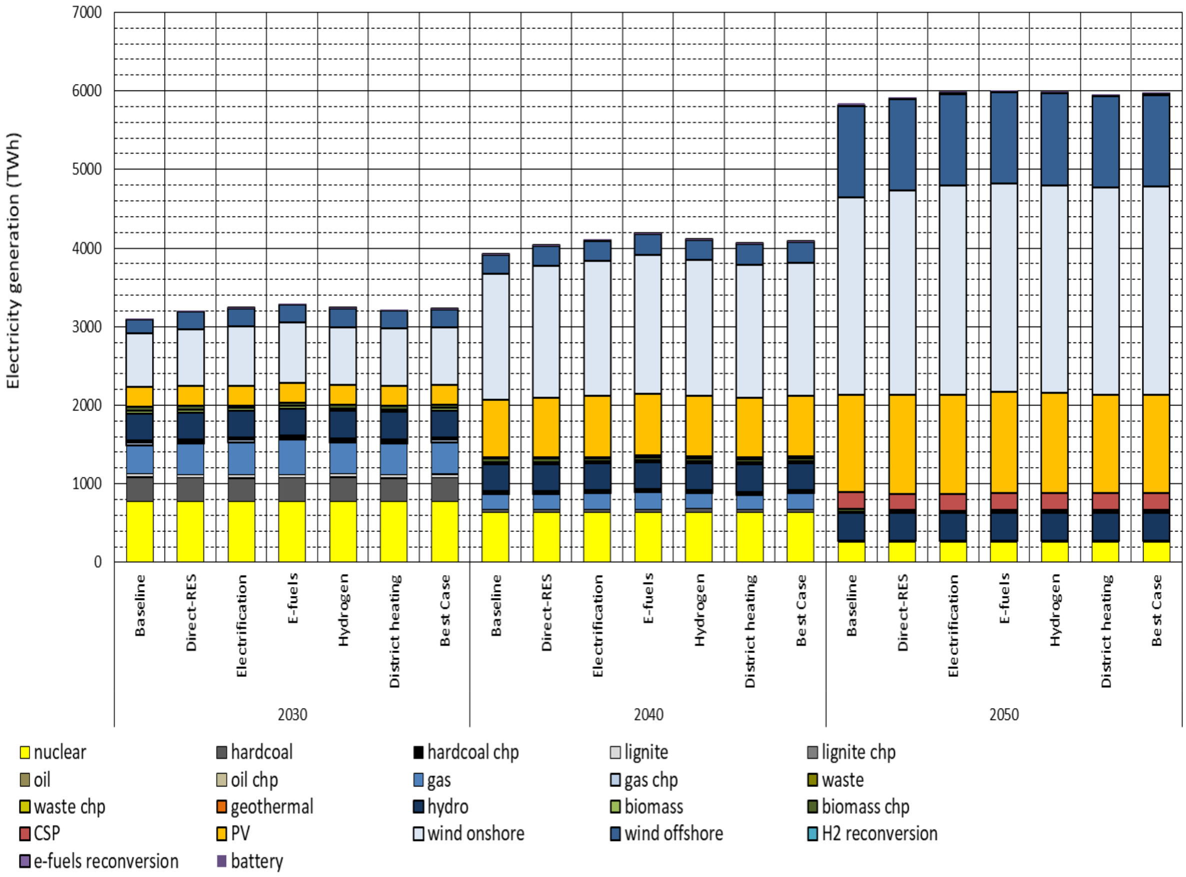


Figure 40: Development of electricity generation in the different scenarios from 2030 until 2050, EU-27.

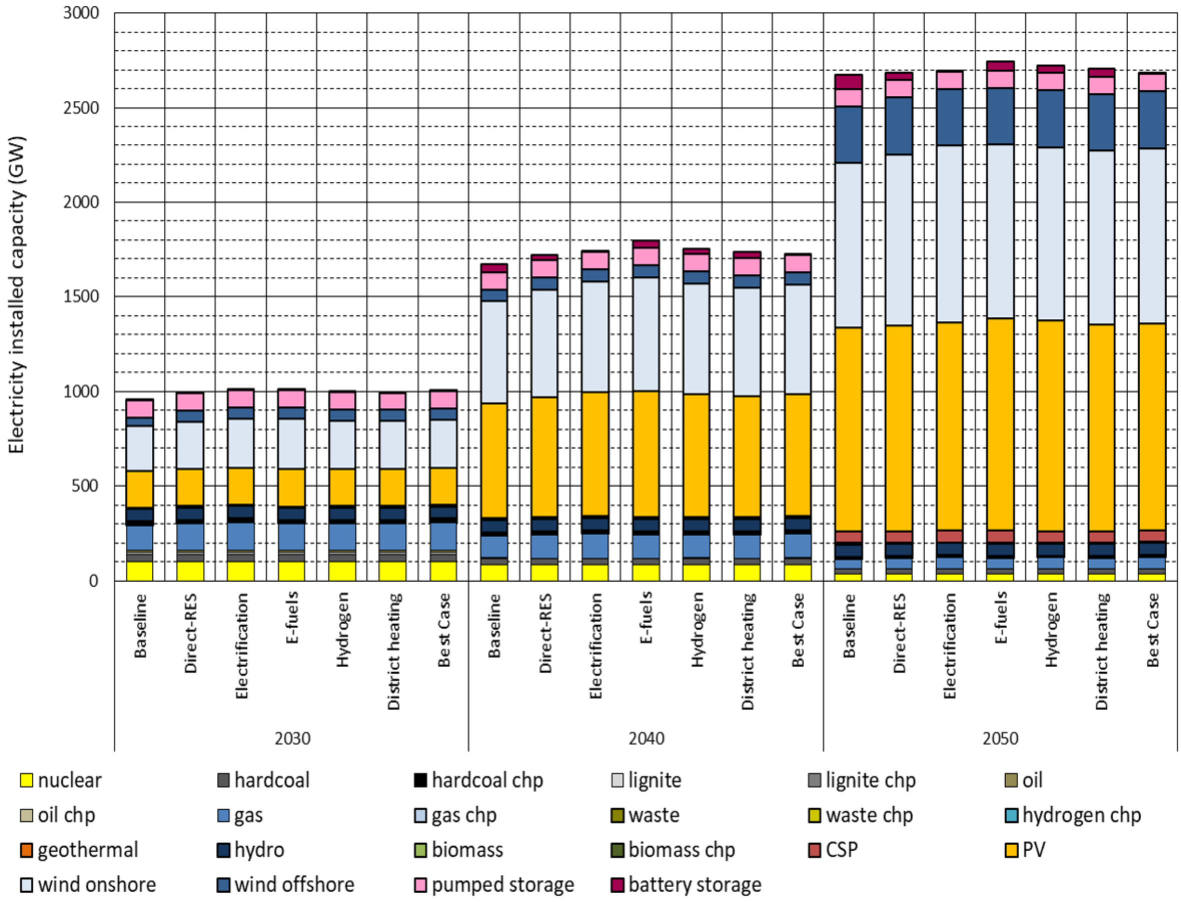


Figure 41: Development of installed capacities for electricity generation in the different scenarios from 2030 until 2050, EU-27.

4.4.3.3. District heat generation and capacity

Different technology options are available in the modelled district heating grids in Enertile. These include fossil-based boilers, fossil-based CHP plants, biomass boilers and CHP plants, electric boilers, large heat pumps using electricity and ambient heat, hydrogen boilers, and heat storages. Decisions on investments in these heating technologies and their use to cover district heating demands are directly integrated into system optimization in Enertile. Furthermore, direct use of renewable energy by solar thermal or geothermal energy is possible. The annual demand for district heat is derived by the Invert model (see chapter 4.4.1) and part of the data exchange between the two models.

The following figure shows the results for district heat generation in the different scenarios until 2050 in the EU 27. In 2030 and 2040, natural gas still plays a central role in district heat supply. Due to the limited carbon budget in 2050 in the technology focus scenarios, natural gas is completely replaced and large heat pumps become the most important technology for district heat supply. Renewable technologies (solar thermal and geothermal) increase until 2050 according to the predefined settings (compare Section 3.3 and 6.3.2.2 for assumptions). The use of biomass, both for boilers and CHP, decreases as predefined in the different scenario settings (compare Section 6.3.2.5 for assumptions). Hydrogen is also used in 2050 for CO2-neutral district heat supply.

The best case scenario shows a predominant use of large heat pumps with 56% of the generation in 2050 coming from them. The use of direct electric heaters is the lowest compared to the other scenarios. This is also observed in figure 37, where the demand for these electric heaters is reduced in the overall scope. The best case scenario shows a similar range of district heat generation in 2050 as the E-fuels scenario with 245 TWh (21 Mtoe).

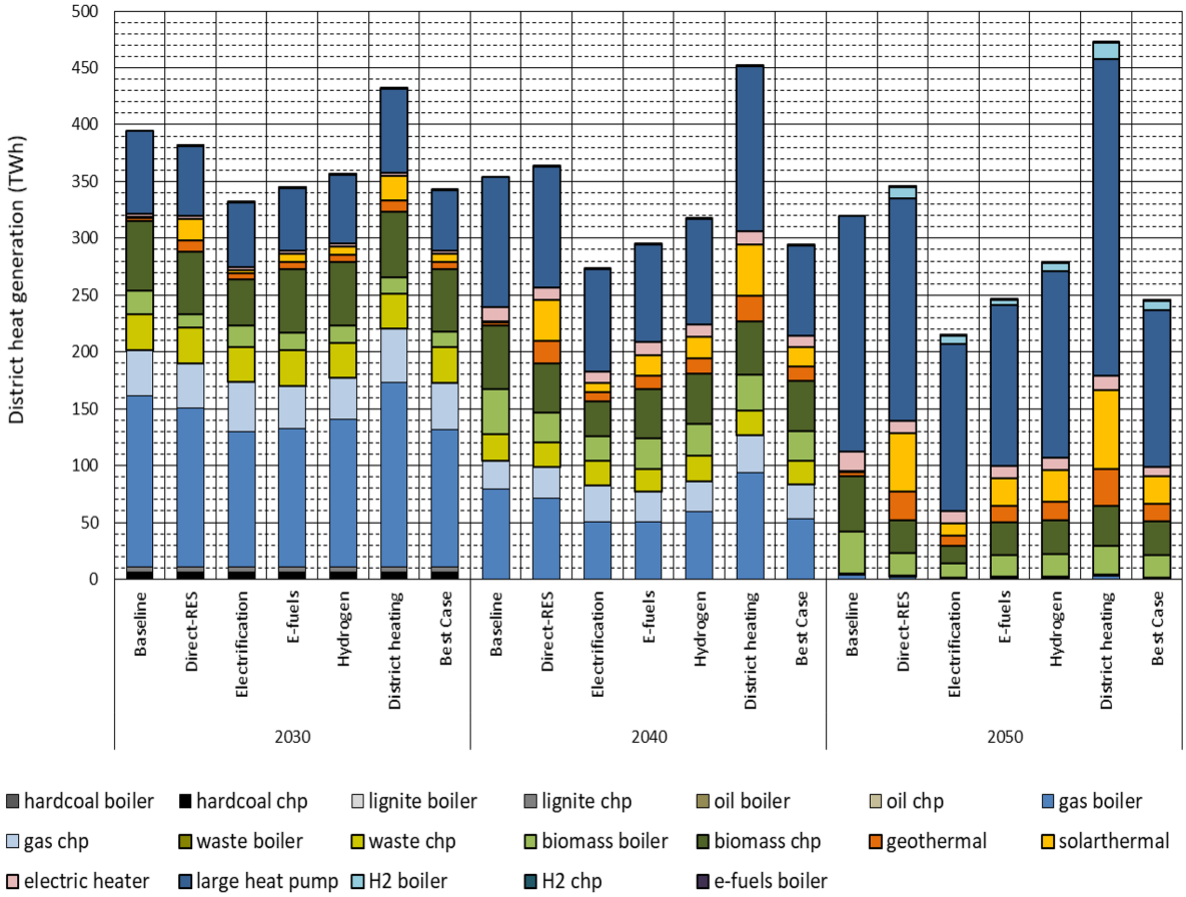


Figure 42: Development of district heat generation in the different scenarios from 2030 until 2050, EU-27.[35]

Figure 43 shows the district heat generation capacities in the EU27 and is complementary to the heat generation shown in Figure 42.

[35] The total demand for district heat in the Direct-RES scenario shown in this Figure does not match the demand shown in Figure 24: as values from the Enertile model are from a previous iteration.

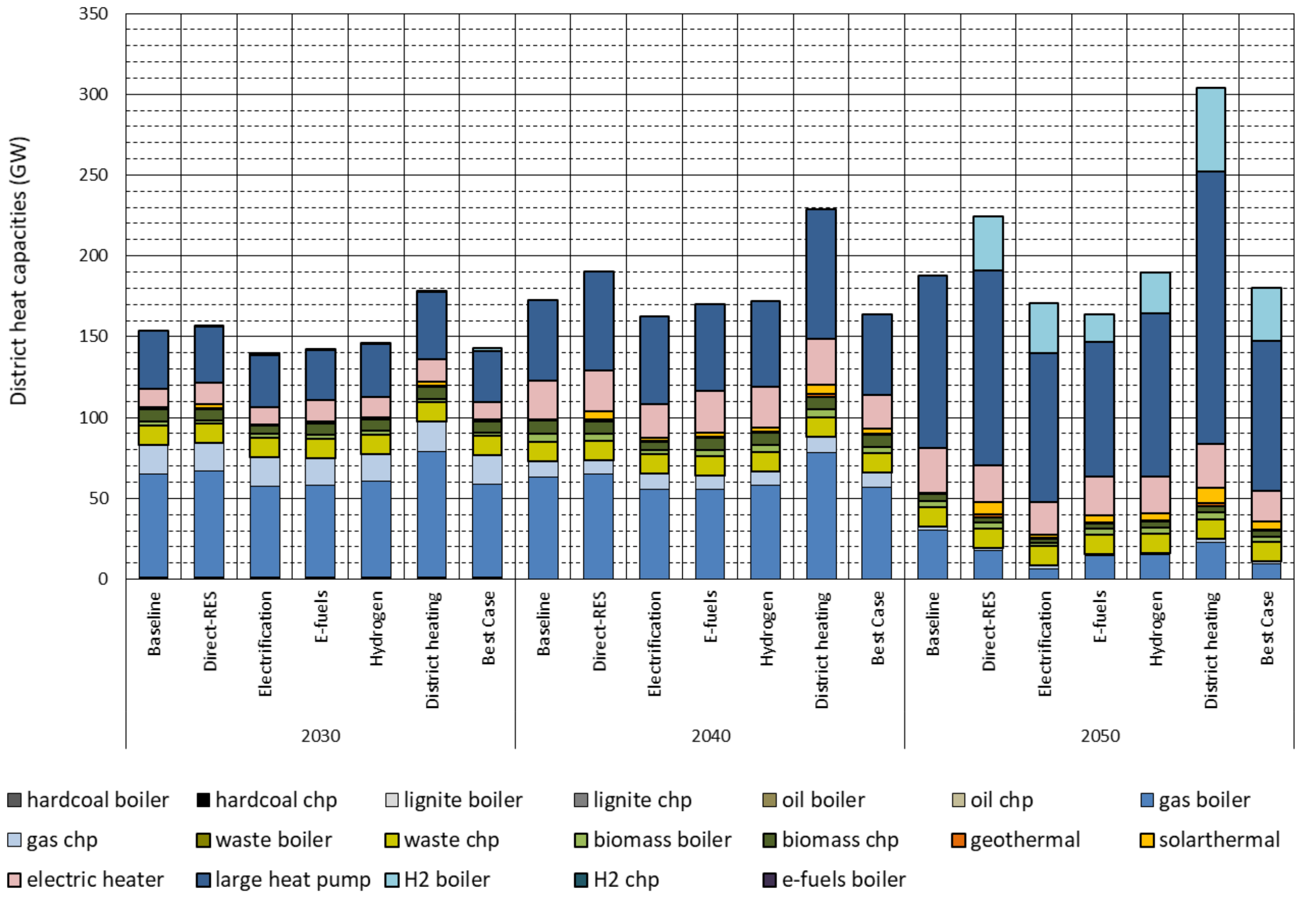


Figure 43: Development of district heating generation capacities from 2030 to 2050, EU-27.

The figure shows the results for district heat generation capacities in the different scenarios until 2050 in the EU 27. Overall, the installed capacities in district heat grids are very slightly induced over time, with the exception of the district heating scenario, in which capacities increase significantly.

Visibly, in 2030 and 2040 gas boiler and gas CHP still provide a relevant contribution to heat grid capacities across the EU, but generally experience a reduction over time, most notably after 2040. Gas boilers, either fired by natural or synthetic E-gas, remain in the system in 2050 with regards to installed capacity, yet their generation is very small, indicating a pure backup role. For gas CHP only marginal capacities remain in 2050.

The role of large heat pumps increases significantly over time and consistently across all scenarios, reaching values of 83 - 168 GW in 2050, highlighting the importance of that technology. In the same vein, but to a far lesser extent, capacities for the electric heater multiply by the factor of around 2, reaching 19 - 28 GW in 2050. Notably, in all scenarios with the exception of the baseline scenario, hydrogen boilers enter the system in 2050 and provide a relevant part of the total installed capacity. Comparing Figure 43 with Figure 42 it becomes clear that the role of these two latter technologies (direct electric resistance heaters and H2 boilers) is mainly for ensuring peak load with only very limited full load hours.

With regards to differences across scenarios, unsurprisingly, the district heating scenario is associated with the overall largest installed capacity in district heating grids, while the electrification, e-fuels and hydrogen scenarios are associated with the smallest installed capacities in 2050. The role of hydrogen varies across scenarios and is largest in the district heating scenario, due to the overall much larger installed capacities, as well as the electrification and

Direct-RES scenarios (as well as the best case scenario that heavily draws on these scenarios). Gas is partly replaced by e-fuels and/or hydrogen in the corresponding scenarios and where available.

To sum up, large heat pumps enter the system early and their installed capacities grow quickly, hydrogen appears between 2040 and 2050. Capacities of gas boilers and CHP is strongly reduced. The total installed capacity per technology varies across the scenarios in amount, but the overall relative contribution per technology is fairly similar.

4.4.3.4. Hydrogen and e-gas demand and supply

Figure 44 shows the results of hydrogen and e-gas demand and supply in the different scenarios until 2050 in the EU 27. Demand is shown below and supply is shown above the x-axis. Similar to the electricity demand, the demand for hydrogen and e-gas can be categorized in different groups. The largest part of demand comprises the exogenous demand from other sectors and from heating applications modelled in INVERT. The other demand categories are endogenously optimized demands for hydrogen and e-fuels. This includes the fuel demand for district heating with hydrogen boilers as well as hydrogen and e-fuels reconversion to electricity. These hydrogen and e-fuel demands are usually covered with electrolysis and methanisation based on renewable electricity on the supply side. Apart from the direct production of hydrogen and e-fuels, import of theses fuels at high prices is possible; which the model recurs to - see Figure 44. Table 16 shows the energy carrier prices for the import of hydrogen or e-fuels.

Table 16: Energy carrier import prices in Enertile.

Prices in €/MWh	2020	2030	2040	2050
Hydrogen	120	100	90	80
E-fuels (synthetic methane)	180	160	150	130

Source: Enertile.

The overall demand differs somewhat between the modelled scenarios and is largest in the e-fuels scenario (1618 TWh or 139 Mtoe in 2050), followed by the hydrogen scenario (1574 TWh or 135 Mtoe in 2050). Demands in the remaining scenarios is around 1.360 - 1.400 TWh (117 - 120 Mtoe) in 2050.

Regarding the development of the demand, in the baseline scenario, e-fuels and hydrogen demands increase significantly from 2030 to 2050, and reach 691 and 660 TWh correspondingly in 2050. In the technology focus scenarios, there is also a significant increase in both demands until 2050, and final demands for e-fuels and hydrogen are roughly the same in 2050 in term of TWh, yet with some exceptions: In the e-fuels scenario, the demand for e-fuels is clearly much larger (922 TWh (79Mtoe) for e-fuels vs. 668 TWh (57 Mtoe) for hydrogen), a ratio that inverts in the hydrogen scenario (701 TWh (60 Mtoe) for e-fuels vs. 839 TWh (72 Mtoe) for hydrogen). Lastly, in the best-case scenario, the demands for e-fuels (695 TWh, 60 Mtoe) and hydrogen (663 TWh, 57 Mtoe) are again roughly similar.

In all scenarios, the role of the e-fuels boiler is irrelevant to heating, and the hydrogen boiler plays a minor role (maximum is 14 TWh (1.2Mtoe) in the district heating scenario in 2050). Reconversion is also not a mayor part of the demand, as e-fuels reconversion does not take place, and hydrogen reconversion only on a small scale (maximum is 41 TWh (3.5 Mtoe) in the electrification scenario in 2050).

With regards to the supply side, in 2050 both the e-fuels and hydrogen are mainly produced locally and complemented by imports. Correspondingly with the demand, the supply increases significantly from 2030 until 2050. The production of e-fuels and hydrogen within the EU increases slightly between 2030 and 2040 and very significantly after 2040, whereas imports of both energy carriers mainly grow between 2030 and 2040 and much less afterward. Again, all scenarios have similar supply patterns with the exception of the e-fuels and hydrogen scenarios in 2050: the overall supply is greater than in the other scenarios and the production of hydrogen is comparatively lower in the e-fuels scenario and vice versa. The import quotas for hydrogen (both scenarios) and for e-fuels (e-fuels scenario) are relatively larger when compared to the remaining scenarios. Specifically, in the e-fuels scenario in 2050, hydrogen imports reach 231 TWh (20 Mtoe) while domestic production in the EU-27 achieves 465 TWh (40 Mtoe, a minimum amongst all scenarios). In the hydrogen scenario, e-fuels production and imports are in line, yet to the upper limit, with the other scenarios, while hydrogen production reaches 616 TWh (53 Mtoe, a maximum amongst all scenarios), and hydrogen imports reach 257 TWh (22 Mtoe) again, a maximum amongst all scenarios). Overall, with the abovementioned exceptions, the supply of e-fuels and hydrogen is fairly similar along all scenarios.

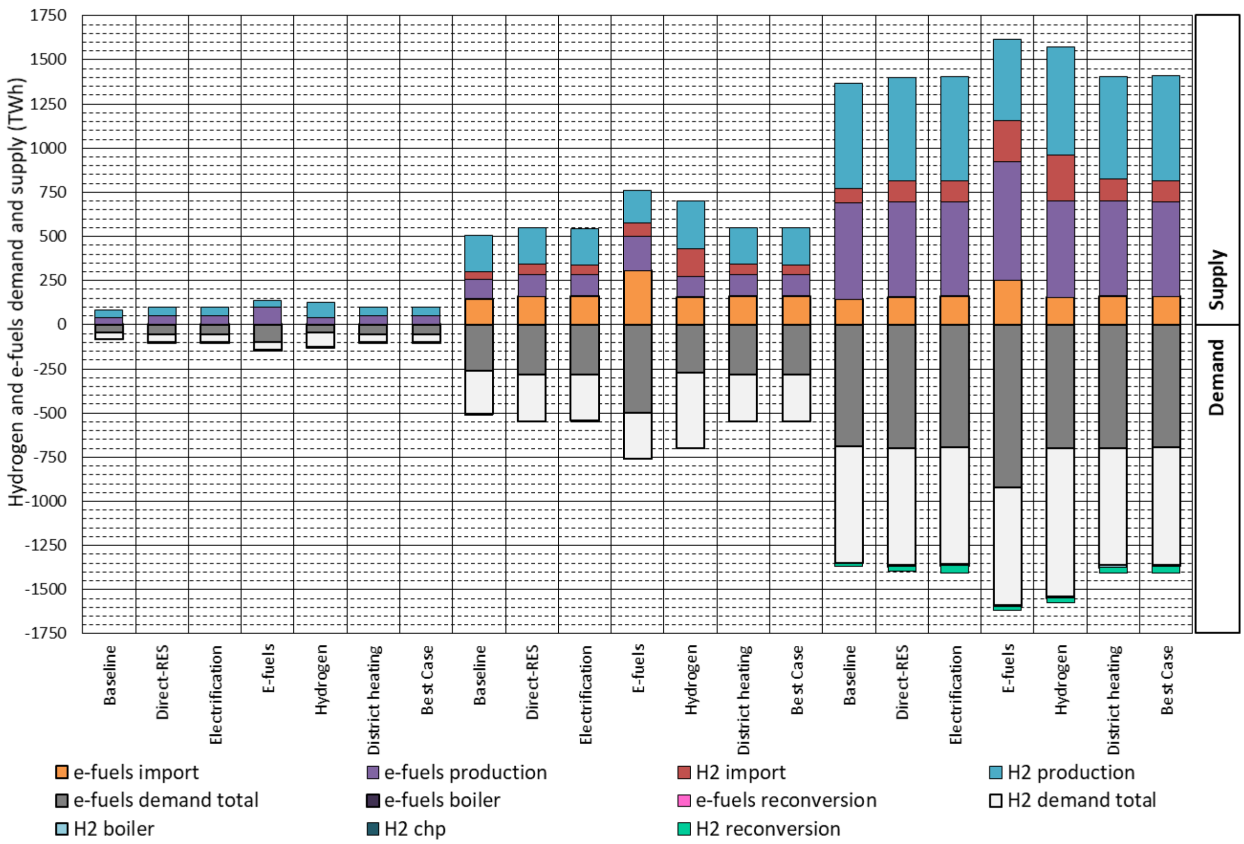


Figure 44: Development of hydrogen and e-gas demand and supply in the different scenarios from 2030 until 2050, EU-27.

4.4.3.5. Electricity peak load

The following figure shows the results of seasonal peak loads of total electricity demand in the different scenarios in 2050 in the EU 27. Included in the peak load are all electricity demand categories as shown in Figure 39.

Seasonal peak loads differ most between the scenarios in Q1 (Jan-Mar) followed by Q4 (Oct-Dec) and are relatively equal in the remaining Q2 and Q3. Where differences exist, the baseline scenario shows the lowest peak, as opposed to the electrification scenario, which shows the highest peak. Generally, the differences between scenarios are rather small. Differences within the same scenario along the year are more pronounced, yet also not large, being the largest difference 170 GW in the electrification scenario.

Seasonal variations can mainly be attributed to the seasonal variation of space heating demand.

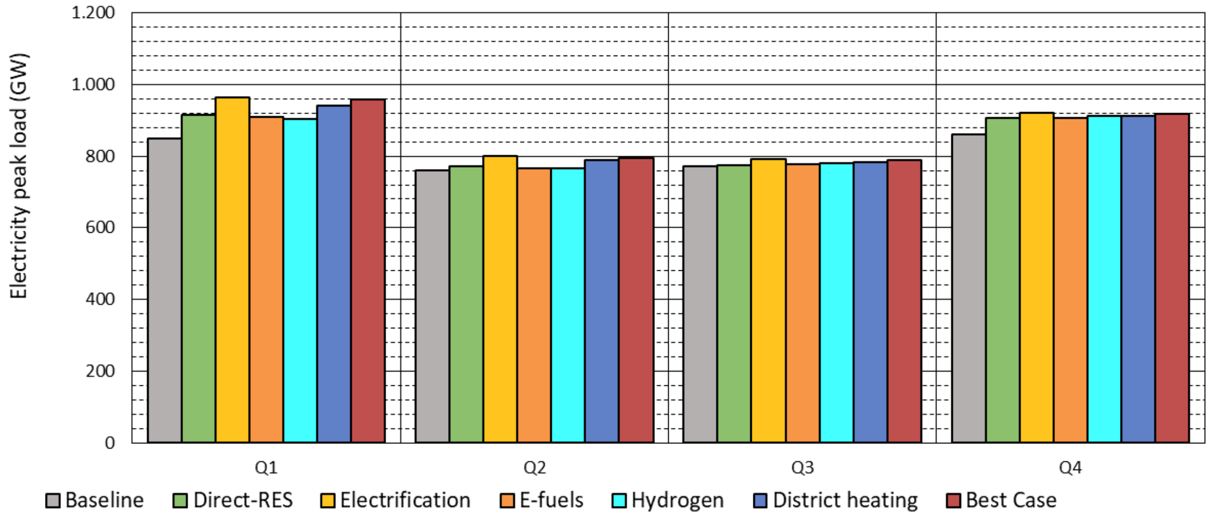


Figure 45: Peak load total electricity demand in the different scenarios in 2050, EU-27.

4.4.4. Results on infrastructure

4.4.4.1. Electricity grid capacities and trading volumes

The electricity transmission grid offers flexibility for the energy system by providing opportunities for inter-regional balancing. Enertile models the transmission of electricity between different model regions using a model of net transfer capacities (NTCs). The expansion of initial cross-border capacities is part of the optimization within Enertile considering the investments required for expansion as well as occurring grid losses.

The following figures show the results of interconnector capacities and electricity trading volumes in the different scenarios until 2050 in the EU 27. As electricity grid expansion is not limited in the scenarios, the cross-border grid capacities and consequently trading volumes both increase considerably until 2050 in all scenarios.

In 2030, all scenarios are rather similar both in terms of cross-border grid capacities and trading volumes (around 251 - 258 GW capacity, the lowest corresponding to the baseline scenario, and the highest to the electrification scenario). In 2050, all scenarios are still similar, but some minor differences emerge more clearly: Cross-border capacity is lowest in the hydrogen scenario (864 GW) and highest in the electrification scenario (885 GW). Trading volumes mostly correspond to that, with the addition that the trading volume in the e-fuels scenario is lowest with 1988 TWh (171 Mtoe) and slightly below the hydrogen scenario with 1999 TWh (172 Mtoe). Unsurprisingly, the highest trading volumes occur in 2050 in the electrification scenario (2068 TWh, 178 Mtoe).

As such, the necessity of international balancing of supply and demand is high in all scenarios and initial grid capacities are excessively expanded. This represents a rather extreme increase with respect to the current state of the electricity grid, but the optimisation in Enertile favours these strong grid extensions over other options that would result in higher costs. This development has several reasons that are related to each other. First, the large share of variable RES electricity generation in 2050 increases the need for international balancing. Furthermore, the high electricity demand makes the exploitation of all good locations for RES generation inevitable and countries with lower amount of attractive RES-E potentials need imports of renewable electricity which can be produced in other countries at lower costs.

The possibility of expanding the interconnector capacities without limits also has a large impact on many other results like the energy costs and the choice and usage of different energy supply technologies. By limiting electricity grid expansion, balancing of supply and demand would need to take place more intensely within each country and the availability of cost-efficient renewables defines the country's electricity mix.

Having this in mind, the data shows that Germany is by far the single largest European electricity importer in 2050 (620 - 646 TWh in 2050 across the scenarios, corresponding to more than 17 % of the total traded volume), followed by France (225 - 250 TWh), Belgium (211 - 242 TWh) and Italy (164 - 175 TWh). Main exporters are France (355 - 403 TWh), Denmark (229 - 233 TWh) and Poland (196 - 208 TWh). Other large electricity exporters are Spain and Sweden. All countries both export and import at different times (depending on demand patterns and the availability of nationally generated renewable energy).

With regards to interconnector capacities, Germany (due to very large imports) and France (important importer and exporter) have the largest capacities with their neighbours (Germany has around 154 - 157 GW or slightly below 10 % of all interconnector capacities in the EU-27 in 2050; France has 136 - 143 GW, as per scenario). Other countries with large interconnectors are The Netherlands, Belgium, Denmark, Italy, Sweden and Poland.

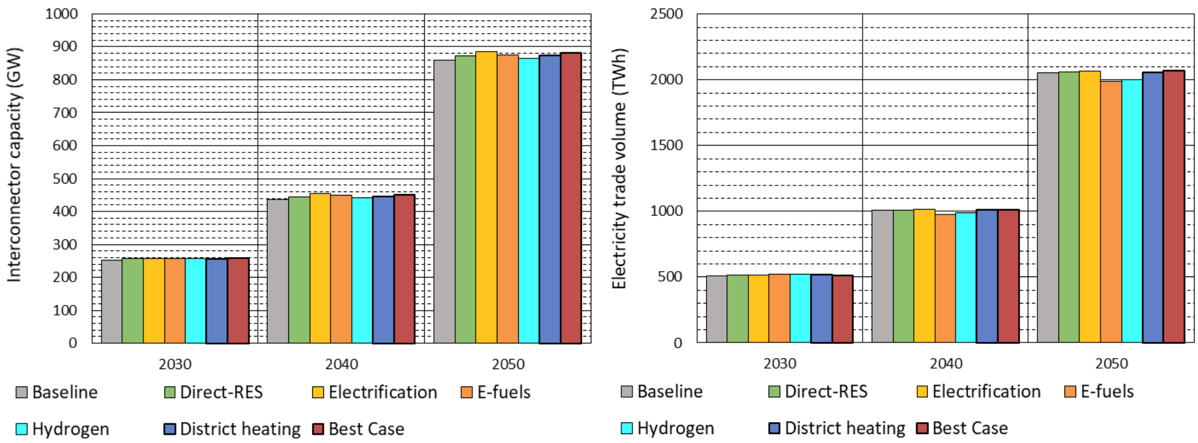


Figure 46: Development of interconnector capacities (left) and electricity trading volumes (right) in the different scenarios from 2030 until 2050, EU.

4.4.4.2. Cost of transport and distribution infrastructure

In order to provide space and water heating services the energy carriers electricity, methane and hydrogen each require a transport grid for long distances and a distribution grid for the last kilometres. However, the scenarios differ in their use of these infrastructures. The next tables show the infrastructure development in these scenarios.

Table 17: Assumptions for the use of transport grid in the scenarios.

Scenario	Electricity grid	Methane grid	Hydrogen grid
Other	Required	Gradual/Complete conversion of grid to hydrogen transport	Transport grid required
Hydrogen	Required	Gradual/Complete conversion of grid to hydrogen transport	Transport grid required
E-fuels	Required	Gradual conversion of grid to hydrogen transport	Transport grid required

All scenarios require a transport grid for electricity. The transport grid for methane needs to be adjusted for the lower transport volume and for the transport of hydrogen by partial conversion of transport routes as hydrogen demand is significant in all scenarios. In the case of distribution grid the scenarios are more contrasting. Only the hydrogen scenario requires a conversion of methane grids to hydrogen distribution grids. In the electricity scenarios major parts of the methane distribution grids can be shut down.

Table 18: Assumptions for the use of distribution grid in the scenarios.

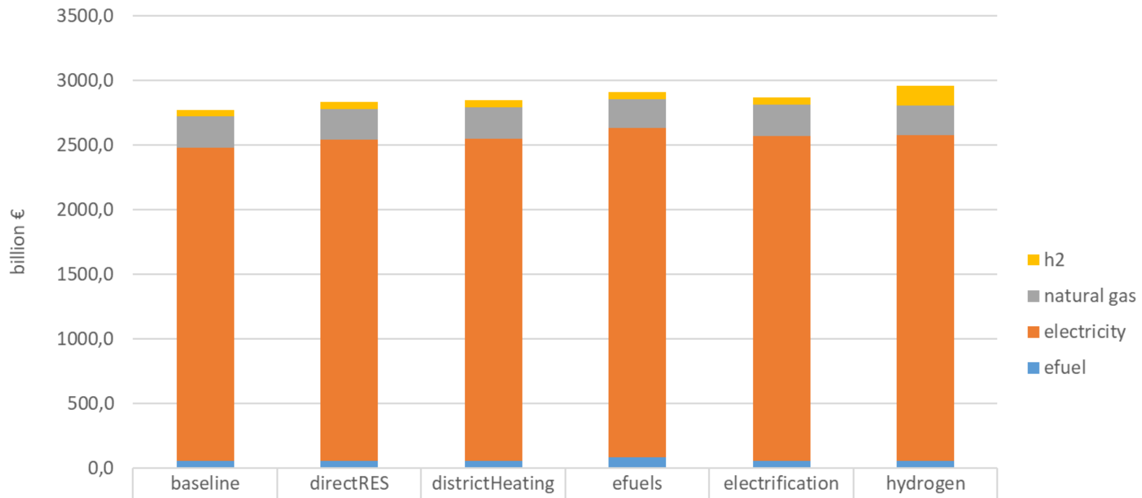
Scenario	Electricity	Methane	Hydrogen
Other	Required may need reinforcements for heat pumps	Partial reduction of the distribution grid	No distribution grid required
Hydrogen	Required	Gradual/Complete conversion of grid to hydrogen	Distribution grid required
E-fuels	Required	Largely unchanged distribution grid	No distribution grid required

The goal of this section is to asses to cost of these infrastructures in the scenarios. In general this requires a detailed modelling. However, in this project only a rough estimation based on other projects is possible. Based on a literature research and own calculations the following assumptions are used which are than scaled with the energy demand in the scenarios.

Table 19: Assumed cost for the grid infrastructures.[36]

Scenario	Transport grid(€/MWh)	Distribution grid (€/MWh)
Electricity	4	12
Hydrogen	5	5
Methane	1	4

However, the transport cost of hydrogen are still connected to considerable uncertainty. In a current literature review[37] the cost of new transport lines varies between 4.6 and 50€/MWh for 600 km and 1.4 and 3.7 €/MWh for retrofitted pipelines which are adapted for h2 transport.



	baseline	directRES	districtHeating	efuels	electrification	hydrogen
h2	51,9	55,0	55,3	53,6	55,6	154,5
natural gas	243,3	239,7	239,7	224,8	239,8	228,8
electricity	2422,1	2483,6	2494,4	2542,5	2513,8	2522,3
efuel	53,1	55,6	55,7	84,6	55,3	54,6

Figure 47: Estimated cost of infrastructure in billion € (2020-2050).[38]

As the partial conversion of the methane grid to hydrogen is not modelled in detail in this project we assume for the cost calculation that the combined grid infrastructure for gas and hydrogen is capable to transport and distribute a minimum of energy amount of (natural gas+hydrogen) (2030: 3000 TWh or 258 Mtoe; 2040 2500 TWh or 215 Mtoe). The rest of the cost estimate is driven by the energy demand calculated in the scenarios.

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[36] Own estimation based on another project (www.langfristszenarien.de)

[37] https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf

[38] We assume a WACC of 2%

Table 20: Cost Estimate of infrastructure in billion €.

scenario	efuel+natural gas	electricity	h2	total
baseline	**296.5**	**2422.1**	**51.9**	**2770.5**
Distribution grid	**237.2**	1816.6	0.0	2053.8
Transport grid	**59.3**	605.5	51.9	716.7
directRES	**295.4**	**2483.6**	**55.0**	**2834.0**
Distribution grid	**236.3**	1862.7	0.0	2099.0
Transport grid	**59.1**	620.9	55.0	735.0
districtHeating	**295.4**	**2494.4**	**55.3**	**2845.1**
Distribution grid	**236.3**	1870.8	0.0	2107.1
Transport grid	**59.1**	623.6	55.3	738.0
efuels	**309.3**	**2542.5**	**53.6**	**2905.4**
Distribution grid	**247.5**	1906.9	0.0	2154.4
Transport grid	**61.9**	635.6	53.6	751.1
electrification	**295.1**	**2513.8**	**55.6**	**2864.5**
Distribution grid	**236.1**	1885.3	0.0	2121.4
Transport grid	**59.0**	628.4	55.6	743.1
hydrogen	**283.4**	**2522.3**	**154.5**	**2960.2**
Distribution grid	**226.7**	1891.8	77.2	2195.7
Transport grid	**56.7**	630.6	77.2	764.5
total	**1,775.1**	**14,978.8**	**425.9**	**17,179.7**

The results indicate that in our estimate the impact of the different scenarios on total grid infrastructure cost is minor compared to the uncertainties of the underlying cost assumptions.

4.5. Conclusions derived from modelling and scenario results

The overall logic of the scenario development was to define boundaries for the relevance of certain energy carriers in supplying space and water heating to buildings, including constraints regarding their potential. Within these constraints, an algorithm identifies the cost-minimal constellation of the use of energy carriers and technologies in different parts of the building stock and the cost-optimal renovation levels. As described in chapter 4.3.1, we did not set these constraints in a too extreme manner but rather let the model some degree of freedom within each scenario to select the cost-optimal package of technologies and renovation measures. Overall, this leads to scenarios which are not considered as extreme scenarios but rather realistic implementations of pathways, with each of the scenarios showing a mix of systems and energy carriers reflecting also the suitability in different parts of the building stock as well as climatic and regional constellations.

In the context of the applied method, it is also relevant to know for which energy carriers in which scenarios the model was constrained mainly by the minimum or by the maximum boundary.

Overall, it turns out that e-fuels and H2 need to be pushed into the model, i.e. in most cases they are very close to the minimum boundary set in the model. This is an indication that these energy carriers are more costly than other systems.

For heat pumps, it rather depends on the type of building whether an efficient use of heat pump is deemed economic. In general, the model has the tendency to move towards the upper limit of the boundary.

Biomass heating systems tend to be economically viable under the considered modelling and scenario assumptions towards climate neutrality. Here, mainly the biomass potential restrictions (and the underlying assumptions regarding more relevant use of biomass potentials in other end-use sectors) are the main constraint limiting a further deployment of biomass heating.

The economic viability of district heating in the model varies between countries. Due to the fact that district heating use was limited to areas with high heat demand densities and corresponding low heat distribution costs, district heating tends to be selected by the optimisation algorithm within the set constraints. However, a relaxation of these constraints would also mean higher district heating distribution costs and thus lower economic viability.

The penetration of individual solar thermal collectors in the modelling result is climate dependent. Moreover, we considered the competing use of roof area (see chapter 4.4.2).

The highest building renovation activities, related investments and thus also the highest final energy demand savings take place in the H2 and e-fuels scenarios.[39] This is due to the fact that building renovation becomes more economically viable the higher the variable energy costs are. And since e-fuels and H2 turn out to have high variable energy costs, high renovation activities are selected by the cost-minimizing model. However, this also means that if these renovation activities would not be feasible due to different barriers, the scenario could not be realized with the costs indicated.

Following main insights can be derived from the modelling. First, if measures and the overall system are optimised (as assumed in our modelling approach) the costs, in particular for the scenarios hydrogen, direct RES, district heating and e-fuels do not deliver a clear criteria for a decision. More relevant are the barriers and policy implications for the decision for one or the other pathway. Second, some measures can be regarded as no-regret options as they are identical for all scenarios: a high level of building renovation, a high diffusion of heat pumps and district heating in suitable areas. Moreover, even in the H2 and e-gas scenario parts of the gas grid would need to be decommissioned, because there would be more economic decarbonisation solutions. Third, the best case scenario – resulting in the lowest cost – is close to the electrification scenario, however, with slightly higher penetration of solar heat and district heating. Building retrofitting is still highly ambitious, but slightly less intensive than in the e-fuels and H2 scenarios.

Barriers and ways of overcoming them are discussed in chapter 5. The realization of each of the considered scenarios strongly depends on overcoming these barriers by a coherent and stringent set of policy instruments, in particular including long-term planning of infrastructure.

[39] The result might seem counterintuitive considering the fact that H2 and e-fuel based heating systems do not require that the building envelope is improved, whereas this is the case for heat pumps or solar heating. The modelling framework takes into account these restrictions of different heating systems, in particular the dependency of the COP of heat pumps with the level of building insulation and required inlet temperature levels to the heating system.

5. Feasibility and Framework Conditions

This chapter analyses the barriers and technological, economic and regulatory framework conditions required in order to facilitate the transition towards the respective target systems studied in Chapter 4.

The methodological approach for deriving recommendations for the technological, economic and regulatory framework conditions is developed based on (Bürger 2013) and includes the following four steps (for an overview see Figure 48):

1. Analysis of the barriers for the deployment of the different space heating options covered in Chapter 4.
2. Analysis of policy instruments available to overcome the barriers identified in the first step.
3. Definition of policy sets for different country clusters and transformation pathways.
4. Recommendations for policies at EU, national and local level.

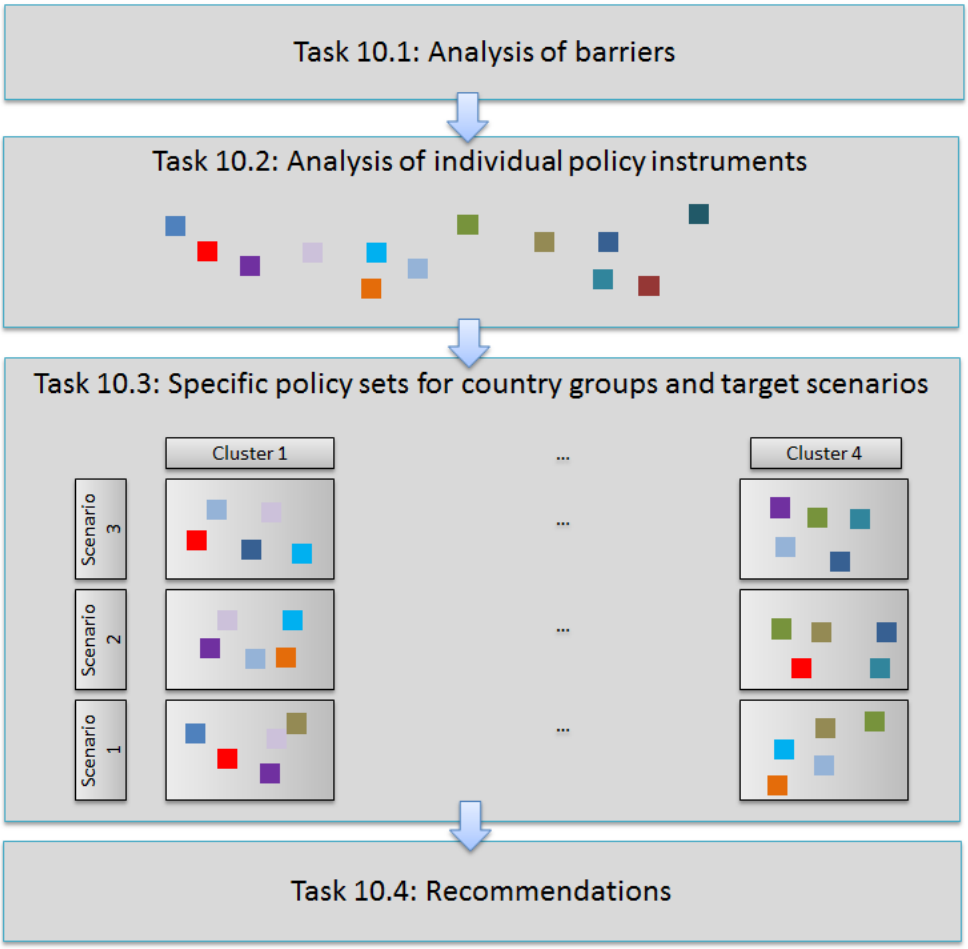


Figure 48: Methodological approach for the analysis of feasibility and framework conditions.

5.1. Background

The results of the scenario analysis in Chapter 4 shows that significant further policy interventions are needed to achieve the decarbonisation of the H&C sector. In all scenarios, the transition pathways until 2050 show considerable gaps with respect to the reference scenario regarding the reduction of energy demand, the phase out of fossil heating technologies and the diffusion of low-carbon heating technologies.

By comparing the results of the different scenarios, key focus areas of policy interventions can be derived (Table 21).

- Across all scenarios, policy interventions are needed to achieve the considerable reduction in energy demand for buildings.
- The role of oil and gas boilers is decreasing rapidly, such that ambitious phase-out regulations are needed across all transformation pathways. This includes the e-fuels- and H_2-pathways, as also in these scenarios a decreasing share of heating is supplied by oil and gas boilers in 2050.
- In the H_2 and e-fuels scenarios, the optimization modelling approach assigns these energy carriers to high-efficient buildings with low energy demand, reflecting the high variable costs of the energy carriers. If used in less efficient buildings, the total costs increase.
- Across all scenarios, policies are needed to support the multiplication of the deployment of heat pumps to harness ambient and geothermal energy with the efficient use of electricity.
- Across all scenarios, policies are needed to support the increasing deployment of solar thermal heating and to ensure that biomass is reduced to sustainable use and allocated adequately to make the best use of the limited resources.
- Across all scenarios, policies to decarbonize district heating are needed to deploy ambient, geothermal, solar thermal energy, as well as H2 and e-fuels and biomass, taking into account sustainability and reduced availability. An expansion and new construction of district heating grids is needed in all scenarios, primarily in the district heating scenario and in the direct RES-H scenario.
- Policies to facilitate the deployment of e-fuels and H_2 are needed in the e-fuels and H_2 scenarios.

Table 21: Overview of scenario results and the need for policy interventions.

	Required developments 2030	Required developments 2050	Need for policy interventions
Reduction of energy demand	Reduction of final energy demand by around 20% with respect to 2017 across all transition scenarios (baseline scenario: 15%)	Reduction of final energy demand by 47-50% with respect to 2017 across all transition scenarios (baseline scenario: 40%)	Significant reduction levels required in all scenarios -> policy interventions needed across all scenarios
Phase-out of individual gas and oil boilers	Reduction of final energy demand for gas by 33-40% with respect to 2017 (baseline scenario: 30%) Reduction of final energy demand for oil by 31-38% with respect to 2017 (baseline scenario: 16%)	Reduction of final energy demand for gas by 84-97% with respect to 2017 (baseline scenario: 69%) Reduction of final energy demand for oil by 78-97% with respect to 2017 (baseline scenario: 48%)	Significant reduction levels required in all scenarios -> policy interventions needed across all scenarios

	Required developments 2030	Required developments 2050	Need for policy interventions
Increase of heat pumps	Increase of final energy demand for ambient energy: 244-396% with respect to 2017 in the transition scenarios (baseline scenario: 60%). In terms of the share of heat demand, the increase is even more pronounced.	Increase of final energy demand for ambient energy: 620-1004% in the transition scenarios (baseline scenario: 139%). In terms of the share of heat demand, the increase is even more pronounced.	Significant increase required in all scenarios -> policy interventions needed across all scenarios
Other RES for individual space and water heating	Energy demand for solar thermal and decentral PV for heating increases by 221-429% with respect to 2017 in the transition scenarios (baseline scenario: 378%) Final energy demand for biomass decreases by 18-26% (baseline scenario: increase by 3%). In terms of the share of heated floor area, the decrease is less pronounced.	Energy demand for solar thermal increases by 560-1089% with respect to 2017 in the transition scenarios (baseline scenario: 919%) Final energy demand for biomass decreases by 45-70% (baseline scenario: increase by 26%). In terms of the share of heated floor area, the decrease is less pronounced.	Significant increase of solar thermal and reduction of biomass required in all scenarios -> policy interventions needed across all scenarios
District heating	The energy supplied by district heating decreases in absolute terms (3-20%) in all scenarios apart from the district heating scenario (+3%), while the share of district heating increases also in other scenarios (more pronounced in the Direct RES- scenario).	The energy supplied by district heating decreases in absolute terms (22-49%) in all scenarios apart from the district heating scenario (+9%), the share of district heating increases also in other scenarios (more pronounced in the Direct RES-scenario).	Policy interventions to foster the deployment of new district heating grids are needed in all scenarios and especially in the district heating and the direct RES-scenario. Across all scenarios, policies to decarbonize district heating are needed.
Use of H_2 and e-fuels	The use of H_2 and e-fuels is reflected in the remaining energy demand for oil and gas in the H_2- and e-fuels scenarios. The demand for gas is reduced by 33% (H_2 scenario) and 35% (e-fuels scenario) as compared to the 38-39% reduction in the remaining transition scenarios. The demand for oil is reduced by 31% in the e-fuel scenario as compared to a 35-38% reduction in the remaining transition scenarios. The reduction is less pronounced in terms of the heated floor area, reflecting the fact that H_2 and e-fuels are assigned to the most efficient buildings by the optimization approach due to their high variable costs.	The use of H_2 and e-fuels is reflected in the remaining energy demand for oil and gas in the H_2- and e-fuels scenarios. The demand for gas is reduced by 84% (H_2 scenario) and 88% (e-fuels scenario) as compared to the 97-98% reduction in the remaining transition scenarios. The demand for oil is reduced by 78% in the e-fuel scenario as compared to an 89-97% reduction in the remaining transition scenarios. The reduction is less pronounced in terms of the heated floor area, reflecting the fact that H_2 and e-fuels are assigned to the most efficient buildings by the optimization approach due to their high variable costs.	Remaining role for gas and oil only in H_2 and e-fuels-scenarios -> focus area only relevant to these scenarios

5.2. Analysis of barriers

For each of the transition pathways, this section analyses key barriers to the deployment of the respective technologies. Section 5.2.1 provides an overview of the barriers for the different decarbonisation elements, while Section 5.2.2 summarizes the conclusions that follow for the analysis of policy instruments.

5.2.1. Barriers for RES-H pathways

The analysis covers different types of barriers, including economic barriers, barriers related to the maturity of technologies and markets, impacts on the electricity sector, resource and space availability, regulatory barriers, barriers related to the buildings stock and end user and investor barriers. The following bullet points briefly summarize the barriers considered in the analysis, for a detailed description of the barriers for each pathway see Table 22 - Table 25.

- **Economic barriers** for the decarbonisation of heating in buildings cover both the investment in energy efficiency and renewable energy measures as well and the operation costs. High investment costs as compared to fossil heating equipment act as a barrier for all of the considered technology pathways, including the investments by building owners in end-use equipment as well as infrastructure investments (e.g. district heating grids). Economic barriers during the use-phase are predominant particularly for the electrification pathway (low prices for fossil fuels as compared to electricity) as well as the hydrogen and e-fuels pathways.
- **Barriers related to technology maturity** occur where the required decarbonisation technologies are not fully developed. Such barriers are particularly pronounced in the (green) hydrogen and e-fuels pathways, where large-scale production, distribution and storage is currently limited to pilot projects. Across all pathways, technology maturity is a barrier for the deployment of new retrofit approaches based on serial renovation supporting a cost-efficient and fast deployment of energy efficiency in buildings. Furthermore, the lack of digital solutions to support the deployment is a barrier for several decarbonisation technologies: For heat pumps, a lack of digital technologies to support the use of flexibility options and demand side management as well as to continuously control the efficient operation are needed for large-scale deployment. Likewise, for district heating the transition to highly efficient systems based on renewable energy requires digital technologies.
- Barriers related to **market maturity (including technology, fuel and installer markets)** are particularly pronounced in the H_2 and e-fuels scenarios, where no markets exist so far. However, market maturity also acts as a barrier in the electrification pathway, as in most EU MS heat pumps currently have a low market share. In district heating, the lack of market maturity for large-scale renewable heat production poses a barrier in most EU MS.
- The **impact on the electricity system** is a barrier in all decarbonisation pathways relying on heat production that involves electricity consumption. This includes decentralised heat pumps, large-scale heat pumps for district heating as well as hydrogen and e-fuels. At the same time, these technologies provide flexibility options for the electricity system.
- **Resource availability** is a key barrier in most pathways and covers the availability of the energy carriers (particularly strong barrier for biomass and hydrogen and e-fuels), the availability of heat sources (particularly pronounced for geothermal installations as

well as water-source heat pumps) and the availability of space (particularly strong barrier for large-scale solar thermal as well as RES-E installations).

- **Regulatory barriers and licensing** are particularly pronounced for technologies with current low deployment, where codes and standards as well as licencing procedures have not been developed (particularly for hydrogen). Regulatory barriers are also relevant for the deployment of ground-source heat pumps as well as the use of the soil or aquifers for heat storage. For district heating, regulatory barriers include the planning and licensing for heat production facilities as well as third-party access to heating grids.
- **The suitability of the building stock** poses a barrier for the deployment of most renewable heating technologies: For heat pumps as well as for RES-based district heating, an efficient deployment requires low-temperature heating systems. For solar thermal installations, rooftops may be unsuitable for the installation. For hydrogen and e-fuels, due to the high costs of the energy carriers, their application in non-efficient buildings leads to high costs.
- **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[40].

Table 22: Barriers for the deployment of efficient heat pumps (electrification).

Deployment of heat pumps - electrification		
Types of barriers	**Electricity generation and Infrastructure[41]**	**Heat pumps**
Economic a) Investment (incl. infra-structure) b) Fuel costs	infrastructure costs for reinforc-ing the distribution grid	Ad a) high investment costs (esp. for geother-mal heat pumps); Ad b) high electricity prices compared to fossil fuels disadvantage the use of electric heat pumps
Technology maturity		Technology less mature for larger buildings Manufacturers refuse to enable or facilitate the monitoring of system performance (e.g. COP display) Lack of technologies and standards to ensure automized demand-side management of heat-pumps to fit demand to renewable energy sup-ply.
Market maturity: tech-nology, fuel and in-staller markets		Installers lack skills to properly install heat pumps
Impact on electricity sector a) Load impli-cations (incl. grid) b) RES-E avail-ability	ad a) load impact especially on the distribution networks in cold periods (at least in countries with low E-share in today's heating sector) load demand and RES generation profile do not match (without heat storage)	

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

[41] Barriers to installing new RES-E production plants not covered

Deployment of heat pumps - electrification		
Types of barriers	**Electricity generation and Infrastructure**[41]	**Heat pumps**
	increases demand for RES-E (at least in countries with low E-share in today's heating sector)	
Resource availability (potentials) and space availability	Additional demand for RES-E -> resource and space availability	Heat pumps require a heat source (air, ground and ground water, river, lake, , excess heat etc.). The availability of ground and water heat sources depends on the geographic and geological characteristics.
Regulatory barriers and licensing (planning regulations, data availability)	Regulation on the use of environmental resources (ambient energy sources) might be unclear; in the management of environmental resources;insufficient expertise by public authorities in licensing geothermal drillings or energy extraction from ground water etc.	Regulation on the use of environmental resources (ambient energy sources) might be unclear; competing interests in the management of environmental resources; geothermal heat pumps: in areas with high density of geothermal heat pumps impact on ground water and soil temperatures; noise limits can pose a barrier for the deployment of heat pumps
Suitability of building stock		Inefficient operation in uninsulated building (high temperature level of heat distribution system)
End user and investor barriers		Split incentives may provide a barrier as investment costs are typically high A lack of information and trust of building owners and a reluctance to switch to new systems provide a barrier.

Table 23: Barriers to the deployment efficient and renewable district heating.

District Heating		
	Heat generation and infrastructure	**End-use equipment**
Economic c) Investment (incl. Infrastructure) d) Fuel costs	Ad a) High investment cost for expanding DH grid; geothermal associated with high risk Ad b) low prices for fossil fuels disadvantage renewable heat generation	-
Technology maturity	Geothermal: Improved drilling technologies could potentially reduce costs Digitalisation not sufficiently integrated in DH schemes; metering and monitoring (system parameters, customer demand parameters etc.) still not fully implemented in many countries -> since the network	

District Heating		
	Heat generation and infrastructure	**End-use equipment**
	operator does not know the exact system parameters, his ability to control the district heating system to meet the real demand situation is limited	
Market maturity: technology, fuel and installer markets	Low temperature DH infrastructure not common in many DH systems	
Impact on electricity sector c) Load implications (incl. grid) d) RES-E availability	For large scale heat pumps see barriers in Table 22	
Resource availability (potentials) and space availability	Biomass: domestic resources limited Solar thermal: space availability and associated costs Heat pumps: resource availability (ambient energy source) + additional demand for RES-E incl. infrastructure Geothermal: potential restricted to specific regions (depending on geologic conditions) Unavoidable waste/excess heat: Uncertainties in long-term availability Large scale thermal storage requires space resources near to urban settlement area	
Regulatory barriers and licensing (planning regulations, data availability)	RES-H (e.g. space requirements for solar collector fields) is often not sufficiently considered in the local planning process Unclear regulation for third party access (especially for RES and waste/excess heat) Regulatory framework does not provide for RES-H to be explicitly marketed as such Geothermal: limited availability of information on geological conditions -> high risk Complex and partly unclear regulation for licensing, diverging regulations at the sub-national level, or insufficient expertise by public authorities dealing with the applications of DHC related topics	Integrated planning process (in the sense of local strategic heat planning) is lacking access to information/data on demand side (quality of building stock, heat demand, age structure of boilers etc.)
Suitability of building stock	-	Trade-off between building envelope related efficiency measures (lowering heat density) and profitability of DH expansion.
End user and investor barriers	Investment risks for waste heat recovery and geothermal systems	

Table 24: Barriers for the efficient deployment of solar thermal heating.

Solar thermal	
	Solar thermal
Economic e) Investment (incl. Infrastructure) f) Fuel costs	Depending on prices for heating fuels, investments in solar thermal are not recovered without subsidies at reasonable time scales Depending on support framework for PV, PV installations are more cost-effective and thus available roof space is preferably used for PV
Technology maturity	No barrier
Market maturity: technology, fuel and installer markets	No barrier barrier for small-scale systems, however small/no market for large-scale installations in most countries.
Impact on electricity sector e) Load implications (incl. grid) f) RES-E availability	No impact
Resource availability (potentials) and space availability	Limited space on rooftops, particularly in multi-family dwellings; Competing technology: roof-top PV For large-scale systems, space availability is a limitation
Regulatory barriers and licensing (planning regulations, data availability)	
Suitability of building stock	Rooftops may be unsuitable for the installation of solar thermal Unfavourable regulations for historic buildings
End user and investor barriers	Split incentives, lack of awareness, lack of information

Table 25: Barriers for the efficient deployment of hydrogen for space and water heating

	Hydrogen		
	Production	**Infrastructure**	**End-use equipment**
Economic a) Investment (incl. Infrastructure) b) Fuel costs	Currently high cost for H2 production Taxes on electricity used in electrolysers	High investment costs for H2 infrastructure -> Use of hydrogen for heating needs to be limited to selected application, e.g. in district heating	Current end-use equipment typically not suitable for hydrogen

	Hydrogen		
	Production	**Infrastructure**	**End-use equipment**
Technology maturity	Electrolysis is mature technology, however at small scale H2 production from natural gas reformation is mature also on large scale, however in order to reduce CO2-emissions it would need to be combined with CCS technologies, which are not available at large scale	H2 Infrastructure currently only in specific pilot projects (e.g. city of Leeds). Blending of H2 in natural gas grids possible up to 10-20% Storage and transport more complicated (and thus expensive) than for natural gas due to smaller molecule size[42]	-
Market maturity: technology, fuel and installer markets	Hydrogen production would need to be scaled up drastically No established market for large-scale electrolysers.	No market for H2 grids Road transport is established but not practical when scaling up the use of H2 Transport by ship not established and no standards developed	Fuel cell market is a niche market, hydrogen as fuel is not available at large scale Uncertain if decentralised use of H_2 is feasible
Impact on electricity sector a) Load implications (incl. grid) b) RES-E availability	b) RES-E availability insufficient within EU -> Imports needed Hydrogen is needed in all sectors	-	-
Resource availability (potentials) and space availability	RES-E availability		
Regulatory barriers and licensing (planning regulations, data availability)	No GO system implemented Regulations, codes and standards typically do not include new gases No procedures for licencing established	Safety regulations not established Differing and typically low levels of permitted hydrogen-blending in the EU MS No procedures for licencing established	Safety regulations not established Regulations, codes and standards typically do not include new gases Billing regulations would need to be changed if blending of H_2 with larger shares is allowed in gas networks
Suitability of building stock	-	-	In order to achieve the low system costs, high efficiency levels of the building stock and combination with

[42] (Burke and Rooney 2018.)

	Hydrogen		
	Production	**Infrastructure**	**End-use equipment**
			solar technologies and thermal storage are required.
Lock in potential		High lock-in potential if current gas grids are replaced by H2 grids	For H2-blending, lock-in of natural-gas based infrastructure and equipment

5.2.2. Conclusions for policy analysis

From the analysis of barriers, the following conclusions are derived for the policy analysis:

- All decarbonisation elements are facing a heterogeneous set of barriers and thus require a mix of policies to support the transformation.
- Across all decarbonisation elements, economic barriers persist where fossil fuel prices are low. Policies that increase the prices of fossil fuels may support the transition across all pathways.
- Resource availability is a key limitation for sustainable biomass for heating. Policies are needed to ensure that biomass use is limited to sustainable levels.
- The use of H_2 for heating faces key barriers: Firstly, from the economic perspective, using H_2 for individual space heating would require extensive investments in H_2 distribution grids, leading to uncertain and potentially high costs for final consumers. Secondly, it is highly uncertain if green hydrogen will be available for heating in buildings and if so in what quantities and at what price. Thirdly, H_2 as a decarbonisation option faces the risk of lock-in if investments in infrastructure and end-use appliances are undertaken despite the large uncertainties. For these reasons, priority should be given to the remaining decarbonisation options for heating in buildings.

5.3. Policy approaches for RES-H

The transition of heating in buildings towards climate neutrality requires overcoming the variety of barriers discussed in Section 5.2 by means of a strong policy mix.

Given the long lifetimes of buildings elements and heating systems, retrofit measures need to be rapidly aligned to the objective of decarbonisation. For example, with an average lifetime of space and water heaters between 20 and 25 years, any replacements of heating systems after 2025 need to be largely based on renewable heating, as fossil fuels play a negligible role in the decarbonized heating energy mix in 2050 (see Figure 24).

The most effective way of aligning investments in building components and heating systems to the objective of decarbonisation is by establishing a **strong regulatory framework** to restrict the use of technologies that are not consistent with the objective (see Section 5.3.1).

In order to address the economic barriers and to ensure a just transition, **economic policy instruments** ensure an affordable transition and provide a level playing field for renewable technologies. Key economic instruments include subsidies and preferential loans for investments in renewable heating technologies as well as energy and carbon pricing (see Section 5.3.2).

To support market and technological maturity and to address regulatory barriers, a set of **supporting complementary policies** is needed to support the transition. This includes R&D support measures, market transformation measures such as collective procurement programmes, capacity building and training for installers, capacity building to support planning skills in local administrations (see Section 5.3.3).

As the transformation of the heating sector has impacts on the use of key infrastructures (district heating, gas grid and electricity grid), **heat planning** approaches are needed to coordinate the expansion and removal of such infrastructures (see Section 5.3.4).

5.3.1. Regulatory instruments

Regulatory instruments need to have a leading role in the transition of the buildings sector, setting the essential requirements and framework. Regulations are needed to shape the necessary transition from fossil fuel heating to renewables in individual and district heating and to reduce energy demand in buildings.

For **individual heating**, the transition from fossil fuels to renewable heating can be supported by regulations that either mandate the use of renewable energies (RES-H obligations for buildings, see Table 26), or that restrict the use of heating equipment using fossil fuels (phase-out regulations for fossil boilers, see Table 27). In both approaches, the stringency of the regulations needs to reflect the requirement that the use of fossil fuels for heating is reduced to almost zero by 2050 (see modelling results in Figure 24). In view of the long lifetimes of the appliances, this means that from 2025 on, newly installed heating equipment needs to be largely based on renewables.

Table 26: Factsheet: RES-H obligations for buildings.

RES-H obligations for buildings	
Description	RES-H obligations in buildings specify a mandatory minimum level of RES-H in decentralized heating. Key design options include the building segments that are covered (e.g. new buildings, existing buildings, public buildings), the trigger point (e.g. major renovation, exchange of heating system) and the level of mandatory RES-H (percentage of total heating demand in the building). RES-H obligations need to be set with an ambition that is consistent with the decarbonisation pathways towards climate neutrality, as low ambition levels may induce lock-in effects.
Examples from MS	RES-H obligations are in place for new buildings in various EU MS. For existing buildings, Denmark has implemented a RES-H obligation in areas with district heating (see e.g.(Keimeyer 2021)). In Germany, two Federal States have introduced RES-H obligations for existing buildings (Baden-Württemberg[43] and Hamburg[44]).
Role of EU legislation	At EU level, provisions to introduce/strengthen RES-H obligations for decentralized heating include Art. 15 RED, provisions on building codes in the EPBD as well as the provisions for public buildings in the EED.

[43] Erneuerbare-Wärme-Gesetz (EWärmeG), see also (Pehnt et al. 2019.)

[44] Hamburgisches Gesetz zum Schutz des Klimas (Hamburgisches Klimaschutzgesetz - HmbKliSchG)

Table 27: Factsheet: Phase-out regulations for fossil boilers.

Phase-out regulations for fossil boilers	
Description	Phase-out regulations for fossil fuels in decentralized heating systems limit the installation and/or use of fossil-based heating systems. Key design options include the building segments that are covered (e.g. new buildings, existing buildings, public buildings) and the use of exemptions (e.g. for hybrid systems).
Examples from MS	Some EU MS have introduced or planned phase-out regulations (see e.g. Keimeyer, 2021). For example, phase-out regulations are currently in place for oil boilers in new buildings in Austria and for national gas in the Netherlands. Germany has introduced a phase-out regulation for oil boilers in new and existing buildings from 2026.
Role of EU legislation	At EU level, provisions to introduce phase-out regulations could be included in the EPBD or in the Ecodesign Directive.

To ensure the considerable **reduction of heating demand in buildings** (halving the demand by 2050 as shown in Table 21), both the renovation rate and the depth of renovations need to be increased considerable. Besides minimum energy efficiency standards for new buildings and for major renovations, a key instrument for increasing the energy efficiency of buildings are minimum energy performance standards (MEPS, see Table 28.

Table 28: Factsheet: Minimum energy performance standards for buildings.

Minimum energy performance standards for buildings	
Description	Minimum energy performance standards for buildings set minimum requirements that need to be fulfilled by all buildings or selected buildings segments. Key design options are scope (e.g. all buildings, residential buildings, non-residential buildings), the trigger point for the obligation (e.g. transactions such as renting or change of ownership, share of worst performing buildings falling under the obligation in given year), and the ambition level of the requirements (which requirements need to be fulfilled)
Examples from MS	Minimum energy performance standards have been introduced in some EU MS, e.g. in the Netherlands for office buildings and in France for rented buildings (for an overview see (Sunderland and Jahn 2021)
Role of EU legislation	At EU level, provisions to introduce minimum energy performance requirements could be included in the EPBD, as foreseen by the renovation wave communication[45].

In **district heating**, regulations are needed to ensure that heat generation, which is currently largely based on fossil fuels, transitions to renewable sources and waste heat. Key regulations to set the key requirements are RES-H obligations for district heating (see Table 29).

[45] (European Commission 2020a.)

Table 29: RES-H/excess heat obligations for district heating.

RES-H/excess heat-quota for DH operators	
Description	RES-H/excess heat obligations in district heating specify a mandatory minimum level (quota) of RES-H and/or excess heat in heating grids. Key design options include the obliged party (e.g. heat producer, grid operators, heat suppliers), the level and development of the mandatory RES-H/excess heat share (in line with the long-term goal), and the introduction of potential flexibility options (e.g. via tradable certificates). RES-H/excess heat obligations need to be combined with a sound verification system through which target compliance can be ensured.
Examples from MS	N/A
Role of EU legislation	At EU level, provisions to introduce RES-H/excess heat obligations for district heating could be supported by strengthening Art. 24 RED.

5.3.2. Economic instruments

Economic instruments are of key importance to address the economic barriers and to ensure an affordable transition for households and firms. Economic instruments comprise instruments supporting the investment in RES-H technologies, as well as carbon pricing, reducing the economic viability of investments in fossil heating systems.

Investment support may cover all elements necessary to drive the transition. For individual heating and buildings components, this includes the investments in heating equipment as well as buildings elements in order to reduce energy demand and/or system temperature. A recent BPIE report[46] estimates that to achieve deep renovation of the EU building stock, an amount of 73 billion EUR per year should be allocated in support of building renovation. The report also highlights the need for advisory services including the establishment of one-stop shops, the roll out of the Building Renovation Passport and respective awareness campaigns as well as technical advice for MS for establishing support programmes. In addition, a need for 13.8 billion EUR/a is estimated to support the upscaling of serial renovation of buildings on an industrial scale.

For district heating, financial support is needed for large-scale RES-H installations and seasonal heat storage as well as for the expansion and transformation of district heating grids. This also includes specific financial support for the conversion of steam-based grids to water-based grids and to the installation of metering and monitoring equipment.

[46] https://www.bpie.eu/wp-content/uploads/2020/05/Recovery-investments-in-deep-renovation_BPIE_2020.pdf

Table 30: Factsheet: Financial incentives for RES-H.

Financial incentives for RES-H	
Description	Financial incentives include a variety of funding and subsidy approaches providing financial support for investments in energy efficiency and/or renewable heating. Key design options are the mechanism of providing the support (e.g. grants, loans, tax deductions), the financing mechanism (e.g. state budget, taxes or levies), the level of the subsidy, as well as the scope (i.e. which technologies are covered). Financial support can be provided for the investment costs or output-based for each kWh of RES-H that is produced by the installation. Financial incentives can also be provided in the form of scrapping schemes, where fossil heating systems are replaced.
Examples from MS	Many MS have implemented support schemes for RES-H with differing designs. For example, the German "Federal Funding for Efficient Buildings"[47] scheme covers a broad range of energy efficiency measures as well as support for renewable heating systems in buildings. The scheme is open for all building and owner types and provides the option of choosing between a loan and a grant. For renewable heating installations, the scheme includes a scrapping approach by providing additional support (higher funding rates) when old oil heating installations are replaced by renewable heating. Some MS have introduced funding schemes that specifically address low-income households. For example, the Irish Warmer Homes Scheme specifically targets vulnerable and energy-poor households providing advice and financial support for energy efficiency measures. Similarly, the Lithuanian JESSICA Holding Fund for multi-family building renovation provides specific conditions for low-income households.
Role of EU legislation	Various EU funding sources provide opportunities to support investments in the decarbonisation of heating in the EU MS, including the Next Generation EU Fund[48] as well as the cohesion and structural funds. For supporting the scale-up of technologies in early development stages as well as for capacity building, funding is provided by the Horizon Europe program.

Carbon pricing (see Table 31) is a key complementary policy to support the transition of the buildings sector. Carbon pricing alone is unlikely to drive the transition at sufficient speed, as a variety of non-economic and structural barriers persist in the buildings sector. This includes split incentives, where investments are borne by home owners, whereas the price of carbon is paid by the tenant. However, carbon pricing can play an important role in ensuring that investments mandated by regulatory instruments (see Section 5.3.1) do not lead to high financial burdens for households and companies. Furthermore, the revenues of carbon pricing may be used for financing support schemes for energy efficiency and renewable heating and to ensure an affordable transition.

[47] https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2021/01/Meldung/news1.html

[48] https://ec.europa.eu/info/strategy/recovery-plan-europe_en

Table 31: Carbon pricing for heating fuels.

Carbon pricing for fossil fuels in the buildings sector	
Description	Carbon or energy pricing aims at increasing the cost of fossil fuels with the aim of (partly) internalizing the social costs associated with the combustion of fossil fuels. Carbon pricing can be introduced through taxes of by means of an emissions trading scheme.
Examples from MS	Carbon pricing for heating fuels has been implemented in several EU Member States. Sweden introduced a carbon tax already in the early 1990s and with more than 115 EUR/t is the highest carbon price globally[49]. More recently, Germany has introduced an ETS for the buildings and transport sector in 2021, with a fixed price path of 25 EUR/t in 2021 to 55 EUR/t in 2025.
Role of EU legislation	In the context of the fit-for-55 package, the EU Commission has proposed to introduce an ETS for the buildings and transport sectors (in addition to the existing EU ETS).

5.3.3. Supporting complementary instruments

The fast transition of heating in buildings requires supporting policies that provide guidance and training for the various actors in the heating market and to support the market transformation.

For the transition of **individual heating** in buildings, heat pumps need to drastically upscale their market share, while ensuring high quality of components and installations. This requires capacity building for professionals installing and inspecting heating systems. Furthermore, market transformation can be supported by collective procurement, where national or local government can provide support for creating procurement networks with actors in the buildings sector. Support for research and development can further support the swift diffusion of RES-technologies across all building segments, including the development and diffusion of digital elements that ensure an efficient long-term performance.

For increasing **energy efficiency in buildings**, one-stop-shop approaches can provide guidance and support to building owners that undertake retrofit measures. Buildings renovation passports can provide guidance for building owners to ensure that staged renovations are conducted consistently. Furthermore, Energy Performance Certificates provide a means to increase information and awareness of the energy performance of buildings. Support for research and development for serial retrofit approaches may lower the costs of building retrofit and reduce the pressure on the labour force needed for building retrofit.

For **district heating**, guidance and support to district heating operators for setting up transformation plans (possibly combined with an obligation) can assist the transition. Furthermore, training/guidelines for licensing bodies and the establishment of regional competence units providing licences may speed up the diffusion of new district heating grids as well as the transformation of existing grids to renewable sources and the use of excess heat. To support the market transformation, public consumers/buildings (schools, public swimming pools etc.) can be offered as anchor customers and public buildings may play and exemplary role with the conversion to low temperature distribution systems. Furthermore, public land can be provided for solar collector fields, seasonal storage etc.

[49] Source: Carbon pricing dashboard, August 2021, https://carbonpricingdashboard.worldbank.org/map_data

5.3.4. Heat planning and citizen involvement

The transformation of the heating sector requires **heat planning** approaches (see Table 29) to coordinate the expansion and dismantling of infrastructure, to identify areas that could be used for centralized RES-H generation, or the geological potential for seasonal heat and cold storage, and to allocate the limited RES-H resources. The rapid decline of the use of gas for heating (see Figure 24) requires spatial planning to establish a coordinated approach for dismantling the gas grid. Likewise, the expansion of district heating needs to be coordinated taking into account local heat densities as well as the availability of local RES-sources and waste heat. Heat planning can be supported by data on local resources including a systematic waste/excess heat register.

Biomass allocation plans are required, as the use of biomass decreases despite the rapid increase of the RES-H share (see modelling results in Figure 24). While biomass is currently by far the most commonly RES for heating, its use needs to be limited to such applications, where other options are not feasible.

Citizen involvement can play an important role for the energy transition in the heating sector. An overview of energy community approaches for heating and the legislative frameworks in different EU MS is presented in Annex 7.7.

Table 32: Factsheet: Heat planning.

Establish mandatory heat planning	
Description	Urban or regional heat planning defines strategies for the decarbonisation of different areas or districts within cities or municipalities. Strategic heat planning supports the efficient use of infrastructures by assigning priority areas for district heating and for other decarbonisation options. Heat planning can be conducted at the level of municipalities and may be supported by the regional and/or national level (e.g. providing guidance on the availability of limited resources such a biomass). Depending on the stringency and concrete implementation of heat planning, this can have regulatory character (e.g. zoning for district heating), or be combined with economic incentives or complementary instruments.
Examples from MS	Examples for MS include Denmark, having a long tradition of urban heat planning and the Netherlands, where heat planning has been introduced as a key element of the Dutch strategy to phase-out natural gas for heating[50].
Role of EU legislation	Provisions to support urban planning in EU MS are currently not part of EU legislations and could be introduced in the EED or possibly the RED.

[50] For details see e.g. the Dutch Long Term Renovation Strategy

5.4. Development of policy packages

5.4.1. Clustering of countries

In order to provide policy packages for specific country groups, the countries covered in the analysis are grouped into four country clusters. We apply two clustering algorithms, “Agglomerative” Clustering and “KMeans”. Both algorithms are implemented in python through scikit-learn[51]. Both are unsupervised learning algorithms that look for similarities in the data points.

The K-means algorithm uses a sum-of-squares criterion and aims to choose centroids that minimise the inertia:

$$\sum_{i=0}^{n} \min(||x_i - \mu_j||^2)$$

While the KMeans algorithm looks at all data points “at the same time” the agglomerative algorithm uses a bottom-up approach. Each data point is assumed to be a separate cluster at first. Then the most similar clusters are iteratively combined. The similarity of the data points and in further consequence the clusters is determined through the minimization of the error sum of the squares:

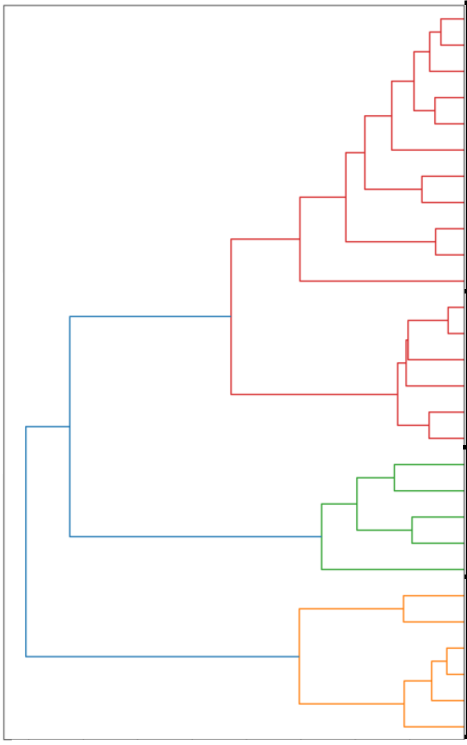
$$d_{ij} = ||X_i - X_j||^2$$

The restrictions of different heating systems and energy carriers used in the modelling activities (chapter 7.4.1) as well as the heating degree days (HDD) have been chosen as input data for the clustering algorithm. The main reason is that the restrictions combine data on the current use of energy carriers with information on the potential for future use. However, some of the information was redundant or not relevant for the clustering algorithm. This for example is the case for the restriction of direct electric heating or oil heating, which are identical across the countries (very low technical restrictions to use these technologies). Thus, we reduced the number of relevant technology or energy carrier restrictions to biomass, district heating, gas, solar thermal and heat pumps. As climatic conditions are only partially reflected in these data, HDD were added to the set of clustering parameters. All these parameters were normalized to 1, i.e. for the case of HDD, the highest value among all countries was set to 1 and all other countries were assigned to the ratio of their heating degree days to this maximum value. For the case of energy carriers and technology restrictions, within each Member State, the highest value was set to one and all the others were related to this parameter.

Figure 49 shows the clustering results of the described algorithms. To illustrate the “similarities” of the different countries a dendrogram is shown on the left-hand side. The distance of the x-axis before two countries of clusters are merged represents the “difference” between those two respective countries/clusters. For example, LV and LT are very similar, therefore the distance on the x-axis is very small and they are merged into one cluster.

The countries in central Europe are merged to a cluster, mainly because of the high predicted use of natural gas. Southern countries are grouped in one cluster as they have high potential for solar thermal energy and very little potential for district heating. Northern countries on the contrary have a very high potential for district heating and high number of heating degree days.

[51] Scikit-learn: Machine Learning in Python, Pedregosa *et al.*, JMLR 12, pp. 2825-2830, 2011.



	Solar thermal	Natural Gas	Biomass	Heat pumps	District Heating	HDD	
HU	50%	74%	19%	51%	29%	51%	Natural Gas
LU	50%	68%	17%	51%	28%	56%	
DE	50%	76%	12%	58%	25%	56%	
FR	50%	65%	16%	51%	19%	45%	
BE	50%	71%	14%	45%	22%	51%	
NL	50%	89%	12%	43%	28%	51%	
HR	65%	62%	22%	52%	22%	43%	
IT	65%	73%	17%	48%	26%	36%	
UK	50%	69%	11%	43%	46%	57%	
SK	50%	68%	18%	51%	46%	59%	
AT	45%	90%	37%	22%	19%	68%	
SI	50%	45%	22%	53%	23%	49%	Diverse
IE	50%	49%	20%	53%	20%	51%	
PL	50%	37%	31%	55%	22%	62%	
BG	50%	32%	20%	53%	32%	47%	
CZ	50%	55%	20%	48%	35%	61%	
RO	50%	45%	25%	50%	32%	55%	
PT	70%	40%	21%	50%	4%	22%	Solar thermal
MT	80%	29%	10%	34%	1%	14%	
ES	75%	54%	16%	44%	23%	34%	
GR	80%	39%	18%	53%	22%	29%	
CY	80%	1%	14%	50%	3%	22%	
SE	50%	18%	18%	65%	69%	94%	District heating
FI	40%	17%	19%	56%	52%	100%	
LT	45%	35%	25%	47%	46%	67%	
LV	45%	32%	25%	48%	47%	72%	
EE	50%	36%	25%	50%	47%	78%	
DK	50%	38%	18%	51%	57%	61%	

Figure 49: Resulting Clusters of the clustering algorithms. The dendrogram on the left shows which countries the agglomerative algorithm clustered in what order.

The country clusters are described in Table 33 and graphically displayed in Figure 50.

Table 33: Proposed country clustering as a basis for the barrier analysis (EU-27+UK).

Country Cluster	Countries	Characterisation
A	CY, ES, GR, MT, PT	Warm climate, low to medium future relevance of district heating
B	BG, CZ, IE, PL, RO, SL	Medium climate, medium to high future relevance of dis-trict heating, moderate availability of gas infrastructure
C	DK, EE, FI, LT, LV, SE	Cold climate, high potential relevance of district heating, low to moderate availability of gas infrastructure
D	AT, BE, DE, FR, HR, HU, IT, LU, NL, SK, UK	Medium to cold climate, medium to high future relevance of district heating, high availability of gas infrastructure,

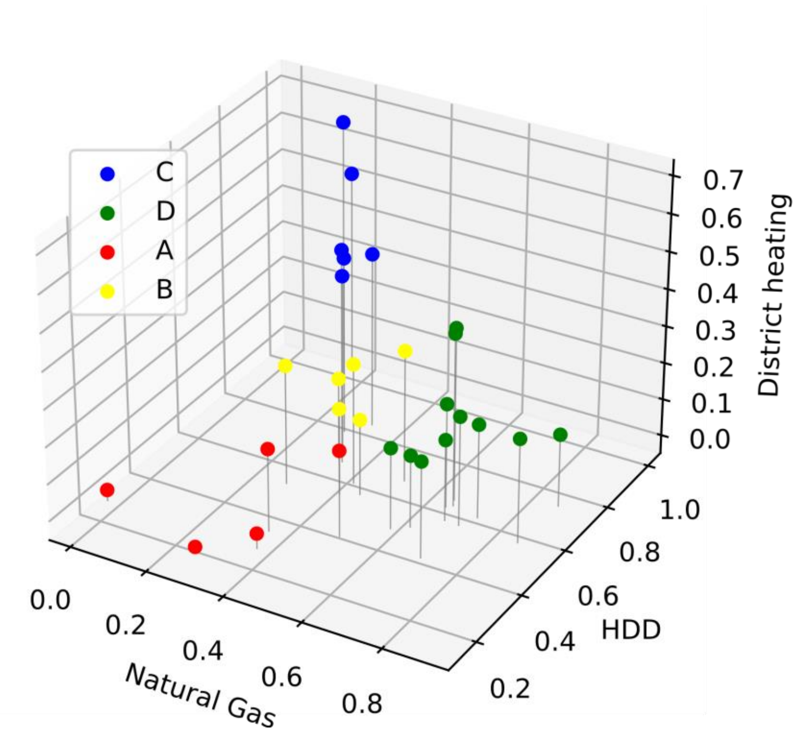


Figure 50: Graphical illustration of the 4 clusters in respect to 3 input parameters: district heating, natural gas and HDD.

5.4.2. Policy packages for country clusters

The policy packages for the decarbonisation of heating in buildings have common elements across all country clusters: For all country clusters, a strong regulatory framework is needed, supported by economic instruments, supporting measures as well as an integrated approach to heat planning. Within this common framework, the priorities for policy intervention differ across the clusters:

- For country cluster A, with a relatively low heating demand due to warm climate as well as a relatively minor role of district heating, a key priority is the decarbonisation of individual heating, focussing on the policy approaches displayed in Figure 51 (red frame).
- For country cluster B, with medium climate, medium to high future relevance of district heating and a moderate availability of gas infrastructure, key priorities are the decarbonisation of individual heating and district heating focussing on the policy approaches displayed in Figure 51 (yellow frame).
- For country cluster C, with old climate and high potential relevance of district heating, low to moderate availability of gas infrastructure, key priorities are the decarbonisation of district heating focussing and the increase of energy efficiency, focussing on the policy approaches displayed in Figure 51 (blue frame).
- For country cluster D, with medium to cold climate, medium to high future relevance of district heating and a high availability of gas infrastructure, all decarbonisation elements are of key relevance, see Figure 51 (green frame).

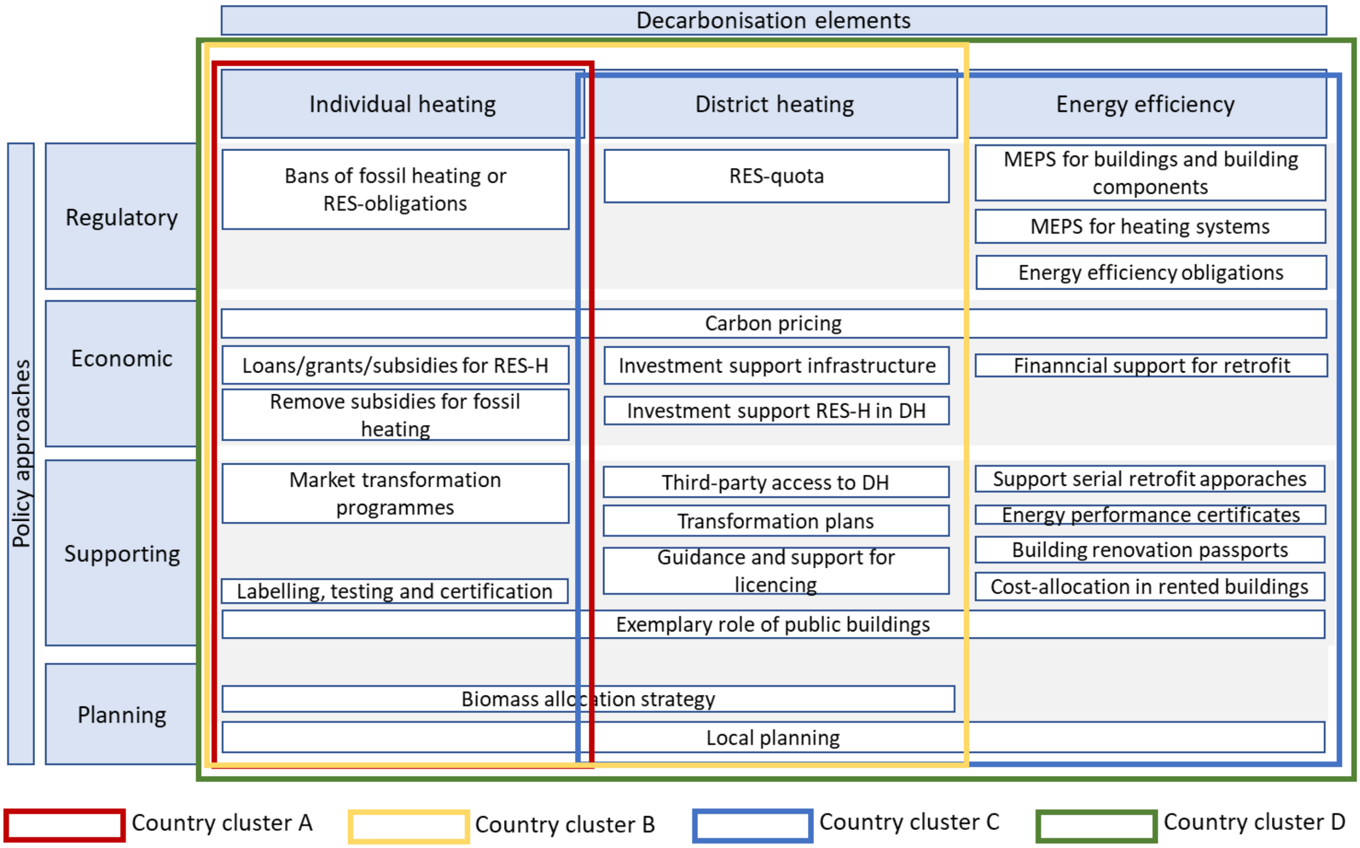


Figure 51: Policy packages for the decarbonisation of space and water heating.

5.5. Recommendations

Establishing an integrated package of policy measures (see Figure 51) requires a supportive interaction between policy instruments at EU, national and local level.

The **EU level** provides the framework for a variety of the policy instruments included in the policy packages:

An overarching indicative **target for the decarbonisation of the heating sector**[52] is set in Art. 23 of the RED, stating that MS shall endeavour to increase the share of renewable heating by an average of 1.1 percentage points per year (1.3 percentage points if waste heat is used). To drive the heating sector towards full decarbonisation, the target needs to be continuously increased and made binding[53] (see Figure 52). A binding target as well as a supporting framework is needed, as the increase of the RES H&C shares in most EU MS fall short of meeting the target (see Figure 53). Furthermore, as the current RES-H shares differ significantly between the MS, for MS with low shares the annual increases need to exceed the EU average in order to reach full decarbonisation.

[52] The target in Art. 23 RED includes process heat, while the scope of this study is limited to heating in buildings.

[53] The Commission proposal foresees a binding target as well as the increase of the 1.3 percentage point target for MS using waste heat to 1.5 percentage point.

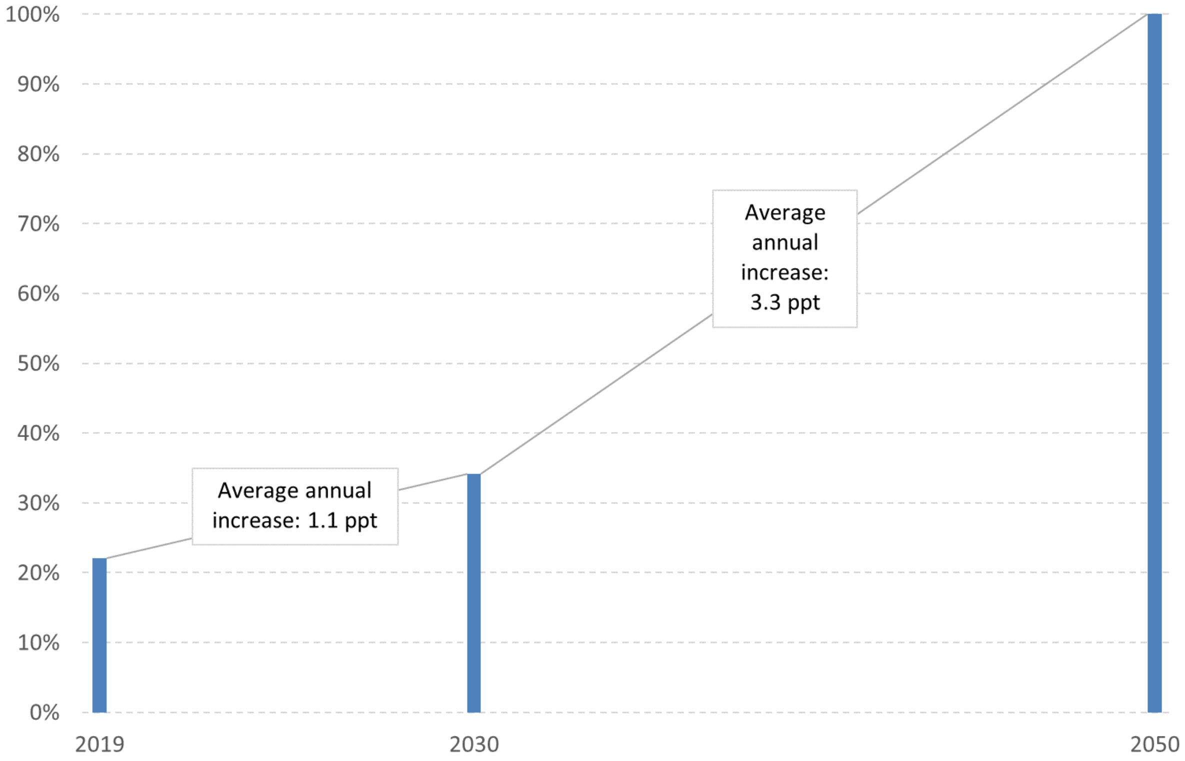


Figure 52: RES-H&C shares in the EU-27 according to EUROSTAT Shares data (2019) and projected share with 1.1 percentage point increase until 2030 and the necessary growth rate towards full decarbonisation in 2050. Source: Oeko-Institut (2021).[54]

[54] https://blog.oeko.de/is-the-eu-heating-sector-fit-for-55-ist-der-waermesektor-der-eu-fit-for-55-eng-deu/

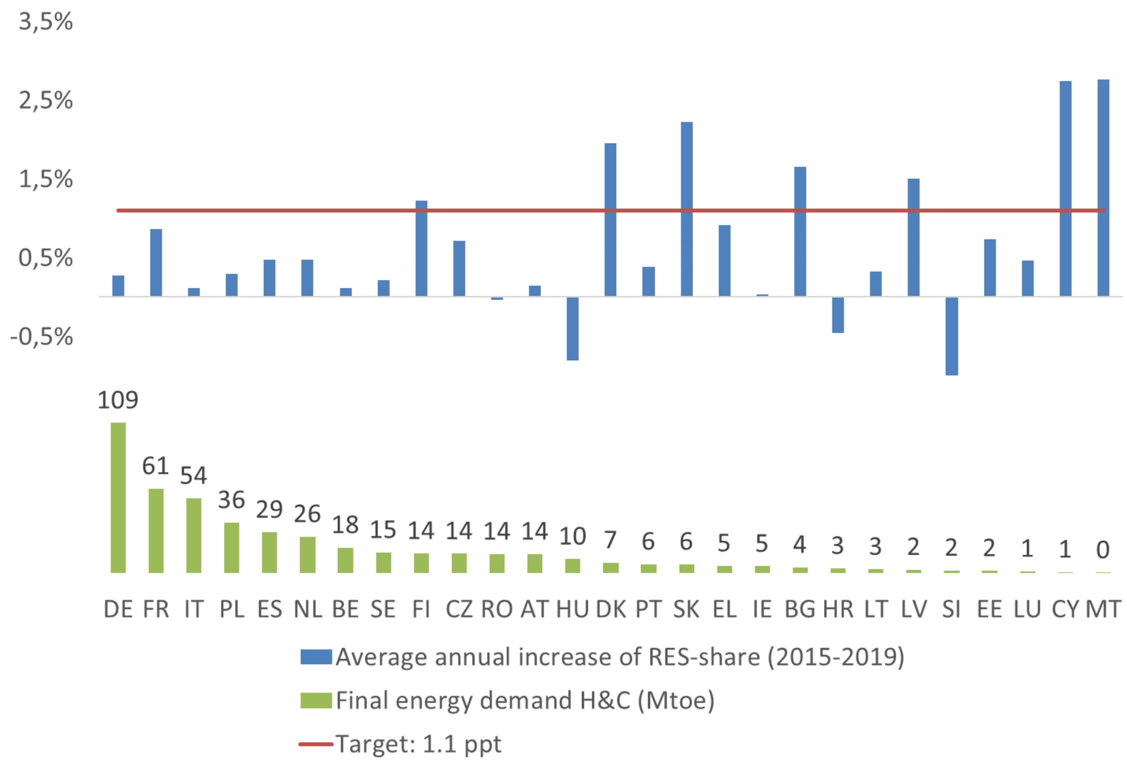


Figure 53: Average annual increase of RES shares in the years (2015-2019) and target of 1.1 percentage point increase. The lower part of the figure displays the final energy demand for H&C in the MS. Source: Oeko-Institut (2021).[54]

The **decarbonisation of individual heating** systems in buildings is partly addressed in the EPBD in the context of the requirements for new buildings and buildings under major renovation to meet the nZEB standard (nearly zero energy buildings). Heating systems are addressed under Art. 8 (technical buildings systems), where a strengthening of the requirements could support the phase-out of fossil fuels in individual heating. Renewable heating in buildings is furthermore addressed in Art. 15 (4) of the RED, mandating a minimum share of renewable heating in new buildings and buildings under major renovation. To ensure a swift transition and to avoid lock-in effects, the provisions should be strengthened by introducing an (ambitious) numerical value for the minimum share. As the diffusion of RES-technologies in all decarbonisation scenarios (see Chapter 4) largely exceeds the current diffusion rates in all technology scenarios, use obligations for RES in existing buildings should furthermore not only be coupled to major renovations but to the exchange of the heating system (which typically has much higher exchange rates than building retrofit).

The **decarbonisation of district heating** is partly addressed in the RED. Art 24 of the RED requires Member States to ensure that district heating and cooling contribute to the overall RES-H target, either by the implementation of measures aiming at increasing the RES share in heating and cooling grids by 1 ppt per year or granting grid access to RES-H or excess heat producers (Third Party Access). In order to achieve a rapid transformation towards a climate-neutral district heating supply, these requirements should be tightened and made more binding within the framework of the RED. In addition to binding targets for the RES-H/excess heat share in district heating, DH operators could be required to develop transformation plans (decarbonisation roadmaps). At the same time, policy instruments are needed that support the corresponding infrastructure development in those Member States that rely on an expansion of district heating. Here, planning requirements could be strengthened, for instance an obligation for municipal heat planning, which could be integrated into the EED.

For **increasing the energy efficiency** of buildings, the EPBD provides key provisions for new buildings and for buildings under major renovation. However, as across all decarbonisation pathways the energy demand needs to be reduced considerably, an extension and strengthening of the requirements for existing buildings is needed. Furthermore, increasing efforts for worst-performing buildings is of great importance not only for energy efficiency but also for RES-HC to support the diffusion of heat pumps and low-temperature district HC (strong increase in distribution of these technologies necessary in all technology pathways). This can be achieved by including provisions for MS to introduce minimum energy performance standards (MEPS) for existing buildings, as announced in the renovation wave communication.

The **national level** plays a key role for designing the policies described in Section 5.3 according to the specific technological, social and economic conditions as well as the characteristics of the building stock and heating market. With the EU level providing the framework, the successful and ambitious transposition of the provisions into national legislations is a key success factor for the decarbonisation of the buildings sector.

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7. Annex

7.1. Annex A: Structure and allocation of EUROSTAT energy carriers

Table 34 : Allocation of EUROSTAT energy carriers to final and primary energy carriers.

ID	Energy carrier label	Energy carrier code	Final energy carrier	Primary energy carrier	Energy carrier group
1	Total	TOTAL	TOTAL	TOTAL	Nonrenewables
2	Anthracite	C0110	Coal	Hard coal	Nonrenewables
3	Coking coal	C0121	Coal	Hard coal	Nonrenewables
4	Other bituminous coal	C0129	Coal	Hard coal	Nonrenewables
5	Sub-bituminous coal	C0210	Coal	Hard coal	Nonrenewables
6	Lignite	C0220	Coal	Lignite	Nonrenewables
7	Patent fuels	C0320	Coal	Hard coal	Nonrenewables
8	Coke oven coke	C0311	Coal	Hard coal	Nonrenewables
9	Gas coke	C0312	Coal	Hard coal	Nonrenewables
10	Coal tar	C0340	Coal	Hard coal	Nonrenewables
11	Brown coal briquettes	C0330	Coal	Lignite	Nonrenewables
12	Gas works gas	C0360	Other fossil fuels	Gas	Nonrenewables
13	Coke oven gas	C0350	Other fossil fuels	Gas	Nonrenewables
14	Blast furnace gas	C0371	Other fossil fuels	Gas	Nonrenewables
15	Other recovered gases	C0379	Other fossil fuels	Gas	Nonrenewables
16	Peat	P1100	Other fossil fuels	Lignite	Nonrenewables
17	Peat products	P1200	Other fossil fuels	Lignite	Nonrenewables
18	Oil shale and oil sands	S2000	Fuel oil	Oil	Nonrenewables
19	Crude oil	O4100_TOT	Fuel oil	Oil	Nonrenewables
20	Natural gas liquids	O4200	Fuel oil	Oil	Nonrenewables
21	Refinery feedstocks	O4300	Fuel oil	Oil	Nonrenewables
22	Additives and oxygenates (e	O4400X4410	Fuel oil	Oil	Nonrenewables
23	Other hydrocarbons	O4500	Fuel oil	Oil	Nonrenewables
24	Refinery gas	O4610	Fuel oil	Oil	Nonrenewables
25	Ethane	O4620	Fuel oil	Oil	Nonrenewables
26	Liquefied petroleum gas	O4630	Fuel oil	Oil	Nonrenewables
27	Motor gasoline (excluding bi	O4652XR5210B	Fuel oil	Oil	Nonrenewables
28	Aviation gasoline	O4651	Fuel oil	Oil	Nonrenewables
29	Gasoline-type jet fuel	O4653	Fuel oil	Oil	Nonrenewables
30	Kerosene-type jet fuel (exclu	O4661XR5230B	Fuel oil	Oil	Nonrenewables
31	Other kerosene	O4669	Fuel oil	Oil	Nonrenewables
32	Naphtha	O4640	Fuel oil	Oil	Nonrenewables
33	Gas oil and diesel oil (exclud	O4671XR5220B	Fuel oil	Oil	Nonrenewables
34	Fuel oil	O4680	Fuel oil	Oil	Nonrenewables
35	White spirit and special boili	O4691	Fuel oil	Oil	Nonrenewables
36	Lubricants	O4692	Fuel oil	Oil	Nonrenewables
37	Bitumen	O4695	Fuel oil	Oil	Nonrenewables
38	Petroleum coke	O4694	Fuel oil	Oil	Nonrenewables
39	Paraffin waxes	O4693	Fuel oil	Oil	Nonrenewables
40	Other oil products n.e.c.	O4699	Fuel oil	Oil	Nonrenewables
41	Natural gas	G3000	Natural gas	Gas	Nonrenewables
42	Hydro power	RA100	Other RES	Hydro	Renewables
43	Tide, wave and ocean	RA500	Other RES	Hydro	Renewables
44	Wind power	RA300	Other RES	Wind	Renewables
45	Solar photovoltaic	RA420	Solar energy	Solar	Renewables
46	Solar thermal	RA410	Solar energy	Solar	Renewables
47	Geothermal	RA200	Geothermal	Geothermal	Renewables
48	Primary solid biofuels	R5110-5150_W6000RI	Biomass	Biomass	Renewables
49	Charcoal	R5160	Biomass	Biomass	Renewables
50	Biogases	R5300	Biomass	Biomass	Renewables
51	Renewable municipal waste	W6210	Waste RES	Waste RES	Renewables
52	Pure biogasoline	R5210P	Biomass	Biomass	Renewables
53	Blended biogasoline	R5210B	Biomass	Biomass	Renewables
54	Pure biodiesels	R5220P	Biomass	Biomass	Renewables
55	Blended biodiesels	R5220B	Biomass	Biomass	Renewables
56	Pure bio jet kerosene	R5230P	Biomass	Biomass	Renewables
57	Blended bio jet kerosene	R5230B	Biomass	Biomass	Renewables
58	Other liquid biofuels	R5290	Biomass	Biomass	Renewables
59	Ambient heat (heat pumps)	RA600	Ambient heat	Ambient heat	Renewables
60	Industrial waste (non-renewa	W6100	Waste non-RES	Waste non-RES	Nonrenewables
61	Non-renewable municipal w	W6220	Waste non-RES	Waste non-RES	Nonrenewables
62	Nuclear heat	N900H	Other fossil fuels	Nuclear	Nonrenewables
63	Heat	H8000	District heating	Biomass	Mix
64	Electricity	E7000	Electricity	Hydro	Mix

7.2. Annex B: Modelling framework and assumptions

7.2.1. Modelling the building sector: Invert/EE-Lab and Invert/Opt

The **building stock model Invert/EE-Lab** is a bottom-up model to simulate energy related investment decisions 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 (+ Norway, Iceland, Switzerland, UK) including type of building, age, state of renovation, existing heating systems, user structure as well regional aspects such as availability of energy infrastructure for e.g. district heating or natural gas on a sub-country level. It simulates investment decisions in the building shell and the heat supply and distribution systems 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.

The derived model version **Invert/Opt** is able to calculate cost optimal scenarios based on a combination of technology options available in different years – both for heat savings (retrofitting measures mainly regarding the building envelope) and heat supply (mainly replacement of heating and hot water supply systems) – and considering diffusion constraints10F[55] such as limited availability of (tradeable) biomass, energy infrastructure or e.g. available roof area suitable for solar technologies) options (see also chapter 3.4.1). Due to the high level of disaggregation (varying from country to country between a few hundred to a few thousands building segments split in several climate regions) of the existing buildings and the high level of detail in the possible renovation options for each of the building types the model leads to a wide spread technology mix even in the optimization mode.

The Invert model has been developed and applied in national and international projects in the EU for more than 10 years now, in many of them reflecting the entire EU building stocks (Invert/EE-Lab 2020).

A more detailed description of the model can be found below.

Invert/EE-Lab is a dynamic bottom-up simulation tool that evaluates the effects of different framework conditions (in particular different settings of economic and regulatory incentives) on the total energy demand, energy carrier mix, CO2 reductions and costs for space heating, cooling and hot water preparations in buildings. Furthermore, Invert/EE-Lab is designed to simulate different scenarios (price scenarios, insulation scenarios, different consumer behaviours, etc.) and their respective impact on future trends of energy demand and mix of renewable as well as conventional energy sources on a national and regional level. More information is available on www.invert.at or e.g. in (Kranzl et al., 2013) or (Müller, 2012).

The basic structure and concept are described in Figure 54.

[55] For the implementation of the cost-optimal solution under diffusion constraints see (Andreas Müller 2015).

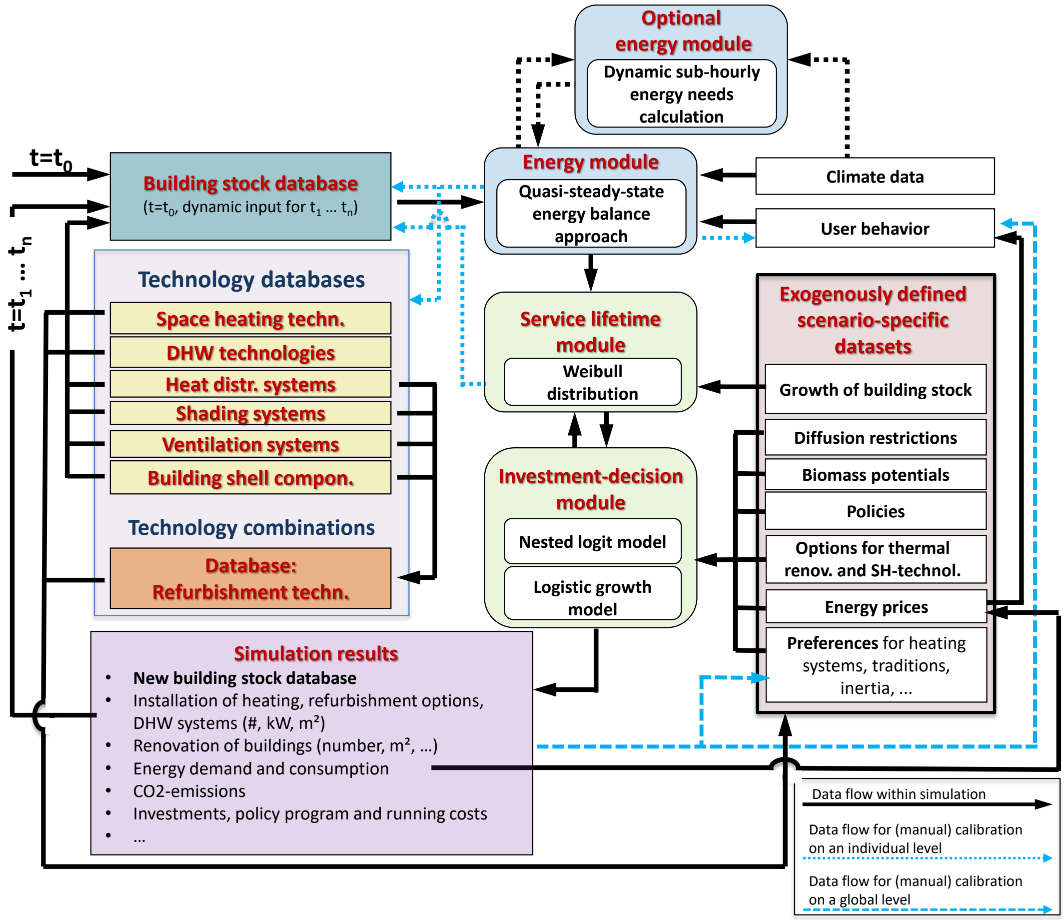


Figure 54: Overview structure of Simulation-Tool Invert/EE-Lab.

Invert simulation tool originally has been developed by TU Wien/EEG in the frame of the Altener project Invert (Investing in RES&RUE technologies: models for saving public money). In more than 40 projects and studies for more than 30 countries, the model has been extended and applied to different regions within Europe, see e.g. (Kranzl et al., 2012), (Kranzl et al., 2013), (Biermayr et al., 2007), (Haas et al., 2009), (Kranzl et al., 2006), (Kranzl et al., 2007), (Nast et al., 2006), (Schriefl, 2007), (Stadler et al., 2007). The modification of the model in the year 2010 included a re-programming process and accommodation of the tool, in particular taking into account the inhomogeneous structure of decision makers in the building sector and corresponding distributions (Müller, 2010), (Müller, 2015).

The basic idea of the model is to describe the building stock, heating, cooling and hot water systems on highly disaggregated level, calculate related energy needs and delivered energy, determine reinvestment cycles and new investment of building components and technologies and simulate the decisions of various agents (i.e. owner types) in case that an investment decision is due for a specific building segment. The core of the tool is a myopic, multinomial logit approach, which optimizes objectives of "agents" under imperfect information conditions and by that represents the decisions maker concerning building related decisions.

Coverage and data structure

The model Invert/EE-Lab up to now has been applied in all countries of **EU-27 (+ GBR, NOR, CH, ISL)**. A representation of the implemented data of the building stock is given at www.entranze.eu.

Invert/EE-Lab covers **residential and tertiary buildings**.

As efficiency technologies Invert/EE-Lab models the uptake of different levels of renovation measures (country specific) and the diffusion of efficient heating and hot water systems.

Basic approach and methodology

The Invert/EE-Lab model

The core of the simulation model is a myopic approach which optimizes objectives of agents under imperfect information conditions and by that represents the decisions concerning building related investments. It applies a nested logit approach in order 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 – in order to reduce complexity in the representation:

$$ms_{n\,jb,t} = \frac{e^{-\lambda_b \cdot r_{njb}}}{\sum_{j=1}^{J} e^{-\lambda_b \cdot r_{njb}}}$$

$$r_{njb,t} = \frac{V_{njb,t}}{\sum_{j=1}^{J} ms_{njb,t-1} \times V_{njb,t}}$$

$\mathrm{ms_{njb}} = $ market share of alternative j in building b for investor type n at period t

$\mathrm{r_{njb}} = $ relative utility of alternative j in building b for investor type n

The model enables the definition of a various number 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 which 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 behaviour 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.

The Invert/Opt model

In contrast to the Invert/EE-Lab model, the Invert/Opt model applies an optimization approach which optimizes the measures applied in each building, so that the system costs for space heating and domestic hot water preparation in buildings are minimized under given restrictions (constrains) for a given country. For each building, about 500-1000 refurbishment options are considered (4-5 building shell related measures, 15-20 heating systems, 2-3 solar thermal systems and 2-3 PV systems). The considered costs components are

- the investment needs for building-shell related energy efficiency measures
- as well as building specific heat supply system costs (such as boilers, PV and solar thermal collectors, ventilation systems with heat recovery, radiators),
- Annual energy consumption dependent energy costs (fuel costs + axillary energy costs)
- operation and maintenance costs driven by heat supply

In addition to the costs and associated energy demand and CO2-emissions of the each building and subsequently the entire building stock the following constrains are considered:

- Upper limit of CO2-emissions per m² for each building
- Refurbishment rate (incl. non-energy related maintenance) per building
- Upper limit of availability of energy carriers per building
- Upper and lower share of building shell related measures that to not reduce the energy needs of the building (maintenance) per building
- Minimal CO2-savings rate of the entire building stock compared to initial emissions
- Upper and lower share of floor area that is heated with certain energy carrier groups (gas, oil, biomass, electricity, district heating, etc.)
- Upper limit of the total energy consumption per energy carriers
- Upper and lower share of building shell related measures that to not reduce the energy needs of the building (maintenance) for the entire building stock.

Outputs from Invert/EE-Lab and Invert/Opt

Standard outputs from the Invert 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€)

During the project Hotmaps (http://www.hotmaps-project.eu/), a methodology was elaborated to breakdown selected scenario results on a 100x100m raster cell level.

Moreover, Invert/EE-Lab offers the possibility to derive more detailed and other type of result evaluations as well. Based on the specific needs of projects and clients, other type of evaluations of the result data set are possible, e.g. in the format of different type of energy saving cost-curves (Toleikyte et al., 2018; Kranzl et al., 2016).

7.3. Hotmaps district heating expansion model

The Hotmaps district heating (DH) model is used for prefeasibility studies of DH grid investments and determination of economic DH areas on regional, national or European scale. Depending on the study area and input parameters, the model may suggest having one, two or more separated DH grids. The model is fully automatized and generates reports in various forms. The model is provided with the Hotmaps open data sets (Pezzutto et al. 2018), which can assist users in preparation of required input data. Figure 55 shows the simplified structure of the model.

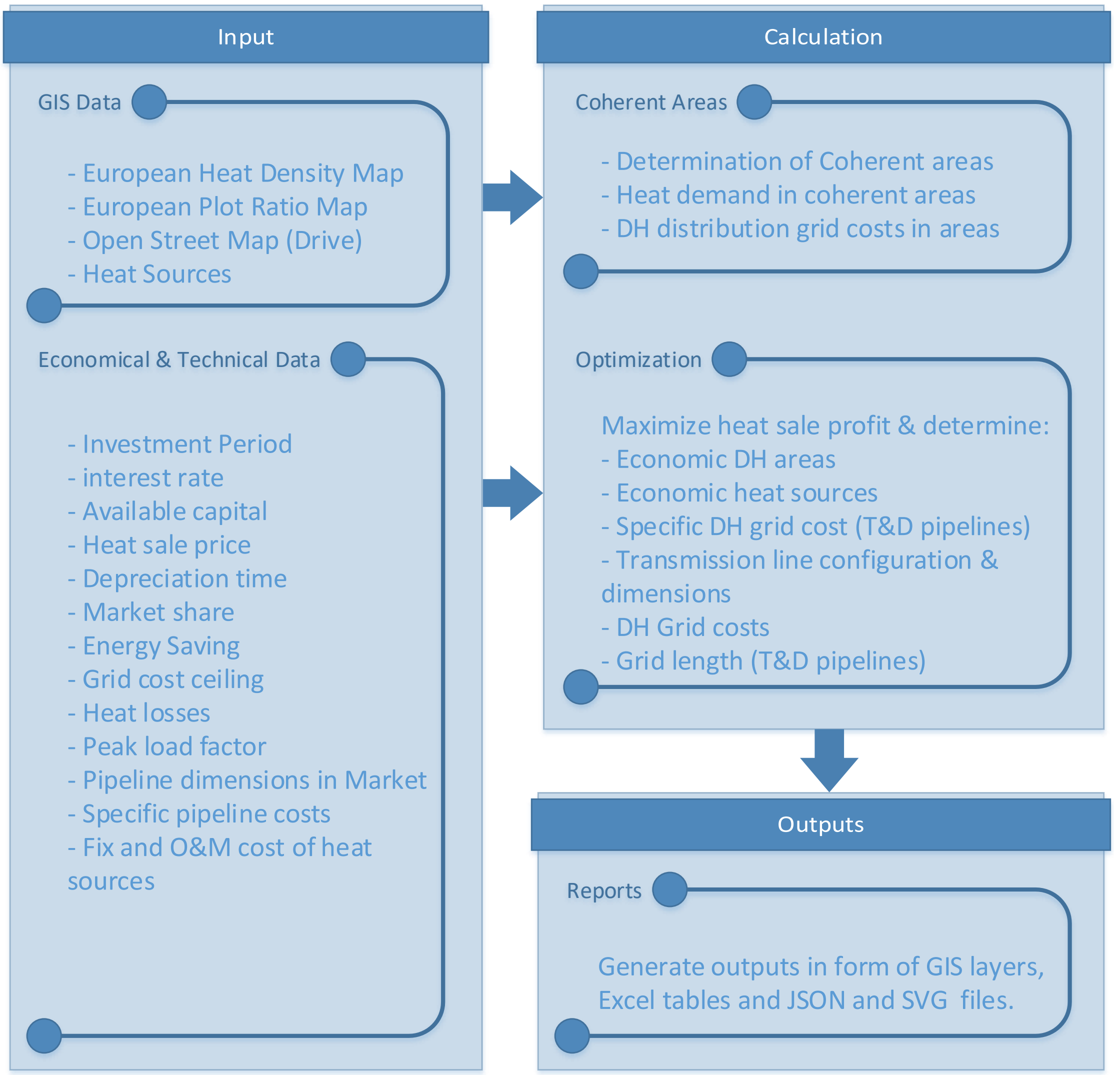


Figure 55: Simplified structure of the Hotmaps district heating model.

For the estimation of distribution grid costs, the concept of effective width (Persson and Werner 2011) has been used. This allows the estimation of distribution grid related parameters such as linear heat density in a fast and efficient manner. By applying innovative mathematical approaches on raster data, the model finds coherent areas[56] swiftly. The coherent areas can be later on used for estimation DH potential or for determination of economic district heating grids.

The **Hotmaps district heating model** considers spatial and economical aspects for determination of economic district heating areas. The input GIS layers are heat demand density and plot ratio maps (which are developed as output of the Invert model, see also (Müller et al. 2019) the methodology builds on work done by Persson und Werner (Persson U. und Werner S 2010; Persson and Werner 2011). The heat density maps work on a hectare level resolution and thus capture the specific structure of local heat demands. The location and capacity of available heat sources can be defined as well. The model is suitable for regions both with and without DH infrastructure, since it can consider the current district heating connection rate of the base year and cost for new DH networks. Energy savings due to retrofitting and renovation of buildings are reflected in the model. It is possible to set a limit for restricting the investment in grid infrastructure to a certain level. The model objective is to maximize the profit from heat sales.

[56] Coherent area is set of cells that are connected to each other and satisfy criteria defined in input data.

The method used for determining economic district heating areas also assures reduced grid investment risks due to customer loss. In addition to the economic district heating areas, the model determines the economic heat sources based on their cost functions, vicinity to the district heating areas and the costs of constructing transmission lines.

Coherent areas show the potential areas for development of the DH. The following indicators can be extracted from coherent areas:

- Total heat demand within each coherent area,
- Total heat demand that can be supplied by DH within a coherent area and within a country,
- Average DH distribution grid cost within a coherent area and within the country.

The scenario settings and more insights into the way the model works is provided in chapter 3.4. The model will be in particularly important for the district heating focus scenario (task 8). However, the model will also be used for the modelling of all other scenarios.

In the following we introduce the DH distribution grid capital cost model for assessing capital cost of district heating networks in a national context and accordingly, identification of the potential DH areas which are used for setting corresponding constraints in the Invert/Opt model.

Persson et al. introduced a methodology to estimate the DH distribution capital costs in status quo (Persson and Werner 2011; Persson et al. 2019). In this methodology, several independent input data such as pipe diameter, construction costs, interest rate as well as demographic data are used. Figure 56 shows the schematic of the procedure to calculate DH distribution grid capital costs.

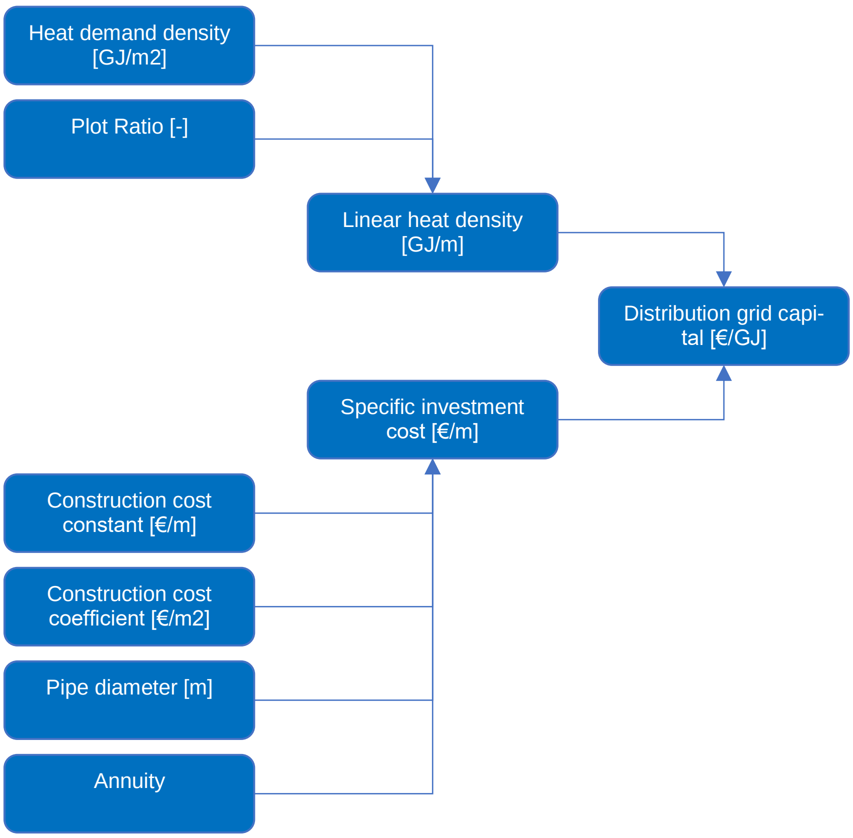


Figure 56: Procedure to calculate district heat distribution grid capital costs.

To apply this method uniformly to the whole country, uniform data on heat demand densities and gross floor area densities are required. From the gross floor area densities, plot ratio can be obtained. Hotmaps[57] project provides such a data set for the basis year of 2015 covering EU-28 countries. The Hotmaps project renovation scenario is further used to obtain heat demand density and heated gross floor area density maps of year 2050.

One key concept when assessing DH network investment cost is the linear heat density and is defined as the ratio of delivered heat to the DH system (Q_T) in a year to the total DH trench length (L).

$$LinearHeatDensity = \frac{Q_T}{L} \quad [GJ/(m.a)]$$

The linear heat density can also indicate the level of heat losses in the grid.

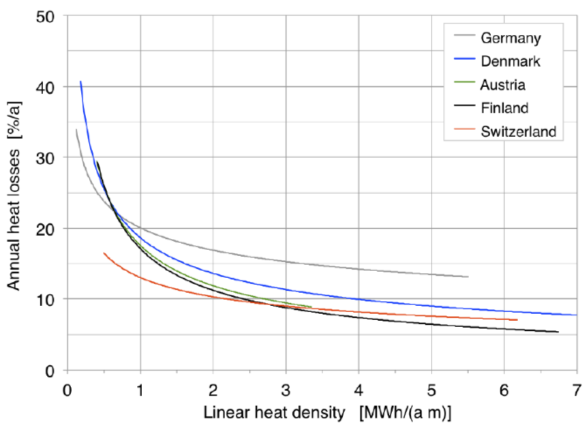


Figure 57: Annual heat losses as a function of linear heat density. Only the potential trendlines are displayed (Source: Nussbaumer and Thalmann 2014).

To calculate the linear heat density analytically, Persson and Werner used demographic data and introduce the concept of effective width (w), which describes the relationship between a given land area (or plot ratio, e) and the length of the district heating trench length within this area.

$$w = A_L/L = \begin{cases} 137.5e + 5 & [m] \qquad 0 < e \leq 0.4 \\ 60 & [m] \qquad e > 0.4 \end{cases}$$

Accordingly, the linear heat density can be formulated as follows:

[57] www.hotmaps.eu

$$LinearHeatDensity = \frac{Q_T}{L} = e * q * w = q_T * w \qquad [GJ/(m.a)]$$

$$q = Q_T/GFA \qquad [GJ/(m^2.a)]$$

$$q_T = Q_T/A_L \qquad [GJ/(m^2.a)]$$

Using the linear heat density, the average pipeline diameter (d_a) in meter is calculated as follows:

$$d_a = 0.0486 \cdot \ln(Q_T/L) + 0.0007 \qquad [m]$$

The specific investment cost (*I/L*) of the distribution grid may be derived using the following formula. The slop and the intercept of the linear formula are referred as to construction cost coefficient (C_2) in EUR/m^2 and construction cost constant (C_1) in EUR/m, respectively. These values are obtained empirically based on the existing networks. Figure 58 depicts the interpolation.

$$\frac{I}{L} = C_1 + C_2 * d_a \qquad [\frac{€}{m}]$$

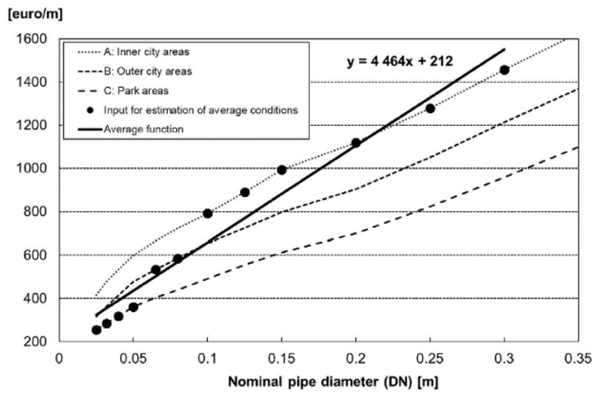


Figure 58: specific investment cost as a function of pipe dimension (Source: Persson et al. 2019).

We assume a constant heat supply by DH grid over its lifetime. Accordingly, the annual capital cost of the DH distribution grid per unit of delivered heat can be obtained as follows:

$$C_{d,T} = \frac{C_{1,T} + C_{2,T} \cdot d_a}{n \cdot \frac{Q_T}{L} \cdot \sum_{t=0}^{n}(1+r)^{-t}}$$

$C_{d,T}$	Annualized distribution grid cost per unit of delivered heat [€/GJ]
L	Total trench length [m]
$C_{1,T}$	Construction costs constant [€/m], here 212 €/m
$C_{2,T}$	and Construction costs coefficient [€/m^2], here 4464 €/m^2
d_a	Pipe diameter [m]
n	Depreciation time, here 30 years

Q_T	Heat demand supplied by DH in year “T” [GJ]
Q_T / L	Linear heat density [GJ/m]
r	Interest rate, here 5%

The method described is used to do identify coherent areas, in which the average distribution grid cost does not exceed the grid cost ceiling are extracted as potential DH areas to determine district heating constraints (see Table 36).

7.3.1. Modelling the electricity sector and grid infrastructure for electricity, gas and H2: Enertile

Enertile is an energy system optimization model focusing on the power sector, but also covering the interdependencies with other sectors, especially heating/cooling and the transport sector. A major advantage of the model is its high technical and temporal resolution. Enertile optimizes the investments into all major infrastructures of the power sector, including conventional power generation, heat generation from district heating including combined-heat-and-power (CHP), RES-H and power-to-heat, renewable power technologies, hydrogen supply, e-fuel supply, cross-border transmission grids, and storage technologies. To cover specific demands for electricity based hydrogen and e-fuels, necessary investments in electrolysers are included. The model chooses the optimal portfolio of technologies, while determining the utilization of these for all hours of each year. Since real weather data is applied, seasonal, daily and weekly variations in heat demand as well as in electricity supply are included in the optimization. At the same time, spatial characteristics and interdependencies between different regions and renewable technologies are implicitly included.

A more detailed description of the Enertile model can be found below.

Enertile is an energy system optimization model developed at the Fraunhofer Institute for System and Innovation Research ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating/cooling, electricity based fuel production (Power to X) and the transport sector. It is a used mostly for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

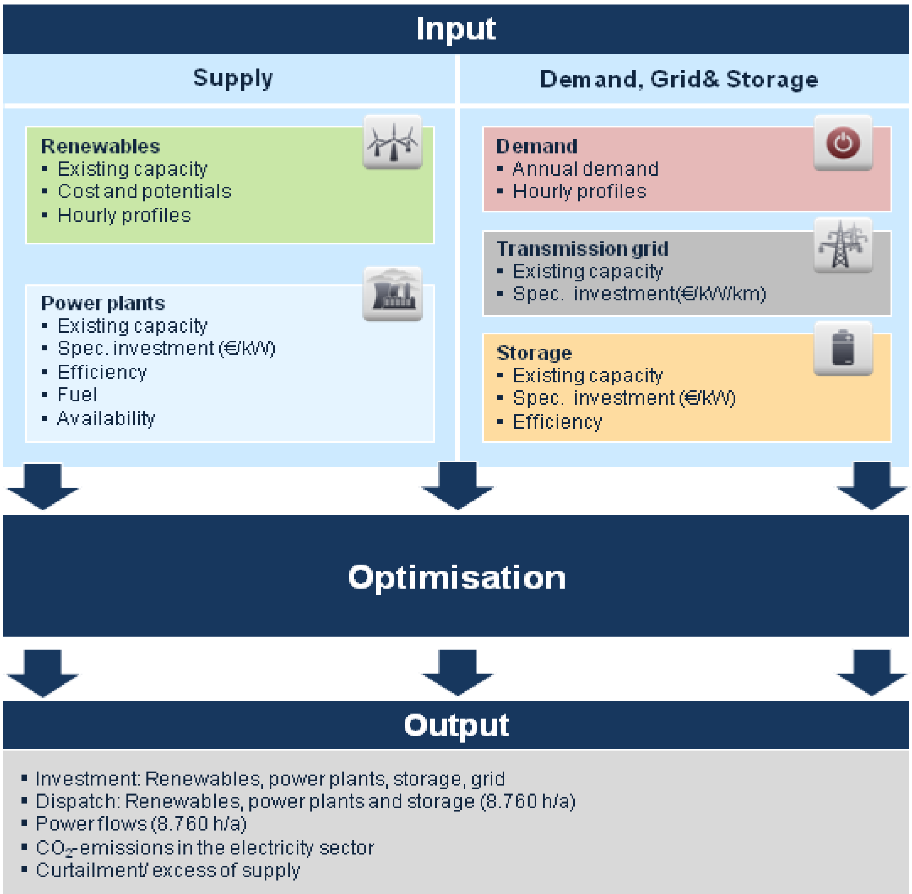


Figure 59: Simplified structure of the model Enertile.

Integrated optimization of investments and dispatch

Enertile optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such demand-side-management (DSM), power-to-fuel and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these for in all hours of each analysed year.

High temporal resolution

The model features a full hourly resolution: In each analysed year 8,760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

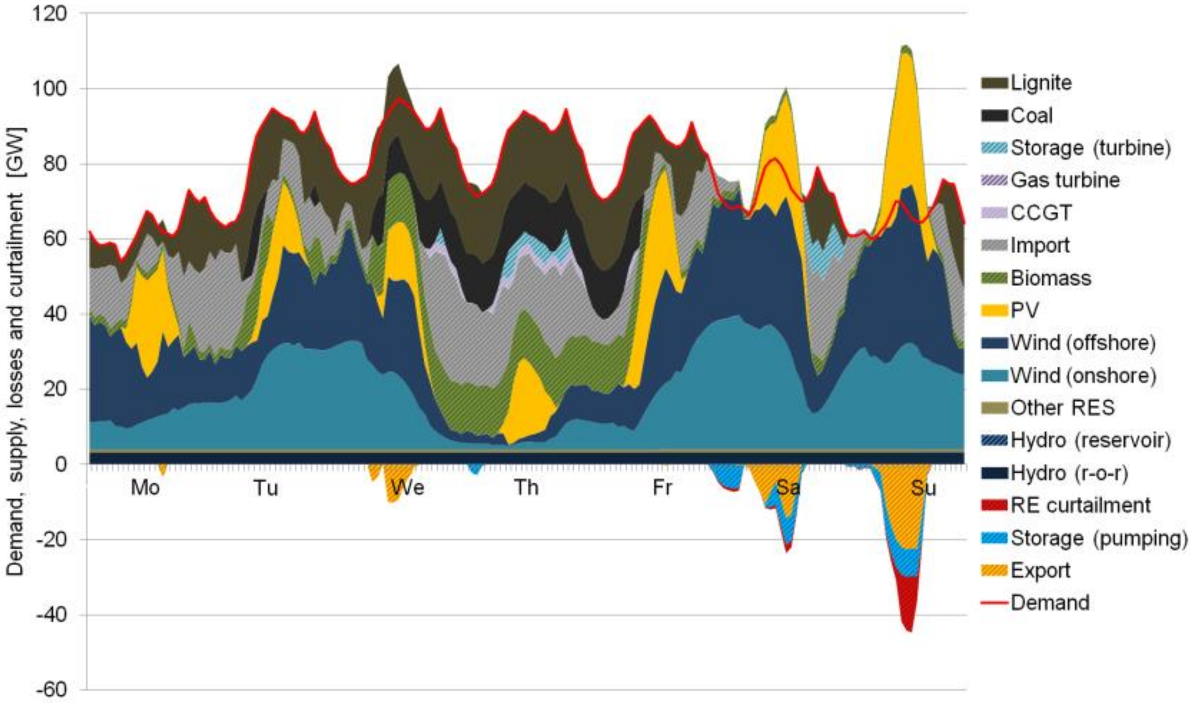


Figure 60: Example of the hourly matching of electricity supply and demand.

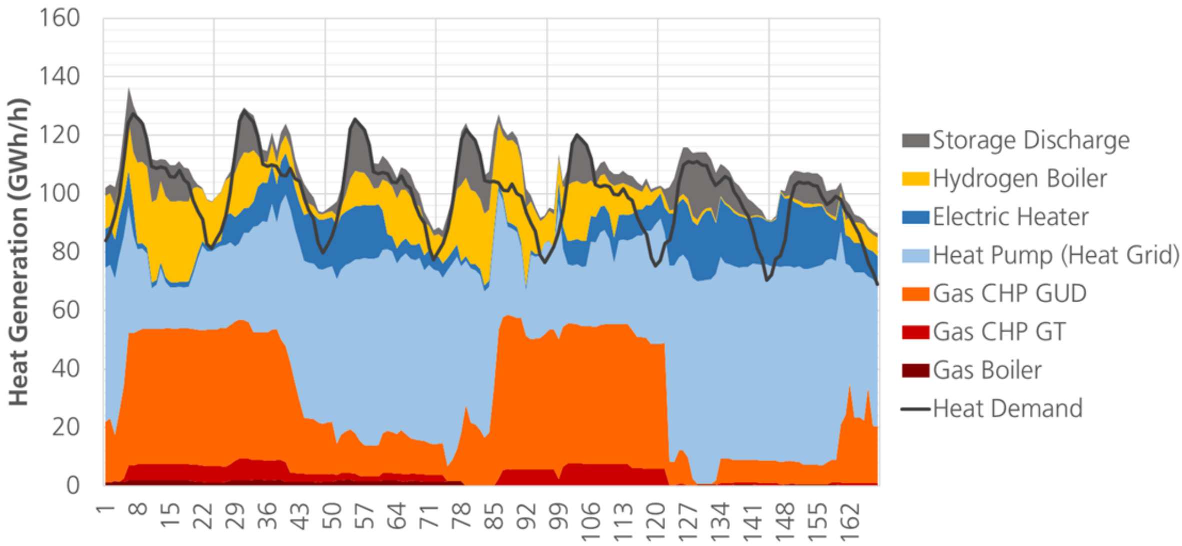


Figure 61: Example of the hourly matching of heat supply and demand in heat grids (sum of all heat grids in Europe).

Detailed picture of renewable energy potential and generation profiles

The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data.

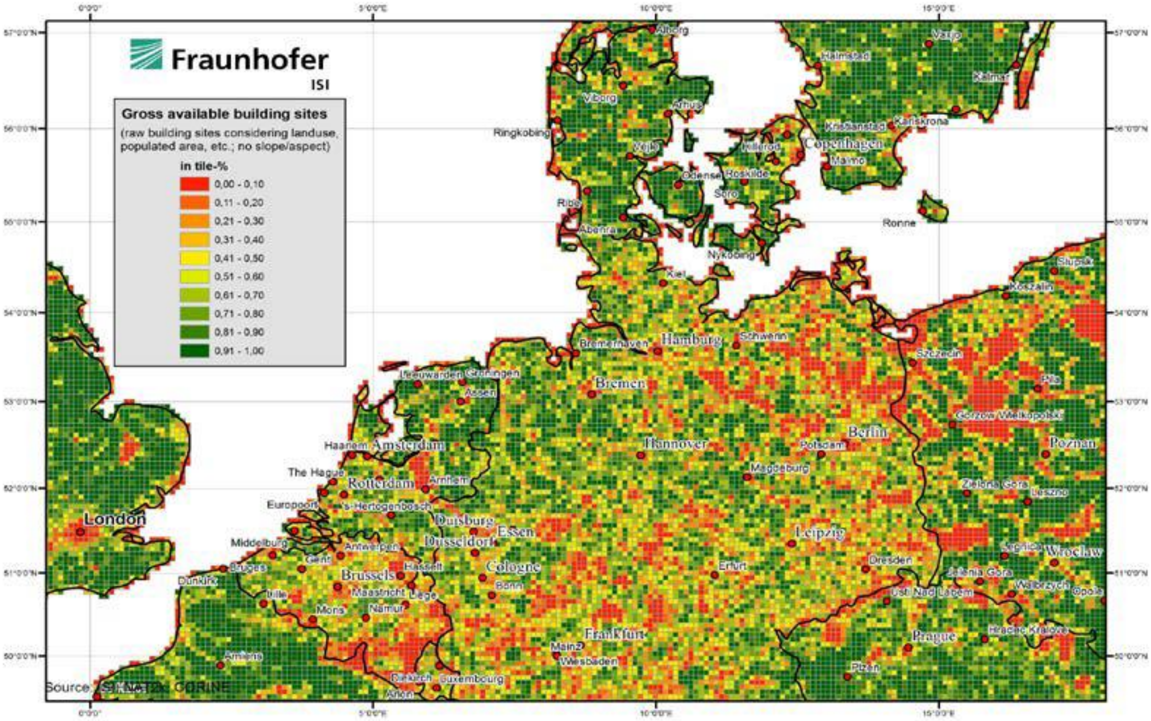


Figure 62: Example of the calculation of solar photovoltaic potential.

Cross-sectoral modelling

Although the model focuses on the power sector, cross-sectoral interdependencies are taken into account. The effects of heat demand on CHP plants considered, as well as the flexibility provided by heat pumps or other power-to-heat systems. The production of electricity based fuels is endogenously optimised. Investments in electrolysers as well as additional electricity production is part of the optimisation problem. The charging of electric vehicles can be performed “smart”, allowing delaying consumption in accordance with the preferences of the users.

High spatial coverage

The model currently depicts and optimizes Europe, North Africa and the Middle East. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option.

The model contains all required data on existing power plants, transport corridors and extensive geospatial and weather data for the assessment of renewable electricity generation cost and profiles.

Outputs from Enertile

- Installed capacity of generation units including renewables
- Location of renewable generation units

- Hourly generation profiles
- Installed capacity of transmission corridors
- Hourly trading flows on transmission corridors
- Annual cost for the modelled parts of the electricity system
- CO2-Emissions, GHG-Emissions
- Hourly Shadow prices on each node

Grid infrastructure for gas and hydrogen grids

Infrastructure needs and costs differ between scenarios and change over time, with rising as well as decreasing demand. Regarding the gas transmission grid, previous analyses (TU Wien, Fraunhofer ISI, Comillas 2019a) have shown that in most decarbonisation scenarios focusing on efficiency, electrification and direct use of renewable energies it will be economical to deconstruct parts of the gas grid. Necessary adaptations of gas infrastructure will be assessed and related costs will be estimated based on these insights as well as further literature and scenario results within this project.

For the scenarios in task 7 (e-fuels and hydrogen) gas infrastructure will remain important until 2050 while gas demand will decrease over time for other scenarios. We assess adaptation requirements for existing gas infrastructure and related costs based on scenario results and a literature review.

Estimating the potential for connecting buildings to the gas grid infrastructure

A relevant part of the scenario specifications in the building sector is the estimation of the potential for connecting buildings to the gas grid infrastructure (see chapter 4.3.1). This is based on the work being done in (Schremmer et al. 2018). The natural gas transmission grid provided by Gas Infrastructure Europe (GIE) [58] was used as a reference for the existing/under development gas pipelines.

Depending on the distance of an area from closest transmission gas grids, regions were classified in three categories: 1. Full potential region, 2. Mid-potential region, 3. Null potential region. Any region in vicinity of 10 km from a gas pipeline is considered as a full potential region. The regions in distances between 5 and 18 km from gas grids fall into the category of Mid-potential region. Any area with a distance of above 18 km from gas grids are considered as null potential region. In the next step, the potentials are refined with respect to the population densities and urban areas determined by Corine Land Cover 2000[59] data set. Accordingly, only potential values are kept that are related to populated urban areas.

7.3.2. Data exchange between models

7.3.2.1. Final energy demand

The final energy demand from heating applications in buildings is calculated by INVERT. For each scenario, the total demand for electricity, district heating, hydrogen and e-fuels is used as input for Enertile and the supply of these different energy outputs is optimized. The interdependencies of the supply of different energy outputs are directly integrated as their supply is optimized simultaneously.

[58] https://gie.eu

[59] https://land.copernicus.eu/pan-european/corine-land-cover/clc-2000

The following annual demand values are used in Enertile: district heating demand, electricity demand from heat pumps, other electricity demand (auxiliary energy demand). Furthermore, hourly load profiles for electric direct heaters calculated by INVERT are directly integrated in Enertile. The annual demand for hydrogen and e-gas is derived as part of the total gas demand using assumptions on shares for the addition of hydrogen or synthetic methane in the gas network. These shares vary in the scenario according to the technology focus and scenario specifications and are described in Section 7.4.2. For electricity demand categories and district heating demand extra charges for distribution grid losses are added on the demand values from INVERT. The percentage increase is 5.5 % for electricity and 10 % for district heating.

7.3.2.2. Energy prices

One output of the Enertile model in the context of the optimization procedure are the hourly marginal costs, also known as shadow prices, of energy demand. They represent the costs arising from the production of one additional unit (e.g. 1 MWh of electricity). For each energy output modelled within Enertile, hourly demand supply equations ensure that the demand is met in every region and hour. Consequently, for each demand-supply equation hourly marginal costs can be obtained. They reflect both the fixed and variable costs of all energy production technologies. This approach presupposes that the market participants are able to realize their full costs on the market and that the investments that are cost-optimal from a system perspective are also refinanced by the market. As the derivative is always greater than or equal to zero, negative prices cannot occur in the selected modelling approach. Therefore, the minimum price is zero. The marginal cost can serve as an indicator for the price development on the energy markets. Therefore, we use these values as energy prices in this project.

Within this project, energy prices obtained by the Enertile model are part of the data exchange to the Invert model. Enertile determines the following prices for energy production: electricity, district heat, hydrogen and e-gases (e-fuels). They represent the production of energy and do not include costs for transport or distribution. The annual average of the hourly prices are transferred to Invert. For the calculation in Invert, the wholesale prices delivered from Enertile are converted into retail prices, i.e. including taxes, grid fees, distribution costs and retail mark-ups. This is explained in more detail in the following, separated by electricity, district heating and gas.

Retail electricity price

For electricity, we assume that the retail price (incl. VAT) derives from the difference between the whole sale prices of today and that in a future period (e.g. 2050) times a factor of 1.2 plus the country specific VAT

$$price_{retail,future} = price_{retail,2017} + 1.2 * (1 + VAT)(price_{wholesale,future} - price_{wholesale,current})$$

Retail district heating price

The district heating prices are modelled in a similar way. We assume that the difference in the retail price derives from the difference in the marginal heat production costs times a factor of 1.2 (plus VAT). Since we lack consistent information of the current marginal costs, we use the values calculated by Enertile for 2030 as proxy for the current situation.

$$price_{retail,future} = price_{retail,2017} + 1.2 * (1 + VAT)\left(cost_{heat\ production,future} - cost_{heat\ production,2030}\right)$$

$$+(1+VAT)\left(distribution\ costs_{future} - distribution\ costs_{2017}\right)$$

In addition, we estimate the impact of changing heat densities and scenario specific connection rates on the retail prices. This part has not been considered yet, but will be part included in the final scenarios.

Retail gas price

For gas, we decomposed the current retail prices into six following components:

- an average European wholesale gas price,
- country specific wholesale prices for hydrogen and gaseous e-fuels
- country specific grid fees for retail customers,
- country specific retail energy taxes,
- country specific VAT and
- country specific additional mark-up observed in the past.

In our calculations, the wholesale energy prices is calculated based on the assumptions, that the gaseous energy carrier delivered to retail customers is composed as follows:

- Hydrogen scenario: 90%HHV Hydrogen, 10%HHV e-fuel (methane)
- E-fuels scenario: 90%HHV e-fuel (methane), 5%HHV hydrogen, 5%HHV natural gas
- All other scenarios: 80%vol natural gas, 10%vol hydrogen, 10%vol e-fuel (methane)

$$price_{gasWS,future} = s_{gas} * price_{gasWS,future} + s_{H2} * price_{H2WS,future} + s_{H2} * price_{e-gasWS,future}$$

For the grid charges, we assume that the current values scale with the gas demand:

$$price_{gasgrid,future} = price_{gasgrid,2017} * \left(\begin{matrix} 0.7 + 0.3 * \\ \min\left(4, demand_{gas,buildings,2017} / demand_{gas,buildings,future}\right)\end{matrix}\right)$$

With respect to taxes and observed mark-up we consider that 70% remain constant in absolute terms, while the remaining 30% scale with the wholesale energy prices.

$$price_{gastax,mark-up,future} = price_{gastax,mark-up,future} * (0.7 + 0.3\ price_{gasWS,future} / price_{gasWS,2017})$$

7.3.2.3. Emission factors

Another output from the Enertile model are the CO2 emissions for supply of electricity and district heat. Within this project, emission factors for electricity and district heat for each year and country are derived from the Enertile model. These emission factors are a key part of the data exchange to the Invert model.

There are several challenges in the calculation of emissions factor. First of all, the allocation of emissions from CHP production to electricity and district heating. There are several concepts that can lead to very different results:

- Distribution of emissions based on the respective fuel shares to be used, taking into account the combined production of electricity and heat (IEA and efficiency method)

- distribution of emissions with reference to reference power plants of uncoupled electricity and heat production (Finnish method)
- distribution of emissions taking into account the separate production of electricity and heat (electricity credit or heat credit method)

Then, the emissions by the use of electricity for district heating, e.g. in heat pumps or electric boilers, have to be considered when calculating the emissions factors for district heating. Furthermore, the consideration of hydrogen or e-fuels can influence the calculation of emission factors. Finally, the accounting of electricity trading volumes (import and export) and the question of whether emissions are produced at the location where they arise or at the location where the energy source is used needs to be addressed. Therefore, the method of calculating these emission factors used in this project is described in more detail.

1. Emissions from CHP production

For the allocation of emissions to electricity and heat we use the IEA method in this project. The IEA method divides the CO2 emissions proportionally in relation to the by-products produced. As a result, the product with the higher efficiency and thus the higher share of output is also allocated the higher share of emissions. This allocation has to be made for each technology individually.

2. Emission factors for domestic electricity production

In an intermediate step, the emission factors for the domestic electricity production are derived as total emissions divided by total electricity generation. The emissions from CHP electricity production from the previous step are included in the calculation of domestic emission factors. These factors represent the approach that emissions arise in the country where the electricity is produced, irrespective of the possible export of this electricity to other countries.

3. Emission factors considering electricity trading

In a final step, the calculation of emission factors is adjusted to consider electricity trading amounts and the associated emissions. These corrected factors represent the approach that emissions occur where the energy is consumed and emissions are therefore "exported" along with the energy. To deduct the associated emissions, the emission factors for domestic electricity production are used as this country's electricity mix defines the emissions. The electricity generation and associated emissions that are exported from a country are subtracted and imports from other countries are added. After this correction of generation and emissions the emission factors are calculated again. The total emissions remain the same, only the country to which the emissions are attributed changes. These emission factors for electricity production considering electricity trading are used in the data exchange to Invert.

4. Emission factors for district heating

Finally, the emission factors for district heating are calculated considering three sources of emissions. First, emissions directly attributed to the production of district heat with conventional fuels. Second, emissions from CHP production allocated to heat determined in step 1. Third, emissions by the use of electricity for district heating, which are derived by the electricity demand for this heat production multiplied by the emission factor for electricity determined in the previous step. Finally, total emissions allocated to district heat production are divided by the total district heat generation to derive the emission factors for district heat.

A challenge in the calculation of emission factors is the consideration of hydrogen or e-fuels. These fuels can influence the emission factors in two ways. On the one hand, production of these fuels increase electricity demand and consequently electricity generation. On the other hand, these fuels are used for electricity production as they offer high potential as long-term storage. This circular production of electricity converted to hydrogen or e-fuels and back to electricity makes it very difficult to determine the total electricity generation used for calculation of emission factors. The use of these fuels in district heat generation makes matters even more complicated. The concept of emission-free produced hydrogen and e-fuels cannot be guaranteed in the transition period as the electricity mix may still contain a significant proportion of conventional fuels.

In the **Invert model**, the energy carrier category Gas & Liquids represents Natural gas, Hydrogen and E-Fuels. In order to appropriately represent the corresponding CO2 emissions, the applied emission factor has to be adjusted accordingly. For the Hydrogen scenario, the Gas & Liquids emission factor is assumed to develop based on a Natural gas emission factor of 217 gCO2/kWh primary energy from 95% of this value in 2030, to 65% in 2040 and 11.65% in 2050. For the Electrification, District Heating and Direct-RES scenario, the emission factor is assumed to decrease from 97% of the Natural gas value in 2030, to 95% in 2040 to 86% in 2050.

7.3.3. Indicators and which models contribute to their calculation

Table 35 indicates which model derives which of the indicators and in which sectoral split they will be provided.

Table 35: Indicators and how they are derived in the modelling framework.

Indicator-Category	Indicator	Unit	Sectoral split						
			Heating systems	Building renovation	DH grid infrastructure	Electricity, gas, H2 grid infrastrstructure	DH generation	Electricity generation	TOTAL
Costs: Total system costs by capital costs, operation and maintenance and variable energy costs	Capital costs (annualized)	M€2020/yr	Invert	Invert	Hotmaps	literature, ISI	Enertile	Enertile	Sum
	Operation and Maintenance	M€2020/yr	Invert	-	-	literature, ISI	Enertile	Enertile	Sum
	Variable energy costs	M€2020/yr	Invert	-	-	-	Enertile	Enertile	Sum
	Total system costs	M€2020/yr	-	-	-	-	-	-	Sum
Investment needs		M€2020	Invert	Invert	Hotmaps	literature, ISI	Enertile	Enertile	Sum
Installed capacities by technologies and used energy carriers		MW	Invert	-	-	-	Enertile	Enertile	Sum
Primary, final and useful energy demand used by energy carrier, end-use and sector	Useful energy demand		Invert	-	-	-	-	-	Sum
	Final energy demand		Invert	-	-	-	-	-	Sum
	Primary energy demand		-	-	-	-	Enertile	Enertile	Sum
GHG-emissions		Mt_CO2	Invert	-	-	-	Enertile	Enertile	Sum
Seasonal and daily variations, resulting peak loads	Electricity peak load season i, Electricity load profiles	GW	-	-	-	-	Enertile	Enertile	Sum

7.4. Annex C: Scenario assumptions

7.4.1. Scenario settings for individual heating and hot water systems

In the following, we will break down the high-level scenario settings to the sectoral level and describe how we will quantify and concretely model them. In the building sector, we apply diffusion constraints for different heating systems. In the following, we explain and document the proposed values for these constraints by energy carrier (for some cases also by technologies) and by scenario.

We apply a stepwise approach: First, for each country modelled, we determine maximum saturation constraints ($s_{i,j}$) for relevant energy carriers and heating systems i in country j which are applied in the baseline run, i.e. without considering any specific technology scenario focus. As a second step, we define further limitations ($l_{j,k}$) for these saturation restrictions set as exogenous conditions for each of the technology focus scenarios (k, task 5-8). They are set in a uniform way for all countries. As a maximum, these limitations may be 100% of the maximum restriction defined under step 1. Third, multiplying the maximum saturation constraints determined under step 1 for each country and the limitations determined under step 2 for each scenario, delivers the restrictions ($r_{i,j,k}$) as input for each of the focus scenarios. They represent the maximum share of the heated floor area on which a certain energy carrier or heating system (i) in a certain country (j) and a certain scenario (k) can be applied.

$$r_{i,j,k} = s_{i,j} \cdot l_{j,k}$$

Table 36 shows the saturation constraints of energy carriers and heating systems (step 1 described above). Thus, the table shows the maximum share of heated floor area in which a certain technology can be installed due to technical constraints. A value of 100% means that a technology can be applied in 100% of the building stock, there are no major technical constraints.

The exploitation rate of different energy sources depends not just on policies implemented to increase the use of such and/or energy prices but are also bounded by socio-economic and technical restrictions. If we consider natural gas, for example, a widespread utilization in households requires the widespread existence of a natural gas infrastructure (pipelines). District heating is additionally bounded to areas with higher heat demand per plot area (heat density) in order to enable low energy losses in the grid and being able to compete with other decentral technologies from a cost perspective. The usage of biomass-based decentral boilers, a widely spread technology in several EU countries, might not be accepted to large extent in urban areas from an emission point of view. In order to cover these aspects in the scenarios, we investigated the possible saturation level of energy carriers in the different countries. Building on data regarding the heat density (Müller et al. 2019), level of urbanization, the natural gas transmission pipelines (Schremmer et al. 2018) and the current technology share (Fleiter et al. 2016) we defined these saturation levels for single-family homes and terraced houses, which are more commonly in rural areas, and multifamily houses and apartment buildings, which are the typical building type in urban areas.

Table 36: Maximum share of heated floor area, in which different space heating technologies can be applied until 2050: saturation constraints of energy carriers and heating system technologies not considering scenario specific constraints. (Müller A et al. 2018)

	Solar thermal/ PV	Natural Gas	Oil	Coal	Wood log [(a)]	Wood chips [(a)]	Pellets [(a)]	Direct electricity for heating	Heatpump Ground source	Heatpump Air source	District heat
AT	45%	67%	100%	100%	48%	48%	78%	100%	54%	56%	46%
BE	50%	71%	100%	9%	9%	10%	22%	100%	37%	49%	22%
BG	50%	32%	100%	25%	25%	10%	25%	100%	46%	56%	32%
CY	80%	1%	100%	9%	9%	10%	22%	100%	40%	55%	3%
CZ	50%	55%	100%	16%	16%	15%	30%	100%	46%	50%	35%
DE	50%	76%	100%	100%	10%	10%	17%	100%	77%	54%	25%
DK	50%	38%	100%	15%	15%	12%	28%	100%	46%	54%	57%
EE	50%	36%	100%	24%	24%	15%	35%	100%	44%	52%	47%
ES	75%	54%	100%	13%	13%	10%	25%	100%	39%	46%	23%
FI	40%	17%	100%	16%	16%	11%	28%	100%	50%	59%	52%
FR	50%	65%	100%	14%	14%	9%	26%	100%	43%	55%	19%
GR	80%	39%	100%	18%	18%	12%	25%	100%	47%	55%	22%
HR	65%	62%	100%	24%	24%	10%	32%	100%	52%	53%	22%
HU	50%	74%	100%	16%	16%	12%	30%	100%	51%	51%	29%
IE	50%	49%	100%	15%	15%	17%	29%	100%	50%	55%	20%
IT	65%	73%	100%	17%	17%	9%	24%	100%	41%	52%	26%
LT	45%	35%	100%	27%	27%	17%	32%	100%	45%	48%	46%
LU	50%	68%	100%	11%	11%	12%	27%	100%	51%	52%	28%
LV	45%	32%	100%	26%	26%	18%	31%	100%	43%	51%	47%
MT	80%	29%	100%	6%	6%	8%	16%	100%	27%	38%	1%
NL	50%	89%	100%	8%	8%	9%	20%	100%	34%	47%	28%
PL	50%	37%	100%	20%	20%	20%	52%	100%	59%	53%	22%
PT	70%	40%	100%	27%	27%	9%	27%	100%	47%	51%	4%
RO	50%	45%	100%	28%	28%	11%	36%	100%	51%	50%	32%
SE	50%	18%	100%	17%	17%	10%	27%	100%	48%	74%	69%
SK	50%	68%	100%	12%	12%	13%	27%	100%	51%	51%	46%
SI	50%	45%	100%	26%	26%	11%	31%	100%	54%	53%	23%

Solar thermal/ PV	Natural Gas	Oil	Coal	Wood log [(a)]	Wood chips [(a)]	Pellets [(a)]	Direct electricity for heating	Heatpump Ground source	Heatpump Air source	District heat

(a) For biomass heating systems, the model considers an additional total biomass potential restriction allocated to decentral heating systems.

Table 37: Limitations for diffusion restrictions set as exogenous conditions for each of the technology focus scenarios.

	Direct RES-H	Electrification	e-fuels	H2	District heating	Best case
Solar thermal	≤100%	≤60%	≤60%	≤60%	≤100%	≤80%
Gas (natural gas, biogas, H2, e-gas)	≤50%	≤50%	≥40% - <100%	≥50% - ≤100%	≤50%	≤30%
Oil (heating oil, bio oil, e-liquids)	≤25%	≤25%	≥15% - ≤100%	≤25%	≤25%	≤25%
Wood log [(a)]	≤100%	≤60%	≤60%	≤60%	≤40%[(b)]	≤60%
Wood chips [(a)]	≤100%	≤60%	≤60%	≤60%	≤40%[(b)]	≤60%
Pellets [(a)]	≤100%	≤60%	≤60%	≤60%	≤40%[(b)]	≤60%
Electricity (pumps and direct electric heating	≤50%	≥50%[(c)]- ≤100%	≤50%	≤50%	≤50%	≤100%
District heat	<50%	<50%	<50%	<50%	≥80% - <100%	≤100%
Gas Heatpump	≤50%	≤50%	≤100%	≤100%	≤50%	≤30%
Gas micro-CHP	≤50%	≤50%	<100%	<100%	≤50%	≤30%

(b) Limitations for diffusion restrictions refer to the values defined in Table 36
(c) For biomass heating systems, the model considers an additional total biomass potential restriction allocated to decentral heating systems.
(d) In the district heating scenario, biomass is limited for decentral use, whereas for district heating a higher biomass potential is available, leading to an identical overall biomass potential restriction for the whole space heating and hot water sector.
(e) The lower limit is implemented on the sum of heated area by heat pumps and direct electric heating.

Table 38: Lower limit of heated areas compared to area in the baseline year 2017 set as exogenous conditions for each of the technology focus scenarios.

	Direct RES-H	Electrification	e-fuels	H2	District heating	Best case
Gas (sum of natural gas, bio gas, H2, e-gas)			≥60%	≥70%		
Oil (sum of heating oil, bio oil, e-liquids)			≥35%			
Biomass (sum of wood log, wood chips, and pellets)	≥75%					
Electricity (sum of heat pumps and direct electric heating)		≥100%				≥100%
District heat	≥100%	≥66%	≥66%	≥66%	≥100%	≥70%

Biogenic energy potential for decentral use

In our scenarios, we consider that biomass is a restricted resource. Therefore, in addition to the share of area that can be heated with biogenic energy carriers, we limit the energetic biomass resources as well. Our assumptions are as followed: The share of biomass in the final energy demand for space heating and domestic hot water can increase by up to 15% compared to the base year, assuming that the energy demand decreases by 50%. In addition, we set an upper limit for the energetic share on the final energy demand (considering a 50% reduction) of one third. The so defined biomass potential is the upper limit that can be used if the cost-resource potential is fully exploited. This full exploitation is only allowed in the Direct RES-H scenario. In the district heating scenario, we restrict this decentral biomass potential by 50%, in the remaining three scenarios 70% of the full resource potential can be utilized. In total, this leads to a resource potential of decentral biomass heating of about 91% of the corresponding biomass use in the base year.

The use of biogas as blending in the gas grid as well as the use of biooil is restricted according to Table 39. Considering the remaining composition of gas in the distribution gas-grid according to

Table 15 leads to corresponding constraints for the use of gas in general. I.e. the biogas potentials – together with the assumptions of the share of other renewable gas components – determine the upper limit of using gas for space heating and hot water.

Table 39: Resource restriction for the decentral biomass utilization.

	Decentral biomass utilization [TWh]	Share of decentral biomass on final energy demand for space heating and domestic hot water preparation	Decentral biomass resource potential (= full resource potential) [TWh]	Decentral biomass potential on final energy demand for space heating and domestic hot water assuming a decreasing in related final energy demand of 50%	Ratio of biomass resource potential 2050 on biomass utilization in base year	Biogas resource potential for use in the space heating and hot water sector [TWh]	Biooil resource potential for use in the space heating and hot water sector [TWh]
	Base year		**2050**				
AT	20.8	25%	13.8	33%	66%	1.6	1.0
BE	7.1	6%	12.3	21%	172%	1.1	0.6
BG	8.8	38%	3.8	33%	43%	1.1	2.0
CY	0.2	5%	0.5	20%	216%	0.0	0.1
CZ	21.0	22%	16.1	33%	77%	1.6	1.3
DE	85.8	12%	97.1	27%	113%	11.0	5.4
DK	10.8	18%	9.9	33%	91%	1.0	1.5
EE	4.5	35%	2.1	33%	47%	0.5	0.5
ES	30.7	19%	26.5	33%	86%	6.0	9.1
FI	13.5	18%	12.5	33%	92%	1.5	5.4
FR	81.6	15%	82.6	30%	101%	13.8	8.9
GR	9.5	18%	8.7	33%	91%	1.5	2.0
HR	12.5	45%	4.6	33%	37%	1.3	0.9
HU	20.0	24%	13.9	33%	70%	2.7	1.4
IE	0.5	2%	2.7	17%	503%	0.8	0.8
IT	76.8	19%	67.2	33%	87%	7.4	3.9
LT	5.6	33%	2.9	33%	51%	0.8	1.3
LU	0.3	3%	0.8	18%	302%	0.0	0.0
LV	6.0	39%	2.6	33%	43%	0.7	1.2
MT	0.0	2%	0.1	17%	519%	0.0	0.0
NL	5.2	3%	14.7	18%	282%	1.9	0.7
PL	31.7	13%	34.7	28%	109%	4.6	6.7
PT	8.8	29%	5.0	33%	57%	0.9	1.1
RO	34.2	42%	13.6	33%	40%	3.9	4.3
SE	11.4	11%	13.6	26%	120%	1.7	5.8
SI	5.2	39%	2.2	33%	42%	0.3	0.3
SK	0.5	1%	3.3	16%	610%	1.1	0.7
EU-27	**513**	**16%**	**468**	**29%**	**91%**	**69**	**67**

7.4.2. Scenario settings for energy supply

7.4.2.1. Demand for electricity, hydrogen and e-fuels in other sectors

As described in sections 4.2.2 and 4.3, the demand for electricity, hydrogen and e-fuels in other sectors is constant in all scenarios. The tables and figures below show the assumed demand values from 2030 until 2050 per country.

Table 40: Development of electricity demand in other sectors from 2030 until 2050 per country (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

Demand in TWh	electric vehicles			other transport			other sectors		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria	0.7	3.3	7.7	3.1	3.2	3.3	65.6	73.0	78.9
Belgium	1.0	4.3	10.1	1.9	2.2	2.4	80.5	94.0	109.3
Bulgaria	0.1	0.9	2.8	0.7	0.6	0.6	29.6	31.7	34.3
Switzerland	0.3	2.2	5.6	3.0	3.0	2.8	68.1	76.3	76.1
Cyprus	0.0	0.1	0.3	0.0	0.0	0.0	3.3	3.9	4.7
Czech Republic	0.3	1.8	4.9	3.2	3.5	3.6	56.5	65.4	73.0
Germany	5.1	35.7	101.4	23.2	39.2	59.9	511.7	542.6	573.1
Denmark	1.2	3.5	7.3	0.8	2.0	3.8	33.7	38.1	42.1
Estonia	0.1	0.3	0.9	0.1	0.1	0.2	7.3	7.8	8.3
Spain	0.9	6.4	17.6	4.1	4.8	5.6	247.8	269.6	285.3
Finland	0.4	2.1	5.6	1.4	1.9	2.7	76.3	84.5	89.8
France	4.1	28.6	93.4	13.8	15.6	17.5	372.8	428.7	475.4
Greece	0.4	2.4	5.9	0.1	0.1	0.1	44.9	50.1	53.1
Croatia	0.1	0.4	1.1	0.5	0.5	0.6	13.3	14.4	15.3
Hungary	0.1	1.0	2.7	1.8	1.9	1.9	39.0	44.2	47.7
Ireland	0.2	1.0	2.7	0.1	0.1	0.2	23.3	26.7	29.9
Italy	1.7	12.2	34.1	7.5	7.7	7.3	271.3	301.0	330.9
Lithuania	0.1	0.3	0.9	0.5	0.5	0.5	10.2	11.1	12.5
Luxembourg	0.0	0.2	0.5	0.1	0.1	0.1	7.6	8.9	9.2
Latvia	0.0	0.2	0.6	0.3	0.4	0.5	7.5	8.5	8.9
Malta	0.0	0.0	0.1	-	-	-	2.1	2.3	2.4
Netherlands	3.9	10.4	19.2	1.8	2.4	3.2	116.5	134.3	150.3
Norway	3.0	7.7	14.4	0.9	1.1	1.5	132.4	148.3	148.0
Poland	0.9	5.1	14.1	7.2	7.5	7.8	164.5	186.9	201.6
Portugal	0.5	2.7	7.1	0.5	0.4	0.4	52.1	57.6	59.7
Romania	0.3	1.7	5.6	2.5	2.8	2.9	52.5	61.2	68.9
Sweden	3.2	12.3	22.7	3.2	4.0	5.3	120.1	132.1	141.9

Demand in TWh	electric vehicles			other transport			other sectors		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Slovenia	0.1	0.8	1.8	0.5	0.6	0.6	13.8	14.7	15.6
Slovakia	0.1	0.5	1.8	1.4	1.4	1.4	29.6	34.7	36.2
United Kingdom	6.3	28.1	67.1	4.4	6.1	6.7	300.9	330.4	359.0
Total EU 27+3	**35**	**176**	**460**	**88**	**114**	**143**	**2,955**	**3,283**	**3,541**

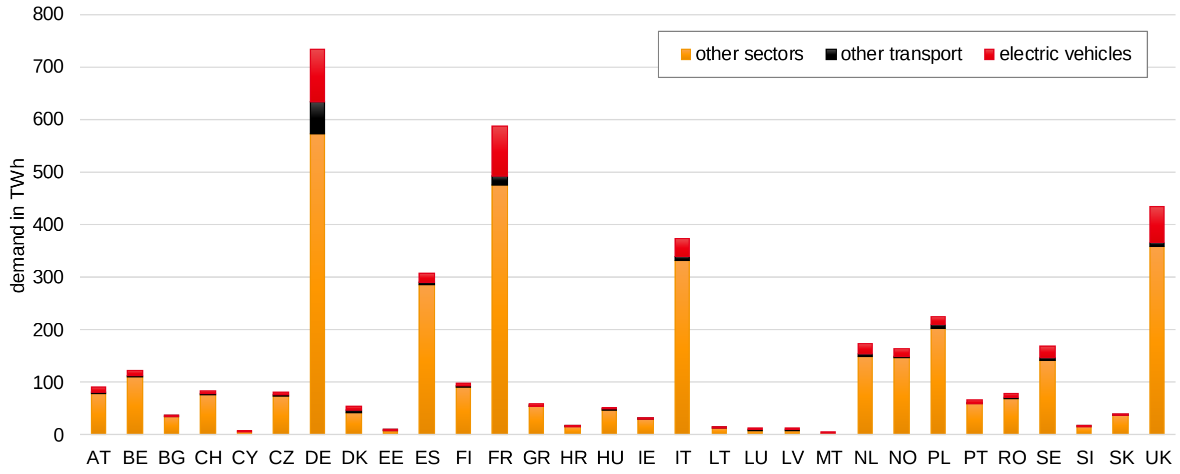


Figure 63: Electricity demand in other sectors (i.e. all sectors excluding space and water heating) in 2050 per country (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

Table 41: Development of hydrogen, e-gas and e-liquids demand in other sectors from 2030 until 2050 per country (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

Demand in TWh	hydrogen			e-gas			e-liquids		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria	1.3	9.2	27.0	0.5	3.4	10.2	0.9	6.1	18.0
Belgium	3.9	26.7	74.5	1.5	10.1	28.1	2.6	17.9	49.9
Bulgaria	0.5	3.1	7.8	0.2	1.2	3.0	0.3	2.1	5.2
Switzerland	0.0	0.7	2.6	0.0	0.3	1.0	0.0	0.5	1.8
Cyprus	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.0	0.1
Czech Republic	1.0	5.9	14.2	0.4	2.2	5.3	0.7	4.0	9.5
Germany	9.8	57.2	143.6	3.7	21.6	54.1	6.6	38.3	96.1
Denmark	0.0	0.1	0.3	0.0	0.0	0.1	0.0	0.0	0.2
Estonia	0.0	0.2	0.5	0.0	0.1	0.2	0.0	0.1	0.4
Spain	2.0	11.2	29.2	0.7	4.2	11.0	1.3	7.5	19.5
Finland	0.5	2.7	6.6	0.2	1.0	2.5	0.3	1.8	4.4
France	5.9	47.8	148.0	2.2	18.0	55.8	4.0	32.0	99.1

Demand in TWh	hydrogen			e-gas			e-liquids		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Greece	0.2	2.0	6.5	0.1	0.7	2.4	0.1	1.3	4.3
Croatia	0.1	0.4	0.8	0.0	0.1	0.3	0.1	0.2	0.5
Hungary	0.9	4.8	11.8	0.3	1.8	4.5	0.6	3.2	7.9
Ireland	0.1	0.8	2.4	0.0	0.3	0.9	0.0	0.5	1.6
Italy	3.5	19.6	50.4	1.3	7.4	19.0	2.3	13.1	33.8
Lithuania	0.4	2.2	5.5	0.1	0.8	2.1	0.3	1.5	3.7
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Netherlands	4.0	22.6	56.7	1.5	8.5	21.3	2.7	15.1	37.9
Norway	0.0	0.1	0.3	0.0	0.0	0.1	0.0	0.0	0.2
Poland	1.9	9.8	23.4	0.7	3.7	8.8	1.3	6.5	15.7
Portugal	0.5	3.0	7.4	0.2	1.1	2.8	0.4	2.0	5.0
Romania	1.6	9.2	22.7	0.6	3.5	8.5	1.1	6.2	15.2
Sweden	0.8	4.6	11.4	0.3	1.7	4.3	0.5	3.1	7.6
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovakia	0.9	4.6	9.2	0.3	1.7	3.5	0.6	3.1	6.2
United Kingdom	3.2	17.6	44.1	1.2	6.6	16.6	2.1	11.8	29.5
Total EU 27+3	**43**	**266**	**707**	**16**	**100**	**266**	**29**	**178**	**473**

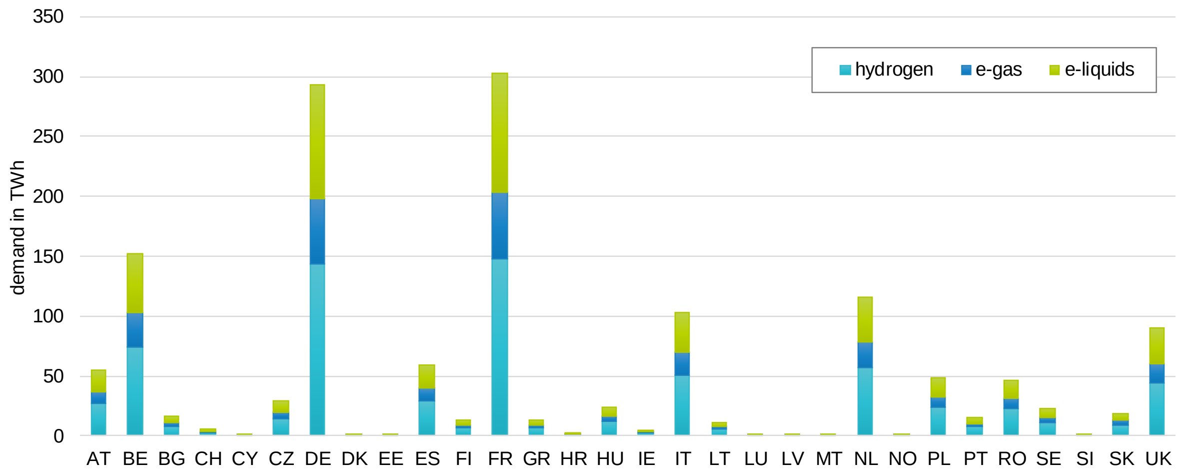
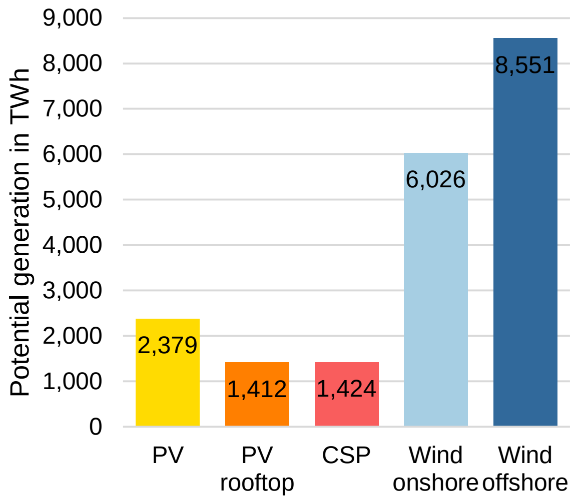


Figure 64: Hydrogen, e-gas and e-liquids demand in other sectors (i.e. all sectors excluding space and water heating) in 2050 per country (based on 1.5TECH scenario (European Commission) and SET-Nav pathway "Diversification" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

7.4.2.2. Renewable energy potential and generation

The capacity expansion of wind and solar energy are among the most important decision variables of the Enertile model. The electricity generation potential for these renewable technologies is determined before the actual optimization in a detailed calculation with high spatial resolution. A worldwide equiangular model grid forms the basis of the calculation, with each tile of around 42 km² (edge length of around 6.5 km) depending on the latitude. Europe accounts for about 240,000 tiles. For each tile, the electricity generation potential for wind and solar energy is calculated. First, land use data (Corine Land Cover 2018[60]) and terrain are considered to determine the available area in each tile. Then, hourly weather time series from several weather years are assigned to the model grid. Finally, for each tile and technology, the installable capacity, the full-load hours, the possible long-term generation output, and the specific generation costs are calculated. As not every single tile can be included in the optimization of the power supply, the technology-specific generation potentials are aggregated for tiles with comparable production costs within a model region. The results are cost-potential curves for five different technologies: utility scale photovoltaics (PV), PV on rooftops, concentrating solar power (CSP), wind onshore, and wind offshore. A more detailed description of this calculation can be found in (TU Wien, Fraunhofer ISI, Comillas 2019b).

The following figures show the total potential for wind and solar energy technologies in Europe in 2050 and the aggregated cost potential curve.



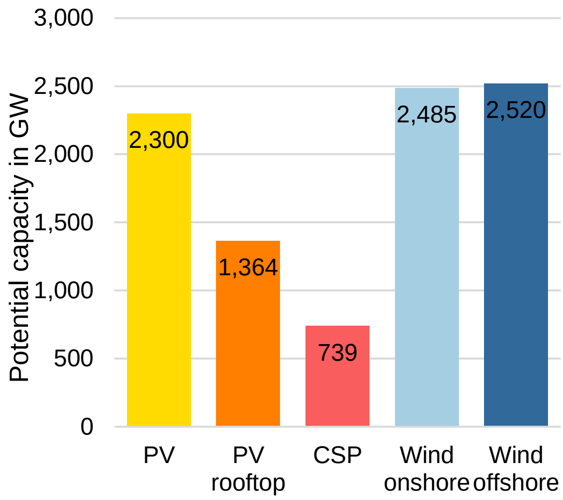


Figure 65: Total potential in Europe 2050: generation and capacity per technology (Fraunhofer ISI).

[60] https://land.copernicus.eu/pan-european/corine-land-cover

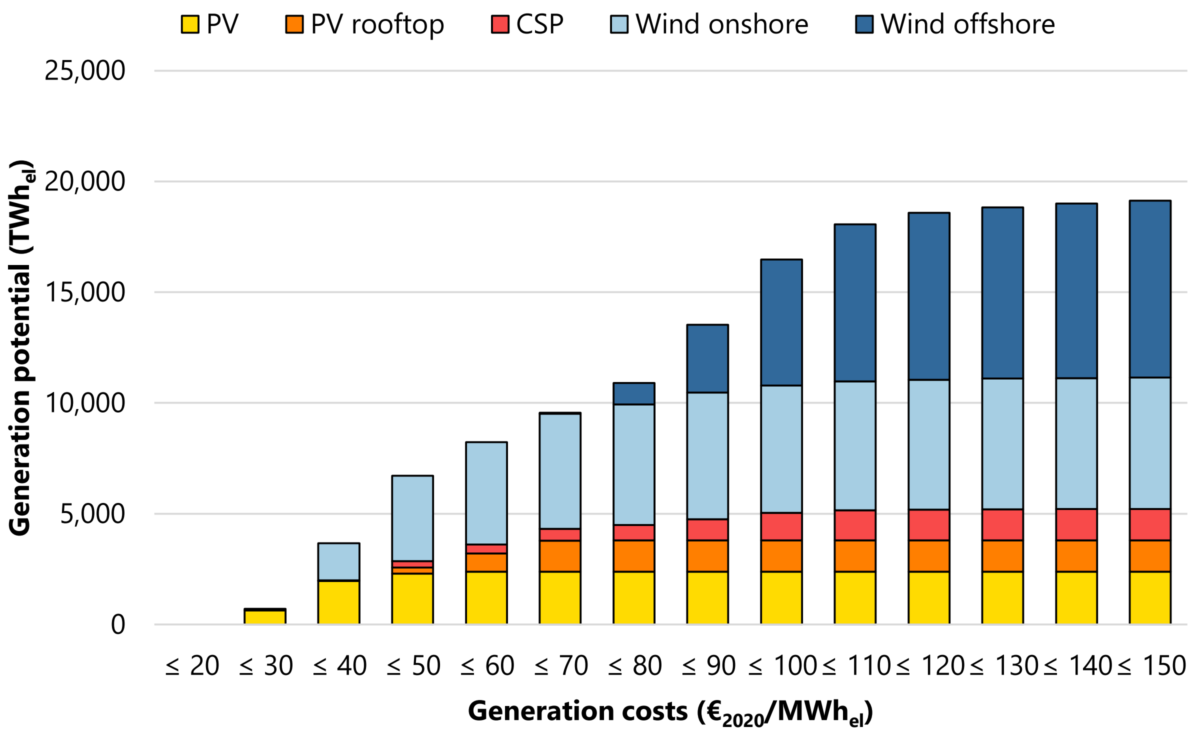


Figure 66: Aggregated cost potential curve in Europe 2050 (Fraunhofer ISI).

The following figures show examples of the detailed results of the potential calculation for wind energy in 2050.

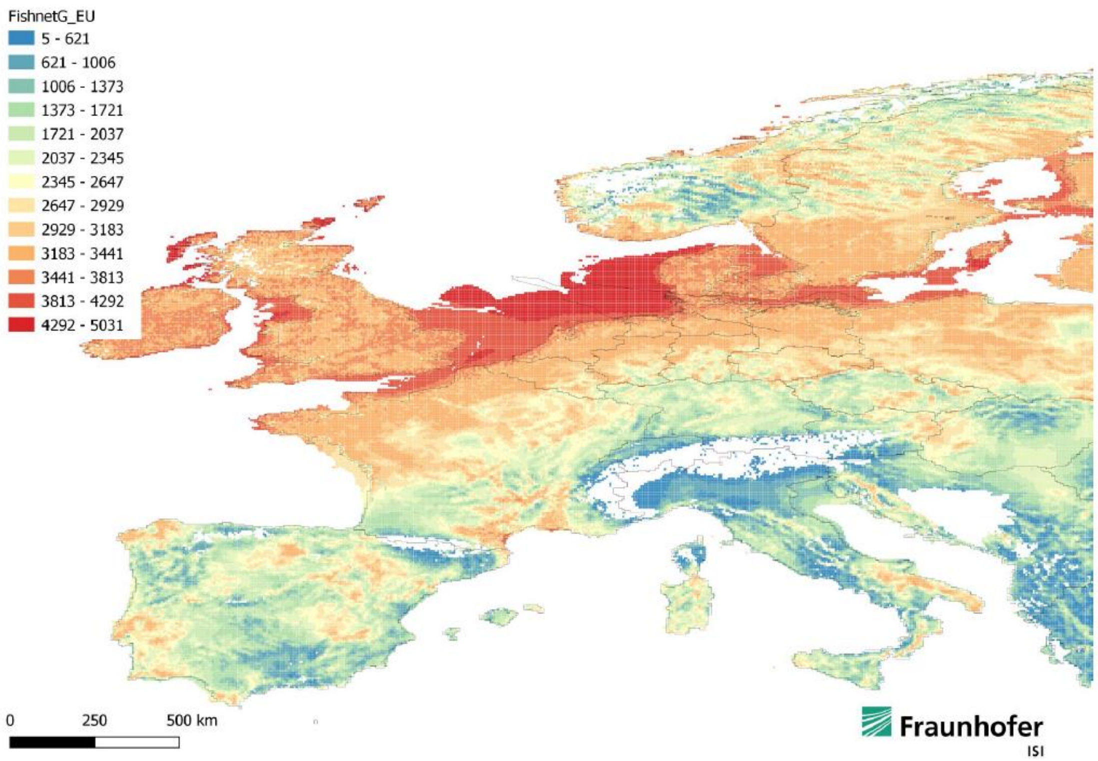


Figure 67: Full-load hours wind energy in 2050 (Fraunhofer ISI).

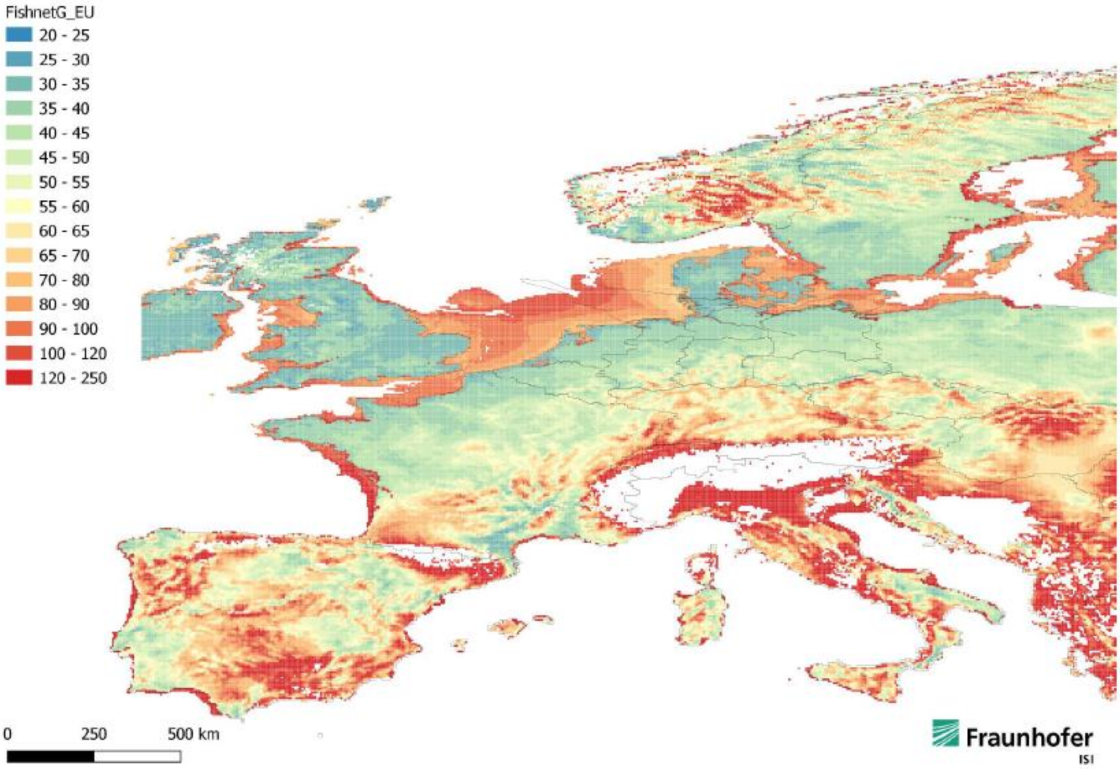


Figure 68: Generation costs of wind energy in 2050 (values in €/MWh) (Fraunhofer ISI).

7.4.2.3. Techno-economic characteristics of investment options

The capacity expansion and operation of conventional power plants and other technologies are part of the cost optimization with Enertile and therefore depend strongly on their techno-economic assumptions. The following table lists the investment options and parameters for the scenario analysis with Enertile. The data is based mainly on two sources:

- Asset project - Technology pathways in decarbonisation scenarios 2018
- Technology Data - Energy Plants for Electricity and District heating generation Danish Energy Agency and Energinet 2016 (version 0007 from 2020)

Table 42: Techno-economic parameters of investment options in Enertile (Asset project 2018, Technology Data 2020).

	Unit	Year	Life-time	Invest-ment	Fixed O&M	Variable O&M	Efficiency (CHP)
				€/kW	€/kW	€/MWh	%
Conventional	Coal steam plant	2030	40	1600	25.6	2.4	43%
	Combined cycle gas turbine	2030	30	775	11.6	3.0	60%
		2040	30	750	11.3	3.0	60%
	Gas turbine	2030	25	400	7.5	1.5	41%
		2040	25	400	7.5	1.5	41%
	Battery storage	2030	10	228	6.3	0.0	95%
		2040	10	216	5.9	0.0	95%
		2050	10	204	5.5	0.0	95%
CHP	Combined cycle gas turbine CHP	2030	30	950	30.0	3.5	48% (88%)
		2040	30	950	30.0	3.5	48% (88%)
	Gas turbine CHP	2030	30	730	30.0	2.7	33% (85%)
		2040	30	730	30.0	2.7	33% (85%)
	Biomass CHP	2030	25	3200	115	2.1	30% (71%)
		2040	25	3050	109	2.1	30% (71%)
		2050	25	2900	103	2.1	30% (71%)
District heating	Gas boiler	2030	25	50	1.9	0.9	104%
		2040	25	50	1.8	0.9	104%
		2050	25	50	1.7	0.9	104%
	Biomass boiler	2030	25	830	47.9	0.7	103%
		2040	25	790	45.4	0.7	103%
		2050	25	750	42.9	0.7	103%
	Electric boiler	2030	20	60	1.0	0.5	99%
		2040	20	60	1.0	0.5	99%
		2050	20	60	0.9	0.4	99%
	Large heat pump	2030	25	590	2.0	1.7	variable
		2040	25	560	2.0	1.7	variable
		2050	25	530	2.0	1.6	variable
	Heat storage	2030	20	22	0.0	0.0	99%
		2040	20	22	0.0	0.0	99%
		2050	20	22	0.0	0.0	99%

Role of nuclear power

Nuclear power generation is driven by political preferences rather than pure economic decision-making. Therefore, nuclear generation capacity is not subject to the cost optimisation procedure in Enertile but included as an exogenous assumption. The capacity expansion or deconstruction of nuclear plants is set exogenously for each modelled country. The nuclear capacity in all scenarios is based on the National Champions pathway of the SET-Nav project (TU Wien, Fraunhofer ISI, Comillas 2019b). In general, nuclear power plants can be prolonged and replaced in the National Champions pathway. The following figure shows the assumed nuclear capacity in individual countries.

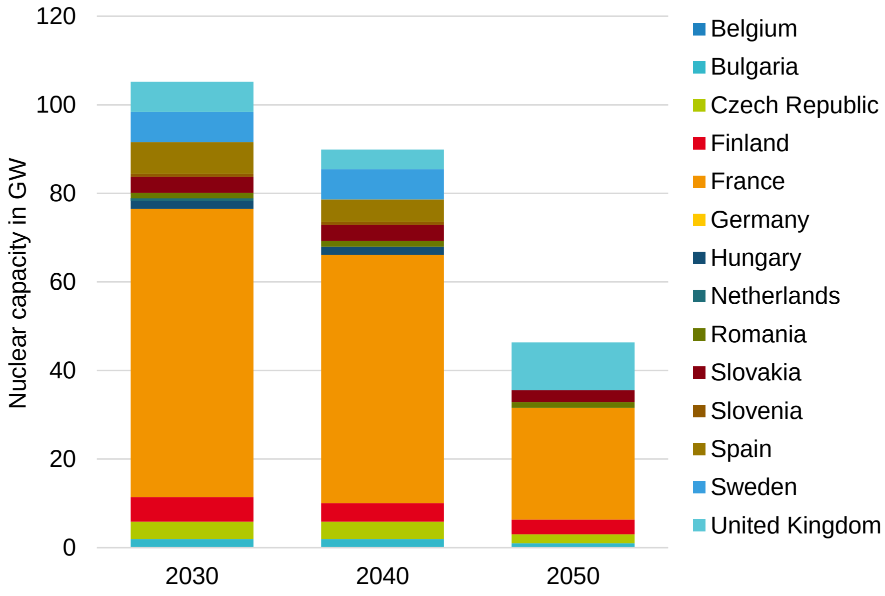


Figure 69: Assumed nuclear capacity per country in GW based on SET-Nav pathway "National Champions" (TU Wien, Fraunhofer ISI, Comillas 2019b)).

Coal phase-out

Many national governments in the EU have announced their intention to phase out coal from their electricity generation (compare for example Beyond-coal.eu). For the scenarios, we implement the phase-out announcement in two ways. First, the timing of the phase-out is considered in our power plant database to ensure that closure dates are met on plant level. Second, the construction of new coal plants is prohibited in countries with concrete phase-out plans. The following table summarizes the status and timing of national coal-phase out announcements in Europe.

Table 43: National coal phase-out status (Beyond-coal.eu and NECPs).

country	Coal phase-out status	phase out until	new plants possible
Austria	Phase-out announced	2020	no
Belgium	Coal-free as of 2020		no
Bulgaria	No phase-out planned		yes
Croatia	No phase-out planned		yes
Cyprus	Coal-free as of 2020		no
Czech Republic	Phase-out under discussion		no
Denmark	Phase-out announced	2030	no
Estonia	Coal-free as of 2020		no
Finland	Phase-out announced	2030	no
France	Phase-out announced	2022	no
Germany	Phase-out announced	2038	no
Greece	Phase-out announced	2028	no
Hungary	Phase-out announced	2030	no
Ireland	Phase-out announced	2025	no
Italy	Phase-out announced	2025	no
Latvia	Coal-free as of 2020		no
Lithuania	Coal-free as of 2020		no
Luxembourg	Coal-free as of 2020		no
Malta	Coal-free as of 2020		no
Netherlands	Phase-out announced	2030	no
Norway	Coal-free as of 2020		
Poland	No phase-out planned		yes
Portugal	Phase-out announced	2021	no
Romania	No phase-out planned		yes
Slovakia	Phase-out announced	2023	no
Slovenia	Phase-out under discussion		no
Spain	Phase-out announced	2030	no
Sweden	Phase-out announced	2020	no
Switzerland	Coal-free as of 2020		
United Kingdom	Phase-out announced	2024	no

7.4.2.4. Further assumptions for renewable electricity supply

Wind and PV generation

The following figure shows the electricity generation from PV and wind in individual countries (Eurobserver report 2019). We assume that these generation amounts can be seen as lower bounds for future developments. It is plausible that countries with renewable electricity generation today will at least keep this level or even increase their renewable generation until 2050. Therefore, further constraints are defined for wind and solar electricity generation based on the current electricity generation amounts in individual countries. The generation values given in the following table are used as minimum conditions for all calculated years (2030, 2040 and 2050).

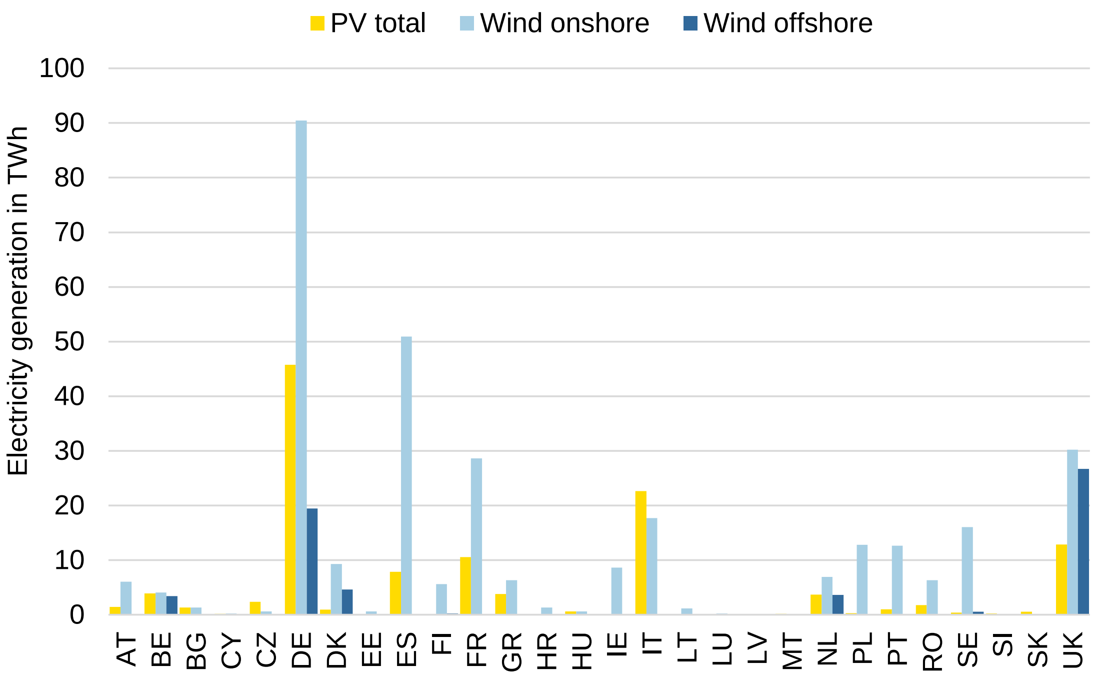


Figure 70: Renewable generation from PV and Wind in 2018 in TWh (Eurobserver report 2019).

Wind offshore capacity

As already shown in the aggregated cost potential curve, wind offshore has comparatively high costs. Nevertheless, several countries have specified expansion targets for wind offshore in 2030 in their NECP reports. In all scenarios, we assume that this capacity expansion is fully realized in 2030 and until 2040 additional 10% are implemented. The corresponding values are also given in the table below. For 2050, we define additional minimum restrictions for the total wind offshore capacity in the EU. The value is directly taken from the EU's offshore strategy "An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future". In all scenarios, we assume that a minimum capacity of 300 GW of offshore capacity is implemented in the EU member states. Norway and the United Kingdom are not included in this target value.

Table 44: Wind offshore capacity targets for 2030 from NECP and assumed minimum capacity expansion.

In GW	2030 (NECP)	2040 (NECP +10%)
Belgium	4.00	4.40
Germany	20.00	22.00
Denmark	5.00	5.50
Estonia	5.00	5.50
Finland	0.04	0.05
France	4.92	5.41
Ireland	3.50	3.85
Lithuania	0.70	0.77
Latvia	1.00	1.10
Netherlands	11.00	12.10
Norway	4.50	4.95
Poland	3.80	4.18
Portugal	0.30	0.33
Sweden	1.19	1.31
United Kingdom	40.00	44.00

Other renewables for electricity generation

The electricity generation from other RES like hydro and geothermal energy are mostly predetermined based on hourly profiles. In the following, the assumptions on hydro and geothermal energy are shortly described.

Hydro energy

In 2018, 349.8 TWh (30 Mtoe) of electricity were produced with hydro energy (without pumping) in Europe (Eurobserver report 2019). The following figure shows the hydro electricity generation in 2018 per country. We assume that this production remains constant until 2050.

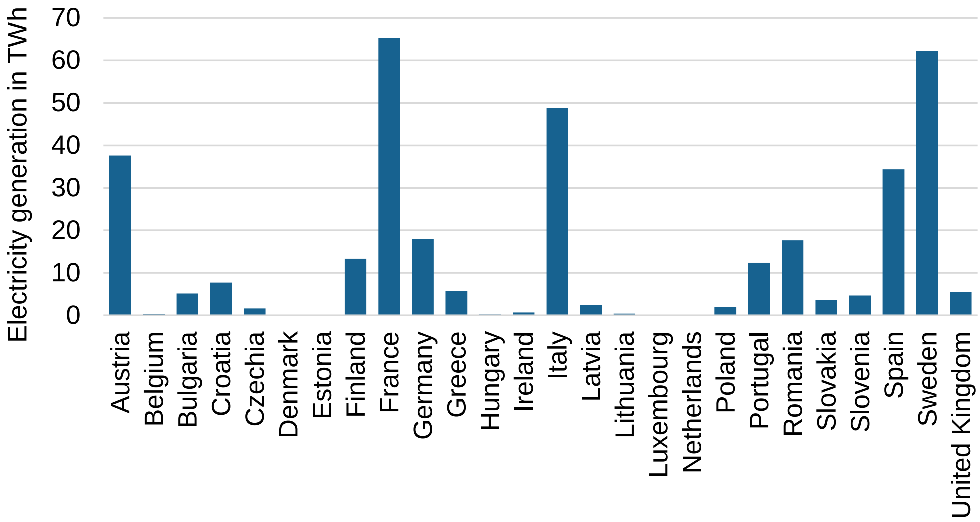


Figure 71: Hydro electricity generation in Europe in 2018 in TWh (Eurobserver report 2019).

Geothermal energy (electricity only)[61]

In 2018, 6657 GWh of electricity were produced with geothermal energy in Europe (Eurobserver report 2019). The following figure shows the geothermal electricity generation in 2018 for the six countries. We assume that this production remains constant until 2050.

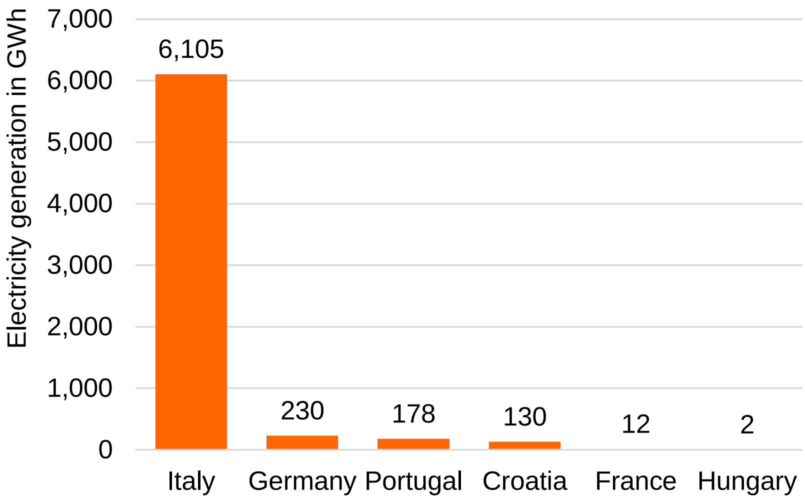


Figure 72: Geothermal electricity generation in Europe in 2018 in GWh (Eurobserver report 2019).

7.4.2.5. The use of biomass and waste in electricity and district heat supply

Biomass

We assume the use of biomass for electricity and district heat supply is generally declining until 2050, as the potentially available biomass is rather scarce and more urgently needed for

[61] The assumptions for geothermal district heating are described in chapter 4.3.2.

decarbonisation in other sectors like industry and transport. The following figure shows the current use of biomass (solid biomass and biogas) for electricity and district heat supply in European countries (Eurobserver report 2019). In 2018 117 TWh of electricity were produced with biomass, with 62.5 TWh from electricity only plants and 54.8 TWh from CHP production. Furthermore, 137 TWh of district heat were produced with biomass, with 88.1 TWh from heat only plants and 49.2 TWh from CHP production.

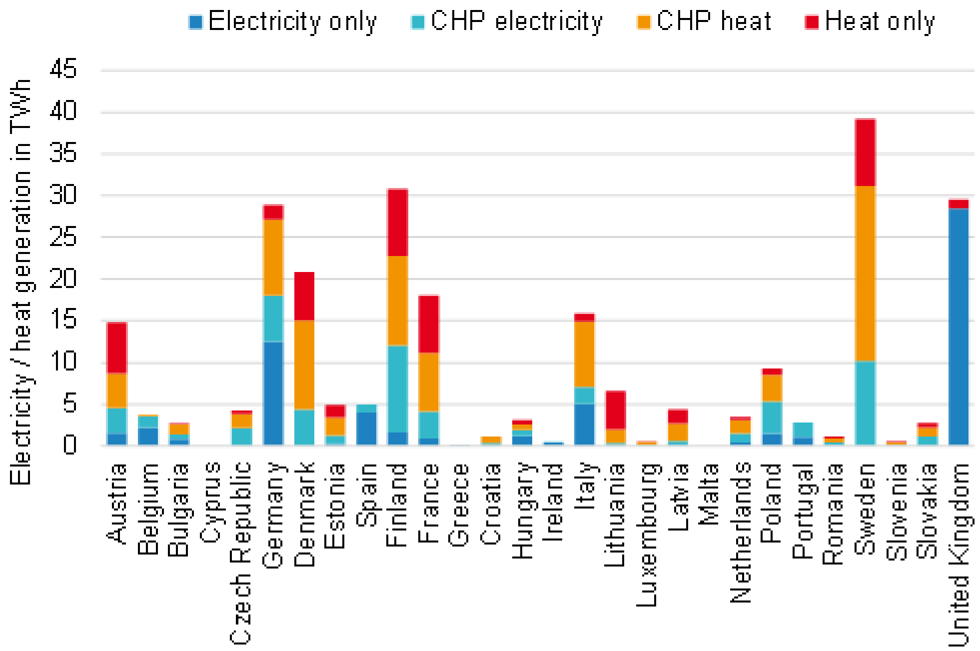


Figure 73: Electricity and district heat production from biomass (biogas and solid biomass) in Europe in 2018 in TWh (Eurobserver report 2019).

As described in section 4.3, if 100 % corresponds to today's use as shown above, biomass for electricity only plants is reduced to 80 % in 2050 in the baseline scenario and to 50 % in all other scenarios. The available biomass for CHP and heat only is implemented as an upper bound in the optimization in Enertile. Below this limit, the actual usage of biomass in district heating is optimised. For CHP and heat only plants different assumptions are used for the scenarios (compare section 4.3). Again, if 100 % corresponds to today's use as shown above, the maximum available biomass is reduced until 2050 as follows:

- baseline scenario 80 %
- direct RES-H, e-fuels and hydrogen scenarios 50 %
- electrification scenario 25 %
- district heating scenario 60 %

The same developments are applied to all countries.

Renewable municipal waste

Renewable municipal waste can also be used for electricity and district heat generation. The following figure shows the current use of waste for electricity and district heat supply in Europe (Eurobserver report 2019). In 2018, 22.9 TWh of electricity were produced from waste, with 10.4 TWh from electricity only plants and 12.5 TWh from CHP production. Furthermore, 33.4

TWh of district heat were produced with waste, with 6.4 TWh from heat only plants and 27.0 TWh from CHP production. We assume that the availability of municipal waste will decrease until 2050. The following table shows the maximum electricity and district heat generation in GWh assumed in all scenarios (100 % corresponds to 2018 values). The generation values are implemented as maximum restrictions in the optimization and therefore can be seen as upper bounds, which cannot be exceeded.

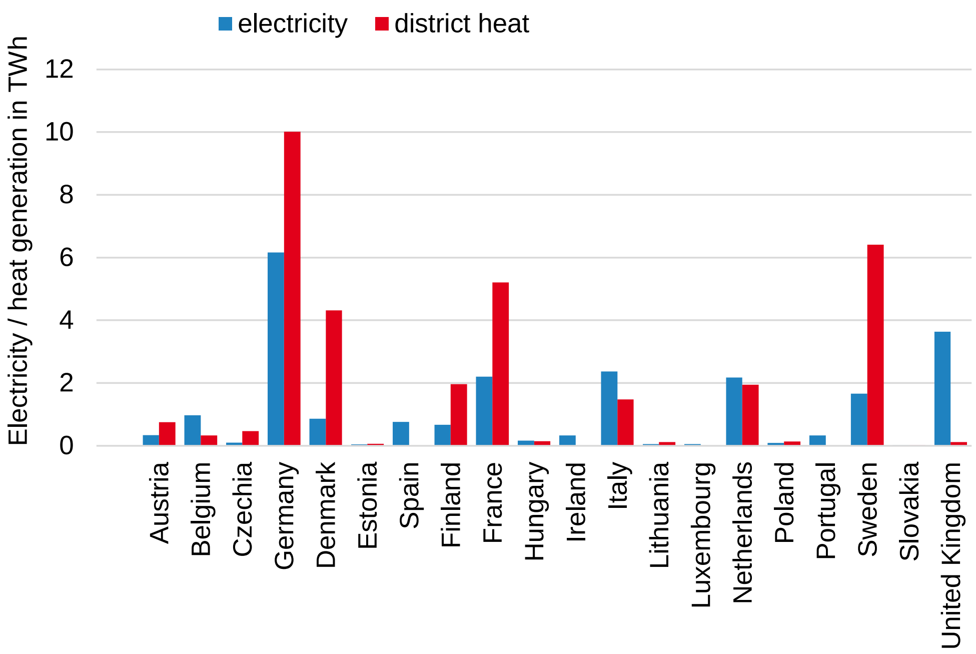


Figure 74: Electricity and district heat production from waste in Europe in 2018 in TWh (Eurobserver report 2019).

Table 45: Assumed maximum electricity and district heat generation from renewable municipal waste until 2050 in GWh (100 % corresponds to 2018 values based on (Eurobserver report 2019)).

Electricity				District heat			
2018	**2030**	**2040**	**2050**	**2018**	**2030**	**2040**	**2050**
100%	100%	90%	80%	100%	100%	90%	80%
22,945	22,945	20,651	18,356	33,429	33,429	30,086	26,743

7.4.2.6. Assumptions for hydrogen and e-fuels

On the one hand, a broad use of electricity-based hydrogen and e-fuels increases the total electricity demand. On the other hand, these fuels can offer flexibility to the power sector, as its long-term storage properties can be used as an electricity storage. In hours with low load and high renewable electricity generation, hydrogen or e-gas can be produced and stored. Through this storage, the hydrogen or e-gas demand in the different demand sectors can be met. In hours with high load and low renewable power generation, the hydrogen or e-gas can be burned in a gas turbine to generate emission-free electricity.

Therefore, Enertile models three formal components: First, an electrolyser to produce hydrogen; second, a hydrogen storage system that can meet both exogenous demand from the other sectors and endogenous demand for electricity generation using hydrogen; and finally, a conversion unit such as a gas-fired power plant. A network infrastructure for hydrogen is not explicitly modelled and costs for storages are not included. The same methodology is applied for e-fuels.

Import from outside the EU

Generally, hydrogen or e-fuels can either be produced with renewable electricity in the EU or be imported from countries with very god potentials for renewable electricity generation outside the EU. Typically, the countries in question are in the MENA region (Middle East & North Africa). To ensure solvability of the optimization problem, import of hydrogen and e-fuels is allowed in all scenarios but at high prices (compare section 4.3.5). In general, prices for e-liquids are higher than for e-gas which are higher than for hydrogen. The import prices used in the modelling are given in the table below. Transport cost are included.

Table 46: Assumed import prices for hydrogen and e-fuels.

	2030	2040	2050
Hydrogen	100	90	80
E-fuel	160	150	130

Technology assumptions

To cover specific demands for electricity based hydrogen and e-fuels, necessary investments in generation technologies are included in the optimization. Furthermore, the cost-efficient capacity expansion and operation of reconversion technologies like gas turbines based on hydrogen or e-gas are included. As all scenarios have a certain hydrogen and e-fuel demand, these technologies are incorporated in all scenarios. The technology assumptions for hydrogen and e-fuel generation are given in the table below. The reconversion technologies for hydrogen and e-gas are directly based on the conventional gas technologies (reconversion means burning of hydrogen/e-fuels to generate electricity).

Table 47 : Assumed technology data electrolyzer, P2G and P2L

Unit	Year	Life-time	Invest-ment	Fixed O&M	Variable O&M	Effi-ciency
			€/kW	**€/kW**	**€/MWh**	**%**
Electrolyser	2030	20	481	21.7	0.0	66%
	2050	20	404	20.5	0.0	68%

Unit	Year	Life-time	Invest-ment	Fixed O&M	Variable O&M	Effi-ciency
			€/kW	€/kW	€/MWh	%
	2050	20	327	19.3	0.0	71%
Methanation/Power-to-liquid (and Direct Air Cap-ture)	2030	20	1275	49.2	0.0	47%
	2040	20	948	36.4	0.0	49%
	2050	20	832	31.6	0.0	52%

7.4.2.7. Assumptions for electricity grid expansion

The electricity transmission grid offers flexibility for the energy system by providing opportunities for inter-regional balancing. This is particularly valuable when high shares of RES are present. Enertile models the transmission of electricity between different model regions using a model of net transfer capacities (NTCs). The expansion of initial cross-border capacities is part of the optimization within Enertile considering the investments required for expansion as well as occurring grid losses. The possibility of expanding the interconnector capacities without limits also has a large impact on many other results like the energy costs and the choice and usage of different energy supply technologies. By limiting electricity grid expansion, balancing of supply and demand has to take place more intensely within each country and the availability of cost-efficient renewables defines the country's electricity mix. Therefore, the expansion of cross-border transfer capacities is limited as follows. The maximum NTCs for all years are based on the reference grid capacities (of 2027) of the TYNDP 2018 and are implemented for each interconnector. For the year 2030, an increase of maximum 30% of the TYNDP 2018 is allowed. In 2040, the capacities are limited to a maximum of 2.5 times the TYNDP values. In 2050, the capacities are limited to a maximum of 5 times the TYNDP values.

7.4.3. Assumptions for infrastructures

While electricity transmission grids are optimized within Enertile, gas and hydrogen transmission infrastructures are assessed based on resulting demands. The following table summarizes assumptions for the use or availability of different infrastructures in the scenarios.

Table 48: Assumptions for the use of infrastructures in the scenarios.

Scenario	Electricity grid	Gas grid (incl. e-gas)	Hydrogen grid
other	Unlimited network expansion (cost optimization for transmission grid with Enertile)	Gradual closure of the gas grid, no comprehensive gas distribution grid in 2050	no hydrogen distribution grid, supply in demand centres conceivable
hydrogen			Comprehensive transmission and distribution grid for hydrogen available, Conversion of gas grid to hydrogen partly possible
e-fuels		Conversion of the gas grid to e-gas	no hydrogen distribution network, supply in demand centres conceivable

For the scenarios in task 7 (e-fuels and hydrogen) the existing gas infrastructures will remain important until 2050. With high demand for hydrogen, parts of the existing gas grid can be adapted to transport hydrogen instead. With high demand for e-gas, the existing gas grid can easily be used to accommodate e-gas. In the other scenarios, gas demand will decrease over time making the operation of a comprehensive gas distribution network in 2050 no longer cost-efficient. In these scenarios, a gradual deconstruction of parts of the gas grid will be necessary. In scenarios with no focus on hydrogen, a grid for hydrogen will not be available and the supply will rather take place decentralized at filling stations or industrial plants.

7.5. Annex D: Additional scenario results

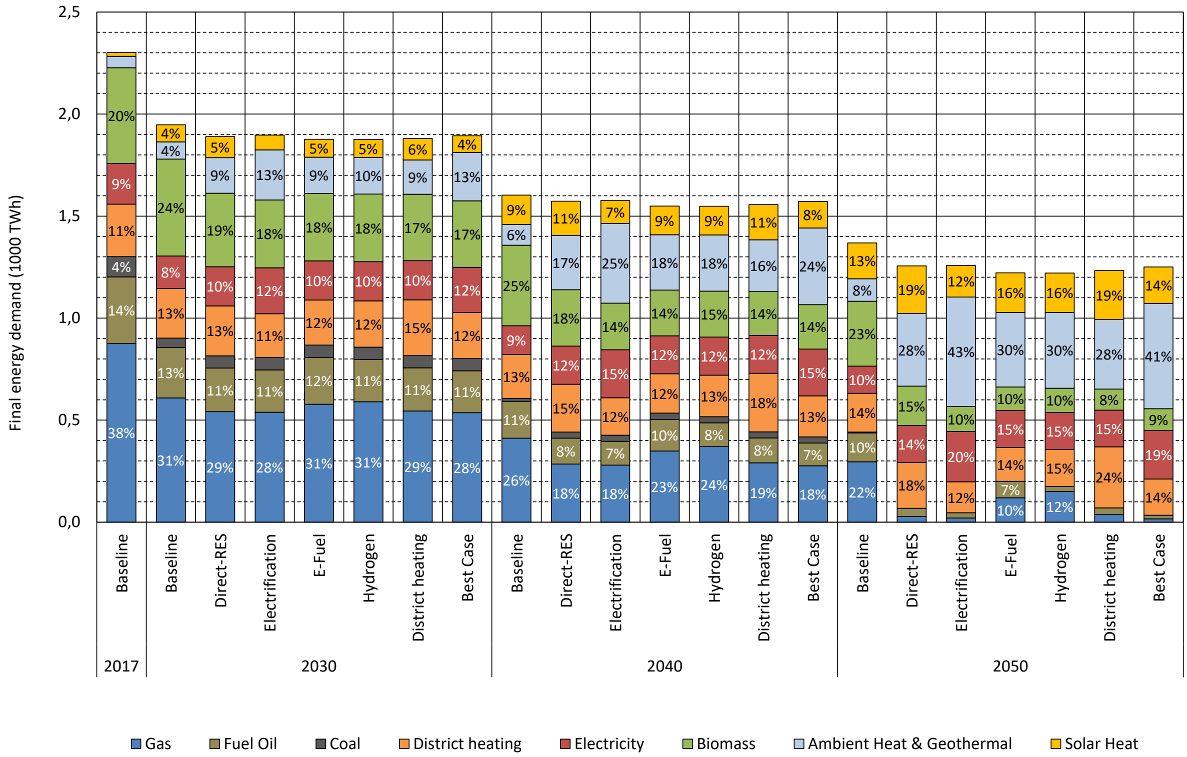


Figure 75: Final energy demand for space and water heating in residential buildings by energy carriers, EU-27, 2017, 2030, 2040 and 2050 across scenarios.

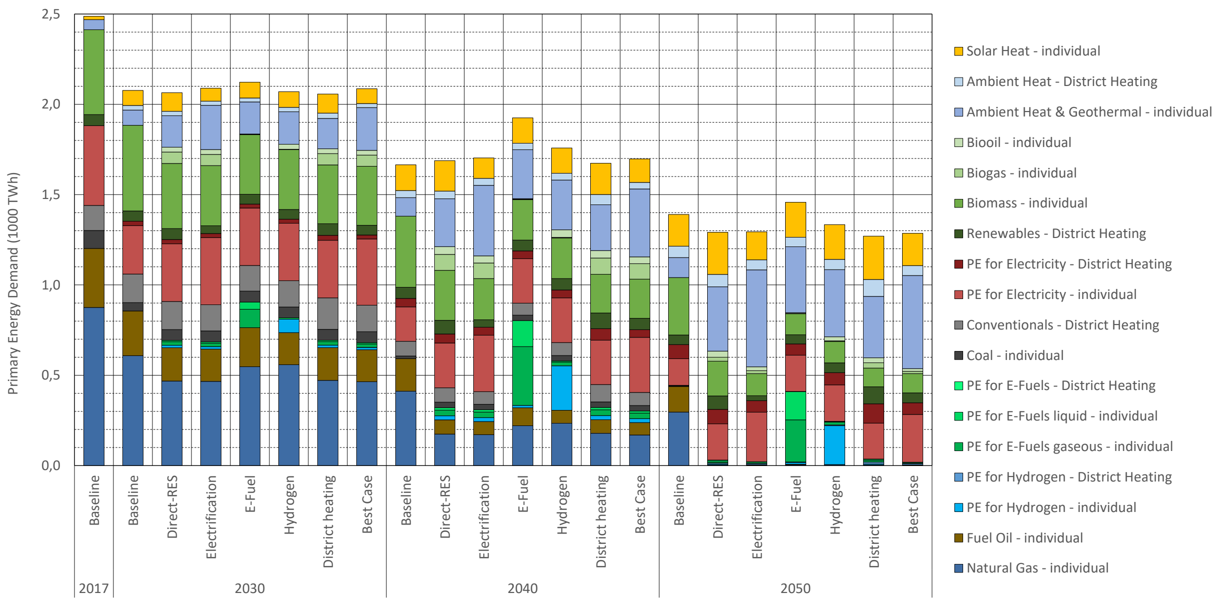


Figure 76: Primary energy demand for space and water heating in residential buildings by energy carriers, EU-27, 2017, 2030, 2040 and 2050 across scenarios.

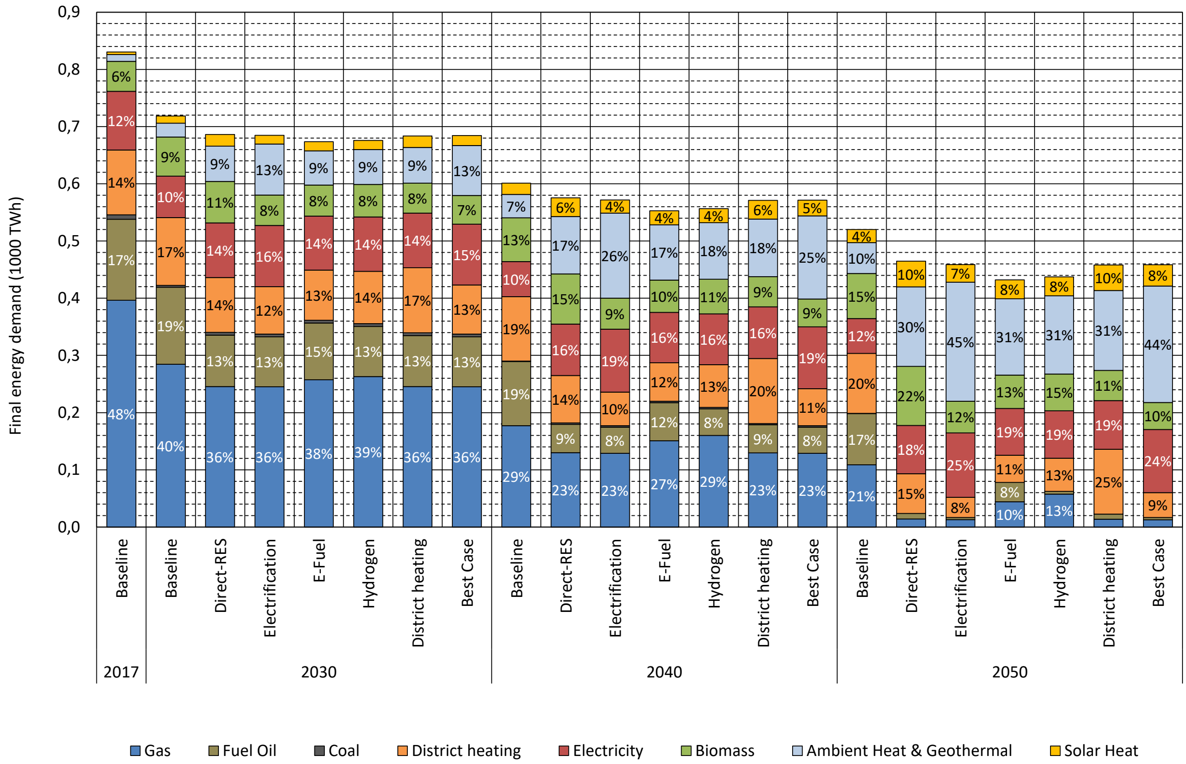


Figure 77: Final energy demand for space and water heating in tertiary buildings by energy carriers, EU-27, 2017, 2030 and 2050 across scenarios.

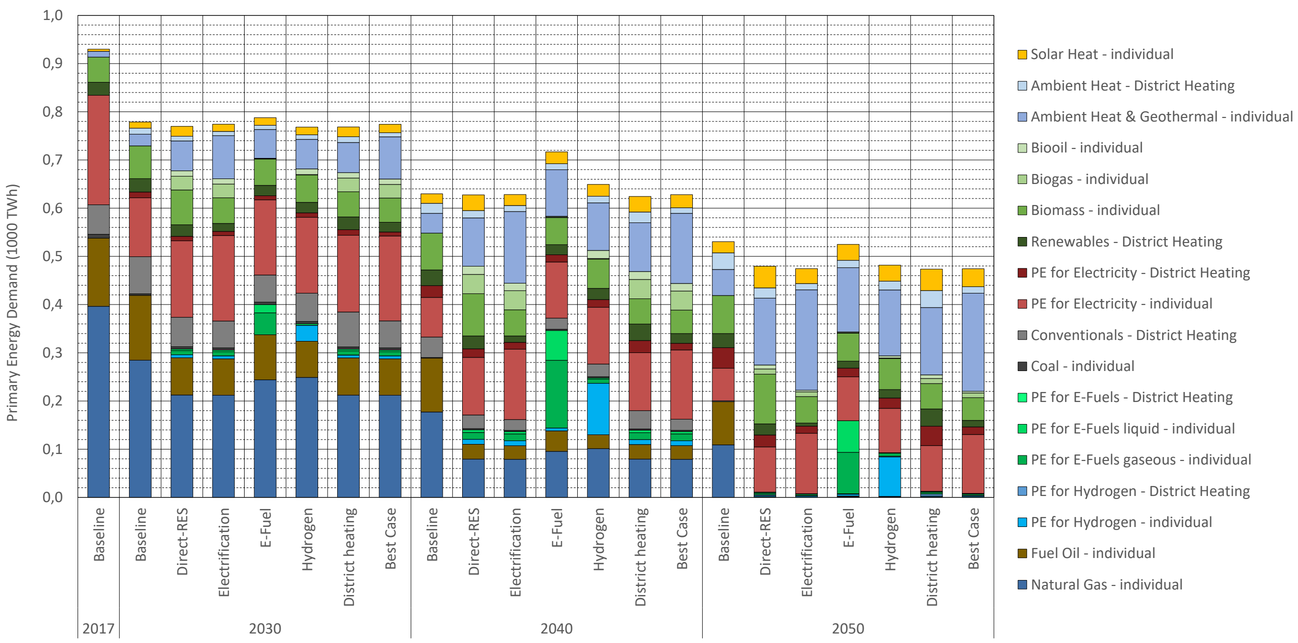


Figure 78: Primary energy demand for space and water heating in tertiary buildings by energy carriers, EU-27, 2017, 2030, 2040 and 2050 across scenarios.

There are two ways of indicating GHG-emissions for the sector space and water heating: The first option is to calculate it from GHG-emission factors for electricity or district heating (see Figure 29). However, due to the import/export interlinkages between MS of the EU, there are methodological differences and uncertainties linked to these factors. Therefore, a second option is to display the primary energy demand and GHG-emissions for the aggregate of the space and water heating sector and the full, total upstream supply sector (i.e. including e.g. electricity generated for the use in other sectors) as shown in Figure 79. In a similar way, this is shown for primary energy demand (Figure 80).

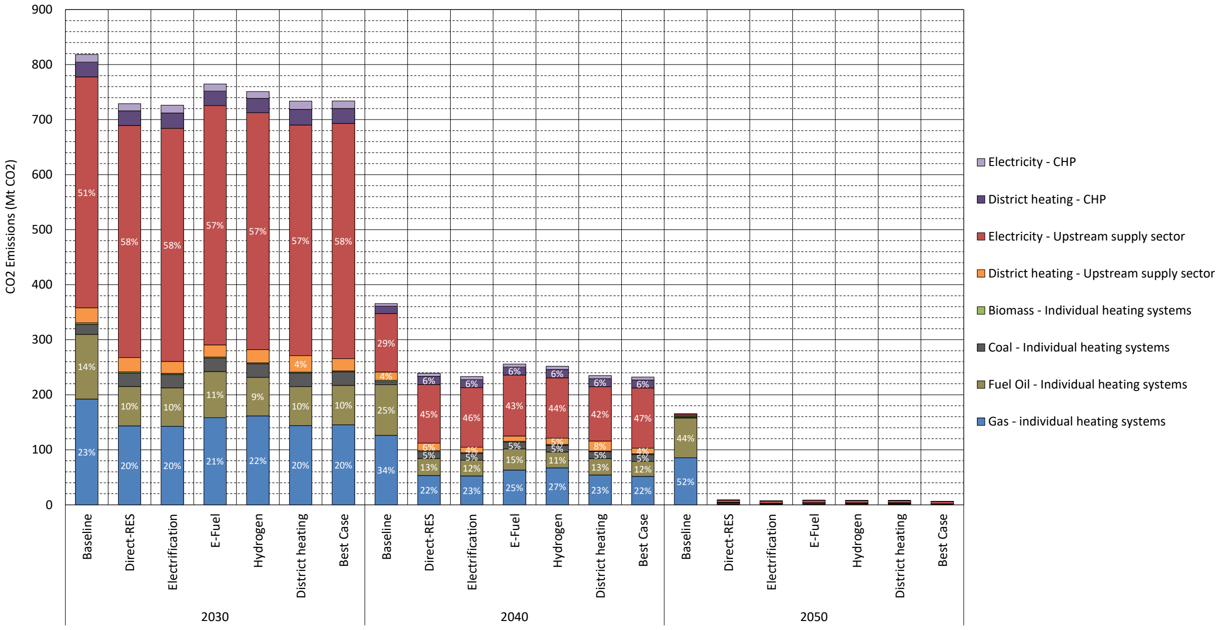


Figure 79: GHG-emissions, EU-27, 2030, 2040 and 2050 across scenarios (space and water heating and including GHG-emissions from the total upstream supply sector).

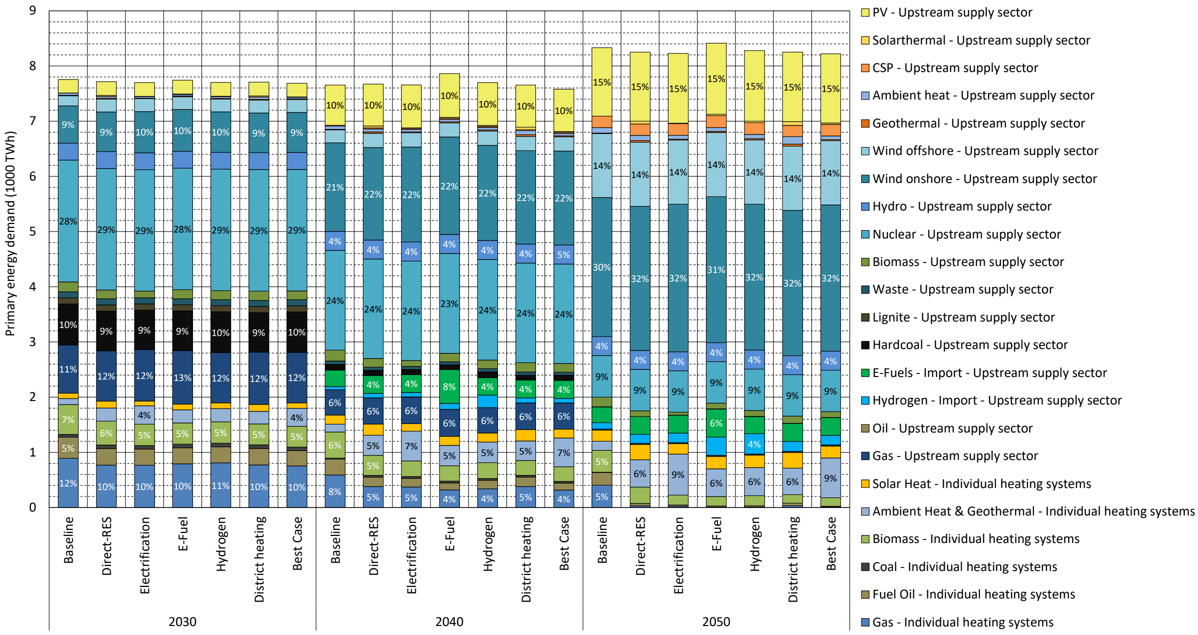


Figure 80: Primary energy demand, EU-27, 2030, 2040 and 2050 across scenarios (space and water heating and including primary energy demand from the total upstream supply sector).

Figure 81 shows the share of the primary energy demand which is actually delivered to the building for space and water heating, i.e. geothermal and ambient as well as solar heat being used on-site are subtracted from Figure 80.

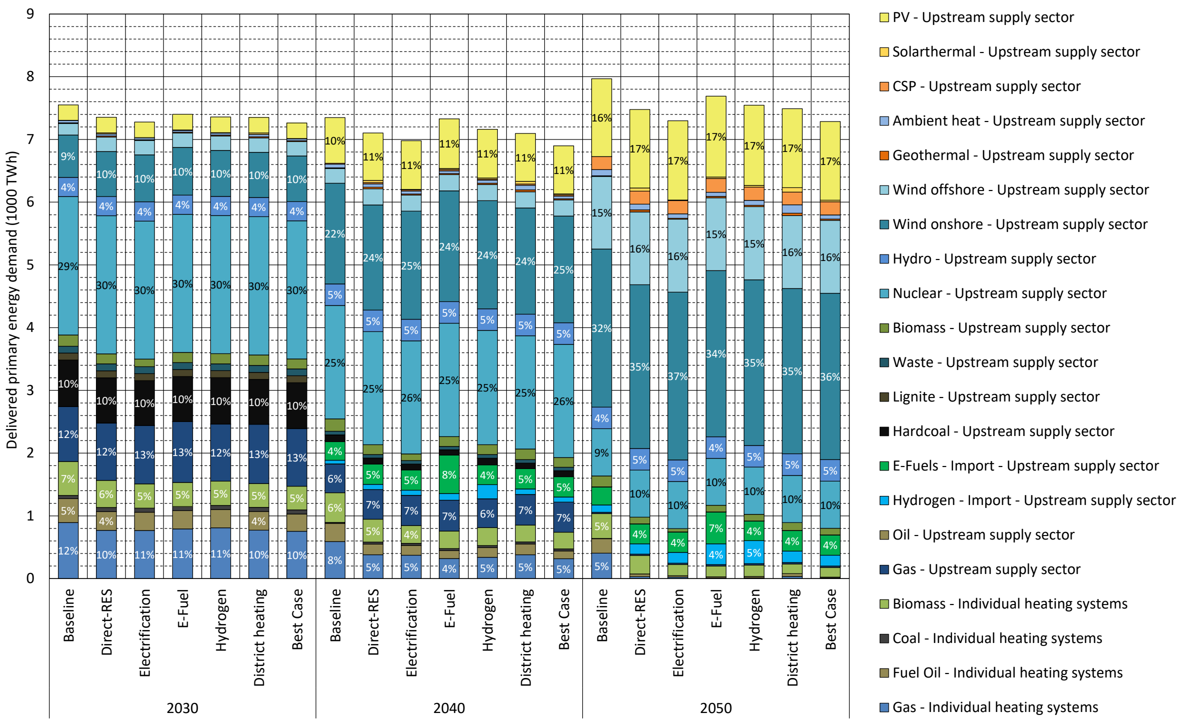


Figure 81: Delivered primary energy demand, EU-27, 2017, 2030 and 2050 across scenarios (space and water heating and including primary energy demand from the total upstream supply sector).

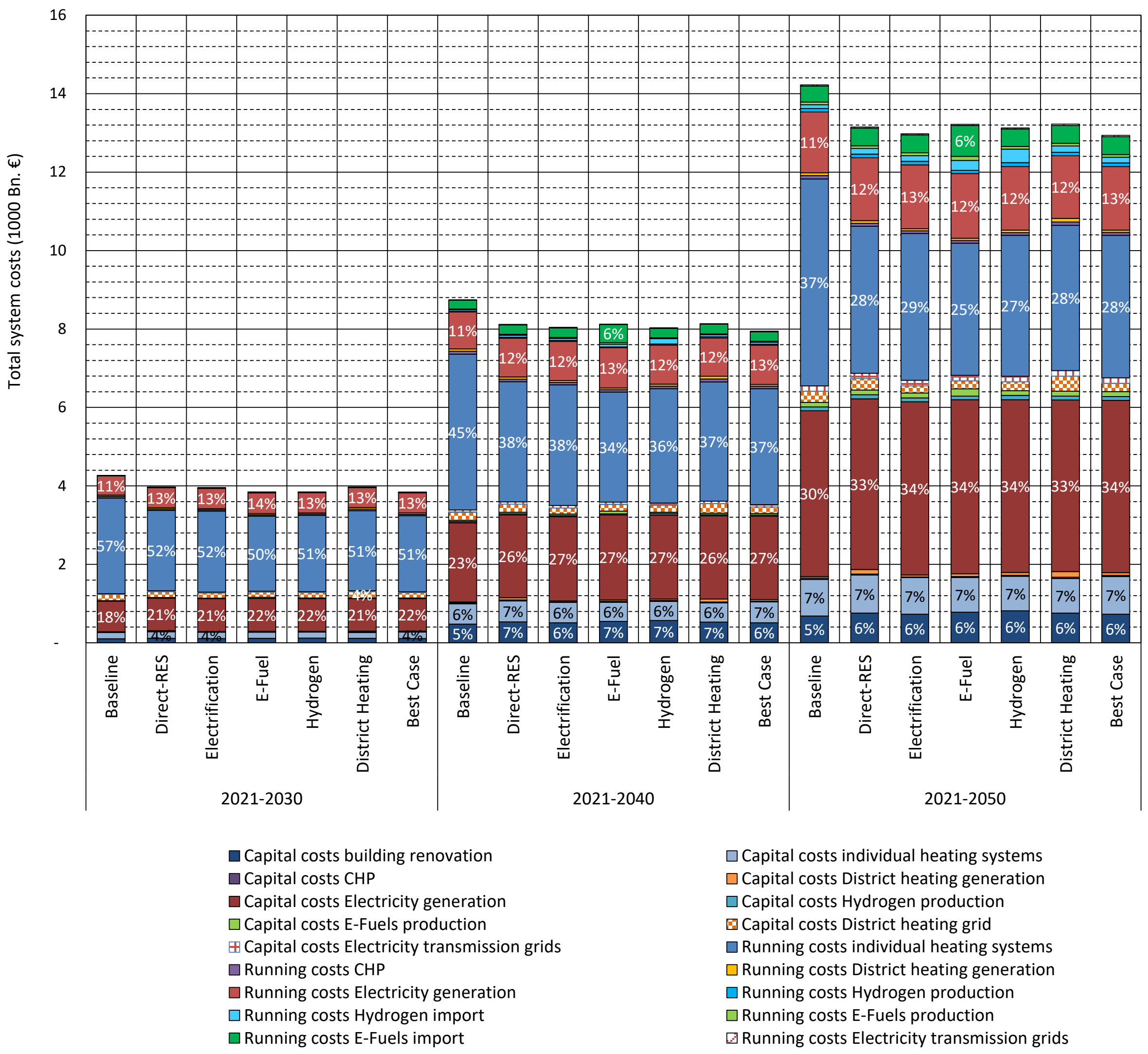


Figure 82: Total system costs, EU-27, cumulated 2021-2030, 2021-2040 and 2021-2050, space and water heating including total upstream supply sector.

7.6. Annex E: Additional information on renewable energy communities

Table 49: Overview of projects related to renewable energy communities.

Name and Link	Duration	Relation to Energy Communities	Countries/regions
Planheat	2016-2019	Tool for simulating and comparing alternative low carbon and economically sustainable scenarios for heating and cooling	Antwerp (**Belgium**), Velika Gorica (**Croatia**), Lecce (**Italy**)
Interreg COA-LESSCE	2017-2021	Aimed at promoting local renewable energy in various countries including Germany and Bulgaria	UK, Spain, Germany, Italy, Hungary, Romania, Bulgaria
Interreg POWERTY	2019-2023	Aimed at increasing the use of renewable energies in vulnerable groups and tackling "energy poverty"	UK, Spain, France, Poland, Lithuania, Bulgaria
RES H/C SPREAD	2014-2016	Aimed at developing six pilot regional plans for heating and cooling from renewable energy that could further support the planning efforts of other regions	Castilla y Leon (**Spain**), Emilia Romagna (**Italy**), Riga (**Latvia**), Rhodope (**Bulgaria**), Western Macedonia (**Greece**) and Salzburg (**Austria**)
REPLACE	2019-2022	Aims to inform and motivate end consumers to replace their old and inefficient HC appliances with better, environmentally-friendly alternatives by developing and testing locally adapted, tailor-made replacement campaigns	Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Germany, North Macedonia, Serbia, Slovenia, Spain
SocialRes	2019 - 2022	Aims to close non-technological research gaps regarding social innovation in the EU energy sector and foster the development of new cooperation patterns among the key enabling actors for energy democracy: cooperatives, energy aggregators and crowdfunding platforms.	Germany, France, Spain, Italy, Ireland, Portugal, UK, Croatia, Belgium
CoolHeating	2016-2018	Aims to support the implementation of "small modular renewable heating and cooling grids" for communities in South-Eastern Europe.	Austria, Denmark, Germany, Croatia, Slovenia, Macedonia, Serbia, Bosnia-Herzegovina
Community Power	2013-2016	Aims to speed up the development of renewable energy projects, inform and engage citizens, create opportunities for public-private finance of community renewables projects in Eastern European countries.	Czech Republic, Denmark, Spain, Hungary, Ireland, UK, Belgium, Germany, Bulgaria, Latvia, Poland, Slovakia
Key Issues for Renewable Heat in Europe (K4RES-H)	2005-2007	Analysed public policies supporting renewable heating and cooling (RES-H), identified best practice and developed concrete guidelines applicable at local, regional, national and European levels.	Belgium, Spain, Italy, Germany

Name and Link	Duration	Relation to Energy Communities	Countries/regions
Heating communities with renewable energy (RENEW HEAT)	2014-2020	Promoting utilization of renewable energy resources (heating with woody biomass) and energy efficiency	Croatia, Bosnia and Herzegovina
GENerating energy secure COMMunities through smart Renewable Hydrogen (GenComm)	2017-2020	Developing a sustainable, renewable community-scaled, hydrogen (H2)-based, energy model based on the results of 3 pilot plants that will use local renewable sources to supply electricity, heating and transportation fuels	Scotland, Germany, France, Luxembourg, France, Belgium, Ireland, England
Geothermal Energy for Rural Municipalities and Estates (GERME)	2007-2013	Develop a cross-border strategy for geothermal energy utilization in municipal heating systems of small rural municipalities and estates and provide know-how for key decision-makers and community activists	Latvia, Lithuania
Green Hit: Renewable energy for small localities	2007-2013	A showcase of using biofuel for district heating in small localities	Finland, Russia
Micro Combined Heat and Power System for Households (H-CHP)	2014-2020	Aims to promote the uptake of Combined Heating and Power systems (CHP) in the region using solid renewable biomass and gasification methods that will be appropriate for remote households	Sweden, Finland, Ireland, Scotland
Ground heat solution for the village hall and the school buildings of Vuokkiniemi	2007-2013	Drilling of 10 ground heat wells, installation of heat pumps, boilers and new radiator network in order to improve the welfare and quality of life of the inhabitants by geothermical, ground heating technology	Finland, Russia
REScoop MECISE	2015-2019	Aims to mobilise citizens and municipalities in the transition to a more sustainable and decentralised energy system	Belgium, Spain, UK, France
Bioenergy Villages (BioVill)	2016-2019	Aims to transfer and adapt experiences gained in countries where bioenergy villages already exists (Germany and Austria) to countries with less examples in this sector (Slovenia, Serbia, Croatia, Macedonia and Romania), by strengthening the role of locally produced biomass as a main contributor for energy supply on local level, considering opportunities of market uptake or expansion for local farmers, wood producers or SMEs.	Germany, Austria, Slovenia, Serbia, Croatia, Macedonia, Romania

7.7. Annex F: Renewable energy communities in the RED II

The data and information presented in Annex E was collected in the first half of the year 2020. Any developments after this timeframe are not part of the report.

7.7.1. Background and approach

RECs have a long tradition in various EU Member States and their potential role in the transition to a decarbonised energy system has been widely acknowledged. The revised RES-Directive[62] (RED II) recognizes the potential role of RECs in promoting the use of energy from renewable sources and includes various elements to support RECs.

While the term “renewable energy communities” is being used differently in various contexts, here we follow the definition provided in the RED II (see Table 50).

Table 50: Definition of renewable energy communities in the RED II. (European Parliament 2018).

‘renewable energy community’ means a legal entity:
(a) which, in accordance with the applicable national law, is based on **open and voluntary participation**, is **autonomous, and is effectively controlled by shareholders or members** that are **located in the proximity of the renewable energy projects** that are **owned and developed by that legal entity**;
(b) the shareholders or members of which are **natural persons, SMEs or local authorities, including municipalities**;
(c) the primary purpose of which is to provide **environmental, economic or social community benefits** for its shareholders or members or for the local areas where it operates, **rather than financial profits**;

Article 22 of the RED II is dedicated to RECs and establishes the requirements for Member States to support the development of RECs. In particular, Article 22 (1) outlines the requirement for Member States to ensure that final customers are entitled to participate in RECs. Article 22 (2) requires Member States to ensure that RECs have the right to engage in generating, storing, consuming (including self-consuming) and selling renewable energy and to access suitable markets individually or through aggregation. Furthermore, energy communities have the right to share energy. Article 22 (3) and (4) require EU Member States to carry out an assessment of the existing barriers and the potential for RECs and to provide an enabling framework that promotes and facilitates the development of RECs (See Table 51). Member States are required to report on the main elements of the framework and its implementation under the reporting obligations according to the Governance Regulation (EU) 2018/1999 (Article 22 (5)). Article 22 (6) addresses the cross-border participation and Article 22 (7) requires Member States to take into account specificities of RECs when designing support schemes.

In addition, RED II also foresees that relevant authorities help the development of RECs in their planning, regulations and administrative procedures, for examples as regards spatial and infrastructure planning[63].

[62] (EU) 2018/2001

[63] See Article 15(4) which states : 3. Member States shall ensure that their competent authorities at national, regional and local level include provisions for the integration and deployment of renewable energy, including for renewables self-consumption and renewable energy communities, and the use of unavoidable waste heat and cold when planning, including early spatial planning,

Table 51: Elements of the framework to promote and facilitate the development of RECs according to the RED II. (European Parliament 2018).

Member States shall provide an enabling framework to promote and facilitate the development of RECs. That framework shall ensure, inter alia, that:
(a) unjustified regulatory and administrative barriers to RECs are removed;
(b) RECs that supply energy or provide aggregation or other commercial energy services are subject to the provisions relevant for such activities;
(c) the relevant distribution system operator cooperates with RECs to facilitate energy transfers within RECs;
(d) RECs are subject to fair, proportionate and transparent procedures, including registration and licensing procedures, and cost-reflective network charges, as well as relevant charges, levies and taxes, ensuring that they contribute, in an adequate, fair and balanced way, to the overall cost sharing of the system in line with a transparent cost-benefit analysis of distributed energy sources developed by the national competent authorities;
(e) RECs are not subject to discriminatory treatment with regard to their activities, rights and obligations as final customers, producers, suppliers, distribution system operators, or as other market participants;
(f) the participation in the RECs is accessible to all consumers, including those in low-income or vulnerable households;
(g) tools to facilitate access to finance and information are available;
(h) regulatory and capacity-building support is provided to public authorities in enabling and setting up RECs, and in helping authorities to participate directly;
(i) rules to secure the equal and non-discriminatory treatment of consumers that participate in the REC are in place

designing, building and renovating urban infrastructure, industrial, commercial or residential areas and energy infrastructure, including electricity, district heating and cooling, natural gas and alternative fuel networks. Member States shall, in particular, encourage local and regional administrative bodies to include heating and cooling from renewable sources in the planning of city infrastructure where appropriate, and to consult the network operators to reflect the impact of energy efficiency and demand response programs as well as specific provisions on renewables self- consumption and renewable energy communities, on the infrastructure development plans of the operators.

The analysis follows the approach outlined in Figure 83:

- As a first step, a literature review is conducted with the aim of summarizing successful approaches, opportunities and challenges for RECs in the EU Member States.
- As a second step, based on the findings of the literature review, the regulatory framework and the barriers and drivers for RECs for heating are analysed for four focus countries.
- As a third step, stakeholder interviews are conducted to fill the remaining gaps from the previous steps and to derive recommendations on the regulatory framework of the key elements and pillars of RECs in the context of the transposition of the requirements of Article 22 of the RED II in the EU MS.

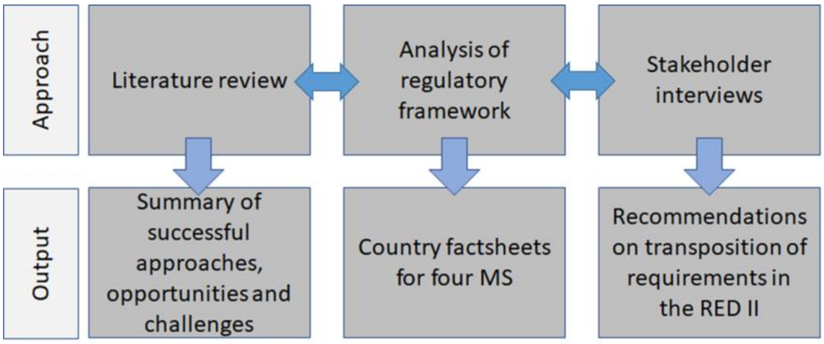


Figure 83: Methodological approach for Task 11.

7.7.2. Literature review

The aim of the review is to summarize the relevant aspects covered in the literature, with a focus on the main question of how the deployment of RECs for heating may be supported at the level of the EU and its Member States. A further aim is to provide a screening of the status of development of RECs in the EU Member States in order to select four focus countries for a detailed analysis.

Section 7.7.2.1 provides an overview of the data sources and the recent developments in the literature. Section 7.7.2.2 reviews the rationale and motivations for RECs. Section 7.7.2.3 discusses policy support measures and governance of RECs. Section 7.7.2.4 provides an overview of the development of RECs in selected EU MS or regions.

7.7.2.1. Overview and data sources

RECs have received a rapidly increasing interest in the past years, which is reflected in the growing number of scientific publications in the field, as well as the increased in EU funded projects related to RECs.

While most of the studies address RECs in the electricity sector, the heating sector is also increasingly covered. The review focuses mainly on RECs for heating, however where relevant studies covering the electricity sector have been included, e.g. to provide a general overview on the role of RECs also in countries where community energy is so far mainly limited to electricity.

The literature discusses RECs from a variety of perspectives, including their role in the transition to renewable energies, the various governance structures applied, technological considerations, and the role of social factors and acceptance.

7.7.2.2. Rationale and motivation for renewable energy communities

RECs are seen as “essential in Europe’s low carbon energy transition”, as they not only re-evaluate the role of consumers, but also reduce greenhouse gas emissions (Beggio and Kusch-Brandt 2015; Dóci and Vasileiadou 2015; Jenssen et al. 2014; Mlinarič et al. 2019). (Rydin et al. 2015) find that RECs contribute to the transition to clean energy not only through the generation of less energy from fossil fuels in contrast to more RE, but also through socio-cultural impacts, such as increasing the acceptance of RE sources and positively influencing people’s awareness of green energy. A case study of Italy, Portugal, Spain, Belgium, France and Denmark finds that introducing technical, financial and infrastructural energy efficiency measures to existing RECs results in energy usage reduction (Sifakis et al. 2019). In a survey covering Belgium and France, (Hoppe et al. 2019) find that self-reported energy-saving behaviour and actions are more common in members of RECs that non-members.

The motivations and engagement patterns of REC members and finds that these are greatly heterogeneous based on the level of institutionality within a REC, members’ geographical proximity in contrast to their bond by common interest, and their openness to experimenting with technological and institutional innovations (Bauwens 2016). Similarly, (Süsser et al. 2017) find a link between place and local entrepreneurship, and social acceptance of RECs. In the literature, the following factors for motivation to participate in a REC are named (Koirala et al. 2018; Dóci and Vasileiadou 2015; Balcombe et al. 2013):

- Concern for the environment; climate change awareness;
- Economic benefits such as saving or earning money; value increase of the home;
- Acceptance of renewable energy sources;
- Background knowledge of or interest in RE or the REC itself;
- Energy independence, security and self-sufficiency;
- Trust in the community or in the RE technology;
- A generally improved home environment.

Furthermore, support from different levels of governance, the aim for energy independence and, to some extent financial incentives are “crucial motivators” for the establishment of RECs (Bomberg and McEwen 2012). In addition, while local level governance and its initiating competences are important for increasing participation in RECs (Bauknecht et al. 2020), a “networked governance”, giving members of RECs the opportunity to make a difference at higher levels, i.e. national, international and global, could stimulate the willingness of people to participate (Tosun and Schoenefeld 2016). Trust or distrust in the national and local governments, in different institutional stakeholders and the community itself are also found to influence the success of RECs, albeit mistrust and distrust have been observed to push community energy projects forward, rather than jeopardize their existence (Lehtonen and Carlo 2019).

Social factors also affect the willingness of members to invest in the REC, as well as the size of their investment. For example, members who know someone within the cooperative and to a lesser extent people who identify themselves with the values of the community are inclined to financially contribute larger amounts to it (Bauwens 2019). Ultimately, the social factors which influence investment correlate to those, affecting acceptance and motivation for participation in RECs, mentioned previously. For instance, (Höfer and Rommel 2015) find that people with previous knowledge of cooperatives and environmental concerns invest more. Socio-demographic factors such as age, gender, level of education, income and wealth, duration of membership and personality traits also have an impact on financial contributions (Bauwens 2019; Höfer and Rommel 2015; Azarova et al. 2019).

(Rydin et al. 2015) assess the social impacts of an existing REC in the UK and find that similar projects can generally increase people's knowledge of the potential of RE, stimulate the further diffusion of RES and benefit the overall sustainability awareness of participants, as well as their energy consumption.

7.7.2.3. Policy support and governance

The literature outlines several means through which RECs are supported on a national level (Dóci et al. 2015; Meister et al. 2020; Creamer et al. 2018):

- State funding and financial incentives such as tax deduction schemes and subsidies;
- Intermediary and planning competences;
- Simplification of administrative procedures;
- Promotion of competition;
- Promotion of energy transition practices; general governmental interest in RECs;
- Feed-in tariffs, focused on creating long-lasting, economically viable RECs.

On the contrary, lack of supporting policies and incentives on a national level and governmental preference for distributed generation schemes have been stated as reasons for an insufficient energy transition progress and a meagre number of RECs in various countries (da Silva and Horlings 2020; Romero-Rubio and Andrés Díaz 2015; Fuentes González et al. 2019).

Support on a local level has an important impact on the development of RECs, and municipalities are seen as an important driver for energy decentralization (Creamer et al. 2018). The activities of most RECs are region-bound and consumer participation remains at a local level (Wierling et al. 2018). Various support factors of municipalities in regard to RECs are found in the literature (Creamer et al. 2018; Meister et al. 2020; Mey et al. 2016):

- Mobilizing inhabitants to create a REC;
- Creating legitimacy around a REC; encouraging acceptance of the project;
- Providing financial support and expertise;
- Providing land or facilities;
- Acting as shareholders, investors or buyers of energy;
- Networking and negotiating with various stakeholders;
- Expediting planning or administrative procedures.

(Eadson 2016) discusses the need for a "stronger network of intermediaries", such as organizations and universities for the deployment of RECs, given their support factors, which largely correlate to the ones of national and local governments (i.e. funding, raising awareness of RES, etc.).

Governance of renewable energy communities

In a case study of German community energy initiatives, (Brummer 2018) names three factors, which influence the internal governance of such projects – their generally small size, the contribution nature of their financing strategies, and the voluntary participation in their administration. The author observes multiple issues with small-scale RECs' governance in Germany, as instead of the rapid, expert judgement that business management often requires, RECs tend to loosen the grip on formal governance procedures and adjust them to their liking in order to avoid their tedious and strict conditions. These simplified governance methods include:

- Not hiring management, technology or finance experts, due to low finances;
- Engaging less qualified participants for complex decision-making tasks;
- Averting considerations of various options and "short-cutting" important discussions, due to time limitations;
- Counting votes inaccurately for convenience purposes;
- Neglecting possible repercussions when knowing "that nobody else is ready to take on the task", and thus jeopardizing democratic decision-making within the REC (Brummer 2018).

7.7.2.4. Renewable Energy Communities in selected EU MS

The literature review shows that the development of RECs as well as their coverage in the literature differs widely: While for some countries there is extensive literature covering RECs from a variety of perspectives, other countries play a minor role in the literature.

Renewable energy communities are predominant in Northern-Western European countries with high disposable incomes, as both purchasing power and an adequate social capital are necessary for investing in a community energy initiative (Caramizaru and Uihlein 2020).

The EU countries which receive most interest in the literature on RECs are Germany, England, the Netherlands, Scotland, Italy, Denmark and Spain, which reflects the fact that RECs have a long tradition in these countries and/or have recent legislations that are fostering their deployment.

The following subsections provide an overview of the findings on RECs in selected EU Member States.

Eastern European countries

(Capellán-Pérez et al. 2020) provide the first comprehensive assessment of the status of RECs in Eastern Europe, covering the following 16 countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Macedonia, Montenegro, Latvia, Lithuania, Poland, Romania, Serbia, Slovakia and Slovenia. The authors find that within this group of countries, Croatia is taking a leading role to RECs, however mainly focusing on electricity. Other countries with some small-scale level of deployment (also mainly for electricity) are the Czech Republic, Hungary, Poland, Slovakia and Slovenia, whereas for the remaining countries the authors state that no operational relevant projects were found.

While not focusing on RECs in particular, (Rutz et al. 2019) name the following barriers for renewable heating in South-Eastern Europe:

- Economically weaker than central Europe, lack of capital to cover the higher initial investment costs of clean and modern heating technologies.
- Subsidised low prices of fossil fuels and electricity.
- Limited political support.
- Low regulatory requirements (emission standards).

Southern European countries

The support for RECs has recently been addressed in legislative frameworks in various Southern European Member States, and a growth of RECs is being reported (e.g. Spain, Portugal, Italy, Greece). However, the RECs in these countries operate mainly in the electricity sector, presumably partly due to the fact that heating plays a lesser role in these countries. The following subsections summarize the findings for Spain and Italy.

Spain

RECs have recently grown in number as well as in size in Spain, following the introduction of a more favourable policy framework for renewable energies. (Heras-Saizarbitoria et al. 2018) identify a total of 12 RECs in Spain.

The Spanish government has recently initiated support measures for RECs, including a guide for the development of local energy communities (Guide for the Development of Instruments for the Promotion of Local Energy Communities | IDAE 2020), and the development of a funding line for RECs (Local Energy Communities 2020).

All RECs identified in (Heras-Saizarbitoria et al. 2018) focus on electricity generation, while no RECs for heating are known. Som Energia is the first and largest REC in Spain, which since its establishment in 2009, has attracted more than 42,000 members (Gancheva et al. 2018; Sifakis et al. 2019).

While currently RECs play a minor role in Spain, the literature highlights the potential for RECs in Spain. The governance structure of community energy projects, incorporating features of both a business and a civil movement, as well as RECs' ability to adapt to political changes, network with other cooperatives and increase the acceptance of renewable energy sources have all been stated as factors contributing to RECs' potential (Capellán-Pérez et al. 2018). The country's southern location, its large solar power potential (Perpiña Castillo et al. 2016) and renewable energy resources are also prerequisites for the development of RECs (Capellán-Pérez et al. 2018; Romero-Rubio and Andrés Díaz 2015). A study, encompassing 499 rural Spanish municipalities by (Soltero et al. 2018) shows that implementing biomass district heating systems could result in alleviation of energy poverty, stimulation of business and reduction of CO_2 emissions. RECs in Spain are considered well-founded substitutes to the current energy system for reaching the climate preservation goals of the country (Soeiro and Ferreira Dias 2020).

On the contrary, obstacles for the deployment of RECs in Spain, mentioned in the literature include (Capellán-Pérez et al. 2018; Romero-Rubio and Andrés Díaz 2015):

- Membership growth and territorial spread leading to a larger need for experts and know-how
- Minor presence in the Spanish energy system due to legal, economic, technical and cognitive barriers
- High financial risk
- Insufficient incentives for renewable electricity production
- Lack of financial resources among citizens
- Less sensitivity towards environmental issues.

Italy

A recent study of the Community Energy Sector in Italy identified 17 community energy projects in Italy, with a strong focus on the electricity sector (Candelise and Ruggieri 2020).

The study highlights financial support through feed-in tariffs as the main driver for the development of community energy, showing that most community energy projects were developed between 2008-2013, corresponding to the period of uncapped feed-in tariffs.

Regarding the legal structure, 60 % of the community energy projects in Italy are cooperatives, other approaches include limited companies and non-profit associations.

Italy has recently taken various steps towards supporting community energy and implementing the requirements of Article 22 of the RED II. The Italian Energy Strategy published in 2017 as well as the Italian National Energy and Climate Plan (NECP) mention energy communities. In 2018, the Piedmont region implemented the first legislative initiative explicitly dedicated to the Italian community energy sector ((Candelise and Ruggieri 2020). However, the recent legislative actions regarding energy communities are mainly focused on electricity.

Nordic countries

The Nordic countries have a long tradition of community energy for heating (cooperatives and municipality-owned DH, with Demark being the country with the highest share of community energy for heating among the EU MS. This section provides an overview of RECs for heating Sweden, while Denmark is covered in more detail in Section 7.7.3.1.

Sweden

In 2019, 140 Community Energy initiatives were active in Sweden, among which 78 are wind cooperatives, 32 eco-villages, 10 small-scale heating organizations and nine solar PV communities (Magnusson and Palm 2019).

Regarding the form of organization of the REC in Sweden, Figure 84 shows that the incorporated associations are the most common approach.

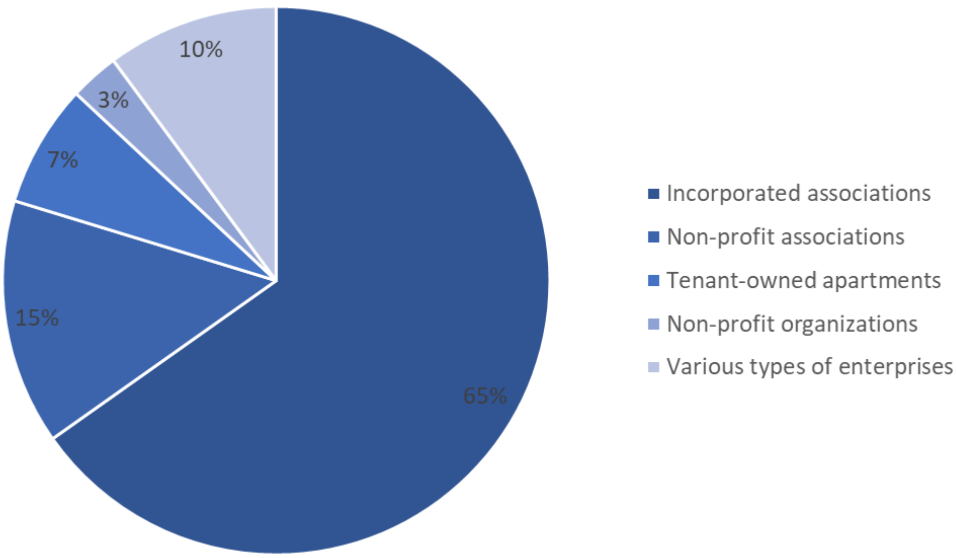


Figure 84: Organisational form of REC in Sweden. Source: Own development based on data in (Magnusson and Palm 2019).

For the heating sector, the following types of community energy projects are relevant:

- The **eco-villages** typically address social, ecological, and economic sustainability, often with innovative system solutions for energy efficiency, including the following examples: resource efficient and/or reused building material, energy efficient housing constructions, renewable energy production for heating and/or electricity (Magnusson and Palm 2019). Eco-villages are commonly small, ranging between a few households up to 50.

- **Small-scale heating systems** are typically located in small, rural villages and communities and operate small-scale district heating systems, with a central production plant and distribution of hot water. These are often organized as limited corporations, however besides financial incentives, important goals are local aspect of supplying the communities as well as stressing usage of local biomass (Magnusson and Palm 2019).

In addition to the citizen-driven energy communities named above, there are also district heating systems owned by municipalities. However, unlike Denmark, where pricing is regulated following the non-profit rule, in Sweden no such requirement applies. While in 1990 virtually all district heating systems were municipality-owned and the non-profit requirement of the Municipality Act applied, after the deregulation of the market in the mid 1990 many systems were acquired by non-municipality owners and heat prices increased considerably after the removal of the non-profit requirement (Werner 2017).

Drivers and barriers for RECs in Sweden

Citizens involved in developing RECs in Sweden report that the interest in taking action for the community and in renewable energy and sustainability are important motivators.

The capabilities and networking skills of the actors involved in the organization are key success factors, as the development of energy communities requires a variety of bureaucratic actions including grants applications, technical system configurations and standards.

Regarding institutional factors, main drivers are the support framework for renewable energies as well as the CO2-taxation, which was introduced in 1991. Furthermore, the long-term perspective of the legislative framework is highlighted as a driving factor (Magnusson and Palm 2019).

Western European countries

Several Western European Member States have a long tradition in REC, both for heating and electricity. This section provides an overview of RECs for heat in Belgium and France, while the detailed analysis for Germany, the Netherlands and Scotland are provided in Sections 7.7.3.2-7.7.3.4.

Belgium

Community energy is not a new concept in Belgium, where multiple energy cooperatives such as the 55,000-member Ecopower - one of the most successful cooperatives in Europe, as well as BeauVent, Coopem and EnerGent were established in the last 30 years. While these usually cover multiple municipalities and regions and thus their classification as “renewable energy communities” under Article 22 of the RED II is questionable, they still share a wide range of features with RECs. These include, amongst others, an open participation to all natural and legal persons, energy generation from renewable sources and financial investments in further RE projects (Hannoset et al. 2019). Generally, electricity from renewable energy sources and both connection and use of its grid is prioritized in Belgium (Anciaux 2019a).

A recent report identified 34 RECs in Belgium (Caramizaru and Uihlein 2020). Most community energy projects in Belgium are initiated by the Federation of groups and cooperatives of citizens for renewable energy in Belgium (REScoop.be). Those include Vlaanderen and Wallonie (both encompassing 16 cooperatives), which mainly produce electricity from wind energy, but also heat from biomass (REScoop.eu 2020).

Regulatory framework and support for renewable heat and RECs

Energy in Belgium is split into multiple levels of governance and for the private user is mainly a matter of regional competence. Based on the work of (Hannoset et al. 2019; Friends of the Earth Europe et al. 2018; Anciaux 2019a), the most important supporting frameworks for renewable heat and RECs in Belgium are:

Flanders

- Municipal support: the Belgian city of Ghent provides financial, technical and planning support for citizens who want to invest in energy efficiency and renewable energy;
- Quota system for renewable heating and cooling, provided by the Flemish municipalities and grid operators, responsible for arranging premium schemes;
- In 2018, various policies, dealing with certification of installers, RD&D and energy-efficiency were introduced by the Flemish government.

Wallonia

- The concept of "RECs" was introduced in a Decree by the government of the Wallonia region in April 2019. The legal concept and the framework of the Decree are almost identical to those of Article 22 of the RED II, although the Belgian law imposes a stricter geographical limitation to RECs, as consumers need to be in a "local perimeter" of the energy network, and as it deals with the electricity sector only. The law also presents the possibility for a tariff, based on the energy consumption of the community, which brings reduced charges;
- Support for the generation of renewable heat through energy subsidies, investment incentives and a zero-percent interest loan for users who wish to increase the energy efficiency of their home;
- The same incentives as in Flanders are present, as well as a building obligation for the use of renewable heating, which obliges certain new and existing buildings (based on floor area) to install thermal solar collectors or installations with a similar energy saving capacity.

Brussels

- The support scheme "Subsidy Primes énergie 2018" provides financial subsidies for residential buildings for the generation of heat from renewable sources.

France

According to the webpage of the French association for community energy (Énergie Partagée, Energy by citizens,for citizens 2020), currently 277 citizen energy projects are active or in development in France (status May 2020). While most of these projects operate in the area of electricity production (PV, wind and hydro), the webpage lists six projects involving biomass for heating and five projects related to methanization (three of which being currently under development).

The French Energy and Climate Law (law project relating to the energy and the climate 2019) introduces a framework for "Communauté d'Energie Renouvelable" (CER) or 'Renewable Energy Communities', however the focus is largely on self-consumption of renewable electricity (Peraudeau et al. 2019).

In the context of RECs for electricity, France introduced a citizen participation bonus in 2016 in line with Article 119 of the Energy Transition for Green Growth Act (LTECV) (Amazo et al. 2020) of 2015 as an incentive for project developers to involve community actors in the financing of RE projects.

7.7.3. Case studies: Overview of focus countries

Based on the findings described in the previous section, four countries have been selected for further analysis: Denmark, Germany, the Netherlands, Scotland. The rationale for the country selection is summarized in Figure 85.

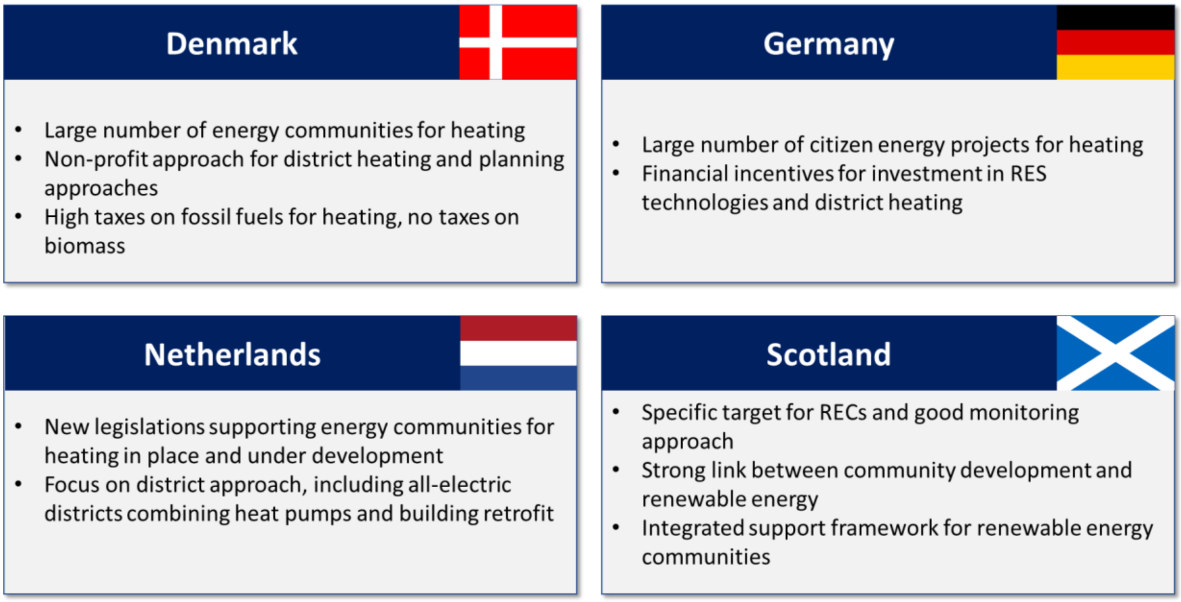


Figure 85: Overview of countries included in the case study analysis.

7.7.3.1. Denmark

Denmark has a long tradition of community-owned district heating. District heating covers about 65% of the space heating and hot water supply in Denmark. More than 60% is generated from renewable sources with an increasing tendency (State of Green, 2018). District heating cooperatives and municipality-owned district heating are the most common ownership models in Denmark.

Number and types of RECs

Number of RECs for heat

The Danish Utility Regulator (DUR) publishes information about the number of consumer co-operative- and municipal-owned district heating facilities. There are 388 citizen-owned district heating energy communities of which 47 are owned by municipalities and 341 by cooperatives (Gorroño-Albizu et al., 2019). Municipal district heating networks are usually located in bigger cities, whereas cooperatives rather operate heating networks in rural areas. Most district heating cooperatives can be considered RECs. However, heat for district heating is commonly generated by a mix of fossil and renewable heat sources and in some cases, primarily fossil fuels might be used, conflicting the requirement for (mostly) renewable heat sources. Furthermore, regarding the definition of RECs in the RED II, the Danish approach partially differs from the definition in cases where obligations for end-users to connect to the district heating network are in place.

Legal forms

In Denmark, if a municipality possesses administrative powers over the provision of a certain service such as water, waste or heating it must handle its activities through a separate company, typically organised as a Public Limited Liability Company (Aktieselskab – A/S), or a Private Limited Liability Company (Anpartsselskab – ApS)

In general, municipalities are responsible for heating and charge consumers for the connection to the district heating grid and the consumption. For this purpose, usually separate companies, in most cases Public or Private Liability Companies, are founded, that i.a. manage the municipality's heat supply. Historically, in rural areas, where the municipality did not manage the heating network, local cooperatives emerged. For cooperatives, the most common model is the cooperative limited company, which entails requirements like for example a general assembly of the stakeholders (Roberts et al. 2014).

Number of participants

The size of renewable energy communities managed by cooperatives can have different dimensions. There are small heat networks with 50-300 connected households and bigger cooperatives with hundreds or thousands of members. Membership in a cooperative usually does not automatically demand active engagement in the cooperative's affairs. Most cooperatives are practically managed by a small group of people, often with technical expertise.

Organisation and management

There are regular board meetings and assemblies managing the affairs of the cooperative. The members of the cooperatives can purchase shares of the local district heating association and be involved in decision making processes (Danish Energy Agency 2015). In the special case of district heating, there can be stricter rules like a limitation of membership to persons that are connected to the local grid. Important decisions are typically approved in the yearly meetings of the general assembly, while the general management activities are conducted by the management board.

Regulatory framework and support schemes

In Denmark, the approval of heating projects and the heating plans are the responsibility of the municipalities (heating supply law), which cooperate with utility companies and other stakeholders like cooperatives.

The City Council decides on heating planning and expansion of heating supply in the local area. In areas with heating through gas or district heating, there is an obligation to connect to the heating network and pay a connection fee to the heating supply company. For the approval of heating infrastructure projects, the factors of economic viability, reasonable consumer prices and socio-economic benefits have to be considered.

For district heating in Denmark, the non-profit principle applies (heating supply law), which makes sure that consumers only pay for defined 'necessary expenses'. Municipalities are not allowed to indirectly tax consumers, increase their income through heating supply services or give subsidies to the utility service users (Danish Energy Agency, 2015).

High taxation rates of fossil fuels and no taxation for biomass as heat source incentivizes district heating and makes it attractive also for cooperatives. There are no specific support programs for renewable heating cooperatives.

Combined heat and power (CHP) is connected tightly to district heating, as the resulting heat energy is often used in the district heating grid. CHP plants receive financial support, which also benefits district heating cooperatives in the end.

Technical support and guidance

Knowledge sharing is an important aspect for energy cooperatives that is supported in Denmark. The Danish District Heating Association (Dansk Fjernvarme[64]) offers seminars and training about production, management and legal questions regarding district heating. The interaction and exchange is particularly relevant for smaller cooperatives, where limited or no full-time professionals are involved in the management.

7.7.3.2. Germany

Germany has a long tradition in citizen participation in the energy transition, dating back to early 20th century electricity cooperatives (Holstenkamp 2018) (Yildiz et al. 2015). More than 6,000 cooperatives were established between 1895 and 1932 (Kitsikopoulos 2020) and around 40 of them continued their activities after World War II and until the liberalization of the German energy sector in 1998 (Yildiz et al. 2015). One of the first such cooperatives, EGR (Elektrizitäts-Genossenschaft Röthenbach) was founded in 1918 and is still active.

Number and types of RECs

Number of RECs for heat

As Germany does not provide statistical data on the number of renewable energy communities for heat, data from various databases were combined to estimate a total of approximately 291 renewable energy communities for heat, spread around the 16 German Federal states (Figure 86). Data was mainly drawn from official statistics at the federal level, where official information could not be found, the Netzwerk Energiewende Jetzt[65] database was used.

Figure 86 shows that RECs for heat are far more common in Western Germany than in Eastern Germany. (Yildiz et al. 2015) indicate that the lower disposable income and wealth in Eastern Germany are factors which specifically affect the development of renewable energy communities negatively.

[64] https://www.danskfjernvarme.dk/

[65] www.energiegenossenschaften-gruenden.de

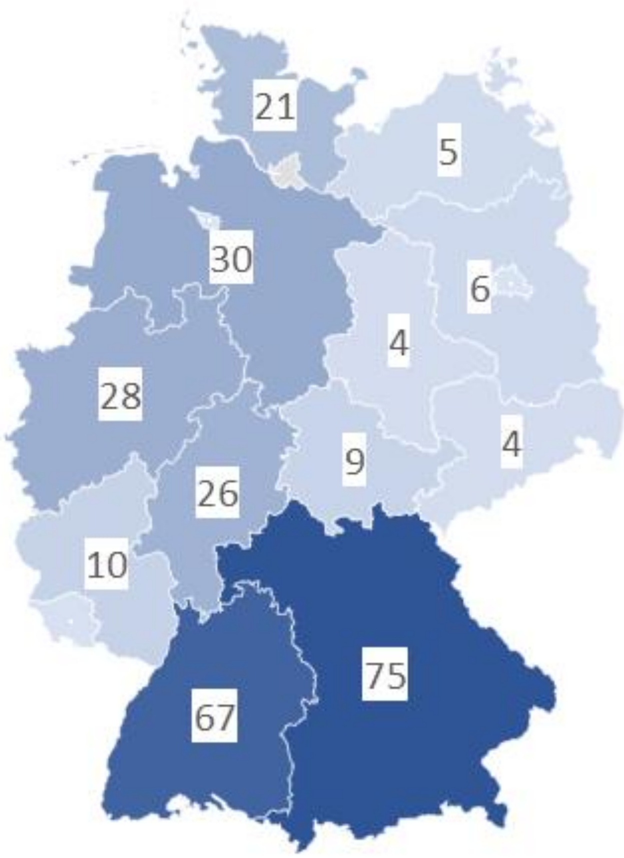


Figure 86: RECs for heat in the 16 German Federal States. Authors' depiction based on various databases.

Legal forms

The most commonly used terminologies for energy communities in Germany are Energiegenossenschaften (energy cooperations) and Bürgerenergiegesellschaften (citizen energy communities), which are often quoted as synonyms. However, (Kahla et al. 2017) distinguish between the two by the common function of energy communities as umbrella organizations for smaller citizen energy communities.

In Germany, only citizen energy communities are provided with a legislative definition. The Renewable Energy Sources Act of 2017 (EEG 2017)defines "Bürgerenergiegesellschaft" in §3 (See Box 1).

Box 1: Definition of citizen energy communities according to § 3 (15) of the German Renewable Energy Sources Act.

Citizen energy communities according to the EEG are communities,

- which consist of at least ten natural persons as voting members or voting shareholders,
- in which at least 51 percent of the voting rights are held by natural persons who have had their registered main place of residence in the urban district or county for at least one year before the bid is submitted, in which or where the wind turbine (s) is supposed to be erected according to the location information in the bid, and

- in which no member or shareholder holds more than ten percent of the voting rights.

RECs are found in various legal forms in Germany (Table 52). In present times, based on findings by (Kahla et al. 2017), the most common legal form for renewable energy communities is the GmbH & Co. KG, which has dominated since 2007.

Table 52: Legal forms of RECs in Germany. Own development based on IEA-RETD (2016).

Energy Cooperatives (eingetragene Genossenschaften – eG)	This legal form requires at least three members to exist and is mainly used for photovoltaics, wind farms, district heating and power networks. It allows for municipalities, citizens, and companies to co-participate and shares are usually purchased in order to become a member, or loans are provided to fund other RES initiatives. Each member has only one vote, regardless of purchased shares. There is an annual dividend for shares larger community energy projects.
Closed-end funds (Limited Liability Company & Company Limited Partnership - GmbH & Co. KG)	The closed-end funds are used for larger, more expensive projects, where multiple investors are involved, although only one or more people handle business matters full-time – investors and management are separated but often an advisory board connects them. This legal form is suitable for citizens who do not wish to be involved in the business matters of the REC.
Combination of cooperative and closed-end fund	The cooperative buys shares of the management or as an investor or buys out the management of a GmbH & Co. KG, becoming fully responsible for the management.
Civil-law partnership (Gesellschaft bürgerlichen Rechts -GbR or BGB-Gesellschaft)	This is a simple legal form, suitable for small renewable energy plants, for example photovoltaic systems. Shareholders (also acting as management) can be as few as two people, informal agreements are enough, and it is not mandatory for capital to be official. This legal form is risky, as “partners of the company have unlimited liability against their personal assets for all obligations of the GbR” (p. 3).
Shared ownership	Could be a joint ownership between public energy utilities and RECs, or a partnership between municipalities or other local authorities and RECs’ members.
Other legal forms in Germany	Mainly used for financial involvement in renewable energy initiatives – mainly based on profit participation rights or bonds.

In Germany, municipalities commonly engage in the supply, production and distribution of energy through the form of public or municipal utilities (Stadtwerke), whose activities are largely based upon regional (Bundesländer) Municipal Codes (Roberts et al. 2014), which determine the limits of their economic engagement. Stadtwerke are usually organised as limited liability companies (Gesellschaft mit beschränkter Haftung – GmbH), or public companies (Aktiengesellschaft – AG) to initiate renewable energy projects (Roberts et al. 2014). The Stadtwerke may be publicly owned or owned entirely or partially by a private company through shareholding structures. In the latter case, the Stadtwerke may contain a governance structure that allows local residents to be involved in decision making (Roberts et al. 2014).

Types of RECs for heat

Community energy projects in Germany commonly utilize technologies such as biogas plants, solid biomass, CHP woodchip boilers and to a lesser extent solar thermal installations.

Figure 87: Bioenergiedorf Jühnde. Source: www.genossenschaften.de

Bioenergy villages are an important embodiment of renewable energy communities in Germany, as during their short history, they have gained significant popularity around Germany and are now a well-known concept, which continues its expansion. (Brohmann et al. 2006) call bioenergy villages “the most radical conversion from conventional to renewable energy supply ever happened in Western Europe in the last five years”, in course of their examination of the so-called Jühnde model, named after the first-ever bioenergy village in Germany from 2006.

These community-led bottom-up initiatives cover at least 50% of their heat and electricity demand with locally produced biomass and if necessary other renewable energy sources (Fachagentur Nachwachsende Rohstoffe e. V.). This makes bioenergy villages a very important example of renewable energy communities for heat.

According to a database by the German Agency for Renewable Resources (FNR) there are currently 163 bioenergy villages in Germany, while 45 are on their way to becoming one. The process of creating a bioenergy village is different from that of creating a renewable energy community, since at least 50% of homeowners in the village must be willing to participate in order for the project to advance further. However, as in the case of renewable energy communities, bioenergy villages require a cooperative to be founded and put into a legal form before they can move on to the project’s implementation phase.

Typical size and number of participants

Most commonly, RECs in Germany have between 51 and 100 members, closely followed by those with 101 to 200 participants. 95% of shareholders in community energy are private persons, while 2% are enterprises, 2% are farmers and 1% are municipalities, institutions or churches (DGRV Genossenschaften 2018).

An analysis of 30 bioenergy villages, as presented in the FNR database[66], showed that on average there are approximately 89 households participating, which is a 64% participation rate in relation to the number of all village households. The bioenergy villages were researched alphabetically and selected according to the availability of data about the number of households in the area and the percentage of households connected to the grid.

German renewable energy communities have been found to be marked by a participation bias towards middle-aged men with high incomes (Yildiz et al. 2015; Radtke 2014), which may negatively impact general participation openness and/or willingness.

Organisation and management

There is no legally required minimum capital for the establishment of a renewable energy community. Each member holds one or more shares and the risk capital in the form of the shares and any additional agreed amount is determined during the start-up phase, so that there is no incalculable risk of membership (DGRV Genossenschaften 2018). According to the same report, a renewable energy community consists of three management parts – the general assembly, the supervisory board and the board of directors. The members of the supervisory board and the board of directors are themselves usually members of the cooperative. The general assembly chooses the supervisory board, while the supervisory board monitors and controls the activities of the board of directors. In communities with less than 20 members the supervisory board can be waived, and the executive board can consist of only one person. Figure 88 sums up the organization and management practices of renewable energy communities:

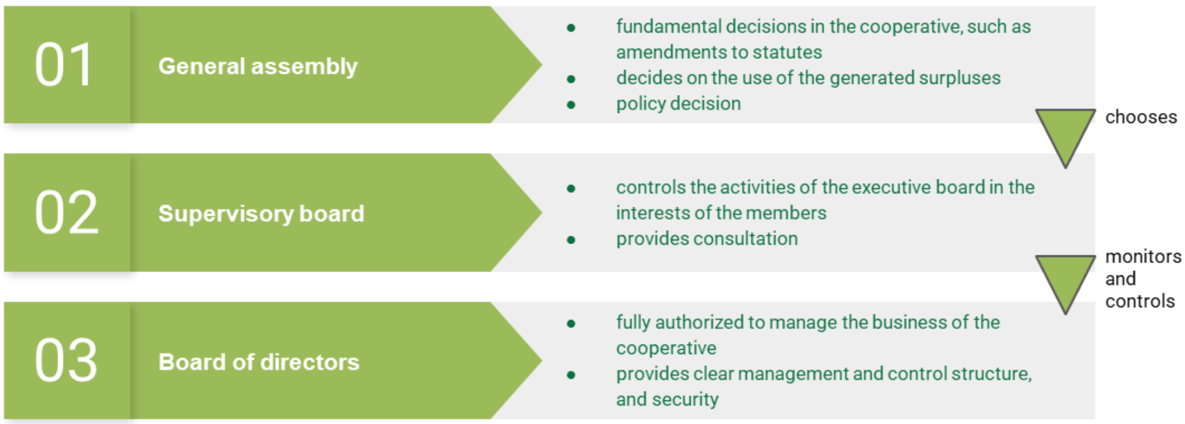


Figure 88: Organization and management of renewable energy communities. Own image based on (DGRV Genossenschaften 2018).

Heat cooperatives are usually financed with a mix of members' contributions and user connection charges, non-repayable public grants and long-term bank loans (Degenhart 2010). According to (Flieger et al. 2012) the most important means for funding community energy projects are the cooperative shares. One reason is that even though, additional financing

[66] https://bioenergiedorf.fnr.de/bioenergiedoerfer/liste/

measures are likely to be undertaken, a renewable energy community must be financially stable on the inside to avoid outside uncertainties. To provide more flexibility, the amount of equity is not legally determined but is rather shaped according to the needs and abilities of the community (DGRV Genossenschaften 2018). Shares in renewable heat communities usually cost between 200€ and 2.500€ with few exceptions (Degenhart 2010). The number of shares per member also varies, and there is sometimes a minimum or a maximum amount that has to be purchased – for example, members of the Honigsee[67] biogas community must buy at least 15 shares, while these of the Gussenstadt[68] renewable energy community can purchase no more than 100 shares. Personal liability is limited to the amount of the contribution (DGRV Genossenschaften 2018). In some cases, such as the Honigsee one, municipalities can also purchase non-voting shares, as this benefits not only the community's financial situation but also provides the municipality with a dynamic interest rate on its participation rights share. As stated in (Degenhart 2010), the Honigsee project was financed 15% through members' shares, 15% through the municipality, 30% through grants and 40% through federal loans.

An increasingly emerging means of supplementary financing is the subordinated loan from members to the cooperative, which in the event of bankruptcy stands behind all other liabilities and can only be reimbursed once they have been paid (Flieger et al. 2012). Subordinated loans have the advantage that they receive interest in the agreed amount from the start and earnings are therefore predictable, unlike the profit distributions on the cooperative shares.

Alternative methods for financing are profit sharing certificates, as well as the so-called investing members. However, as the latter expect a reasonable return of investment, their success as investors is questionable as long as cooperatives are not profit-oriented (Degenhart 2010).

Regulatory framework and support schemes

Renewable energy communities for heat are not specifically addressed by policy targets or support schemes, however, the various financial support programmes for renewable energies are open to the participation of RECS.

The final German NECP[69] from June 12 2020 provides limited details on the implementation of Article 22, stating that the regulatory framework for renewable energy communities provides support and advancement of the development of such communities through the following:

- just and non-discriminatory to end users,
- 87 existing funding schemes,
- special privileges in the tenders for funding onshore wind energy,
- in the event of an award, renewable energy communities receive funding not only on the basis of their own bid value, but on the basis of the value of the highest bid that has been awarded on the same bid date (uniform pricing).

Based on (Morris 2019; Sternkopf 2019) and (Roesler and Hassler 2019), the main financial support schemes for community energy in Germany include:

Table 53: Main financial support schemes for community energy in Germany. Own development based on Morris (2019), Sternkopf (2019) and Roesler and Hassler (2019).

[67]https://www.unendlich-viel-energie.de/media/file/34.AEE_DGRV_Energiegenossenschaften_2013_web.pdf

[68]https://www.eg-gussenstadt.de/wp-content/uploads/2019/08/energiegenossenschaft-gussenstadt-satzung-2013.pdf

[69] https://ec.europa.eu/energy/sites/ener/files/de_final_necp_main_de.pdf

Renewable Energy Sources Act (EEG)	Established in 2000, this support scheme provides fixed and guaranteed compensation for electricity produced by various renewable energies over a period of 20 years. The framework has had a strong influence on renewable heat, as it has increased the development of biogas plants, where 60% of energy is residual heat (Gaderer 2007; Gömann et al. 2013). The EEG's revisions in 2004, 2009 and 2012 added and increased a compensation for electricity fed into biogas grids, available to operators after verification of the use of a certain amount of residual heat. In the context of RECs, the EEG has also aided the development of bioenergy villages, located close to biogas plants.
KfW Renewable Energy Programme Premium	Private persons, freelancers, small and medium size enterprises, municipalities and local authorities, and non-profit organizations can apply for low-interest loans with grant payback support for the development and expansion of biogas, biomass, geothermal, solar thermal, aerothermal and hydrothermal heat installations.
Heat-and-power Cogeneration Act (KWKG)	This support scheme oversees the financing of old and new CHP plants and the development of their connected heating networks and provides grants for the construction of CHP plants up to 50 kW.
National Climate Protection Initiative (NKI)	An initiative, providing support and funding for renewable heat, efficiency and social issues (i.e. previously unemployed auditors advising low-income households on how to reduce energy consumption and assisting them in applying for funding), energy conservation and renewable energy in municipal buildings, appointing energy experts and mobility transition. From 2008 to 2018, the project funded more than 29,000 community energy projects through multiple plans and campaigns, providing pivotal support for local initiatives.
Market Incentive Program (MAP)	Provides subsidies for heat produced in existing buildings from solar, biomass and geothermal energy for private persons, freelancers, small and medium size enterprises, municipalities and local authorities, and non-profit organizations.
Energy Tax Act (EnergieStG)	Offers investment grants and tax alleviations for CHP plants with a monthly or annual efficiency of at least 70 percent.
BAFA – District Heat Grids 4.0	Provides subsidies for municipalities, cooperatives and associations for the development of low-temperature district heating grids with a renewable share of wind, solar, geothermal, biogas, hydropower or biomass energy higher than 50%.

Technical support and guidance

Procedural and technical guidelines about the establishment of renewable energy communities are found predominantly in publicly produced documents and texts. Such include brochures[70][71], reports[72], handbooks[73] and online databases of procedures and the documents, necessary for their actuation[74].

Moreover, there exist technical support schemes for renewable heat in Germany. Sternkopf (2019) names the Training programmes for installers (Training of Craftsmen), which provide craft training of installation mechanics for sanitation, heating and air conditioning systems. Through the Training courses for installers of small-scale RE systems in buildings (INSTALL+RES) of the European Commission, 163 professionals were trained for installing PV systems and 150 were trained for installing heat pumps, however there is yet for a national body for accreditation of these courses to be established in Germany.

Administrative procedures regarding permits for RE generators in Germany differ from state to state and accordingly to the size of the installation (Roberts et al. 2014). For example, automatic permitting where no application or approval is needed, is possible in the state of North Rhine-Westphalia for installations under 10 meters in height, located outside of residential areas (Roberts et al. 2014). Moreover, no permit is necessary for rooftop PV installations, mini CHP and heat pumps (Gancheva et al. 2018). According to Mignon and Rüdinger (2016, p. 482) due to the large numbers of RECs in Germany, “permitting procedures are highly standardized and without excessive delays”. The length and complexity of the permitting processes for connecting small-scale RE installations in Germany are comparable to other European countries such as the Netherlands and the UK (Vladimirov et al. 2018).

7.7.3.3. Netherlands

The first RECs in the Netherlands were established in the 1980s and focused on producing wind energy (Hufen and Koppenjan 2015). The development of RECs in the Netherland was influenced by the 1989 Electricity Act, which “gave grid access to the RECs, also guaranteeing a standard price”, the liberalization of the Dutch energy market from the late 1990s and early 2000s, the decline of natural gas reserves in the North Sea in 2017 and the Groningen earthquake from 2018, which saw a cutback in the production at the local gas field (Proka et al. 2018).

The National Climate Agreement of the Netherlands (*Klimaatakkoord*) from June 2019 dedicates one of its goals to “Cross-sector cohesion” and in particular to “Participation in the generation of renewable energy”, including that of local communities, or “autonomous energy cooperatives” (Klimaatakkoord 2019). According to the agreement, “In the context of participation by the local environment, a great deal of value is placed on local initiatives”, as a “balanced ownership division” planned for 2030 is sought through a 50% ownership of energy production in local communities, consisting of both citizens and businesses (Klimaatakkoord 2019).

Number and types of RECs

Number of RECs for heat

A total of 582 RECs were recorded in the Netherlands in 2019, where at least 54 of them were aimed at heating (hier opgewekt 2020). These numbers are actively and rapidly growing, as

[70] https://www.genossenschaften.de/brosch-re-wie-gr-nde-ich-eine-energiegenossenschaft

[71] https://www.energiegenossenschaften-gruenden.de/gruendungsbroschuere.html

[72] https://www.coopbund.coop/wp-content/uploads/2015/09/Praxisleitfaden_EGON-fin1.pdf

[73] https://www.kosa21.de/images/Leitfaden_EE/Handbuch_zur_Gruendung_einer_eG.pdf

[74] https://www.genossenschaftsverband.de/genossenschaft-gruenden/informationen-fuer-gruender/so-gruende-ich-eine-genossenschaft/

there were half as many RECs in 2015 – 248 in total (hier opgewekt 2020; van der Schoor and Scholtens 2015). As of 2019, 80% of Dutch RECs develop solar projects, 24% wind projects and an increasing number are involved in heat, mobility and other innovative initiatives.

Figure 89 shows the regional distribution of RECs for heat in the Netherlands, including local heat projects of which residents are the initiators or in which they are closely involved.

There are more renewable energy communities per inhabitant in rural areas then in urban areas, namely one cooperative for every 60,000 inhabitants in densely populated areas, against one cooperative on 10,000 inhabitants in sparsely populated areas.

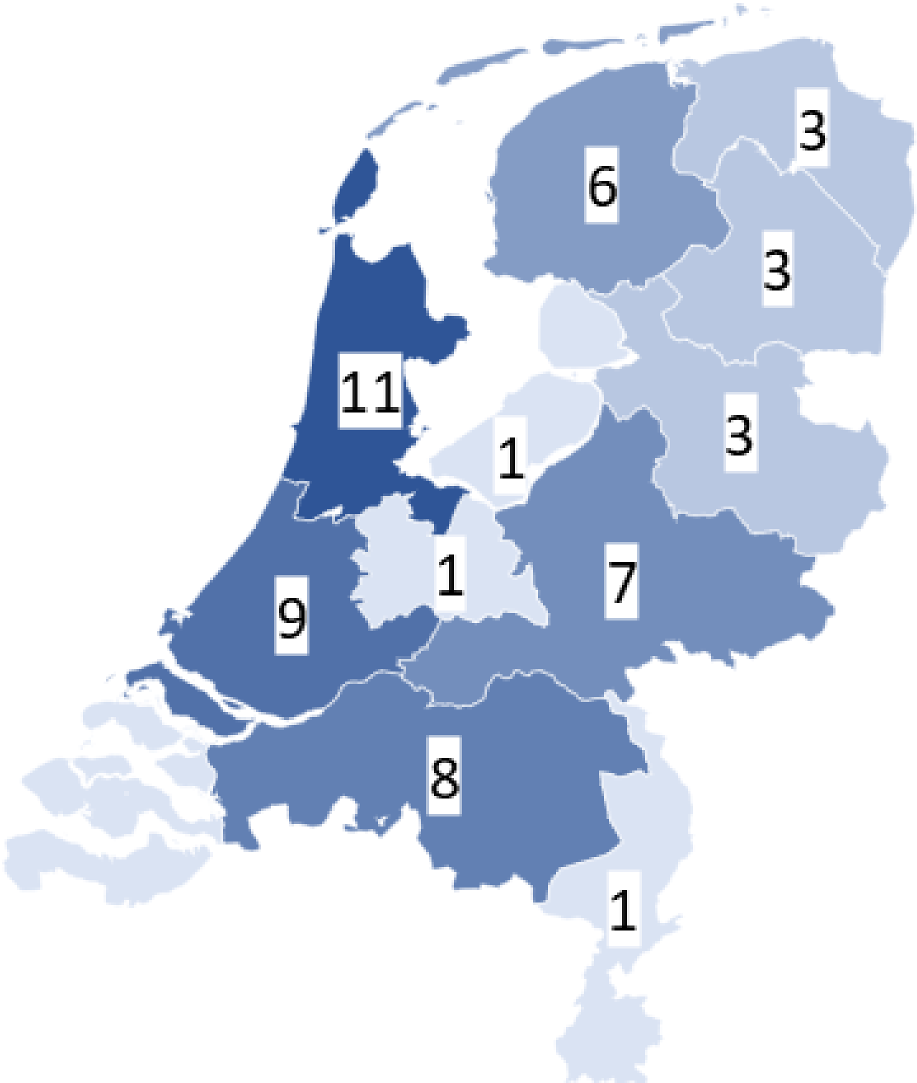


Figure 89: RECs for heat in the Netherlands. Authors' depiction based on the local energy monitor (hier opgewekt 2020).

Legal forms

The most common legal form of renewable energy communities in the Netherlands is the co-operative with limited liability, while others opt for a foundation or a limited liability company (Akerboom and van Tulder 2019). Projects often start as initiatives without a legal form and then develop into cooperatives.

Further legal forms, such as public ownership of energy facilities (governments as owners of utilities), or joint ownership of local authorities, businesses and residents' organizations are currently developing (hier opgewekt 2020).

While citizen energy plays a key role in energy communities, there is also a limited number of cooperatives of farmers, companies and municipalities.

Types

The most commonly chosen strategies for energy communities for heat in the Netherlands are based on district heating. The recently developed RECs under the gas-free district approach (see below) experiment with replacing natural gas with a variety of sources, including district heating using surface water, sewage and waste water, wood waste, heat from soil, from groundwater, as well as all-electric solutions.

Organisation and management

Due to the recent changes in the regulatory framework, RECs and municipalities are currently experimenting with organizational forms, cooperation mechanisms and management structures. Many of the recently developed RECs for heat have been established under the gas-free districts programme, which has the characteristic of experimenting with new organization forms. A detailed analysis of organization and management in RECs for heat in the Netherlands is therefore not possible at the current stage.

Regarding the financing of RECs, the 2019 *local energy monitor* highlights that the role of crowdfunding for recruiting members and obtain financing for RECs in the Netherlands and names several platforms specialized on energy projects (hier opgewekt 2020).

The National Climate Agreement of the Netherlands states that “pre-financing costs are a significant obstacle” for the development of community participation in RE generation (Klimaatakkoord 2019). According to the document, the possibility of “a scheme that would allow the funding for the studies and corresponding project support required for a successful permit application” for local energy initiatives will be examined, in which funding will be returned on completion of the project, thus creating a revolving fund.

Regulatory framework and support schemes

In the Climate Agreement, the Netherlands outline the district approach for decarbonizing heating. The “gas-free districts programme” (Netherlands Enterprise Agency 2020) aims to make 100 districts gas-free and scaling-up the experiences to more districts. The first lot of 27 test beds began in 2018, where each of which were provided with about € 4 Million from the Municipal Fund.

Furthermore, municipalities are required to develop heat visions, outlining a selection of districts and their transformation pathways towards gas-free districts.

A tendering scheme to support districts to become gas-free is in place and RECs are being involved in these test-beds.

Aside from these recent developments, some of the most important supporting frameworks for RECs and RECs for heating in the Netherlands are:

- The Dutch Government supports “green project” investors, utilizing geothermal or solar thermal energy, by granting them tax benefits, which enable banks to offer low-interest rate loans for such projects (Anciaux 2019b);

- Private persons and small businesses are provided with a subsidy for the purchase of solar thermal collects, heat pumps, biomass boilers and pellet stoves (Anciaux 2019b);
- Entrepreneurs, seeking to invest more than € 450 in aerothermal, hydrothermal, biogas, biomass, geothermal or solar thermal energy plants are eligible for a tax deduction scheme (Anciaux 2019b);
- A national energy transition measure, presented in the Coalition Agreement 'Confidence in the Future' of 2017 is to seize the previously mandatory connection to natural gas systems for heating in new buildings as of 2020 and to secure customers with a “a right to heating”, enabling them to connect to a power or a heat grid (Government of the Netherlands 2017);
- The Sustainable Energy Organization, which represents the majority of RECs in the Netherlands, is supporting 30 municipalities, five network operators, and 12 provinces in their aim to develop their REC network, with the help of civil society organizations and partner companies. The strategy includes an increase in the amount of energy production and a growth in the number of members to 1 million, with at least 200,000 customers switching to sustainable heat by 2025 (ODE Decentraal 2017);
- A fiscal incentive scheme, also called the postcode scheme, was introduced in the final version of the Netherlands’ NECP from November 2019. The scheme alleviates customers’ tax payments “on the share of the jointly generated renewable electricity” and aims to generally reduce procedural burdens (The Ministry of Economic Affairs and Climate Policy 11/2019).
- In many regions, the province supports the regional cooperation, including subsidy schemes for local energy initiatives and financial support for networking.

Technical support and guidance

The Heating Expertise Centre (ECW)[75] has been established to provide support to municipalities in developing heat visions for the transition of homes and buildings in districts and neighbourhoods. To this end, a guideline consisting of two parts has been developed and is publicly accessible: The Initial Analysis, made by the Netherlands Environmental Assessment Agency (PBL) and the guide for local analysis, prepared by the Expertise Centre for Heat (ECW).

In the Initial Analysis, the Netherlands Environmental Assessment Agency (PBL) calculates the costs for five decarbonisation strategies, where for each strategy two different options for efficiency improvements of buildings are considered. The five strategies covered are 1) Electric heat pumps, 2) District heating with medium to high temperature levels, 3) low-temperature district heating, 4) green gas, 5) hydrogen.

The website contains a viewer showing the results of the Initial Analysis in the form of maps. Furthermore, detailed for individual districts is provided on request.

[75] https://expertisecentrumwarmte.nl

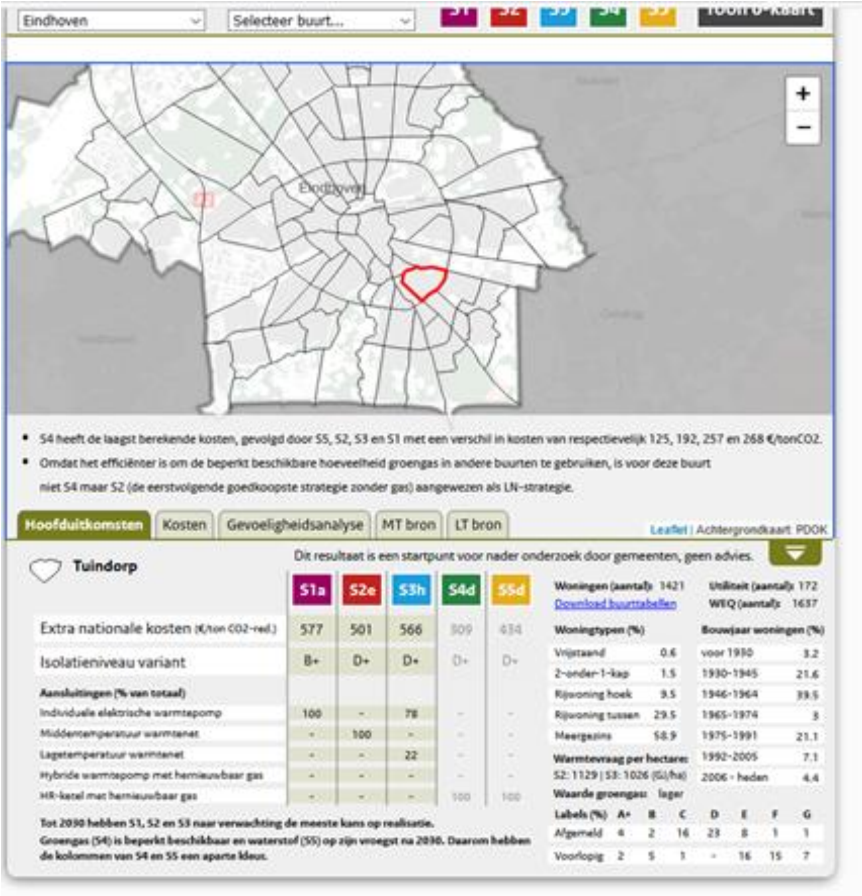


Figure 90: Exemplary result of the Initial Analysis provided on the ECW website. Source: ECW website[76]

The nationwide organizations HIER opgewekt and Energie Samen provide training courses and knowledge sessions, further support is provided by the provincial umbrella organisations. In addition, a number of commercial service providers are active (hier opgewekt 2020)

7.7.3.4. Scotland

Unlike other European countries such as Germany or Denmark, where community energy was already experiencing its boom in the 1980s, the first REC in Scotland – a wind turbine, was set up in 1982 (van Veelen 2017).

Number and types of RECs

Number of RECs

As of June 2019, 731 MW of community and locally owned renewable energy capacity was operational in Scotland, 264 MW (36%) of which thermal (heat) capacity and 37 MW (5%) combined heat and power (Grillanda and Khanal 2020a).

With respect to heating, the most relevant technologies operated in REC in Scotland are heat pumps (33% of installations and 8% of capacity), biomass (5% of installations and 26% of capacity) and solar thermal (15% of installations and 2% of capacity).

[76] https://themasites.pbl.nl/leidraad-warmte/2019/index.php

Scotland provides detailed information about the number and types of RECs, as well as examples of them in Scotland in the “Searchable map of local energy projects” toolkit of (Local Energy Scotland 2020b). Reports by the Energy Saving Trust on behalf of the Scottish Government also include data on RECs. Examples of such are (Usmani and Grillanda 2017) and (Grillanda and Khanal 2020b).

Legal forms

(CARES Toolkit 2015b) distinguishes between several legal forms of RECs in Scotland, as shown in Table 54:

Table 54: Legal form of RECs in Scotland. Source: (CARES Toolkit 2015b).

Legal form	Description
Bona fide cooperatives (Co-ops)	May not be a social enterprise, depending on their activities and how they distribute their profits; cannot be established as charities and they are set up to provide benefit to the cooperative members
The Community Benefit Society (Bencoms)	Run for the benefit of the community to provide services for people other than their members; investors who purchase shares receive a small return on their investments (normally between 2–5 %) in turn for the remainder of the dividends being kept for the benefit of the community
Community Interest Company (CICs)	A type of limited company for people wishing to establish businesses which trade with a social purpose (social enterprises), or to carry on other activities for the benefit of the community; a useful legal form for holding local assets, such as land or a community hall, ensuring they are used for the benefit of the community
Private Limited Company	An individual, or group, puts money into the company and in return, they obtain a percentage of ownership in the form of shares;
Private Companies Limited by guarantee (CLGs)	Has no shares and no shareholders, but rather members; The members are bound by a guarantee in the company’s articles of association which, if the company is wound up, requires them to pay the company’s debts up to a fixed sum, usually £1

Types of RECs

The Scottish Energy Strategy and Local Energy Scotland, managing the Community and Renewables Energy Scheme (CARES) programme, define RECs as “community- and locally-owned renewable energy projects”. According to (Grillanda and Khanal 2020b) these are defined as “technologies producing heat and/or electricity from a renewable source, where the owner of the installation is in one of the following categories:

- A community group
- A local Scottish business
- A farm or estate
- A local authority
- A housing association
- ‘Other public sector and charity’, including:

- Charities, including faith organisations
- Public bodies or publicly owned companies
- Further or higher education establishments such as universities and colleges
- Recipients of Scottish Community and Householder Renewables Initiative (SCHRI) grants under the community stream of that programme (but not recipients of grants under the householder stream)
- Recipients of Community and Renewable Energy Scheme (CARES) grants".

In this sense, a community group is defined as "communities of place, i.e. based around a sense of shared location. They often have charitable status. In some instances, the renewable technology and/or income from it may be owned by a trading subsidiary, which may be registered as a separate company" (Grillanda and Khanal 2020b).

(van Veelen 2017) distinguishes between five types of energy communities is Scotland (Table 55):

Table 55: Types of RECs in Scotland, based on Van Veelen (2017).

Type of REC	Description
"Small Is Beautiful"	small-scale community projects, led by volunteers, usually using solar energy and heat pumps
"Community Developers"	asset-owning or non-asset-owning groups, aiming to fund local development projects, which usually use wind or hydro technologies
"Innovators"	innovative projects, utilizing new technologies (smart grid and storage or wave and tidal energy) for energy generation and integration of local supply and demand
"Energy Cooperatives"	renewable energy projects, primarily motivated by environmental concerns and mainly utilizing wind energy
"Transition Towns"	primarily locally defined, urban environmental and sustainability groups

Wind energy is the most used one in Scotland for both community- and locally-owned projects. For heating, biomass is the predominant source, as 184 projects utilize it, while 73 use heat pumps and 13 – solar thermal energy (Local Energy Scotland 2020b) .Figure 91 represents the capacity of operational installations in 2017 by technology type.

For heat pumps, the most common ownership types are housing associations (around 53% of operational capacity), followed by local authorities (around 35% of operational capacity). For biomass, local authorities are the most relevant ownership category with around 34% of operational capacity, followed by the public sector and charity (21%) and local business (20%). For solar thermal installations, around half of the operational capacity falls into housing associations, followed by local authorities (43%).

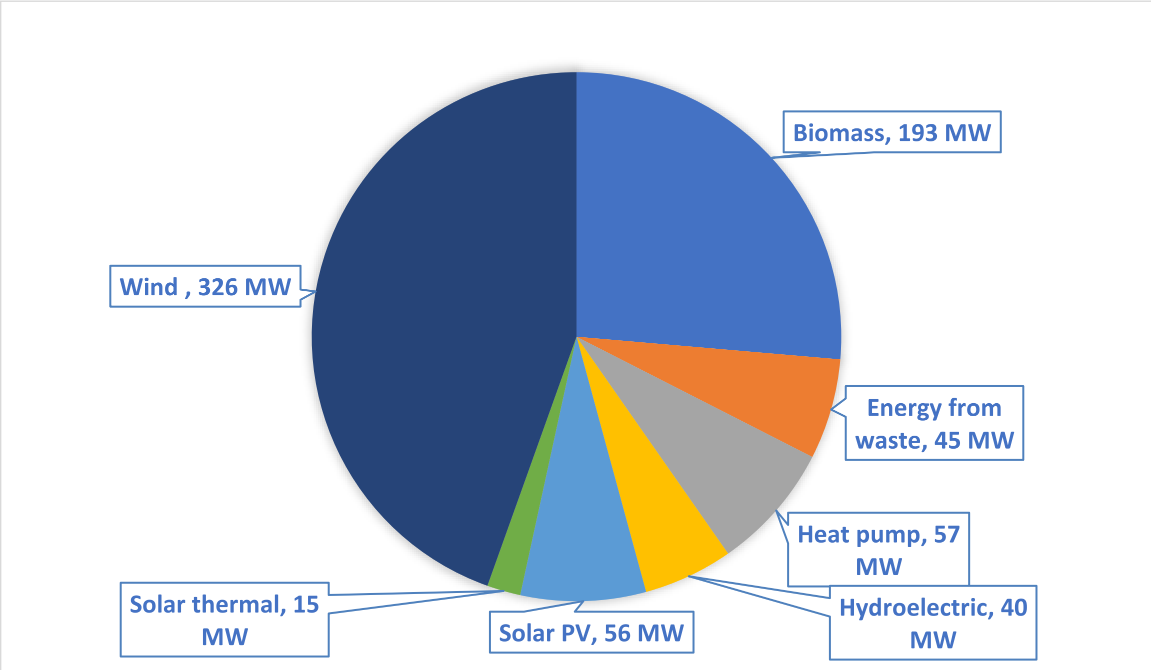


Figure 91: Capacity of operational installations by technology type. Source: (Grillanda and Khanal 2020b)

Organisation and management

RECs in Scotland comprise of a board or a leadership team, which includes trustees or directors, who are "accountable for the community group actions" and do not receive any payment, as well as members from the general public (CARES Toolkit 2015b). A community could also elect a chairperson, but this practice is not mandatory. The leadership team is responsible for overseeing various elements of the initiative such as providing aid with conflict resolution, keeping financial records and providing information about the REC to the public.

Support schemes

Scotland is one of the few countries in Europe, where community energy initiatives have become a standard through strong regulatory support from the government (Savaresi 2019). The regulatory framework is mainly built around the CARES Scheme, which was developed by the Scottish Government and which contains a legislative definition of RECs, their possible legal forms, technical guidance and information about their establishment and financial support for the public. The full scope of the CARES programme will be further discussed in the following text.

The Scottish Energy Strategy of 2017 introduces a 2030-target for heat, which supports the growth of renewable heat to 20% of non-electrical heat demand and the increase in the number of heat pumps and biomass, as well as district heating. To achieve this, the strategy is developing new Local Heat & Energy Efficiency Strategies (LHEES) and district heating regulations. The Scottish government has also committed to backing up the development of local energy efficiency and heat strategies, namely by "Providing the basis for public and private infrastructure investment in energy efficiency and heat decarbonisation, including district heating", as well as encouraging decarbonisation projects (Scottish Government 2017).

The strategy also aims for at least 50% of new renewable energy projects to have an element of shared ownership, as the Government considers shared ownership as the key to reaching the set targets of 1 GW of community and locally-owned energy by 2020 and 2 GW by 2030.

Table 56: Financial support for renewable energy.

Scheme	Description	Main focus
The Scottish Community & Householder Renewables Initiative (SCHRI)	Provides grants for domestic or community renewable energy projects	Community energy
Renewable Heat Incentive (RHI)	Individuals, communities and enterprises can apply for a guaranteed, long-term income for every kWh they produce from renewable heat technologies such as heat pumps and solar thermal water systems	Renewable energy
Clean Energy Cashback - Feed in Tariffs (FiTs)	Generation tariff from energy suppliers to householders and communities who generate their own electricity from renewables such as solar power	Renewable energy
Community and Renewable Energy Scheme (CARES)	(1) CARES Enablement Grant – "can be used to fund feasibility for energy systems or renewable energy projects, investigation of shared ownership opportunities or work to maximise the impact from community benefit association with renewable energy projects" (Community Councils 2018) (2) CARES Development Loan – directed at community energy initiatives "with a reasonable chance of success" (Community Councils 2018) (3) CARES Innovation Grant – grant funding for innovation or improving project development	Community energy
Home Energy Scotland Loan	Funding for household energy efficiency in the form of efficient heating and lighting and installing renewable energy measures.	Renewable energy
Renewable Energy Investment Fund (REIF)	Funding for projects, which operate in the areas of community owned renewables, and renewable district heating	Community energy
Scotland's Energy Efficiency Programme (SEEP)	Offers a range of financial mechanisms such as low-cost loans for households to install energy efficiency and low carbon heat measures, and loans for district heating projects	Renewable energy and energy efficiency

The Scottish Government's CARES programme provides a variety of services aimed at the development of community energy such as advice, support, mentoring and project guidance. The most important feature of the programme, however, is the wide range of financial support for RECs that it offers, and upon which Scotland's exemplary supporting factors for local energy initiatives are built. There are three types of funding available through CARES (Local Energy Scotland 2020a):

- CARES development funding - loans and/or grant funding of up to £150,000 for development risk mitigation
- CARES capital funding - loan or grant capital funding for "renewable energy measures like installation of solar PV panels, energy storage batteries, or for ancillary measures that support the installation of heat pumps"
- CARES enablement grant - up to £25,000 for non-capital aspects of a project, aimed at "start-up costs of feasibility studies, community consultations and other preparatory costs".

CARES provides not only funding, but also information about technology options, business planning, setting up an organisation, project development and a community benefits toolkit for RECs in its online database, called The CARES Toolkit. This online resource distinguishes between three stages of a local energy initiative's development and different means of financing for each stage (Table 57):

Table 57: Main kinds of financing for RECs by project stage. Source: (CARES Toolkit 2015a).

Stage	Financing
Project Development	- **Grant funding**: for example, CARES Start-up grant; - **Debt funding**: for example, CARES Pre-planning loan; - **Equity** provided by project owners
Project Construction	- **Debt**: CARES Renewable Energy Investment Fund (REIF) or Bank Loans; - **Equity** provided by project owners: for example, through a community share offer
Project Operation	- **Revenue** from the project should be sufficient to cover operating costs and loan repayments

Technical support and guidance

Community Energy Scotland provides practical help for RECs in the form of advice and support for skills development, grant and loan provision, energy generation, awareness increase, education and knowledge, training and networking. The webpage of (Local Energy Scotland 2020b) offers a free downloadable guide for the process of developing a renewable energy project called The CARES Toolkit.

Co-operative Development Scotland (CDS) supports co-operative business models by raising awareness about such models in the media and providing general and legal advice, as well as support for the development of community initiatives through classes. The program is not solely focused on community energy, however, as "community co-operatives" can be anything from wind turbines and hydro energy sources to shops and pubs (Scottish Enterprise 2020).

Advice is also offered by the Scottish Government as part of the Scotland's Energy Efficiency Programme (SEEP) and the Scottish Energy Strategy. In 2014, the national Community Energy Policy Statement was issued by the Scottish Government for public consultation. It provides information about RECs and the future of CE in Scotland.

The CARES programme provides multiple detailed reports about how the different development stages of a REC should be carried out. Its database significantly contributes to the knowledge and expertise needed for the creation of a REC, as it includes how-to reports on the technical, business, project- and community management topics surrounding community energy initiatives. The programme also provides (based on (Local Energy Scotland 2020a)):

- "Free, expert and impartial advice from our Local Development Officers
- Free online toolkits and project guides to help you identify what might work for you
- Mobilisation support for capital projects – design review, costs and procurement support
- Ongoing support with project development and delivery
- Mentoring and community online discussion in our Facebook group"

7.7.4. Synthesis and policy recommendations

From the analysis presented in the previous sections, the following recommendations are derived.

- **Dedicated policy targets** for RECs have proven to support the development of RECs. In Scotland, an integrated policy framework based on specific targets for the deployment of RECs provide guidance and support for the deployment of RECs.
- **Financial support for investments** is an important driver for the creation of renewable energy communities for heating. In view of the considerable investment costs related district heating, support schemes for infrastructure investments and investments in RES-technologies are crucial for the economic feasibility of RECs. Financial support schemes may be directed specifically at RECs (such as the CARES scheme in Scotland) or may be open to any entities including RECs (e.g. support schemes by KfW and BAFA in Germany). In the latter case, it is essential that the funding guidelines include RECs as admissible beneficiaries.
- **Support schemes for feasibility studies** are an important element of the financial support framework.
- **Technical support and guidance** is needed at all levels. Information needs to be easily accessible and ideally linked to further support measures.
- **Municipal planning** is a strong enabler for RECs for heating, as shown in the Danish case study as well as the recent experiences from the Netherlands. When introducing municipal planning regulations, it is essential to consider the cooperation between municipalities and citizens to facilitate the successful creation of renewable energy communities.
- **Regulatory framework for district heating**, including pricing regulations and non-profit requirements are a driver for RECs.
- **Pricing structure of fossil fuels and renewable alternatives** are important drivers, as the business case for renewable heating communities becomes more feasible where decentralized fossil-based solutions are less profitable due to high prices of fossil fuels.
- **Monitoring of progress and lessons learned** to further support the development.

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