Heat Roadmap Europe 4

Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps

Paardekooper, Susana; Lund, Rasmus Søgaard; Mathiesen, Brian Vad; Chang, Miguel; Petersen, Uni Reinert; Grundahl, Lars; David, Andrei; Dahlbæk, Jonas; Kapetanakis, Ioannis Aristeidis; Lund, Henrik; Bertelsen, Nis; Hansen, Kenneth; Drysdale, David William; Persson, Urban

Heat Roadmap Europe

Quantifying the Impact of Low-carbon Heating and Cooling Roadmaps

Deliverable 6.4

Project Number:	695989
Project acronym:	HRE
Project title:	Heat Roadmap Europe: Building the knowledge, skills, and capacity required to enable new policies and encourage new investments in the heating and cooling sector.
Contract type:	H2020-EE-2015-3-MarketUptake

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 695989.

Deliverable number:	D6.4
Deliverable title:	A final report presenting the heating and cooling scenarios, including a description about how these results can be used by lead-users
Work package:	WP6
Due date of deliverable:	31 August 2018
Actual submission date:	31 August 2018 – revision submitted on 05 October 2018
Start date of project:	01/03/2016
Duration:	36 months
Author(s)/editor(s):	Susana Paardekooper, Aalborg University Rasmus Lund, Aalborg University Brian Vad Mathiesen, Aalborg University Miguel Chang, Aalborg University Uni Reinert Petersen, Aalborg University Lars Grundahl, Aalborg University Andrei David, Aalborg University Jonas Dahlbæk, Aalborg University John Kapetanakis, Aalborg University Henrik Lund, Aalborg University Nis Bertelsen, Aalborg University Kenneth Hansen, Aalborg University David Drysdale, Aalborg University Urban Persson, Halmstad University
Reviewer(s):	Ulrich Reiter, TEP Energy Carsten Rothballer and George Stiff, ICLEI
Project Coordinator	Brian Vad Mathiesen, Aalborg University

Dissemination Level of this Deliverable:	PU
Public	*PU*
Confidential, only for members of the consortium (including the Commission Services)	*C0*

Contact: Department of Planning,
Aalborg University
A.C. Meyers Vænge 15,
Copenhagen, 2450
Denmark

E-mail: info@heatroadmap.eu
Heat Roadmap Europe website: www.heatroadmap.eu

Deliverable No. D 6.4: Public Report

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 695989. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the funding authorities. The funding authorities are not responsible for any use that may be made of the information contained therein.

Table of Contents

List of Figures

List of Tables

Nomenclature

Scenarios

BL 2015 / BL 2050	Baseline Scenario for 2015 / Baseline Scenario for 2050
CD 2050	Conventionally Decarbonised Scenario
HRE 2050	Heat Roadmap Scenario for 2050

Country Codes

EU	European Union
HRE4 Countries	Listed below; the 14 largest EU member states in terms of heat demand, totalling 90% of the EU heat demand.
AT	Austria
BE	Belgium
CZ	Czech Republic
DE	Germany
ES	Spain
FI	Finland
FR	France
HU	Hungary
IT	Italy
NL	Netherlands
PL	Poland
RO	Romania
SE	Sweden
UK	United Kingdom

Abbreviations

CCS	Carbon Capture Storage
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
HP	Heat pump
HRE	Heat Roadmap Europe project series starting in 2012
HRE4	Heat Roadmap Europe 4 (H2020-EE-2015-3-MarketUptake)
MS	Member States (of the European Union)
PES	Primary energy supply: all energy that is used, before conversion, as input to supply the energy system
PV	Photovoltaic
RES	Renewable energy sources

Executive Summary

The aim of Heat Roadmap Europe (HRE) is to create the scientific evidence required to effectively support the decarbonisation of the heating and cooling sector in Europe and democratise the debate about the sector. This HRE project is the 4th in a series of analyses that combines local (geographic) data with knowledge on energy savings and detailed all sector hour-by-hour energy system analysis. The project covers 90% of the European heat market by modelling 14 countries and their energy systems individually, allowing for an insight towards the overall European perspective.

Together, heating and cooling represent the largest energy sector today, but by redesigning the energy systems in Europe using only proven and market available technologies, it is possible to combine end-use savings with heat pumps and district heating and cooling using excess heat, efficiency and renewable sources to stay within the 1,5 - 2°C global temperature change threshold. To decarbonise and reduce energy system costs, fossil fuel consumption is replaced with energy efficiency and renewable energy. This has the potential to significantly improve the balance of payments compared to today and create more jobs in Europe when increasing expenditures on local energy efficiency and use of local resources [1]. It also creates a heat supply which more resilient to fuel price fluctuations, as more expenses are tied to investments. The scenario development in HRE makes it evident that by 2050:

- CO_2 emissions can be reduced by 4.340 Mton or 86% compared to 1990 using only known technology in the heating and cooling sector. This is in line with the Paris Agreement and approaches a nearly zero carbon energy system.
- By redesigning the heating and cooling sector the total costs of decarbonisation can be reduced by 6% annually compared to conventional methods of decarbonisation. In all future scenarios less financial resources are spent on fuels and more on investments.
- The use of fossil fuels in HRE can be reduced by almost 10.400 TWh in 2050 compared to the 2015 reference. This also influences the amount of investments needed and balance of payments. HRE would heavily reduce the need for natural gas imports. The amount of natural gas decreases in HRE 2050 by about 87% compared to the 2015 reference, the remainder only being used in industry and flexible combined heat and power. In 2016 54% of the energy consumption was met by imports, 88% of oil was imported and 70% of the consumed natural gas was imported [2]. The imported natural gas had a value of €50-65 billion in 2016.
- Natural gas and inefficient electric heating in buildings can be phased out. Such solutions can be replaced by a combination of refurbishment and end use savings, individual heat pumps and district heating using excess heat and heat from renewable sources. Since renewable energy covers 87% of the total primary energy supply in HRE, and the remaining fossil fuels are primarily in transport,

industry, and flexible combined heat and power, almost all of the heating and cooling demands is covered sustainably.
- The solutions proposed are in line with the Smart Energy System approach enabling a conversion towards 100% renewable energy [3].

Based on the data, knowledge, methodologies, and scenarios developed and made available by the HRE project, it is clear that the European Union should focus on implementing change and enabling markets for existing technologies and infrastructures in order to take advantage of the benefits of energy efficiency in a broader sense and for the heating and cooling sector specifically. Typically, decarbonisation of the energy system is done using only electrification and some degree of refurbishment.

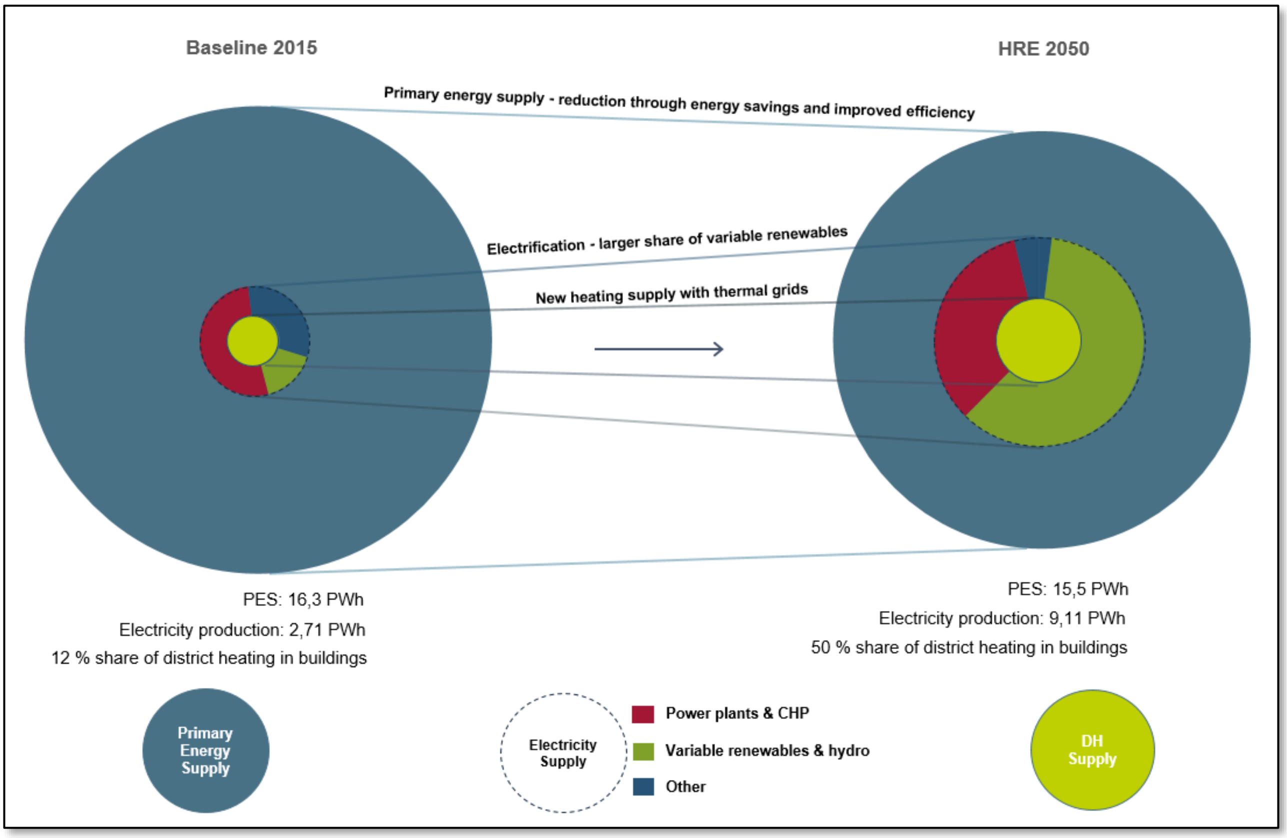


Figure 1. Illustration of the energy system changes implemented in the Heat Roadmap Europe Scenarios towards 2050 with regards to primary energy supply (PES), electrification and new thermal grids.

In the HRE scenarios, reductions in the primary energy supply are created by combining several energy efficiency components in the form of further end-use savings, district heating and cooling grids and use of excess heat (for urban areas). This is combined with electrification using heat pumps (at an individual building scale in rural areas, and in the form of large-scale heat pumps in district heating and cooling grids). Like in other decarbonisation scenarios, further electrification of the energy system happens in the form of electric vehicles and the production of green gasses using hydrogen and carbon sources. The combination of electrification, thermal grids and energy savings has benefits across the energy system and for the integration of renewable energy capacities (Figure 1).

On the country level, action and implementation plans should include and develop adjustment efforts in order to consider approaches to 1) energy savings, 2) thermal infrastructure expansion, 3) strategic location and availability of excess heat utilisation and heat production units, and 4) individual heat pumps outside urban areas. These are the main technologies that contribute to the efficiency, decarbonisation, and affordability of the heating and cooling sector.

End use savings in delivered energy are vital to efficiency, decarbonisation and affordability. This is particularly true for space heating in existing buildings, where higher renovation rates and depths are needed. With the current policies and targets, a 25% reduction in total delivered energy can be reached in 2050, also considering an increased amount of buildings. This represents an annual refurbishment rate between 0,7% and 1,0% towards 2050, and implies that all policies are fully implemented. In HRE it is recommended to increase the target to at least 30% savings for space heating in buildings. This requires a higher refurbishment rate of 1,5% to 2%, and deeper renovations when they occur [4]. In order to achieve both the current ambitions for savings and the levels recommended in HRE, a very strong focus should be put on implementation on country and/or regional level regarding the effectiveness of policies and implementation strategies, in order to ensure the EU and country level energy savings goals are met.

The **expansion of thermal grids** is crucial to redesign the energy system and enable better integration of renewable energy and excess heat sources. District heating can cost-effectively provide at least half of the heating demand in 2050 in the 14 HRE countries, expanded from about 12% of the heating market today in the 14 countries or 90% of the EU heat markets covered here. While there are differences from country to country going beyond half towards 70% of the heat market in the 14 countries as a whole can provide additional energy efficiency and strategic benefits. This requires thermal grids to be recognised as an important infrastructure in the Energy Union as well as targeted EU level and country level policies that enable city or regional development of and financing of district heating infrastructure.

Excess heat recovery from industry and heat from power production is key to an efficient and resilient heating and cooling sector, and has the potential to support local industries, economies, and employment. These sources could cover at least 25% of the district heat production considering their location. This requires a concerted change in planning practices to ensure that they are within geographic range and fairly distributed among different potential district heating areas and cities. This is the case for local industries, waste-to-energy facilities, future bio-, green gas or electro fuel production sites, and potentially also data centres, sewage treatment facilities and other types of non-conventional excess heat. Further sources of excess heat, for example that which requires heat pumps to be upgraded, should be investigated. These lower temperature sources are not included in the analysed scenarios, which means that the analysed of both industrial excess heat and large-scale heat pumps are likely to be on the conservative compared to the real potential.

Future **production and storage units** for district heating should be more varied and versatile to integrate low-carbon sources and enable flexibility. Production facilities include biomass boilers, various renewables, different types of excess heat, and the use of combined heat and power (CHP) and large-scale heat pumps. Overall CHP covers 25-35% of the heat generation, but operates only in response to the needs of the electricity markets. This means the heat is created as an unavoidable by-product of flexible electricity production, and its use contributes purely contributes to the overall energy system efficiency. Large heat pumps 20-30% using mainly renewable energy and the remainder from excess heating (25%) and other renewable sources such as geothermal and solar thermal heating (5%). Renewable sources such as deep geothermal energy and solar thermal heating can only be exploited to their full potential in the energy system if district heating is present, and are a valuable resource for district heating systems that do not have obvious sources of industrial excess heat. The capacity of boilers can cover the peak demands over the year, however boilers should not produce more than 10% of the district heating demand corresponding to times with peak demands or low production from other sources.

The most important thermal energy storage to consider should cover on average 2-8 hours in larger cities and 6-48 hours in smaller cities. These types of short-term storages are crucial to balance the electricity grid as well as to handle fluctuating local low value heat sources. Seasonal storages may be relevant to locally increase the coverage of excess heat otherwise it is wasted in the summer period from e.g. industry, waste incineration or solar thermal.

Individual heat pumps will be key to enabling resource efficiency and electrification in areas where district energy is not viable, and should provide about half of the heat demand or lower depending on the local conditions for the built environment. Since the investment required to unlock their potential is high and often borne by building owners, focus should be on policies and implementation strategies that encourage switching from individual boilers and inefficient electric heating to more efficient alternatives in non-urban areas. The policies should be targeted at areas not suitable for district heating, in order ensure the overall energy efficiency, flexibility and decarbonisation of the system. The policies should also be combined with targeted measures for energy savings as this improves the efficiency of the heat pumps and reduces the peaks in the electricity grids in cold periods. The small individual heat pumps and in practice likely to be combined with solar thermal and biomass boilers as part of the supply in some areas in Europe. However, in this study all individual heating is supplied by heat pumps as a modelling method due to the purpose of the analysis and their distinct advantage in efficiency and integration with the electricity sector. Thermal storage in combination with these are important, but the flexibility is limited compared to the district heating system with thermal storage, heat pumps, combined heat and power, etc.

The HRE project aims at democratising the debate about the heating and cooling sector by providing data, analyses, methods and information at several levels and to multiple stakeholders. The overall objective in the HRE project is to provide new capacity and skills for lead-users in the heating and cooling sector, including policymakers, industry, and researchers at local, national, and EU level. These data, freeware tools, methodologies, analyses, results, and local geographical data are made available online. By providing the scientific evidence required to support the decarbonisation of the heating and cooling sector in Europe and transferring this knowledge and tools to key lead-users across policy, industry, and research, this can enable new policies and prepare the ground for new investments in new markets.

To **create the science-based decision support** in HRE several unique methods for energy planning have been combined. Key to the project is the combination of mapping and all sectors energy systems modelling, in order to be able to understand not just the system effects of energy efficiency but also the spatial dimension. Therefore, HRE brings together energy system analysis with spatial planning tools and provides an in-depth understanding of thermal demands in built environment and industry.

This includes a **detailed spatial analysis** in order to be able to understand the local nature of heating and cooling, and in order to more accurately appreciate infrastructure costs. A Pan-European Thermal Atlas with hectare level mapping of thermal energy demands and resources has been developed in HRE, and is available online.

In addition, a **bottom-up and in depth analysis of the thermal sector** and thermal demands has been carried out for the built environment and industry using the Forecast model, since they are often overlooked in standardised statistics. This forms the basis of the strategic heating and cooling development and underlies an understanding of what kinds of energy savings are possible.

These are combined in the development of the **energy system analysis**, since an hour-by-hour energy system analysis approach including all sectors is necessary in order to ensure lower overall costs and avoid suboptimal design within the heating and cooling sectors. In HRE, an evolutionary optimisation tool (JRC-EU-TIMES) and an hourly simulation tool (EnergyPLAN) have been soft-linked to be able to use the strengths of both models. Together, this allows for a quantification of the effect of energy efficiency and decarbonisation within an integrated energy system.

About Heat Roadmap Europe

Heat Roadmap Europe 4 follows as instalment a series of previous studies that have been carried out since 2012 [5–7], which have resulted in a total of 18 different reports, primarily relating to the long-term changes that are necessary to implement in order to decarbonise the heating and cooling sector in Europe. The acronyms 'HRE' and 'HRE4' are used for brevity and consistency, where '4' distinguishes the new data and methodological improvements produced during this current study, as HRE4 builds on the foundation set by the three previous studies and expands its research scope in terms of both energy sectors and geography.

HRE4 project with a consortium of 24 partners has received funding from the European Union's Horizon 2020 research and innovation programme since 2016 until 2019. It addresses the topic EE-14-2015 "Removing market barriers to the uptake of efficient heating and cooling solutions" of the Energy-efficiency call, by quantifying the effects of increased energy efficiency on both demand and supply side, in terms of energy consumption, environmental impacts and costs.

In order to fulfil Coordination and Support Action Grant objectives and requirements, HRE4 has been executing a strategy of dissemination measures in order to communicate the research findings to the relevant stakeholders, who by position and profession can use the scientific evidence for facilitating the market uptake of efficient and sustainable developments in heating and cooling sectors. Thus, on the one hand HRE is advancing on scientific research which:

- Involves the most detailed spatial mapping of heat demands and renewable heat resources up to date;
- Includes the potential for reducing heat demands through cost-efficient energy efficiency measures in both the heating and the cooling sector;
- Integrates industrial sectors to quantify heat demands;
- Models both long term projections and hour-by-hour energy systems.

On the other hand, it is heavily occupied with measures for coordination and support as:

- Developing user manuals of the research findings and tools, as a way to standardise new knowledge and render it intelligible to non-scientific officials;
- Hosting workshops, strategic panel discussions where policy-makers are invited;
- Participating in events, as conferences, for promotion of project tools and findings;
- Active presence on social media, where the results are communicated to broader audiences;
- Awareness-raising activities in the digital media, such as informative videos and instructional webinars.

Key findings in Heat Roadmap Europe

1	**The heating and cooling sector can be fully decarbonised based on technologies and approaches which already exist, are market-ready and have successfully been implemented in Europe.**

- The HRE 2050 scenarios show that a redesigned and sector-integrated heating and cooling solution can improve the European Union's energy efficiency, economy, and environmental impacts while successfully enabling the transition away from fossil fuels.
- The redesign contributes to keeping global temperature rise under 1,5-2°C as agreed in the Paris Agreement by decarbonising by about 4.300 Mtonnes per year or 86% compared to 1990 levels counting in also non-energy and other sectors such as agriculture. The energy sector emissions are reduced by about 2.700 Mtonnes of CO_2, or by 89% percent compared the 2015 reference. The redesigned energy system does not hinder but enables further implementation of renewable energy. (Figure 2)

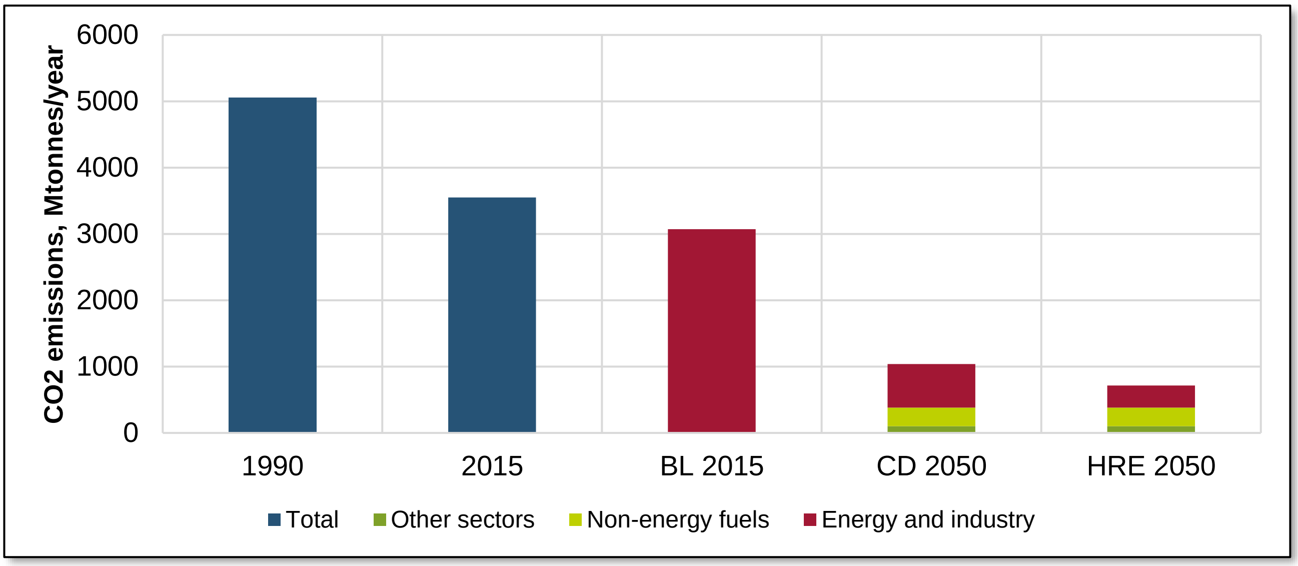


Figure 2. Historical, current and future CO_2 emissions for the 14 HRE4 countries; including the years 1990 [8] (the base year for the Paris Agreement), 2015 and the three 2050 scenarios; i.e. the Baseline (BL) 2050, which represents the development of the energy system under currently agreed policies; the Conventionally Decarbonized (CD) 2050, which represents the development of the energy system under a framework that encourages renewables, but does not radically change the heating and cooling sector; and the HRE 2050, which represents a redesigned heating and cooling system, considering different types of energy efficiency and better integration with the other energy sectors.

- Energy efficiency and decarbonisation in the heating and cooling sector is achieved with the use of already existing technologies, i.e. ambitious renovations of the existing building stock; 3rd generation district heating and cooling grids; efficient heat pumps; and better utilisation of the potential synergies between the energy sectors.

- HRE presents a robust no-regrets pathway: the technologies used are all mature, market-ready and have been implemented in parts of Europe. The challenge is to create integrated knowledge, planning tools, business tools, innovative collaborations and incentives to realise their potential. In most cases it is political and regulatory barriers rather than technical barriers.

2	**Energy efficiency on both the demand and the supply side are necessary to cost-effectively reach the decarbonisation goals.**

- End-user savings alone are not sufficient to decarbonise the heating and cooling system and will increase significantly due to higher investments. Supply side solutions alone require much higher investments in renewable energy and may not be sustainable. Energy efficiency on both the demand and supply side is necessary for a deeper decarbonisation. End-user savings reduce the energy systems' primary energy demand by around 4% (613 TWh) in HRE in 2050 and represent around 30% of total potential savings, with more efficient supply options reducing primary energy a further 8% (1.405 TWh) – which makes up the remaining 70% of total savings.
- An integrated approach to the heating and cooling sector requires more investments to establish energy efficient technologies and infrastructure compared to a focus only on achieving energy efficiency on the demand side. However, overall this reduces energy system costs by approximately 6% (67,4 billion €) annually overall. (Figure 3)
- The reduced consumption of fossil fuels in the heating and cooling strategies in the HRE 2050 scenario almost completely eliminates the dependence on imported natural gas for heating purposes in Europe. The strategies also heavily reduces the vulnerability of citizens to very high heat prices and the risks of energy poverty. Fossil fuels can be reduced by almost 10.400 TWh in 2050 compared to today. The amount of natural gas decreases in 2050 by about 87% compared to today. As comparison 54% of the energy consumption was met by imports, 88% of oil and 70% of natural gas was imported in 2016 [2]. The imported natural gas had a value of 50-65 billion €.
- The reduced expenditure on fuels and higher spending on the suggested investments in local energy efficiency and local resources has the potential to improve local employment and the European balance of payments and reduce expenditures on imported fuels.
- Achieving energy efficiency requires both goals and active policies to support the implementation of infrastructures for heating and cooling within the individual member states' own contexts on the EU level as well as the local level. The existing policies used should be monitored periodically for compliance and changed or expanded if they do not have the desired level of energy savings. A framework for

expanding and establishing thermal infrastructure should be initiated and in line with policies for gas and electricity grids, it should have an EU level and a national level.

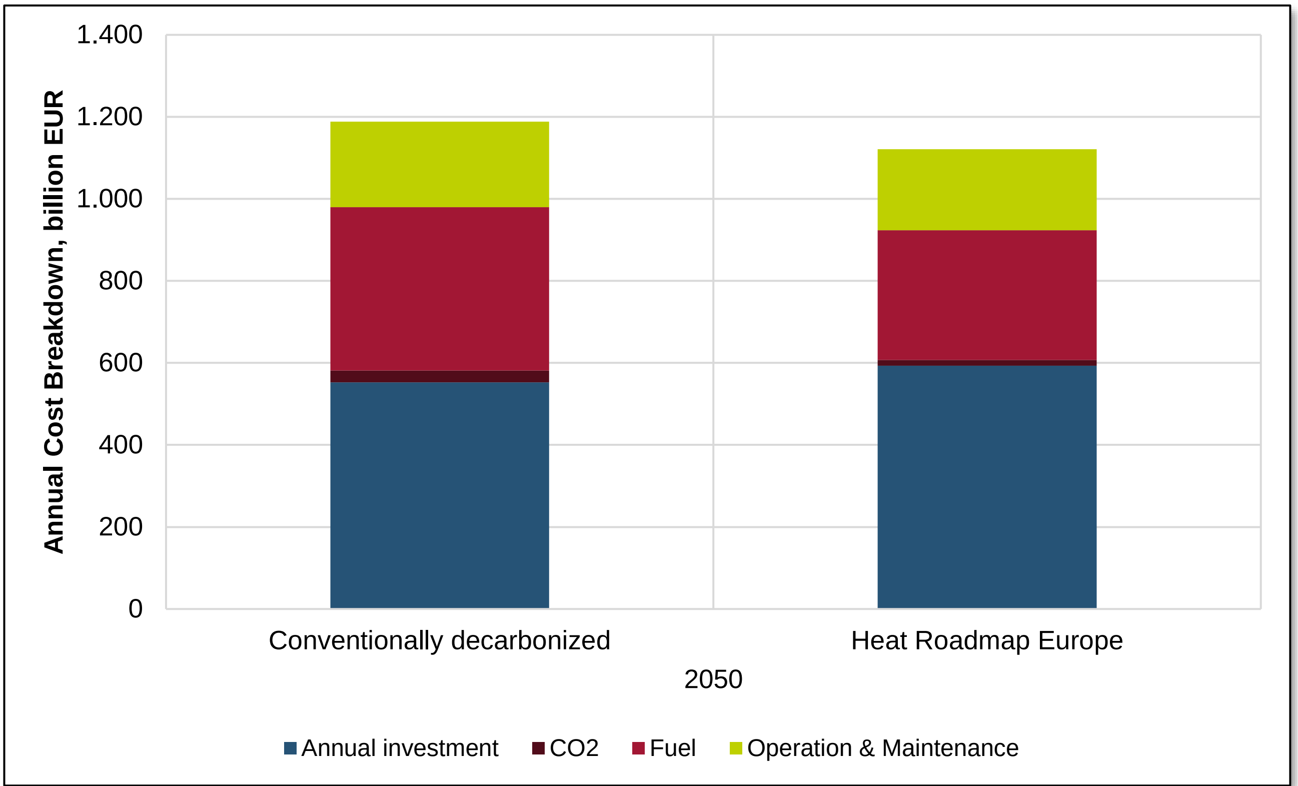


Figure 3. Annual total energy systems costs for the decarbonized 2050 scenarios. The Conventionally decarbonized energy system focusing on increasing the renewable energy penetration and some degree of energy savings reaches an 80% reduction in CO_2-emissions while the HRE 2050 scenarios reaches 86% at a lower cost using deeper renovations and an integrated new energy system design.

3 More support is needed for implementation and higher energy saving targets for deeper renovation of the existing building stock and investments in industry.

- **End use savings** are vital to efficiency, decarbonisation and affordability. In existing buildings higher renovation rates and depths are needed. With the current policies and targets, a 25% reduction in total delivered energy for space heating can be reached in 2050, also considering also an increased amount of buildings. This represents an annual refurbishment rate between 0,7% and 1,0% towards 2050, and requires that all policies are fully implemented [4]. In HRE it is recommended to increase the target to at least 30% savings for space heating in buildings. This requires a higher refurbishment rate of 1,5% to 2%, and deeper renovations when they occur [4].

- Both the current and the higher target suggested here require a shift to a much stronger focus and enhanced approach towards **policy implementation** and realisation on a country level, with regular re-evaluations of progress and impact. A higher ambition than 30% for Europe would be precautionary as experience shows that implementation may fail to succeed [9,10] and the results in HRE for most countries show that the socio-economic costs for going higher are very low and within the uncertainties of the analyses.
- HRE finds that all countries should have a higher ambition level that the current EU level target would lead to. Especially Belgium, the Czech Republic, Hungary, the Netherlands, Poland, and Romania should have a higher energy savings target. No savings are implemented in the hot water demands.

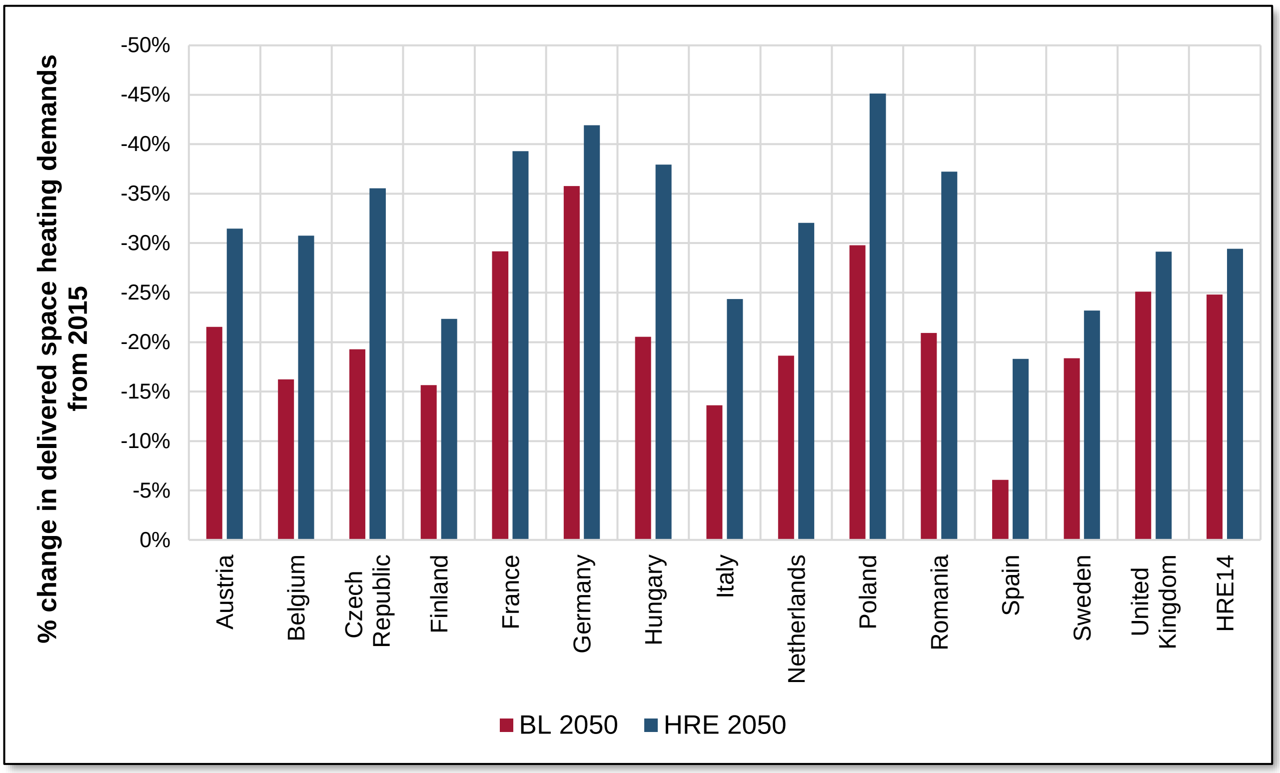


Figure 4. Heat Roadmap Europe and Baseline 2050 (current policies) changes in the delivered space heating in 2050 if fully implemented.

- The HRE4 results show that energy savings in industry and the service sector are highly cost-effective from a socio-economic and energy perspective, meaning that efficiency standards and financial incentives for process heat savings should also be ensured in member states. The savings recommended in Heat Roadmap Europe are 8% for process heating, which is the highest considered technically feasible within the proven-technology approach in HRE. Like for space heat savings, a strong focus on implementation can be recommended. (Figure 5)

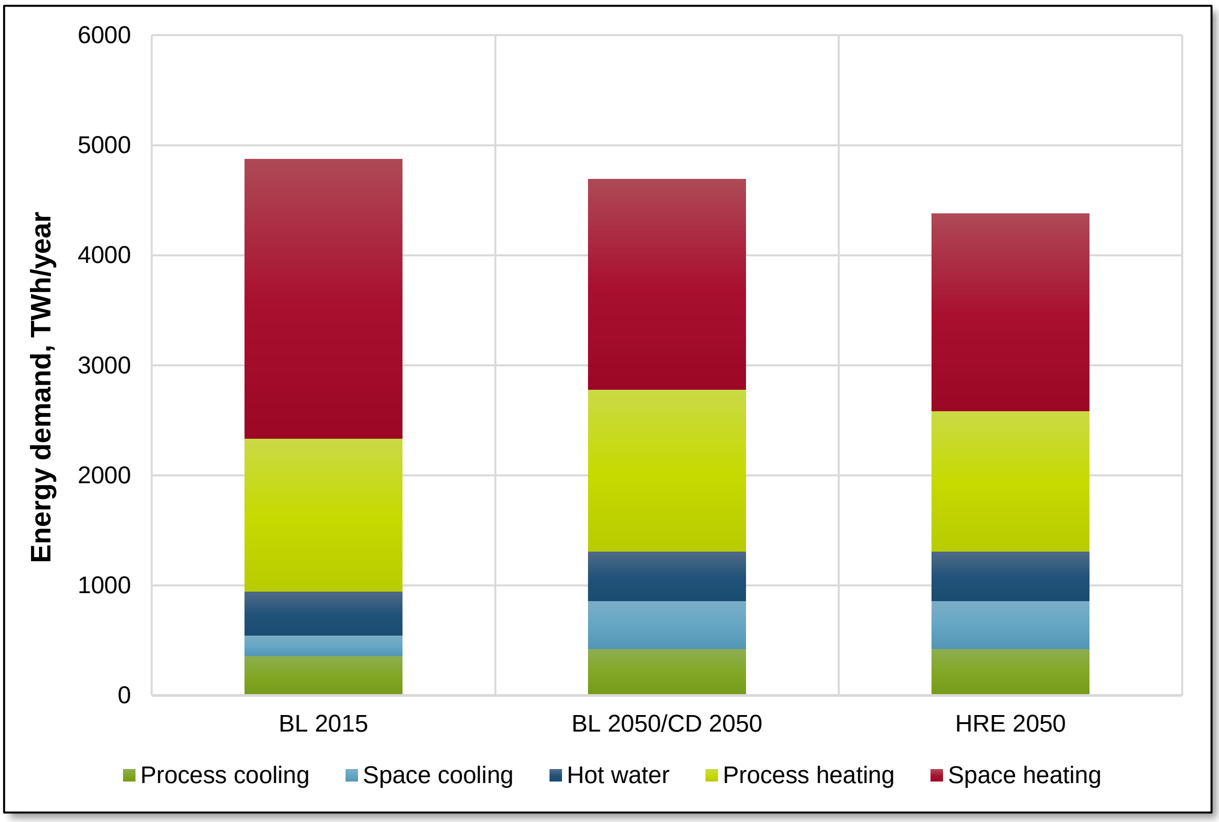


Figure 5. Heating and cooling demands reductions in the baseline (BL) and decarbonized (CD) scenarios and in Heat Roadmap Europe 2050.

4 **In the vast majority of urban areas, district energy is technically and economically more viable than other network and individual based solutions, and can be 100% decarbonised through the use of renewables, large heat pumps, excess heat, and cogeneration.**

- The analyses show that district heating cost-effectively can provide at least half of the heating demand in the HRE4 countries while reducing the primary energy demand and CO2-emissions. For the 14 HRE countries combined, a 0,5% total cost change interval gives a market share of district heating in a 32-68% range in combination with the 30% end demand energy savings. The scenario level (45%) where about half of the heat market is covered with district heating is based on economic metrics and effects on the energy system only.
- Due to a number of additional strategic benefits, such as security of supply as well as jobs and industrial development it can be recommended to go beyond the

modelled or current district heating share towards 70%. While there are differences from country to country, going beyond the modelled level towards the maximum feasible level can further lower the price fluctuations citizens will experience, lower geopolitical tensions connected to energy supply and create an even more fuel-efficient system. (Figure 6)

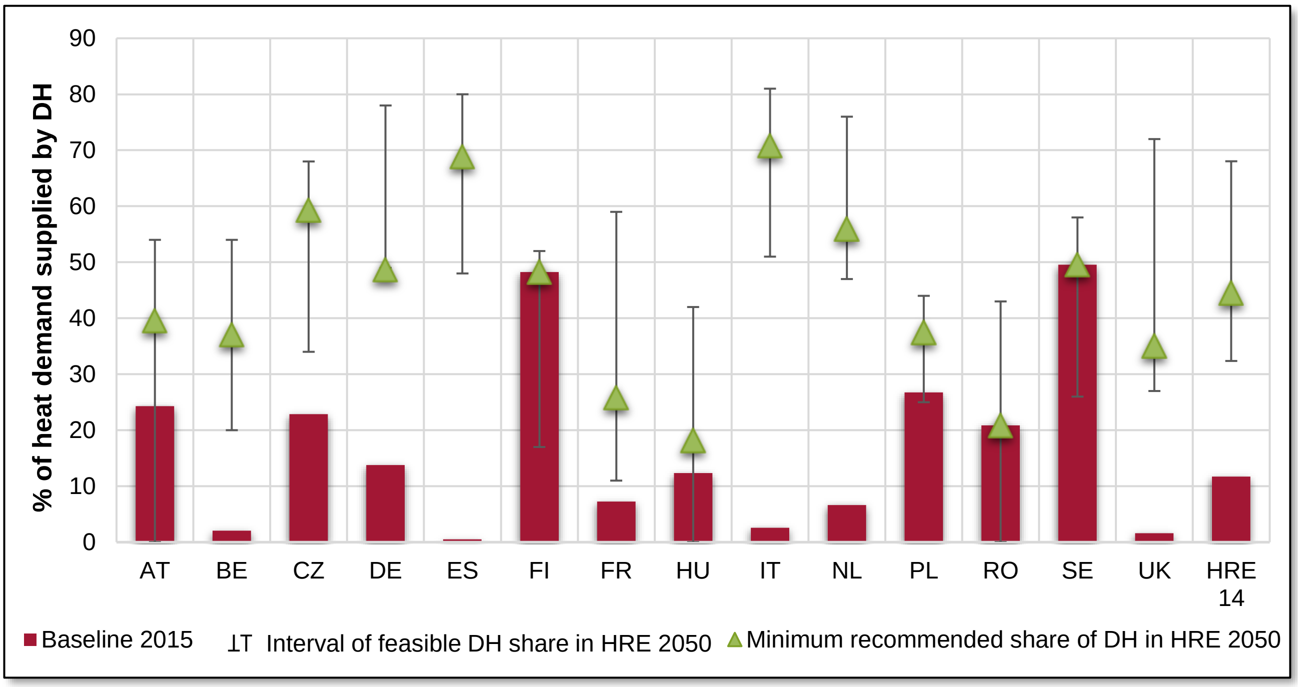


Figure 6. Baseline share of district heating in 2015 and the minimum recommended level of district heating share in HRE4. The range bars represent the amount of district heating that is economically feasible within a 0,5% total annual energy system cost change sensitivity. The recommended minimum levels take into account cost efficient levels and current level of district heating. Going beyond this level can generally increase energy efficiency.

- The level of district heating recommended is robust against a situation where the implementation of energy savings and refurbishments fails.
- Future production and storage units for district heating must be more varied and versatile to integrate low-carbon sources and enable flexibility. Excess heat from electricity production (CHP) covers 25-35% of the heat generation, large heat pumps covers 20-30% using mainly renewable energy. The remaining heat supply is from industrial excess heat (25%) and other renewable sources such as geothermal and solar thermal heating (5%). Renewable sources such as deep geothermal energy and solar thermal heating are geographically and temporally constrained, and can only be exploited to their full potential in the energy system if district heating is present. The capacity of boilers can cover the peak demands over the year. Heat only boilers play a marginal role in the heat supply mix (less than 6%).
- The most important thermal energy storage to consider is in local feasibility studies can cover on average 2-8 hours in larger cities and 6-48 hours in smaller cities.

These types of short-term storages are crucial to balance the electricity grid as well as to handle fluctuating local low value heat sources. Seasonal storages may be relevant to locally increase the coverage of excess heat otherwise it is wasted in the summer period from e.g. industry, waste incineration or solar thermal.

- Full electrification of the heating supply is more costly and neglects the potential to recover energy from industry and power generation, limiting the overall efficiency of the system and possibility for coupling electricity, heating and using heat storage. With 50% district heating or more in combination with electrification overall the grid costs are spread between thermal and electricity grids. Lower shares of district heating will increase the cost for electricity grids in decarbonised energy systems. A further benefit of higher district heating shares are potential higher usages of domestic fuel or EU fuels creating a better balance of payment and potential increase in jobs.

5	**In areas with limited district heating and cooling feasibility, individual supplies should be from heat pumps that can contribute to the integration of variable renewables.**

- In rural areas, heat pumps should become the preferable individual solution based on their high efficiency, providing about half of the heat demand or lower. The level depends on the local conditions for the built environment. High standards of energy performance and deep renovations are necessary in order to implement heat pumps effectively and ensure high coefficients of performance (COPs) along with a high level of comfort.
- Heat pumps reduces the dependency on fuel boilers in a bioenergy-scarce decarbonised future and increases the use of fluctuating renewable electricity sources. It can also to some extent contribute to the energy system flexibility [11]. While these heat pumps can in reality be combined with solar thermal and biomass boilers as part of the supply in some areas in Europe, in this study all individual heating is supplied by heat pumps as a modelling method due to the purpose of the analysis and their distinct advantage of efficiency and integration with the electricity sector.
- Thermal storage in combination with these are important, but the flexibility in these storage is limited compared to the district heating system with larger thermal storage that have much lower costs, larger heat pumps, combined heat and power, etc. [12,13].
- Operational incentives for building residents should first and foremost promote energy savings and then flexible interaction for consumers to help balance the electricity grid and not maximise self-consumption since optimising in the building level will most likely result in higher costs for the overall energy system [14].

6	**Cooling demands are less significant compared to the heating demands, but are expected to increase in the future. The knowledge about solution designs is expected to improve in the future.**

- Cooling demands are expected to increase in all countries according to the saturation levels, which could more than double. However, even in the most southern HRE4 countries, heat demands dominate the sector, as in 2050 cooling represents 20% of the thermal energy demand in the modelled scenarios.
- In HRE4, a full overview is presented for the first time of the potential cooling technologies looking towards 2050 [15]. These solutions contribute to the efficient use of energy through high seasonal efficiency, absorption of different types of excess energy, and the recovery of energy from seawater and lakes.
- The cooling demands differ from heating in that they are more balanced between space cooling and process cooling, and dominated by the service and industries rather than the residential sector. This requires a broader understanding of how district cooling could be modelled and replicated on a spatial level.

7	**The heating and cooling sector can play an important role by integrating the increasing shares of variable renewable energy and enhance the grid flexibility.**

- HRE has an integrated approach, which aims utilise the synergies between the energy sectors through the use of heat pumps, thermal storage, combined heat and power, and industrial heat recovery.
- The use of renewable electricity and thermal storage in the heating and cooling sector can help balance the electricity grid when high levels of variable renewable energy are introduced.
- The modelling shows that an energy system with a strategically decarbonised heating and cooling sector can support a similar amount of wind capacity as a conventionally decarbonised energy system. At the same time up to 30% more of the electricity produced by the installed variable renewable energy capacity can be functionally absorbed and used in the energy system due to the enhanced flexibility in the heating and cooling sector.
- The redesign of the suggested European energy system represents a step that can enable a deeply decarbonised energy system. Extending the HRE designs to use a Smart Energy Systems approach to include transport and electrofuels could provide a pathways towards 100% renewable energy to fully decarbonise the Energy Union [16–18].

8	**Tools and methodologies that are specific to the sector are necessary in order to coherently model, analyse, and design the heating and cooling system within the energy system. This is an important part of developing pathways and strategic plans that contribute to a decarbonised energy system for the future**

- Heating and cooling is the largest sector in the European energy system, and without a decarbonisation of this sector it will not be possible to achieve the reductions in CO_2 emissions needed to prevent global temperature rises.
- This includes detailed spatial analysis in order to be able to understand the local nature of heating and cooling, which is necessary since infrastructure costs for thermal energy are higher and thermal energy sources cannot travel well without increased losses.
- An in-depth and bottom-up understanding of the built environment and industries is necessary to understand and analyse the thermal sector and thermal energy demands. This forms the base of any strategic heating and cooling development and creates an understanding of possible energy savings.
- An energy system analysis approach is necessary to ensure that a decarbonised energy system does not exist in isolation. A combination of a tool that can model energy systems as they evolve through time, and a simulation tool that can analyse the hourly variations of demands and resources (and necessary capacities) has allowed for a coherent analysis of the design and development of a heating and cooling sector that can be integrated into a wider decarbonised energy system.

Key messages for lead users who can remove barriers for implementation

The HRE scenarios give an insight on where current policy could bring the European energy system, and what technologies could be used to achieve deeper decarbonisation at a lower cost. The scenarios also provide a basis for understanding how markets will likely develop under current policy, and what markets need further development of framework conditions in order to contribute to full decarbonisation.

The scenarios are designed to be used mainly for national and EU level policy-makers, energy agencies, industries/companies that produce energy technologies, consume large amounts of energy, or finance energy projects, as well as researchers and NGOs acting at EU, national, and region/city levels.

The scenarios developed in the HRE 4 project cover the 14 largest EU member states, and represent 90% of the heat demand of the EU. They cover the entire energy system (heating, cooling, electricity, transport), but focus on the decarbonisation of the heating and cooling sector, and the role that this can play in decarbonising the European energy system looking towards 2050.

Though the outputs and analysis of the scenarios and the Heat Roadmaps is presented here, the scenarios and main data sources are also made available to lead users on the HRE website in the following ways:

- Hour-by-hour energy system simulations of the scenarios across all sectors are freely available for download, where lead-users can use them in the accompanying freeware to better understand the system dynamics, and use them as a basis for further scenario development.
- Excel spreadsheets and visualisation tools are available to compare the results of the scenarios, and to explore the heating and cooling demand profiles.
- The Pan-European Thermal Atlas is accessible online and shows the spatial nature of heating and cooling demands and (sustainable and renewable) resources.

By making these and the deliverables publicly available, lead-users and the public can take advantage more directly of the HRE4 results, and they can play a supporting part for the dissemination and capacity building activities in the project.

EU policy makers and executives of the EC, parliament and institutions:

- HRE demonstrates the importance and effectiveness of integrated energy solutions for reducing carbon emissions in electricity, heating, and transport sectors that can tap into synergies and enable reaching the targets at lower economic cost. This emphasises the need for coordination across the EU directives that govern the

built environment, industry, (renewable) energy sectors, efficiency, and efficient design.
- The decarbonisation of the heating and cooling system is possible, using already existing and mature technologies. The transition towards increased competition in heating and cooling markets and decentralised, more flexible and more complex energy systems requires a new approach towards a framework development that will encourage market uptake.
- Significant technical and non-technical barriers for energy efficiency and renewable energy need to be removed or overcome. Regulatory recommendations from HRE may prove crucial for unlocking local to national potential for increasing competition in the heating and cooling markets and facilitating the entry of investors into these sectors.

National policymakers and energy authorities:

- The integrated systems methodology towards sustainable energy allows HRE to offer multiple heating and cooling solutions which feasibly and effectively support national climate and energy targets, as well as the strategic policies meant to address them, such as National Energy Efficiency Action Plans (NEEAP) and National Renewable Energy Action Plans (NREAP).
- HRE‛s technologically-neutral approach can identify dominant technical and market barriers in the heating and cooling sector so that decision-making processes can be streamlined to overcome these obstacles and stimulate positive decarbonisation impacts across the country.
- Regulatory recommendations from HRE may prove crucial for unlocking local to national potential for increasing competition in the heating and cooling markets and facilitating the entry of investors into these sectors.

Energy policy-makers and technical staff of local and regional authorities:

- Local and regional authorities are uniquely positioned to advance the decarbonisation of heating and cooling systems due to their various responsibilities as planners, regulators, facilitators of finance and as local role models with on-the-ground expertise. This is especially the case for complex and decentralised technologies such as large-scale renovations, district energy, and collaborative efforts that bring industries together.
- HRE can contribute to capacity building and skill development in the heating and cooling sector by creating new tools and methodologies, but also by supplying relevant data, all of it accessible to the local and regional decision-makers needing it most.
- Policy guidelines, business cases and free-to-use online resources tools, as provided by HRE, can prove to be invaluable aids for local and regional stakeholders developing, implementing or upgrading Energy Action Plans (e.g.

SEAPs, SECAPs, REAPs), or even seeking to bring to life cross-cutting Smart City strategies, including as support to the achievement of climate and energy targets (e.g. under the Covenant of Mayors).

Energy companies at (supra-) national, regional, and local level

- HRE's findings, business cases and guidelines can enable energy companies to plan for cost-effective developments contributing to the decarbonisation of their heating and cooling sector, and thus prioritise areas with the most potential and gain a competitive advantage as early-movers in the markets where they operate.
- Most energy efficiency solutions, such as district heating/cooling and larger-scale renovations, require an active and collaborative involvement of energy companies and network operators to help achieve targets, thereby opening up new chances for energy companies to benefit from new market opportunities and expand their areas or fields of operations.
- Energy companies at all levels should take advantage of relevant tools and data generated by HRE, in particular 1) the online interactive mapping platform (Pan-European Thermal Atlas, Peta4) outlining the location and scale of sustainable energy resources and 2) detailed insights breaking down the baseline of the heating/cooling sector, in both cases supporting companies to prioritise areas, resources and demands with the most potential.

Energy and heating and cooling technology manufacturers, engineers, and consultants

- HRE's main identified solutions promote the use of sustainable technologies and measures which have the potential to align strongly with Europe's manufacturing and engineering specialisations, existing infrastructures and domestic resource potentials, as opposed to (piping in) imported foreign fossil fuels.
- HRE's findings can enable energy companies to plan for cost-effective developments, and continue to be on the forefront of efficient heating and cooling design, renewable energy development, and smart and flexible system design. Manufacturers and engineers can use a leading market uptake development to prioritise areas with the most potential and gain a competitive advantage as early-movers in the markets where they operate.
- The most detailed breakdown of the current state of Europe's heating and cooling sector to date has been generated and made available by HRE, allowing relevant heating and cooling technology companies a new insight into how their own markets might evolve.

Large energy consumers, including industry:

- The absolute energy demands for process heating and cooling is not expected to decrease between now and 2050, and will become a topic of relatively larger import as space heating savings are increasingly realised. The HRE profiles include types of energy use in large heating and cooling consumers based on temperature level and sector, and HRE is able to provide the most in-depth overview of heating and cooling available in Europe today.
- There is a great potential for significant energy and cost savings to be recouped by European industries and other large energy consumers, as shown by HRE, through which these sectors can substantially contribute to our overall transformation into a decarbonised society.
- HRE shows that the overlap between large energy consumers and facilities with potential for excess heat is high, meaning large energy consumers could benefit from the increased utilisation and valorisation of excess heat. The spatial and energy analysis in HRE maps out and refines the minimum accessible large potentials to be found in (low-temperature) excess heat, highlighting not only its value for more energy efficient systems, but also for new business cases beneficial to large energy consumers striving to reduce their own energy costs or even discover new revenue streams.

Financial sector

- Most energy efficiency solutions, such as district heating/cooling and larger-scale renovations, require an active and collaborative involvement of business model development and ownership arrangements, thereby opening up new chances for financers to benefit from new market opportunities and expand their areas or fields of operations.
- HRE4 findings will encourage the opening of new market places and entry of investors in such markets to achieve the most cost-effective and efficient heating and cooling solutions. By understanding the (synergetic) mechanisms and advantages that integrated heating and cooling strategies bring, financing institutions and assessors can be better prepared to engage with complex, multi-stakeholder projects.
- HRE4 demonstrates how close to €3 trillion of investments in renewable energies, energy efficiency infrastructures and technologies will reduce energy demands, carbon emissions, and energy costs in Europe. It further breaks down the priority areas and characterises their payback profiles.

Introduction

In Europe, there is a clear long-term objective to decarbonise the energy system, but it is currently unclear how this will be achieved in the heating and cooling sector. The Heat Roadmap Europe 4 (HRE4) project will enable new policies and prepare the ground for new investments by creating more certainty in relation to the changes that are required.

The overall objective in the HRE project is to provide new capacity and skills for lead-users in the heating and cooling sector, including policymakers, industry, and researchers at local, national, and EU level, by developing the data, tools, methodologies, and results necessary to quantify the impact of implementing more energy efficiency measures on both the demand and supply side of the sector.

This report describes the development and findings of the HRE scenarios. The purpose is to quantify the impact of increased energy efficiency in the heating and cooling sector in Europe and for 14 European Union member states in particular. These countries represent the largest countries in terms of heat demand, and by 2050 will represent 90% of the total European heat demand. Based on detailed energy demands and energy system analysis, various heating and cooling scenarios have been designed for the countries and their impacts were quantified, allowing for the development of low-carbon heating and cooling roadmaps (Heat Roadmaps). This report presents the Heat Roadmap Scenarios looking towards 2050 (HRE 2050 scenarios); their design and development, different energy demands, different energy supply technologies, their role within the wider energy system, and how they compare to the Baseline Scenarios (BL 2015 and BL 2050) and the Conventionally Decarbonised Scenario (CD 2050). This way, the results demonstrate the impact of increased energy efficiency in the heating and cooling sector.

In order to do develop the Heat Roadmaps, scenarios have been designed and analysed using the data, tools, and methodologies developed in the HRE4 project. The development of these scenarios include varying levels of energy demand savings, gas network based options, various forms of electric thermal energy supply, building-scale renewable based options (including solar thermal and bioenergy), and several models of district energy using solar thermal, geothermal, combined heat and power, industrial surplus heat, waste incineration. The holistic design, analysis, and evaluation of these scenarios is supported by the knowledge, data, and methodologies that have been developed, improved, and updated in this project.

Background

This HRE4 project builds strongly on three previous studies, which have been developed since 2012 [5,6,19,20]. The overall thrust of this work has been to find ways to increase the efficient delivery of heating (and subsequently cooling) to consumers, integrate renewable energy sources into the heating and cooling sector, and contribute to the decarbonisation of the European energy system. Throughout this work, approaches and methodologies have emerged which are underpinned by several principles:

- An in depth understanding of the thermal sector and thermal demands is required, since they are often overlooked in standardised statistics. This is both the case for heating, where knowledge on the building stock is typically poor and district heating that is difficult to represent, and cooling, which is typically hidden within the electricity sector. This forms the base of any strategic heating and cooling development and underlies an understanding of what kinds of energy savings are possible.
- Spatial analysis is necessary to be able to understand the local nature of heating and cooling, and in order to more accurately appreciate infrastructure costs. This is especially important when considering district energy, since the cost of infrastructure is proportionally higher than the cost of supplying the energy.
- An energy system analysis approach is necessary in order to ensure that a decarbonised energy system does not exist in isolation, but can be integrated into a wider decarbonised energy system and the synergies within the system can be used.

Based on this, scenarios and strategies have been developed which largely hinge on energy savings through better energy performance of buildings and reductions in energy demands in industry; the use of thermal networks in urban areas which integrate new efficient and renewable energy sources to the system, and highly efficient and flexible use of individual heating technologies in rural areas. Based on the combination of these principles, the Heat Roadmaps have been designed in HRE4.

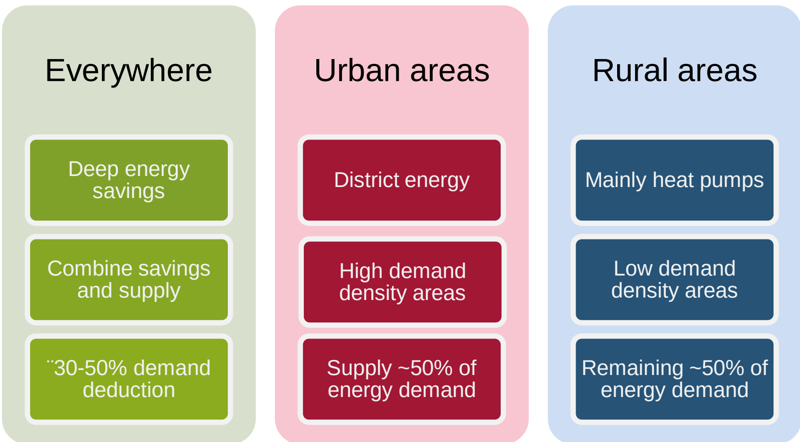


Figure 7. Heating and cooling strategies

Focusses in HRE4

In this study, the objective is to encourage investments in the heating and cooling sector by quantifying and demonstrating how energy efficiency can save energy, increase the share of renewable energy, and contribute to a decarbonised European energy system. This is done by coordinating and improving the existing knowledge on the heating and cooling sector, and developing Heat Roadmap scenarios.

The objectives of Heat Roadmap Europe are built on two main pillars:

- Quantifying the impact of implementing more energy efficiency on both the demand and the supply side of the heating and cooling sector
- Developing and the data, tools, methodologies, and results necessary to build new knowledge, capacity and skills.

The first focus has been to create the most detailed profiles to date of the demands and energy carriers of the heating and cooling sector and in the context of a Baseline scenario. This has included a more detailed understanding of the different energy carriers than have been available from previous studies; an in-depth assessment of the current and future technologies (and their respective performances and costs) for cooling. This project included industrial heating and cooling demands for the first time. The profiles of the heating and cooling sector, and their projections towards the future, also allow for an analysis of the technical potential and cost of bundles of measures which can reduce these demands at a delivered energy level, in order to be better integrated with the energy system analysis.

The second focus has been the spatial analysis of the location of heat demands and resources in order to assess the cost of energy networks, and be able to identify the spatial potential of resources that can be used locally within the heating and cooling systems. In order to do this, hectare-level heat demand densities have been combined with an enhanced spatially contiguous analysis model to better reflect the nature of district energy infrastructures in urban and rural areas. In addition, a resource allocation model has been developed which allows for an unprecedented quantification of the available resources for district energy at differing levels of market penetration, for the 14 EU countries considered in HRE4.

The final focus has been on integrating these results within energy system analyses looking forwards 2050. This has been done using to energy system models (including the heating and cooling, electricity, and transport sector) looking towards 2050. Compared to previous studies, this study has included a more detailed analysis of the development of the energy system between 2015 and 2050; increased attention to the role of storage and large scale heat pumps in the interactions between the heating and electricity sectors, and a more detailed analysis of the price and amount of available bioenergy resources. In addition, the energy system analysis is supported by country-specific differentiated costs for various technologies, and a robust understanding of the costs of cooling technologies. Using these, and the outputs of the demand profiling and spatial analysis, comprehensive heating and cooling scenarios can be developed through the energy system analysis.

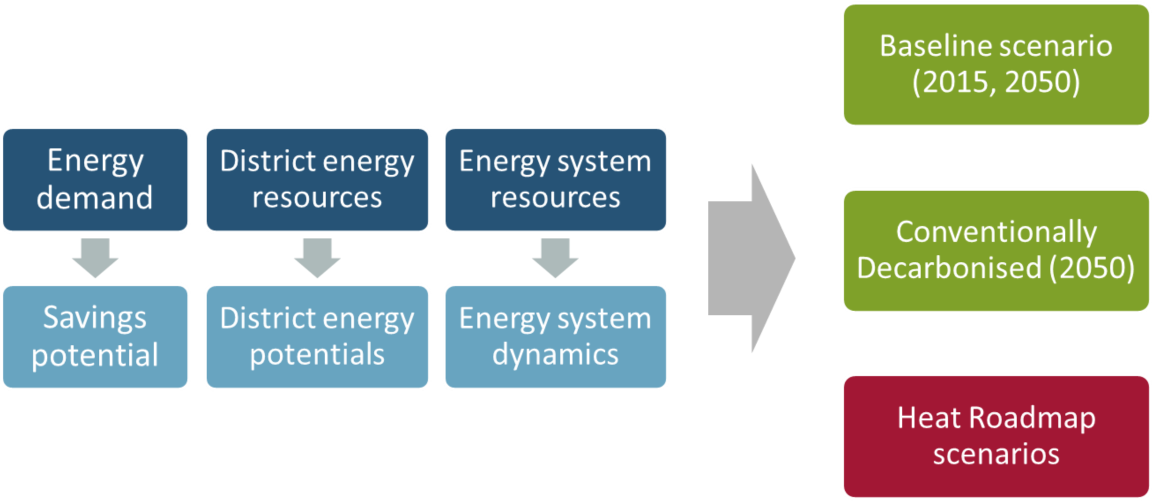


Figure 8. Conceptualization of inputs for scenario models

For each country, four main scenarios have been developed to support the HRE strategies. These scenarios function to represent different, alternative, energy system simulations that can inform the strategies and actions needed to result in a heating and cooling system that can support an affordable, efficient, decarbonised energy system.

The first two scenarios represent Baselines, the first one replicating the system as it stands in 2015 (BL 2015). This serves to validate the models and data that support the analysis, but also to provide a starting point and comparison to the forward looking scenarios. The second represents a Baseline for 2050 (BL 2050), using an approach that takes into account currently agreed policy (particularly; the EU and national legislation that applies currently, including the Clean Energy Package as presented in March 2018). Based on this, the development of the built environment, industry, electricity and transport sectors is projected. In doing so, the scenario also functions to represent how far the current policy will bring us, and a comparison point for the other scenarios in terms of achieving efficiency, decarbonisation and affordability. The Baseline for 2050 already includes significant savings compared to today [4].

The third scenario represents a 'Conventionally Decarbonised' energy system (CD 2050) and takes a point of departure in BL2050. It projects a higher support for renewable energies leading up to 2050, but does not focus explicitly on increased savings in the heating and cooling sector, and does not drastically change the supply technologies for heating and cooling in comparison to the Baseline for 2050. This means that heat pumps are deployed almost elusively at the building level, the expansion of district energy is not considered, and with that resources like excess heat from industry, deep geothermal, and large-scale solar thermal are mostly left untapped. In addition, there is less focus on the interactions between the thermal and electricity sectors, preventing the strategic use of the synergies that can be created within those interactions. Through the CD scenarios, a comparison with the Baselines and Heat Roadmap Scenarios can be made on a scenario that is decarbonised – but which does not integrate the energy system to a high level.

The Heat Roadmap scenarios (HRE 2050) represent an alternative which focusses on developing energy efficiency on both the demand and the supply side of the heating and cooling sector. This focus on combining savings and efficient supply includes the simulation of a high level of performance of building and deep savings in the industry sector, but also the recovery of otherwise unused excess heat, use of (relatively efficient) renewables like geo- and solar thermal, and the use of heat pumps at both building level (in rural areas) and in district energy networks (in urban areas). This leads to a much deeper interconnection of the heating and cooling sector with the other parts of the energy system (through Cogeneration, large heat pumps, individual scale heat pumps) and more flexibility, resulting in the better integration of renewable electricity sources in the wider system. These alternatives can then be compared based on efficiency (through the primary energy use of the scenarios), decarbonisation (by looking at the resulting CO_2 emissions and renewable energy usage), bioenergy use, and cost.

The combination of these four scenarios for all the HRE4 countries allows for two questions about heating and cooling to be addressed:

- Would a system with higher levels of energy efficiency be an improvement to a scenario where no further policy is developed?
- Could a system with higher levels of energy efficiency contribute towards a better decarbonisation than conventional approaches?

Based on the analysis of these scenarios, strategies can be developed at the country level for the 14 HRE countries, which can take into account and inform the local nature of heating and cooling, but function within the wider energy system. This also informs the ongoing work to use these results to develop business strategies, business cases, build capacity and enable new policies that can contribute to developments at a local, national, and EU level can support the efficient and affordable decarbonisation of the energy system.

Approach and Methodology

The objective in HRE4 is to demonstrate how heating and cooling can be decarbonised by quantifying the effect of energy efficiency and renewable in the heating and cooling sector on an energy system level. By creating these Heat Roadmap scenarios (and the data, tools, and methodologies that have been developed in order to make them), new knowledge, capacity, and skills are built that allow for the development of more robust policies at local, national, and EU level. Together, this encourages investments and market uptake of technologies which can contribute to the efficiency and decarbonisation of the heating and cooling sector. By showing how the European heating and cooling sector can be decarbonised within the context of the wider energy system, HRE4 can contribute support the European Energy and Climate Package and the EU's overall commitment to attain a nearly zero energy system and reach the 2°C global warming target. In order to understand how the outputs can contribute, it is important to understand the underlying approaches and methodologies used to create the data and scenarios.

The Heat Roadmap Scenarios are developed and simulated using data from different sources and models. Using the 2015 and 2050 Baseline development of the detailed heat demands and energy carriers, a comprehensive understanding and analysis of the different types of heating and cooling demands can be made. The use of spatial data on both the demand and resource side allows for the matching of local demands and resources at a high resolution, which can then be aggregated to a national level, and energy system data on both the development of the energy system over the years and on an hourly level within certain years.

Aims and approaches

The main aim of the Heat Roadmap scenarios is to demonstrate and understand how to cost-effectively use energy efficiency, be decarbonised, and design a pathway for decarbonised heating and cooling that fits within a broader decarbonised energy system. This means that the heating and cooling system is decarbonised in a way that enables the electricity sector to further decarbonise (for example by providing further flexibility for the effective integration of variable renewable sources), and that does not stand in the way of further decarbonisation of the transport and industry sectors by using unnecessary amounts of bioenergy.

The different scenarios (BL 2015, BL 2050, CD 2050, HRE 2050) are all technically functional in that they supply all energy demands in all hours of the year, and respect the various grid stability and resilience restrictions; they all represent possible alternatives, but are not all equally preferable. The scenarios are all developed based on design criteria and compared and assessed along several parameters, rather than being cost-optimised within various (qualitatively considered) constraints. These parameters in HRE4 are normally a combination of consideration for the following:

- CO_2 emissions that result from the energy system, indicating a level of decarbonisation
- Primary Energy Supply, as an indicator of the efficiency of the system
- Socio-economic cost, to indicate the affordability and competitiveness of the various systems
- Bioenergy and biomass consumption, to indicate the reliance on (scarce) resources that may not fit stronger sustainability principles.

Particularly the CD 2050 and HRE 2050 scenarios are results of iterative design along these assessment parameters, allowing for a detailed analysis of their interaction and the different trade-offs that occur. This descriptive approach still results in the identification of one solution which is preferable over the other alternatives, but is more deeply grounded in the design, approach and simulated understanding of the compared scenarios.

Ambitious decarbonisation requires integrated approaches

Within the context of the HRE project, 'decarbonised' is taken to mean between an 80% and 95% reduction in CO_2 emissions by 2050, compared to 1990 levels. This is based on the current long-term goal and commitments made by the European Union towards the Paris Agreement [21]. The conventionally decarbonised energy system reduces CO_2 emissions by 80%, while the Heat Roadmaps aim to be closer to 95%. This is at the more ambitious end of the current long-term goal of between 80% and 95%, and substantially more ambitious than the Energy Roadmaps published in 2011. However, as an understanding of what is needed to be consistent with the 1.5°C limit agreed in the Paris Agreement develops, targets are expected to move towards a deeper level of decarbonisation, and a fully renewable energy system in the long term.

For this reason, the deeper level of decarbonisation for 2050 is chosen to allow the Heat Roadmaps scenarios to illustrate a possible alternative within a nearly zero carbon energy system. While the HRE scenarios combined do not achieve a 95% reduction of CO_2 levels compared to 1990, the scope of the project specifically only covers the redesign of the heating and cooling sector, with appropriate regard to the industry and electricity sectors. This means that no changes have been made to the non-thermal parts of the industry sector and the transport sector. However, even within this limited scope an overall reduction of 86% compared to the 1990 levels is achieved.

This aims of the reduction in CO_2 cover not only the heating and cooling sector, but includes the wider energy system (electricity, industry, and transport), agriculture, waste, and land use and land-use change. For this reason, the decarbonisation of the heating and cooling sector is approached within the context of a decarbonised energy system, including biomass availability, industry, transport, and the electricity sector. By developing scenarios for the heating and cooling sectors within this framework, it is ensured that a decarbonised heating and cooling system works within a broader decarbonised energy system, rather than in isolation.

This is important for several reasons, the first being the efficient allocation of resources between the sectors. This ensures that resources available are used in a wat that respects the comparative advantage some sectors have for efficiency and decarbonisation. By consider the energy system as a whole, it is possible to decarbonise where it makes the most sense. Sectors like (heavy) transport and industry are much more difficult and expensive to decarbonise, so there is an advantage for the overall system in reserving (increasingly scarce) bioenergy resources and the remaining carbon emissions for those areas where alternatives are least available. This also means that the heating and cooling sector is effectively fully decarbonised in the Heat Roadmaps, since there are relatively larger efficiency and renewable energy potentials.

In addition, the consideration of the heating and cooling sector within the context of an integrated energy system allows for the exploration of the synergies between the heating and cooling and other sectors. This approach, developed from a Smart Energy System perspective, is demonstrated in the importance of thermal grids, excess industry heat, heat pumps, and various storages in the Heat Roadmaps show the importance of this is allowing for an overall more efficient and affordable energy system [22].

Primary energy as an indicator of energy efficiency

The objective of energy efficiency is to reduce the amount of energy that is needed in order to fulfil the (useful) demands of an energy system, so in HRE4 the objective of energy efficiency is to reduce primary energy supply (see Figure 9). This means that efficiency is both considered in the reduction of useful energy demands (for example, through a higher thermal energy performance of buildings), the minimisation of energy lost in transport and distribution, and the reduction and recovery of energy lost in the transformation phase. This approach, as opposed to for example final energy approaches, ensures that the total resources in the energy system are minimised.

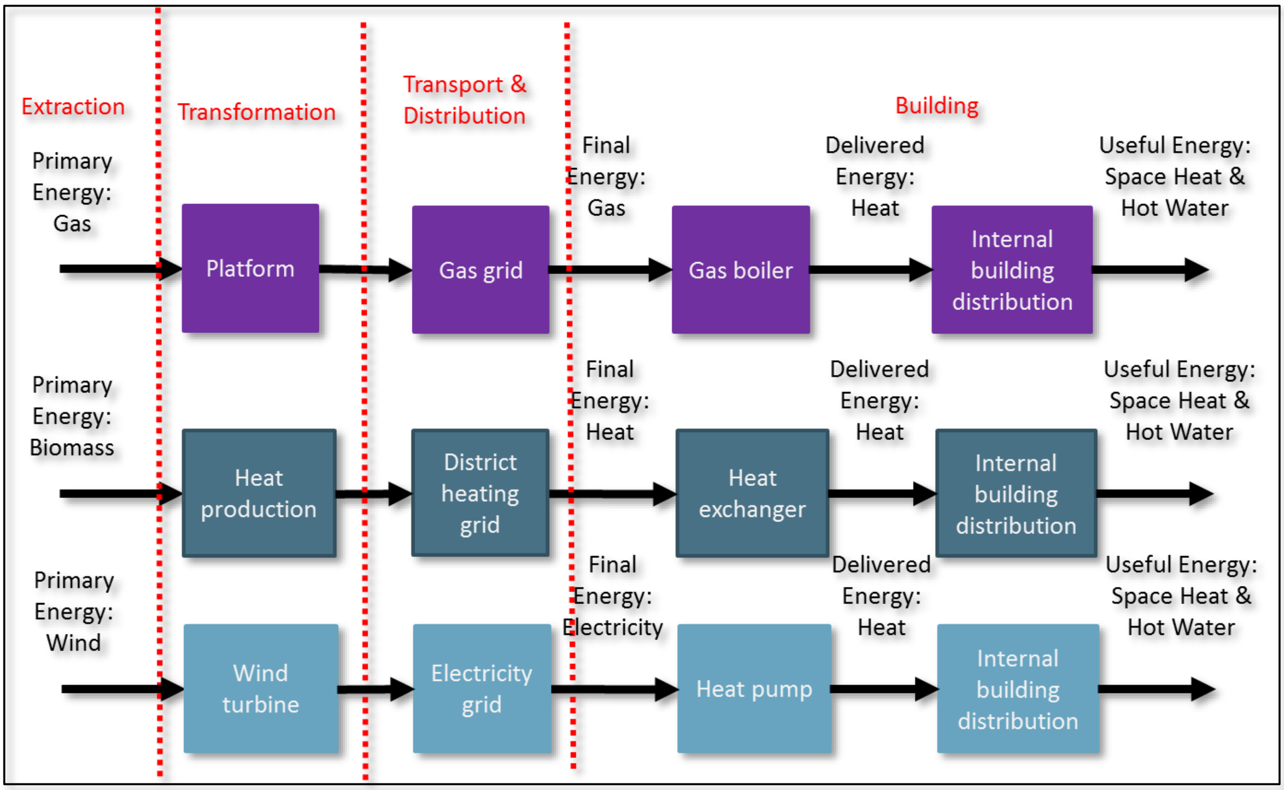


Figure 9. Defining primary energy, final energy, delivered energy and useful energy for several types of building heat supply systems

Socio-economic energy system costs

The aim of Heat Roadmap is to quantify and model energy system scenarios to support public decision making and planning. This reflected in an economic and cost approach that supports a social perspective. This allows for the development and design of a future scenario without sub-optimal decision making based on current market design, an assessment and evaluation of what the system would look like for society at large, and a direction for where public funding and policy should be steering towards. For more information on the economic approaches in HRE4, see Deliverable 5.4 [23].

A social discount rate of 3% is considered in the cost reporting of the scenarios. Where only one year is modelled, discount rates are used to annualise costs, rather than for intertemporal decision making. Given that the scenario development in HRE4 is primarily aimed at understanding how decarbonised energy systems can be designed and planned, there is an inherent implication that the future is afforded importance and the time value of money is low. The social and planning approach means that risk premia are kept low since there is an assumption that risks can be spread over both society at large and all the different technologies in the system. The consideration of access to capital in HRE4 is also based on the removal of explicit barriers to access capital for energy efficiency, and through improved knowledge and access to data also the removal of other barriers to decision making.

In the HRE4 scenarios, the scope of the costs considered is relatively expansive, covering the heating, cooling, electricity, transport, and industry sectors. This means that the costs reported for the energy systems cover not just the heating and cooling system but the other sectors too. Because of this in the scenarios there are costs for e.g. vehicles, fuel production technologies, or hydrogen storage too – even though these do not fall under the direct scope of HRE. However, in order to have an integrated approach and understand the role of a redesigned heating and cooling system within the wider energy system, the inclusion of these costs is necessary.

In terms of the built environment, costs to that are specifically related to energy savings are included, but not the cost of the general renovation itself. For example, if a wall is treated to be insulated at a higher standard, the additional insulation material is accounted for, but the finishing of the walls (which is expected to happen within the context of natural, non-energy related renovations) is not. For more information on the cost curves for heating and cooling demand reductions in the built environment and industry, see Deliverable 4.2 & 4.3 [4].

The energy system cost calculation assumptions used in the Heat Roadmap scenarios include a range of technology costs for the years 2015 and 2050. Most of these technologies and their corresponding costs are direct inputs to the EnergyPLAN tool which is used for the energy system analyses in HRE4. A comprehensive list of the technologies included as inputs in the latter can be found in [24]. From this list, the costs of certain technologies were prioritized, as seen in Deliverable 6.2 [25], according to their relevance and level of impact in the future heating and cooling scenarios. The cost data for each of the technologies in question included three main input parameters:

- Specific investment costs – generally defined as the total investment cost for a technology unit over the unit's capacity.
- Fixed operation and maintenance – defined as a percentage of the investment cost.
- Lifetime – i.e. technical lifetime of the technology, in order to be able to discount and annualise these costs.

In addition to the technologies listed in [24,25], costs specifically related to the HRE4 scenarios and not explicitly defined in the EnergyPLAN tool were also included as additional inputs to the model. These inputs correspond to the cost estimates for heat and cold savings from Deliverables 4.2 and 4.3 [4]; additional electricity grid capacity for heating, district heating and cooling infrastructure and substations from Deliverables 2.2 [26] and 3.2 [15]; and individual cooling units and district cooling chiller plant costs from Deliverable 3.2 [15]. Since these are based on more thorough analysis than the other energy system costs in HRE4, these are separated and used in detail by the EnergyPLAN model.

In addition to the technologies listed in [24,25], costs specifically related to the HRE4 scenarios and not explicitly defined in the EnergyPLAN tool were also included as additional inputs to the model. These inputs correspond to the cost estimates for heat and cold savings from Deliverables 4.2 and 4.3 [4]; additional electricity grid capacity for heating, district heating and cooling infrastructure and substations from Deliverables 2.2 [26] and 3.2 [15]; and individual cooling units and district cooling chiller plant costs from Deliverable 3.2 [15]. Since these are based on more thorough analysis than the other energy system costs in HRE4, these are separated and used in detail by the EnergyPLAN model.

The cost database that is used for the Heat Roadmap scenario development and assessments is part of the data that was created in the HRE project that can support other researchers and decision makers. It is available from the EnergyPLAN website.

Compared to previous instalments, it provides an updated cost on many technologies like heat pumps, solar thermal, excess heat recovery, and cooling appliances among others. In addition, it is differentiated between the 14 EU countries studied to both reflect the nature of the EU common market, but also the differences in local markets and prices.

The cost of each of the main technologies considered can vary substantially from one country to the next. Thus, the methodology developed in Deliverable 6.2 [25] for deriving country-specific costs was applied to the reference costs from the EnergyPLAN cost database. This allowed to differentiate the costs in the base region, obtained from the database, to the costs in other target countries based on the target country's labour costs, and the labour share from the total investment costs for each technology. It should be noted, as mentioned in Deliverable 6.2, that this methodology does not address uncertainties related to a given technology such as having a comparably high market share in the base region and thus reduced component costs in that specific location. It neither differentiates countries' learning curve cost reductions, nor does it account for convergence under the European single market since it uses the same differentiation of labour costs between the 14 EU Member States (MS) in 2015 and 2050. These counteracting limitations mean that there are levels of uncertainty, especially looking towards 2050. However, the methodology does allow for a simple and replicable differentiation between costs of technologies between countries, and has been reviewed extensively by the partners and Advisory Board in order to best approximate current differences.

Precautionary principles and use of proven technologies

Modelling and designing energy systems, both in simulation and optimisation tools, involves following a heuristic approach to determine the kind of technologies to be included; how they are considered to be able to develop, and what constraints are considered [27]. In the HRE scenarios, the design of systems are not constrained in terms of what kinds of technology choices could be made in the future (allowing for radical technological change and system redesign), but there are some explicit assumptions about what kinds of technologies can be considered. This has an effect on the resulting system design and how the system is decarbonised in the HRE scenarios.

These design choices are mainly based around the use of proven technologies, rather than relying on the radical improvement or innovations of future technologies, and a moderately precautionary principle regarding nuclear and bioenergy usage. This means that the final Heat Roadmaps may represent a radical change compared to the current energy system, but are also conservative scenarios since the technologies necessary to implement this system already exist. This is congruent with the understanding in HRE that the need is not for technological innovation, but for improved knowledge, data, planning practices and policies to ensure that decarbonisation targets are met and markets start transforming.

One of the main assumptions in terms of the technologies that are available in the future is the exclusive use of proven technologies, which are existing, functioning, and well-established in markets today. The most notable result of this is that carbon capture storage (CCS) is excluded as an option, as the carbon is taken as an important resource and carbon capture and utilisation technology was used rather than accounting carbon as a waste product. If CCS is developed in the future, an energy system based on energy efficiency through energy savings, district heating, and heat pumps in rural areas would still be beneficial with regards to reducing the need for energy, reducing the needed (power) capacity [28]. This means that the redesign of the heating and cooling system without CCS would not diminish its feasibility, but does not rely on its approach.

The exclusion of CCS means that decarbonisation has to happen by effectively removing the fossil fuel share from the primary energy mix, and supplying energy through renewable resources. For the remaining technologies, some learning and improvements are considered, but the measures and technologies that are considered in the Heat Roadmap scenarios are all relatively well developed and market mature in different parts of the European energy system.

Regarding biomass, there are several reasons why a precautionary approach to bioenergy reliance could be justified. Firstly, one of the key advantages of an energy system with a higher level of renewables for Europe would be an improvement to the balance of payments through the reduced importation of fuel. If bioenergy is imported, this negates this benefit, and might contradict energy-security objectives. However, the main concern is that over-use of bioenergy in order to decarbonise the energy system will have sustainability implications. Bioenergy can reduce the use of fossil fuels and contribute to environmental sustainability, but other environmental impacts that come from bioenergy may be of concern.

Additionally, a reduction of CO_2 also includes reductions in the agriculture, forestry, and land-use sectors. When considering the appropriate level of bioenergy, land-use changes need to be considered in order to understand the real contribution bioenergy can make to reducing greenhouse gas emissions [29]. While these interactions are not directly within the scope of the HRE project, they do provide an impetus to avoid the use of bioenergy where possible. For this reason, the design of the HRE scenarios does not seek to minimise bioenergy use exclusively, but does not exceed the use of biomass from the conventionally decarbonised energy system. This is constrained by the current LULUCF regulation, but further developments are expected [29]. This means that a more precautionary approach may be appropriate in future research.

Additionally, a reduction of CO_2 also includes reductions in the agriculture, forestry, and land-use sectors. When considering the appropriate level of bioenergy, land-use changes need to be considered in order to understand the real contribution bioenergy can make to reducing greenhouse gas emissions [29]. While these interactions are not directly within the scope of the HRE project, they do provide an impetus to avoid the use of bioenergy where possible. For this reason, the design of the HRE scenarios does not seek to minimise bioenergy use exclusively, but does not exceed the use of biomass from the conventionally decarbonised energy system. This is constrained by the current LULUCF regulation, but further developments are expected [29]. This means that a more precautionary approach may be appropriate in future research.

Nuclear is not expanded beyond that which is expected to be developed under current policy and objectives within the Baseline towards 2050 and HRE 2050 includes nuclear at a lower level compared to today. Using the current or a lower level would not change the recommendation in HRE 2050. While nuclear is a proven technology in the sense of having been applied, its relationship to sustainable energy is not unequivocal [30].

The second concern is that while carbon free, the uranium required for nuclear energy is in its essence not renewable, and sea water and lower grade source extraction is not considered mature. In addition, spent fuel and high-level waste remain problems which have been largely unaddressed [31,32]. Since the underlying objective of the HRE approach is not to design an energy system that can eventually enable a 100% renewable energy system, it is contradictory to rely on higher levels of nuclear energy in 2050.

The approach is to design a system that shows how we can reach decarbonisation using existing technologies, that does not stand in the way of an eventual transition to a

100% renewable energy system for a no-regret pathway. If technologies like CCS or new energy sources do emerge, these can then contribute to decarbonisation at faster rates or less cost, but if they do not develop the decarbonisation of the energy system is still possible. This also aligns to the purpose of the HRE projects, which is not to trigger innovation of technologies, but to encourage the market uptake of existing technologies that can bring us towards decarbonisation.

Model and data development

Energy tools are used to understand, describe, and quantify the impact of potential changes to the energy system. In order to do so, they must consider the right level of detail and accuracy, perspective, timeframe, and time-step. The purpose of the different models in HRE4 is to combine an in depth assessment of the heating and cooling sector, including its spatial nature, with an energy system analysis. Multiple tools are used and in order to be able to provide data and scenarios based on different perspectives and specific approaches. This means that each of the main models has a specific scope, strength, and level of detail that has been aligned in order to develop the Heat Roadmap scenarios (see Table 1). All of these tools have either undergone improvements and enhancements in the process of the modelling in HRE4, or have gotten access to different data and methodologies as part of the coordination and knowledge sharing efforts in this project.

Table 1. Overview of tools

Tool	FORECAST	Peta4	JRC-EU-TIMES	EnergyPLAN
Scope: Sectors considered*	Built environment & industry	Geography of built environment and resources	Heating, cooling, industry, electricity, transport and transformation.	Heating, cooling, industry, electricity, transport and transformation.
Type of model	Optimisation	Spatially explicit regression	Optimisation	Simulation
Timeframe	Evolution: 2015 through to 2050	Single year: 2015	Evolution: 2015 through to 2050	Single years: 2015, (2030) and 2050
Time-step	Annual	Annual	12 time-slices, 24 periods in the power sector	Hourly
Economic perspective	Private end-user	Socio-economic	Mix of socio-economic & private end-user	Socio-economic

There are a variety of overlaps and contrasts in terms of the different models used in HRE4. Peta4 and FORECAST both represent detailed models for the heating and cooling sector exclusively, although with different timeframes and modelling approaches. Much of this detailed heating and cooling data was then aggregated in order to be able to be processed and analysed within the energy system models. FORECAST and the JRC-EU-TIMES have different scopes, but both focus on transitions and drivers through time, through a multi-annual (constrained) optimisation approach. This is particularly important for the Baseline and Conventional Decarbonisation scenarios, since it allows the models to answer what the development of the given sector would be under certain conditions. Particular years can then be analysed in detail.

The JRC-EU-TIMES and EnergyPLAN models both consider the entire energy system, and understand the connections between heating and cooling, the electricity sector. However, they differ in their timeframe and time-step, and due to that also in the level of analysis of the operation of the energy system. Peta4 and EnergyPLAN have very different scopes and modelling objectives, but they are both models that can treat district energy in a way that is more refined than comparable models, and due to their limited time frame can provide a high level of detail and granularity within that. Based on their respective strengths and scopes, the models have been combined in HRE4 with the purpose of coordinating knowledge across leading experts in the full variety of expertise that exists in the heating and cooling sector, to create one set of congruous and meaningful results.

The Pan-European Thermal Atlas (Peta4)

The Pan-European Thermal Atlas has been developed as part of the work in WP2 and is available on the HRE website [33]. The Peta model is a geographic representation of heating and cooling demands in the 14 EU Member States included in the project. Peta 4.2 also includes excess heat potentials, prospective district heating networks an availability of renewable energy sources: geothermal, solar irradiation and biomass.

The Pan-European Thermal Atlas (Peta) is an interactive map that can be used for district energy planning. For HRE4, an updated version was created that models heat demands to the hectare level, and identifies continuous heat and cold demand areas that have potential for district energy. In addition, Peta spatially identifies (sustainable) resources like geothermal, solar thermal, excess heat, biomass, and heat for heating and cooling, and allows for efficient allocation to the local potential DH areas.

The reason for including all of this information is that the main aim of Peta is to map and quantify the spatial distribution of the significant elements that constitute the European heating and cooling market. Mapping out both demands and resources enables e.g. to identify key regions that are feasible for district heating and cooling. Mapping like this has to some extent been done in previous HRE studies, but not to the same detail as in Peta 4.2. Another important aspect is that by having a spatial explicit model of demands and resources, allows resource economic analysis to be made, which are further used as inputs for the energy system analyses.

In relation to the resource atlases, some of the maps comes from other European projects. The geothermal potentials are from the GeoDH project, the biomass data is from the BioBoost project, the solar district heating potential is from the IEA task 52.

For additional information, please refer to the technical report "Methodologies and assumptions used in the mapping" under Deliverable 2.3: A final report outlining the methodology and assumptions used in the mapping [34].

FORECAST

The Forecasting Energy Consumption Analysis and Simulation Tool (FORECAST) is a modelling platform that aims to develop long-term scenarios for future energy demand of individual countries and world regions until 2050. Based on a bottom-up modelling approach, considering the dynamics of technologies and socio-economic drivers, the model allows to address various research questions related to energy demand including scenarios for the future demand of individual energy carriers, calculating energy saving potentials and the impact on greenhouse gas emissions, as well as abatement cost curves and ex-ante policy impact assessments.

The Forecasting Energy Consumption Analysis and Simulation Tool (FORECAST) is a modelling platform that aims to develop long-term scenarios for future energy demand of individual countries and world regions until 2050 using a bottom-up modelling approach. It considers the dynamics of technologies and socio-economic drivers.

In HRE the delivered baseline is calculated using the bottom-up tool FORECAST [35]. A more detailed description of the FORECAST tool is presented in the annex of Deliverable 3.3 and Deliverable 3.4 [36] and a guide for lead-users is presented in Deliverable 3.5 [37]. The heating and cooling profiles for the 14 MSs for 2015 following the FORECAST method is presented in Deliverable 3.1 [38]. The way in which FORECAST is combined with the other modelling tools is described in Deliverable 5.1 [39].

JRC-EU-TIMES

The JRC-EU-TIMES tool optimises on an annual level focusing somewhat on the investments over years and decades. It models technologies uptake and deployment and their interaction with the energy infrastructure including storage options in an energy systems perspective. It is a relevant tool to support impact assessment studies in the energy policy field that require quantitative modelling at an energy system level with a high technology detail.

The JRC-EU-TIMES model is designed for analysing the role of energy technologies and their innovation for meeting Europe's energy and climate change related policy objectives.

Both JRC-EU-TIMES [40] and EnergyPLAN [41] develop heating and cooling scenarios. They deal with different aspects of the energy system differently. The methodologies and scenarios developed by the JRC-EU-TIMES model and EnergyPLAN are compared in Deliverable 6.3 [42]. In Deliverable 5.2 [43], a baseline annual evolution of the EU energy system was created up to 2050. The way in which JRC-EU-TIMES is combined with the other modelling tools is described in Deliverable 5.1 [39].

EnergyPLAN

EnergyPLAN is an hourly simulation tool of the entire energy system that enables to identify the potential synergies between different energy sectors. EnergyPLAN is a deterministic model that considers different resources, storages and conversion technologies in order to meet the demand at any point in time. The most relevant model outputs are capacities for various technologies, their hourly interactions and resource demands, and the annual sums for the total primary energy used, the amount of CO_2 emissions resulting from the energy system operation, and the different costs. The model enables the assessment of how efficient and decarbonized the energy system is. For more information see the EnergyPLAN website [41].

In order to simulate the hourly operations of the energy systems, hourly distributions are developed for different demands and resources. Time series that have been specifically developed for HRE4 are detailed in Table 2. For more detailed information on the methodology behind the hourly distributions, see Annex 4 of Deliverable 5.4 [23].

EnergyPLAN is a deterministic model, which optimises the operation of a given energy system on the basis of inputs and outputs defined by the user and simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. The main purpose of the EnergyPLAN tool is to analyse the energy, environmental, and economic impact of various energy strategies, with the focus placed on the future energy system and how that will operate, rather than on today's energy system. Therefore, it includes relatively detailed modelling of future technologies, but relatively aggregated modelling of today's technologies such as power plants.

Table 2. Time series data and sources

	Time series	Sources used	HRE4 Countries
Demand Data and Net Electricity Import	Electricity demand	ENTSOE-E Transparency Platform [44]	All
	Heating demand	Meteonorm [45], The Global Renewable Energy Atlas from Aarhus University [46,47]	All
	Cooling demand	Meteonorm [45]	All
	Transport demands	Stratego [48], MATSim [49]	All
	Net Electricity import	ENTSOE-E Transparency Platform [44]	All
Supply Data	Offshore wind	Meteonorm [45], The Global Renewable Energy Atlas from Aarhus University [46,47]	All excluding AT, CZ, and HU (land locked).
	Onshore wind		All.
	Photovoltaics		All
	Solar thermal		All
	Run-of-river hydro	Meteonorm [45], ENTSOE-E Transparency Platform [44]	All
	Reservoir hydro		All excluding HU and NL (no capacity considered). For RO, FI, and SE constructed values are used.
	Nuclear	ENTSOE-E Transparency Platform [44]	Only for BE, CZ, DE, ES, FI, FR, HU, NL, RO, SE, UK.

The most important time series in terms of developing the energy system simulations for HRE4 are heating demand and cooling demand. Space heating demand has been modelled based on a heating degree hour analysis carried out by Aarhus University with a base temperature of 17°C (see Figure 10). It is assumed for all countries that there is no space heating demand during June, July and August. In order to obtain the individual heating demand from space heating demand, domestic hot water usage is added to the series. Where relevant, in order to obtain the hourly district heating demand from the individual heating demand, grid losses are taken into account. Where space heating savings have been applied, for both individual and district heating, time series corresponding to savings in space heating have been computed to ensure the balance between space and domestic hot water is reflected accurately.

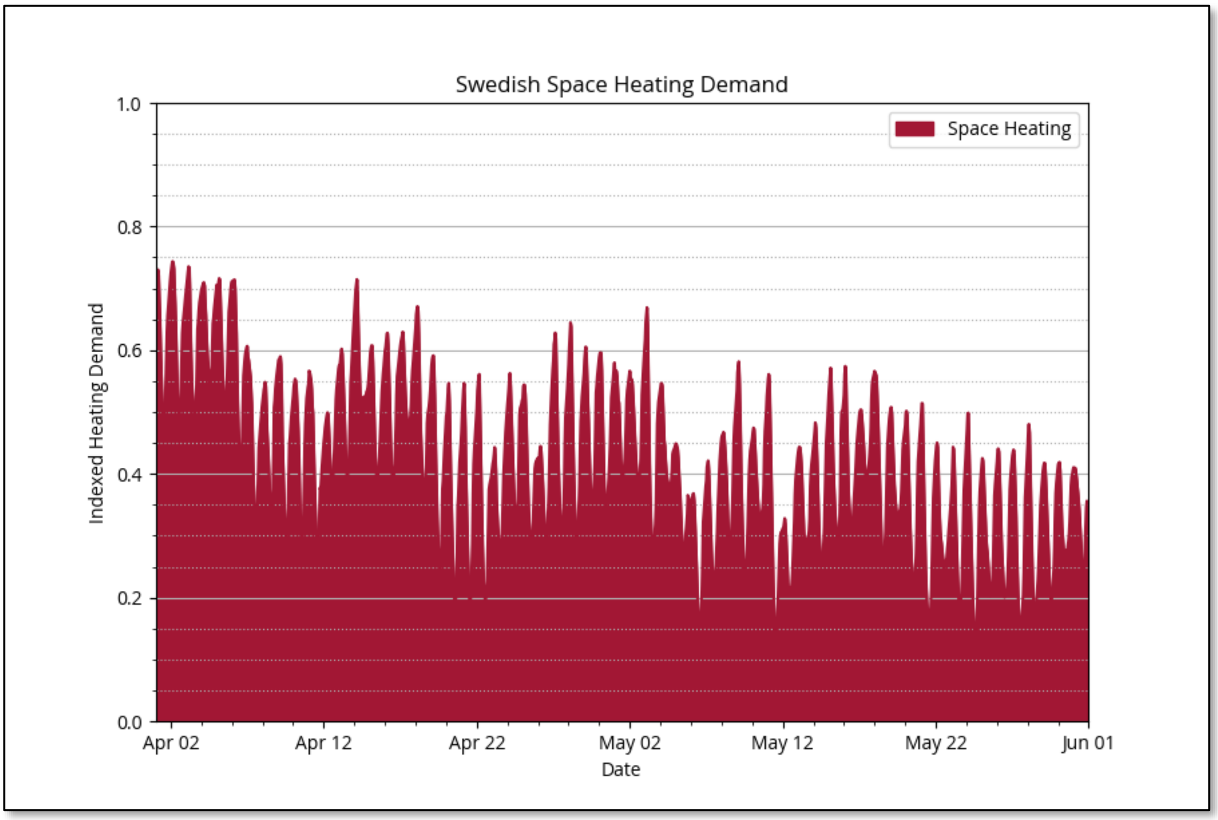


Figure 10: Hourly distribution for Swedish space heating demand for a 2 month period.

The time series for cooling demands (where not covered in electricity) are developed similarly to the district heating time series: First, a cooling degree hour analysis with a set temperature of 16 is carried out, after which a weather-independent constant cooling baseload is added, corresponding to process cooling, kitchens, data centres etc. As with heating, where district cooling is relevant grid losses are considered within the hourly time series for the cooling production units and where savings apply the normalised baseload is adjusted.

The additional time series are developed in order to be able to simulate the energy system as a whole. The time series for new electricity demands are adjusted to the developments in total electricity demand, but not analysed in terms of reductions in sub-demands. The distributions for the supply data are necessary in order ensure that the demands of the energy system are met, and model the operation. Time series are specifically not developed exogenously for power plants, CHPs, boilers, heat pumps (large and small) and other conversion technologies whose resources are not directly dependant on the weather and climate. Instead, the operation of these are modelled as a response to the hourly demands and variable renewable energy sources.

Data flows between the models

In terms of the exchange and flows of data concerned with the combining of different energy models, an overview of the primary data flows can be seen in Figure 11. This data flow set up both allows for the best available data to be used from different expertise, and the heating and cooling sector to be comprehensively modelled in the scenarios [39].

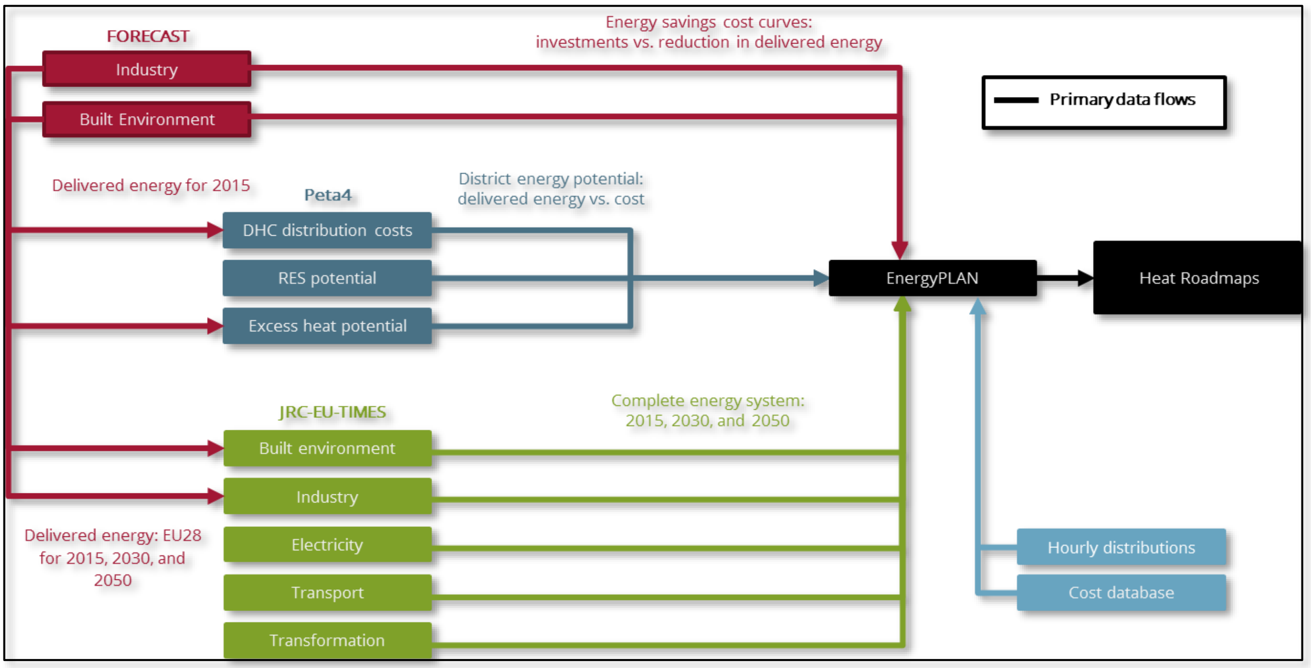


Figure 11. Data flow between the FORECAST, the Peta4, the JRC-EU-TIMES and the EnergyPLAN model.

Scenario development

For each country in HRE4, four main scenarios have been developed to support the HRE strategies. The main approaches and assumptions that underpin these scenarios have been summarised. These scenarios function to represent different, alternative, energy system designs and simulations that can inform the strategies and actions needed to result in a heating and cooling system that can support an affordable, efficient, decarbonised energy system.

Table 3 shows an overview of the main sources of the data for the different energy sectors in the different scenarios. The Baseline includes current policies with regards to savings, renewable energy etc. The CD 2050 scenario is not as the Baseline scenario a direct replication of a JRC-EU-TIMES scenario, but a mix of different sources. In several cases, adjustments have also been implemented to make the scenarios comparable, but this means that the individual values from JRC-EU-TIMES, are not always directly repeated in these scenarios.

Table 3. Main data sources for the different scenarios for the different sectors of the energy system.

Sector	BL 2015/2050	CD 2050	HRE 2050
Thermal demands	JRC Baseline	JRC Baseline	JRC Baseline + HRE4
Heating and cooling	JRC Baseline	JRC Baseline	HRE4
Electricity	JRC Baseline	JRC Baseline and ProRES	JRC Baseline, ProRES and HRE4
Industry and process	JRC Baseline	JRC ProRES	JRC ProRES
Transport	JRC Baseline	JRC ProRES	JRC ProRES

Baseline scenario

The Baseline scenarios (BL 2015 and BL 2050) represent the current situation and the development of the energy system under the currently agreed policies, but without any additional effort to move towards a more decarbonised heating and cooling or energy system. In the long term, the Baseline 2050 is aligned to the EU Reference Scenario of 2016 [50]; however, it includes adherence to the Clean Energy Package measures as proposed in March 2018.

For these reasons, the Baseline scenarios are designed to follow the market developments within the current policy framework and the climate and energy goals which have been set (see Table 4). In practice, this means that the Baseline shows how the energy system and markets would develop without further intervention. The Baseline 2050 includes already substantial energy saving measures compared to today, based on the already agreed policy regarding the energy performance of buildings. For more background and sector- and model-specific assumptions and discussions, see Deliverables 3.3 & 3.4 [36], 5.2 [43] and 6.3 [51].

Table 4. Baseline policy constraints.

	Baseline 2030 policy constraints Clean Energy Package (March 2018)	Baseline 2050 policy constraints
Minimum reduction in primary energy	30% (compared to 1990 levels)	30% (compared to 1990 levels)
Minimum share of RES in final energy:	27%	none
Energy related CO2 reduction	-40%	-49% (compared to 1990 levels)

The purpose of the Baselines is threefold. The first is to function as a reference and comparison point for no further action. This allows for an understanding of what an increased effort, level of investment, and market uptake would mean in general in terms of the performance of the energy system. The second outcome of the Baseline development is the understanding of what the impact of current policy would be on the energy system, with particular regard to the heating and cooling sectors in the 14 EU countries modelled in HRE4. The current policies will entail heat savings of about 25% in the residential sector [4], and the scenario includes a removal of coal boilers and almost all oil boilers in 2050. This can then serve as a starting point of discussion on where additional investments could need to take place, and which markets will develop under current policy frameworks.

For the 2015 Baselines, a key role for the Baseline development has been to serve as a methodological benchmark in the model development and alignment, and ensure validity. Given that 4 main models were used for the scenario development, the making of the Baseline 2015 serves for alignment.

Conventional Decarbonisation scenario

The Conventionally Decarbonised scenario (CD) represents a 2050 energy system under the development of the energy system under a framework that encourages renewables, but does not focus explicitly on increased savings in the heating and cooling sector, and does not drastically change the supply technologies for heating and cooling in comparison to the Baseline for 2050. The Conventionally decarbonised scenario adheres to an 80% reduction in CO_2 levels for the European Union, but relies on a high level of support for variable renewables as a main driver of system change.

Based on this, the CD scenarios are used to replicate what a decarbonised transport and industry sector would look like, and to provide a benchmark for decarbonisation to the Heat Roadmap scenario. Through the Conventionally Decarbonised scenarios, a decarbonised transport and (non-thermal) industry sector can be developed. While these sectors are not the main focus of the HRE, the increased electricity demands from transport and fuel production are important to consider in order to ensure that the redesigned heating and cooling sector takes these into account. For this reason, the elements that relate to the transport sector and fuel production in the Conventionally Decarbonised energy system and the Heat Roadmap scenarios are aligned.

Conversely, the second function is then to compare the design of the energy systems and results to understand the impact of increased energy efficiency and further integration of heating and cooling with the rest of the energy system. The Conventional Decarbonised Scenarios uses the Baseline 2050 development in the heating and cooling sector e.g. in the residential sector the 25% savings, elimination of coal and almost all oil boilers (Table 4). The Conventionally Decarbonised energy system functions as the main point of reference with regards to how the Heat Roadmaps achieve decarbonisation. By comparing the Conventionally Decarbonised scenarios with the HRE scenarios, it becomes possible to make a valid analysis regarding if a system with higher levels of energy efficiency contribute towards a further decarbonisation. Through this, it is possible to consider to what extent the approaches that are taken in the Heat Roadmap scenarios are effective, and in which ways a redesigned heating and cooling sector can contribute to the decarbonisation of the energy system within the context of a wider decarbonised energy system. For more background and an methodological review, see Deliverable 6.3 [51].

Heat Roadmap scenarios

The HRE scenarios represent an energy system which is decarbonised, but also has a redesigned heating and cooling sector. The focus on combining savings and efficient supply includes the simulation of a high level of performance of building and deep savings in the industry sector, but also the recovery of otherwise unused excess heat, use of (relatively efficient) renewables like geo- and solar thermal, and the use of heat pumps at both building level (in rural areas) and in district energy networks (in urban areas). This leads to a much deeper interconnection of the heating and cooling sector with the other parts of the energy system (through cogeneration, large heat pumps, individual scale heat pumps) and more flexibility, resulting in the better integration of renewable electricity sources in the wider system.

The HRE alternatives can then be compared based on efficiency (through the primary energy use of the scenarios), decarbonisation (by looking at the resulting CO_2 emissions and renewable energy usage), bioenergy use, and cost. This is a key step in being able to quantify and explain the differences between both the current energy system (through the Baseline 2015), a scenario where no further action is undertaken (through the Baseline 2050) and a conventionally decarbonised energy system.

Scenario design

Based on these design parameters, the developed scenarios represent simulations of energy systems that fulfil the different energy demands for every hour in the year, and stay within the resource limits. Table 5 provides an overview of the resulting installed capacities.

Table 5: Installed capacities for key electricity and heating technologies for the different scenarios.

Sector	Technology	Unit	BL 2015	BL 2050	CD 2050	HRE 2050
Electricity	Concentrated solar power	GWe	-	-	98,77	98,77
	Dammed hydro	GWe	58,98	84,57	84,57	84,57
	Nuclear	GWe	126,73	109,75	24,37	24,37
	Offshore wind	GWe	2,04	76,55	232,45	248,90
	Onshore wind	GWe	68,46	338,55	1287,13	1229,00
	Photovoltaic	GWe	28,76	362,63	1453,00	1421,00
	River hydro	GWe	28,29	28,79	31,66	31,66
	Geothermal plants	GWe	0,62	6,02	7,12	7,12
	CHP plants (electric capacity)	GWe	63,90	77,76	77,76	92,15
	Condensing power plants	GWe	345,97	510,24	1265,24	1202,35
	Wave & tidal	GWe	-	4,71	25,33	25,33
Heating	DH - Heat pumps	GWe	0,41	0,41	0,41	23,75
	DH - Electric boilers	GWe	-	-	-	23,75
	DH - CHP (thermal capacity)	GWth	87,48	87,48	87,48	103,67
	DH - Boilers	GWth	209,95	209,95	195,27	170,44
	DH - Solar thermal	GWth	(0,01)	(15,05)	(4,48)	(11,88)
	DH - Geothermal	GWth	(0,78)	(0,37)	(0,88)	(4,88)
	DH - Waste incineration	GWth	(2,95)	(0,5)	-	(2,59)
	DH - Excess heat from industry	GWth	-	-	-	(10,92)
	DH - Heat recovery from fuel production	GWth	-	-	-	(17,61)
	Indv. heat pumps	GWth	(6,85)	(26,04)	(28,12)	(287,27)
	Indv. boilers	GWth	(927,44)	(449,05)	(449,05)	-

( ) Estimated capacities based on annual production and hourly distributions.

As can be seen, the decarbonised scenarios (including the Heat Roadmap scenarios) have significantly higher levels of capacities for energy provision. These in large part represent the shift away from costs and investments regarding the use of fuels, towards the investment and use of infrastructures and (variable) renewable energy sources.

Since the decarbonised energy systems (both the conventional and Heat Roadmap Europe scenarios) include a very high level of direct electrification of transport and parts of industry and fuel production, the need for power capacity is significantly higher in these scenarios than the baseline scenarios. For the cooling sector, capacities increase to follow increased demands. For heating, However, the efficiency of the Heat Roadmap Europe scenario, the higher level of interconnection between the sectors (which allows for more flexibility) and the use of collective infrastructures like district heating means that the total required capacity in the Heat Roadmap Europe scenarios for the 14 countries is around 5% less. These differences are a result of the different design assumptions and approaches, and are some of the drivers towards the overall performance of the energy system.

Results for Heat Roadmaps

The scenarios and results for HRE represent a technically feasible, economically viable alternative which could contribute to the deep decarbonisation of the European energy system. They consider only proven technologies to achieve reductions in heating and cooling demand, more efficient supply systems, and to integrate a higher level of renewables, and does not rely on unsustainable amounts of bioenergy. Since the HRE4 countries represent 90% of the heat demand in Europe, the results presented here are a very strong indicator for how and where the heating and cooling sector for all European member states should evolve.

The approach is based on combining energy efficiency on the demand and the supply side of the heating and cooling sector and deeper integration, as a way to achieve deep decarbonisation of the sector. Both savings on the heating and cooling demand side are considered in the form of high standards for the energy performance of buildings and renovation rates, and the efficient supply of heating and cooling through heat pumps, efficient chillers, and district heating and cooling. Iterative simulations are done to determine the feasible levels of different types of the main energy efficiency and decarbonisation measures. This redesign of the heating and cooling sector is then integrated with the wider energy system; in particular, the industry and electricity sectors.

Energy savings in the Heat Roadmaps

The overall objective of the HRE 2050 scenario is to consider energy efficiency from both the demand and the supply side of the heating and cooling sector. The inclusion of the two means that it is possible to identify a balance between energy efficiency on the demand side (high building standards and renovations in the built environment and different savings measures for industry) and energy efficiency on the supply side (heat pumps, recovery of local energy in district energy systems, integration of local renewables).

Space heating is, and remains in all scenarios, the largest demand in the thermal sector. However, policy regarding the energy performance of buildings has been extremely ambitious on the European scale, so if current policy is fully implemented, this has an extremely large impact in terms of space heating, which decreases by 630 TWh in the 2050 Baseline. In HRE, an overall further 5% reduction is recommended in addition to those already included in the Baseline, in order to achieve both efficiency on the demand and the supply side of the heating and cooling sector.

Space heating

Looking towards 2050, the current policy is very ambitious regarding space heating. This is represented in the heating and cooling demand levels in the Baseline and Conventionally Decarbonised scenarios. However, growth in demands in other sectors mean that overall, the Baseline does not reduce the energy demand for heating and cooling drastically compared to 2015, representing only a 4% decrease in total energy demanded.

This shows clearly the need to consider the increased efficiency of the heating and cooling sector from in the form of reducing the energy demands for different types of heating and cooling, but also increasing the efficiency and renewability of the energy which is delivered. Energy efficiency on both the demand and the supply side are necessary and need to be combined to cost-effectively achieve decarbonisation goals for the heating and cooling sector.

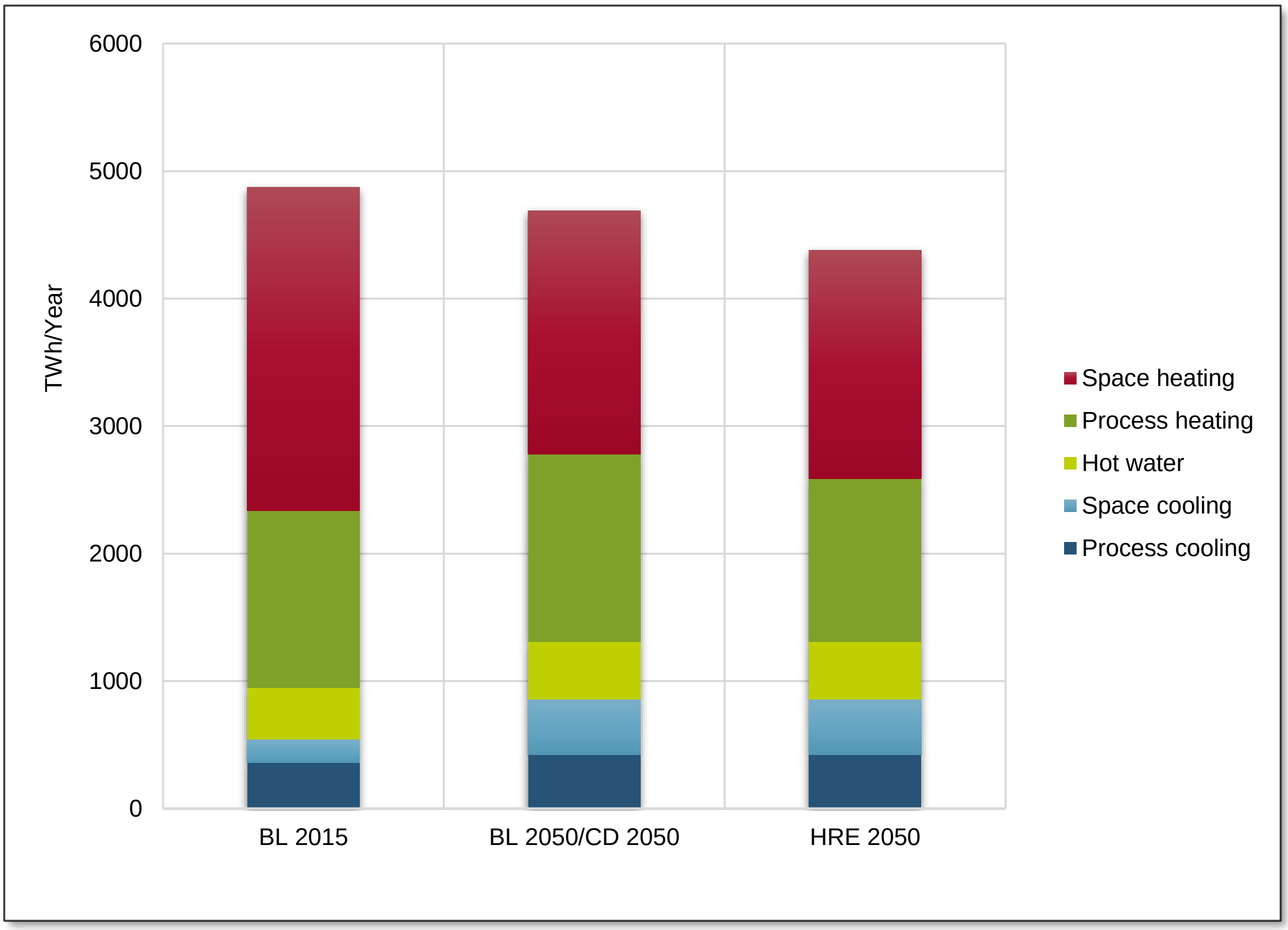


Figure 12. Heating and cooling demands in Baseline, Conventionally Decarbonised and Heat Roadmap scenarios

However, the Baseline scenario looking towards 2050 represents the very ambitious policies that are currently already implemented, particularly with regards to space heating in the residential sector (see Figure 12 above and Table 6 below). In many countries, the currently agreed policy leads to a drastic reduction in residential heating demand which is cost-effective. The development in Baselines and Reference scenarios has two different implications. That which was proposed as radical scenario development less than 10 years ago is now accepted to be possible, assuming the current framework conditions are effective [52]. This also underwrites that framework conditions can be changed, and policy can be passed in order to change what the baseline direction of the heating and cooling sector can be. However, it also emphasises that the focus should now be on implementation of these deep reduction in energy demand, and ensuring that these ambitious policies come to fruition, rather than necessarily driving the standards up even higher.

Table 6. Change in different delivered heating and cooling demands in the Baselines and Heat Roadmap scenarios for 2015 and 2050

	Hot water		Space heating		Process cooling		Process heating		Space cooling		Total	
	BL 2050	HRE 2050	BL 2050	HRE 2050	BL 2050	HRE 2050	BL 2050	HRE 2050	BL 2050	HRE 2050	BL 2050	HRE 2050
Austria	12%	12%	-22%	-31%	18%	18%	12%	-7%	246%	246%	**-1%**	**-13%**
Belgium	44%	44%	-16%	-31%	24%	24%	15%	-4%	52%	52%	**2%**	**-12%**
Czech Republic	14%	14%	-19%	-36%	30%	30%	30%	14%	303%	303%	**6%**	**-8%**
Finland	18%	18%	-16%	-22%	34%	34%	19%	7%	63%	63%	**3%**	**-5%**
France	20%	20%	-29%	-39%	11%	11%	-1%	-19%	229%	229%	**-8%**	**-18%**
Germany	0%	0%	-36%	-42%	-6%	-6%	-2%	-13%	224%	224%	**-18%**	**-25%**
Hungary	7%	7%	-21%	-38%	23%	23%	26%	3%	591%	591%	**4%**	**-12%**
Italy	12%	12%	-14%	-24%	22%	22%	6%	-12%	99%	99%	**8%**	**-1%**
Netherlands	10%	10%	-19%	-32%	16%	16%	23%	11%	87%	87%	**4%**	**-7%**
Poland	-10%	-10%	-30%	-45%	27%	27%	20%	5%	395%	395%	**-5%**	**-18%**
Romania	10%	10%	-21%	-37%	11%	11%	18%	3%	311%	311%	**6%**	**-8%**
Spain	16%	16%	-6%	-18%	17%	17%	-7%	-24%	112%	112%	**18%**	**9%**
Sweden	34%	34%	-18%	-23%	46%	46%	6%	-10%	63%	63%	**1%**	**-7%**
United Kingdom	17%	17%	-25%	-29%	68%	68%	-5%	-18%	79%	79%	**-9%**	**-15%**

In HRE4, the right level of heat savings is sought by doing a sequential analysis in the simulation tool using increasing levels of both heat savings and district heating, and creating a matrix with the varying levels, rather than taking the different measures in steps. This approach represents a departure from previous Heat Roadmaps, where different levels of savings and different levels of heat supply were considered sequentially [53], but better describes the synergies and trade-offs between the two. Based on this analysis, a better balance between reducing energy demand and supplying (sustainable) energy efficiently can be made. Based on this perspective, the level of energy savings is determined by comparing increasing levels of additional delivered energy savings within the context of varying levels of (highly efficient) heat pumps and district energy.

Table 7. Delivered heating and cooling demands by sector in the different scenarios for 2015 and 2050.

Industry	**Unit**	**Hot water**	**Space heating**	**Process cooling**	**Process heating**	**Space cooling**	**Total**
BL 2015	TWh	-	298,3	164,8	1341,5	37,4	1842
BL 2050/CD 2050	TWh	-	255,8	194,5	1434,5	45,3	1930,1
HRE 2050	TWh	-	222,5	194,5	1248,1	45,3	1710,4
BL Change 2050/2015	%	-	-14%	18%	7%	21%	5%
HRE Change 2050/2015	%	-	-25%	18%	-7%	21%	-7%
Residential	**Unit**	**Hot water**	**Space heating**	**Process cooling**	**Process heating**	**Space cooling**	**Total**
BL 2015	TWh	344,1	1649,8	-	-	38,7	2032,6
BL 2050/CD 2050	TWh	386,3	1230,4	-	-	190,4	1807,1
HRE 2050	TWh	386,3	1230,41	-	-	190,4	1807,1
BL Change 2050/2015	%	12%	-25%	-	-	392%	-11%
HRE Change 2050/2015	%	12%	-25%	-	-	392%	-11%
Tertiary	**Unit**	**Hot water**	**Space heating**	**Process cooling**	**Process heating**	**Space cooling**	**Total**
BL 2015	TWh	58,2	591,4	194	46,8	109,4	999,7
BL 2050/CD 2050	TWh	61,5	423,7	226,5	38,4	202,1	952,3
HRE 2050	TWh	61,5	338,98	226,5	30,72	202,1	859,9
BL Change 2050/2015	%	6%	-28%	17%	-18%	85%	-5%
HRE Change 2050/2015	%	6%	-43%	17%	-34%	85%	-14%
Grand total	**Unit**	**Hot water**	**Space heating**	**Process cooling**	**Process heating**	**Space cooling**	**Total**
BL 2015	TWh	402	2539	359	1388	186	4874
BL 2050/CD 2050	TWh	448	1910	421	1473	438	4690
HRE 2050	TWh	448	1791,91	421	1278,77	437,9	4377
BL Change 2050/2015	%	11%	-25%	17%	6%	136%	-4%
HRE Change 2050/2015	%	11%	-29%	17%	-8%	136%	-10%
Difference between BL 2050 and HRE 2050 compared to 2015	**%**	**0%**	**-5%**	**0%**	**-14%**	**0%**	**-6%**

The 60 simulations of energy systems presented in each matrix are designed to be operational (in the sense that they can provide the energy demanded in every hour of the year), so they include the costs required for the electricity production for the heat pumps and supply technologies for the district heating systems. The district heating systems are generally supplied by the available renewables (between 5 and 10%), large heat pumps and cogeneration (around 30% each), around 25% of excess heat from industry and fuel production, and the remainder through boilers. This is because the matrices do not represent fully optimised scenarios for each point, but represent operational acceptance based on a typical merit order. In this way, there have not been any optimisations towards the design of the district heating and electricity systems, but they are designed to cover the full investment costs of all the generation and supply technologies that occur in the Heat Roadmap scenarios.

The iterations of district heating exclude areas where technical feasibility of district is challenging and assume the remainder of the heat demand is provided by (highly efficient) heat pumps. This also means that the top, where no other type of heat supply is introduced, represent a fully electrified scenario for the heating supply system. The level of savings for the residential sector is considered in addition to the ambitious policy ambitions that currently exist.

Table 8. Energy Efficiency Matrices: Relationships between heat savings and supply for France, Germany and the Czech Republic (continues on next page).

France: total energy system costs (M€/year)		**Residential sector space heating savings (additional to a 30% reduction already in the Baseline)**					
		0	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	175532	175582	175266	175452	175883	175978
	5%	175219	175263	174932	175104	175529	175608
	11%	174875	174898	174548	174699	175099	175162
	18%	174566	174570	174197	174329	174706	174752
	26%	174327	174317	173922	174037	174394	174418
	34%	174197	174168	173752	173852	174191	174200
	42%	174190	174142	173709	173789	174107	174101
	51%	174400	174334	173878	173940	174240	174216
	59%	175121	175038	174562	174604	174885	174844
	68%	176559	176454	175961	175986	176246	176185
	79%	185911	185790	185275	185282	185524	185443

Germany: total energy system costs (M€/year)		Residential sector space heating savings (additional to a 35% reduction already in the Baseline)					
		0	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	311635	311779	312185	312795	314351	317562
	5%	310714	310842	311250	311858	313419	316605
	12%	309495	309623	310017	310633	312186	315364
	20%	308139	308268	308656	309254	310787	313979
	30%	306730	306865	307242	307845	309366	312539
	39%	305518	305624	305997	306592	308100	311271
	49%	304485	304600	304960	305555	307073	310248
	58%	303700	303817	304177	304763	306276	309446
	68%	303444	303548	303887	304477	305968	309141
	78%	303994	304110	304431	305017	306506	309669
	90%	312788	312911	313230	313814	315289	318451

Czech Republic: total energy system costs (M€/year)		Residential sector space heating savings (additional to a 20% reduction already in the Baseline)					
		0	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	23407	23344	23328	23341	23369	23287
	4%	23384	23320	23302	23314	23340	23255
	10%	23322	23258	23235	23246	23271	23185
	18%	23245	23177	23154	23163	23186	23097
	26%	23165	23096	23071	23077	23099	23008
	34%	23086	23014	22988	22994	23013	22920
	42%	23041	22967	22940	22943	22959	22866
	51%	22995	22920	22890	22891	22905	22811
	59%	22997	22921	22890	22889	22902	22806
	68%	23091	23012	22979	22976	22987	22889
	78%	24032	23952	23917	23912	23922	23822

The matrices shown in Table 8 represent several of the different results that were found when comparing residential heat savings with different levels of district heating or heat pumps. For the purpose of modelling in the Heat Roadmap scenarios, the level of heat savings and the balance between district energy and individual solutions is chosen using the lowest value in the array. This analysis allows for the comparison of both increased levels of savings and various levels of heat pumps and district heating simultaneously, and a better analysis of the impact of energy efficiency on both the demand and the supply sector simultaneously, rather than sequentially.

However, one of the first observations from the matrices is that in terms of total energy system costs, the differences are not that great. Using a margin of 0,5% of the annualised total energy system costs, it becomes clear that the sensitivities are relatively high, and there are various levels of district energy and energy savings that can contribute to the decarbonisation and increased competitiveness of the energy system.

For most countries, it is clear that there are cut-off points for both heat savings and district energy, after which costs increase. France and Belgium (and to an extent the Netherlands) are the only two countries which have relatively small ranges, and show cut-off areas on all sides of the area with the largest advantages. This means that while the differences are not that large, both over- and under investments in both district heating and space heating measures are possible.

For most countries, the trends resemble the one shown for Germany. In the case of district heating in Germany, implementing more than 49% leads to an increase of costs. Considering different levels of savings, the optimal level of district heating for the residential sector should then be in the range of 49% of the heat market. For heat savings in the residential sector, most countries also display a similar cut-off to Germany after a certain level of heat savings. In Germany, the cut-off occurs after an additional 10% savings on top of the full implementation of current policy, which represents about a 30% reduction in space heating demands compared to 2015. Beyond this, the cost of implementing further savings does not pay off on comparison to the cost of supplying efficient and sustainable heat.

This means that in many countries the challenge in terms of space heating does not lie in the level of ambition of the current policy, but much more in its implementation and realisation. To achieve close to 30% reduction over all the countries modelled in HRE4, both renovation rates and renovation depths have to be increased and the efficacy of the existing policies constantly monitored and reviewed. Without this, decarbonisation becomes both technically more limited (especially in rural areas) and is likely to come at a higher cost.

The exceptions to this trend are the Czech Republic, Hungary, Poland, and Romania. In these countries, the heat savings for the residential sector that are most viable are the highest levels that were considered within the HRE4 project. In all these countries, the heat demand that remains after the already ambitious policy could be cost-effectively reduced by a quarter further. For these specific countries, it may be interesting to conduct further investigation into measures that could be brought to market to contribute to even further heat demand savings. More importantly, for these countries it becomes clear that in addition to implementation, more ambitious targets are needed. This indirectly raises the need for each country to develop goals and active policies to support the implementation of infrastructures for heating and cooling within the individual member states' own contexts.

Process heating and hot water demands

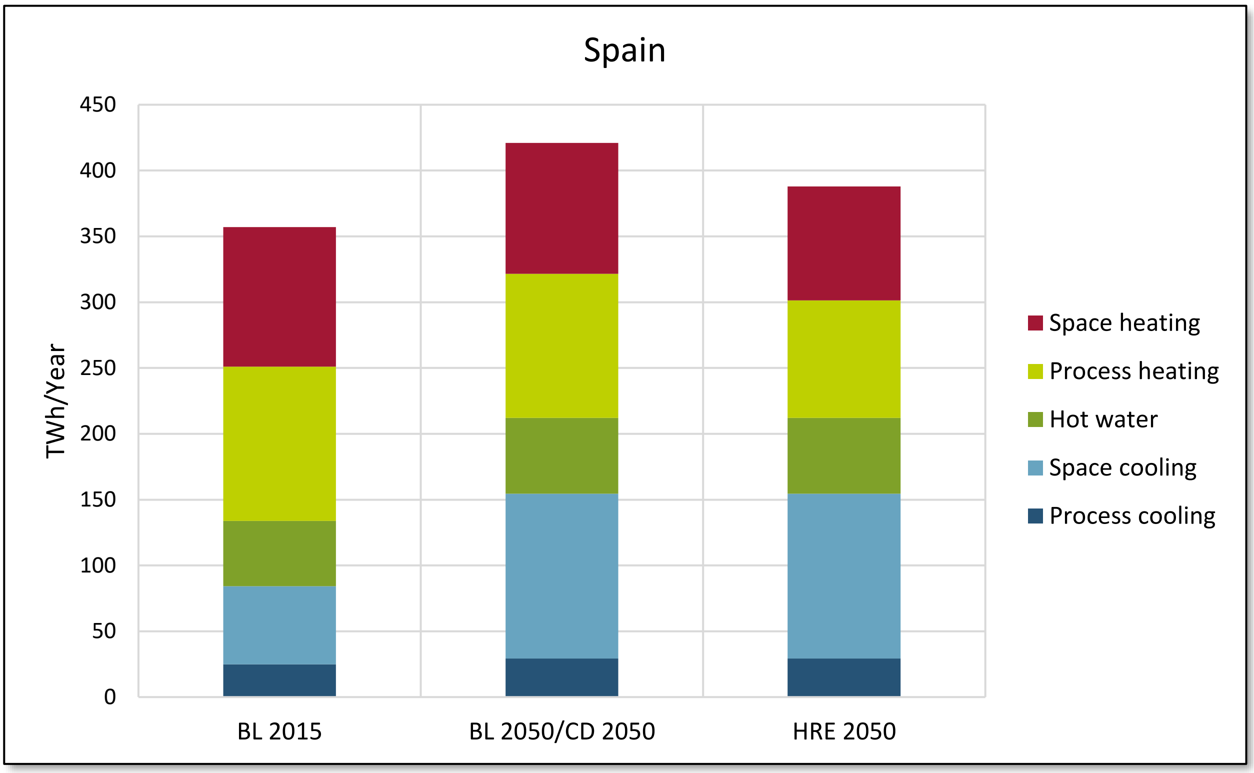
Process heating represents the second largest demand, the overwhelming majority of which is used by the industry sector in Europe. Since current policy has focussed mostly on space heating demands, under current policy savings in terms of process heating and hot water demands are not expected, and absolute demand for hot water and process heating will rise by around 11% and 6% respectively. In this way, HRE4 shows that there is a lack of policies addressing savings in the remaining sectors, and that industrial heating demands need to be addressed in order to decarbonise the whole heating and cooling sector.

In terms of the potential for savings in process heating, additional measures are necessary since all possible considered savings beyond the current policy projections are socio-economically feasible and desirable. In HRE 2050, that means that there should be savings of around 14%, in order to ensure the most cost-effective decarbonisation of the heating and cooling sector. Since these measures are in many ways more diverse than those for space heating (in many cases addressing different temperature levels in different industrial processes), the incentive framework needs to be carefully designed in order to capitalise on this potential.

Hot water demands represent around 10% of the thermal energy demand in Europe, meaning that while significant for the residential sector they do not represent a very large part of the sector overall. Since demands are much more driven by behaviour and population, and measures to building envelopes or processes are difficult. For these reasons, the ability to apply savings in this sector is relatively low and an overall growth of around 11% is expected between now and 2050 in the HRE scenario.

Cooling

Cooling, both in terms of space and process cooling, is the fastest growing part of the heating and cooling sector, but is not expected to represent more than 20% of the heating and cooling sector in Europe in 2050. Even in the warmer countries in Europe, cooling demand do not grow above heating demands.



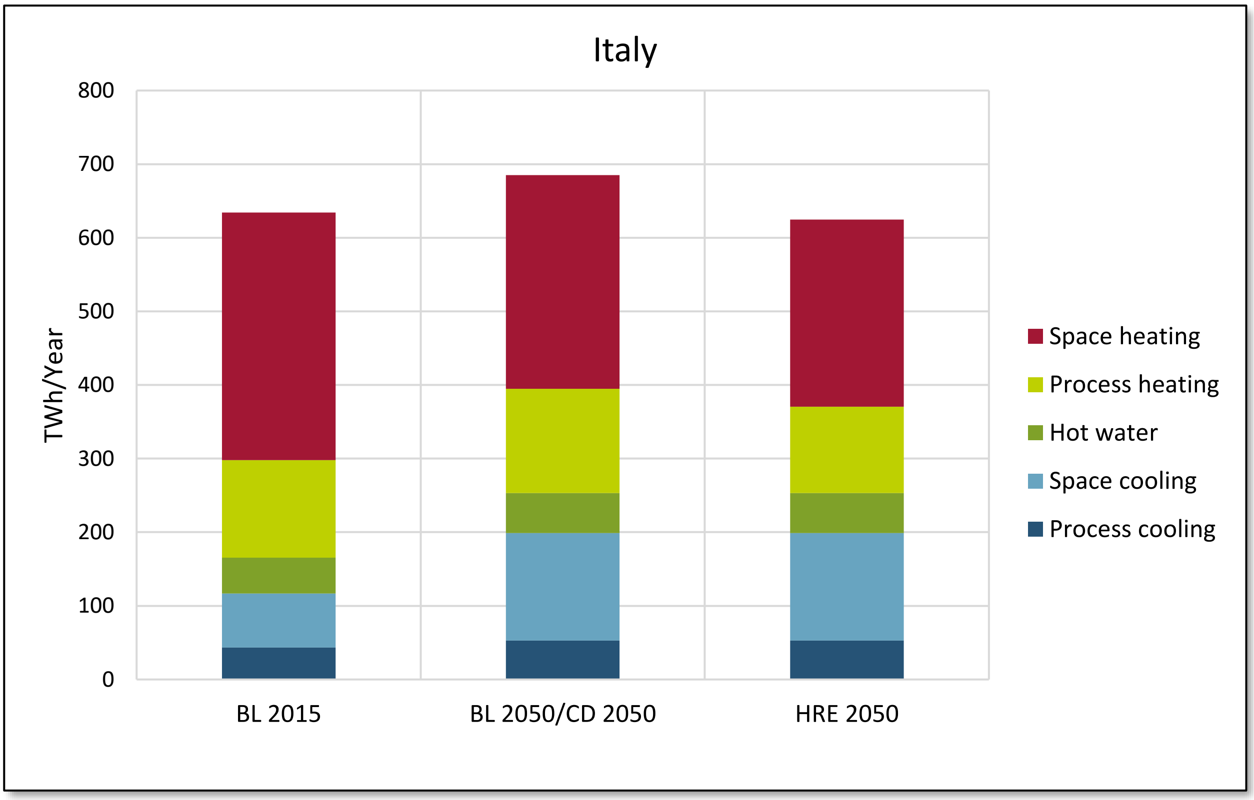


Figure 13. Relative types of heating and cooling demands for the Baseline, Conventionally Decarbonised and Heat Roadmap scenarios for Spain (above) and Italy (below).

Current space cooling demands are also presented in [54,55], while district cooling is available in [56]. Space cooling is expected to more than double towards 2050 (from 186 to 438 TWh), the majority of which in the service sector (which includes among others offices, hospitals, schools, and commercial buildings). In terms of space cooling in the residential sector a five-fold increase is expected, but in absolute terms less than 44% of the 2050 demand is expected to be in the residential sector. At the same time, process cooling in industry is also expected to grow slightly, representing around 4% of the total heating and cooling demand in the HRE 2050 scenario. This means that while the growth for demand is very high (especially compared to space heating, where extremely substantial reductions in demand are considered for 2050), the heating and cooling sector overall is still dominated by space and process heating.

In addition, cooling is also typically produced very efficiently, so the potential for savings is not very high. No additional level of demand reductions (other than passive measures), either for space or process cooling, is considered to be socio-economically viable at a system level when compared to the investment costs of implementing such savings. However, less high confidence level than heating so further work is needed, especially to further explore how heat savings interact with increased cooling demands.

Supply technologies and energy carriers

In addition to energy savings on the demand side of the heating and cooling sector, more efficient supply solutions have been implemented in the Heat Roadmaps. For this, the main measures in the HRE 2050 scenarios have been the implementation of district energy, including also the recovery of otherwise unused excess heat, use of (relatively efficient) renewables like geo- and solar thermal, and the use of heat pumps at both building level (in rural areas) and in district energy networks (in urban areas). This leads to a much deeper interconnection of the heating and cooling sector with the other parts of the energy system (through Cogeneration, large heat pumps, individual scale heat pumps) and more flexibility, resulting in the better integration of renewable electricity sources in the wider system

District heating in urban areas

The costs of implementing district energy and the resources available to the district energy systems are based on spatial modelling, in order to better understand the local nature of both thermal demands are resources, and account for the infrastructure costs and losses that are necessary to transport thermal energy. The least-cost level is identified using same iterative modelling described to determine the optimal level for energy savings.

Providing half of the heating demand in the HRE4 countries reduces the primary energy demand and CO_2-emissions. Considering only costs, a 0,5% total cost change interval gives a market share of district heating in a range of 32-68% when also including the 30% end demand savings. The modelled level (45%) represents about half of the heat market is covered with district heating is based on effects on the energy system only considering economic metrics.

District heating should be heavily expanded to cover around half of the heating market in Europe, compared to around 12% in 2015. For the whole of Europe, this represents a radical shift from the current market and market developments of Europe, and underlines the need for a different and catalysed approach towards district heating within the context of moving towards a deeply decarbonised energy system.

In Sweden, Finland, and Romania the modelled level is under the current level due to the strict least-cost approach. These levels are well within the normal sensitivity range when modelling towards 2050. In fact, the 0,5% total cost range however shows that there are potentials to increase the level of district heating if that allows for more energy efficiency, a better integration of excess heat or renewables, or is in line with other strategic energy planning objectives. Comparing the different countries, the main drivers for high or low levels of district heating are related to the spatial density of the heat demands, and the levels of available excess heat that are in the countries. For both these parameters, the HRE4 approach is conservative, and a better understanding of both may lead to a higher share of viable district energy than considered here. Temperature and climate are less strong drivers, as evidenced by the high potential of district heating in countries like Italy and Spain, where the spatial density is high and the smaller difference between summer and winter loads means that the operation of district heating may even be better distributed.

In terms of the spatial distributions, the improved methodology in the Pan-European Thermal Atlas includes contiguous connected areas within 500 m between clusters of cells, which are used to identify the costs of distribution. For national aggregations (as are used in the supply analysis) this improvement allows for a better understanding of the areas that are actually connected, and a differentiation between the larger, urban and urban agglomeration based district heating systems and the smaller district heating systems of more rural areas. Since these differences cannot be accurately represented within the energy system analysis, a conservative approach is taken which means it is likely that the potential for district heating in smaller cities is underestimated.

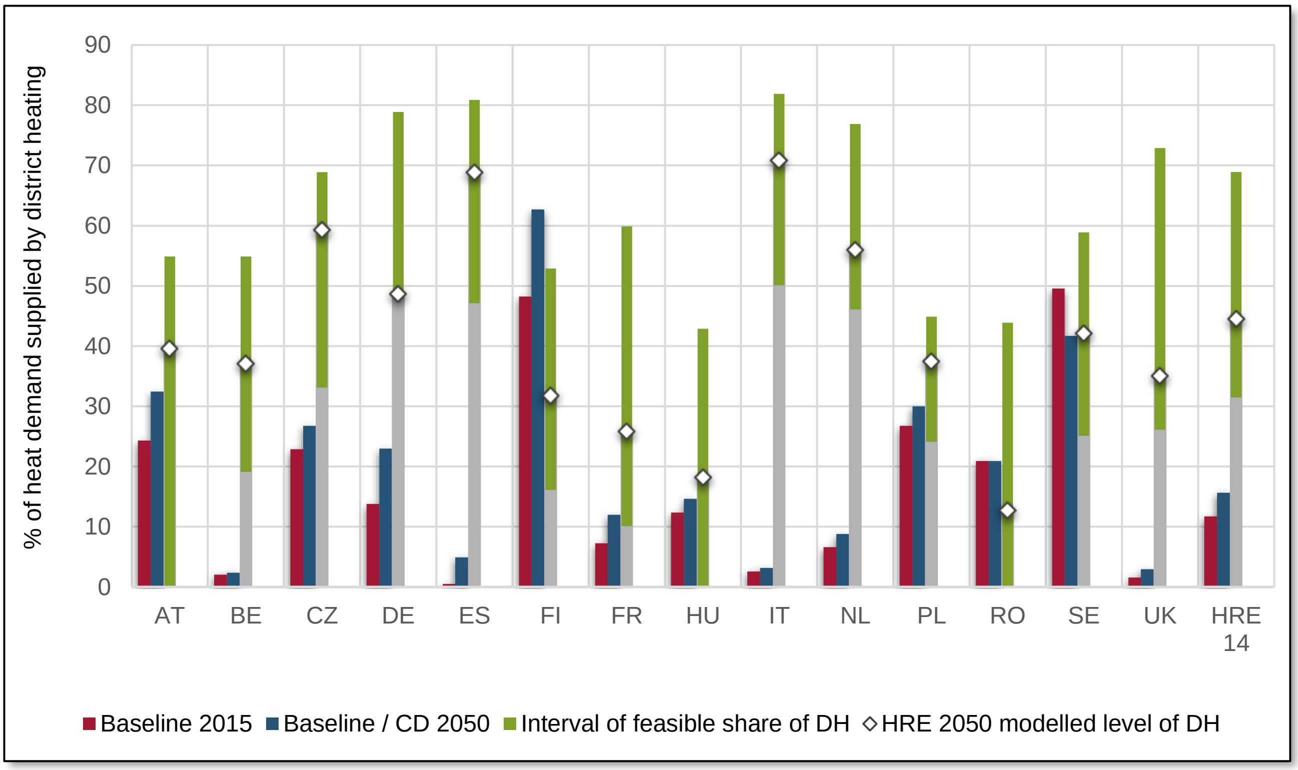


Figure 14. Baseline share of district heating, modelled share and interval of DH shares based on economic metrics. The range bars for the Heat Roadmaps represent the amount of district heating that is economically feasible within a 0,5% total annual energy system cost change sensitivity.

Since the scope of HRE is to quantify the effects of a redesigned heating and cooling system, there is limited scope to take into account wider energy planning objectives. This means that while the share of district heating in modelled in HRE is based on a least-cost approach within the wider energy system, there may be additional strategic energy planning motivations to move beyond the modelled share towards 68%, especially as the cost sensitivity is relatively low. Due to a number of additional benefits, such as security of supply, as well as jobs and industrial development it could be advantageous to go beyond the modelled level or the current level. While there are differences from country to country, going beyond the modelled level towards the maximum feasible level can further lower the price fluctuations citizens will experience (since the costs of the system are proportionally more tied in investments, and less on operational costs), lower geopolitical tensions connected to energy supply and, if more renewables or different sources of excess heat can be recovered due to an extended geographic scope, create a more fuel-efficient system.

District heating supply

The district heating sector is designed so that no fossil fuels are used directly, in order make the sector fully sustainable. However, the use of excess heat from cogeneration and from industry activities may not be considered fully renewable, but does contribute greatly to the overall efficiency of the energy system. To exclude the excess heat sources from industry and cogeneration (which may still include some fossil fuels, even in a deeply decarbonised energy system) ignores the potential to recover energy already used in industry and power generation, limiting the overall efficiency of the system and possibility of coupling the electricity and heating sector.

The main sources for district heating, taken over the 14 countries covered in HRE4, are cogeneration and large-scale heat pumps (supplying around 38% and 25% respectively), with large shares for excess heat from various industrial activities (see Figure 15. District heating source shares in HRE 2050 combined for all the 14 countries). Geothermal and large scale solar thermal are also used, with (biomass) heat only boilers producing less than 6% of the district heating supply.

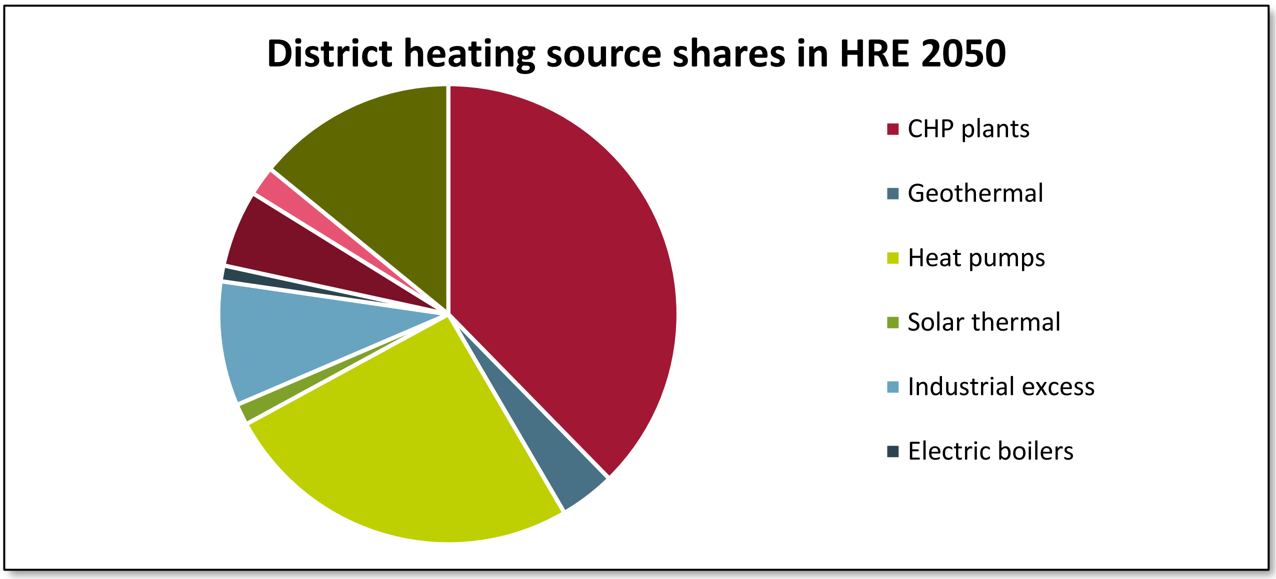


Figure 15. District heating source shares in HRE 2050 combined for all the 14 countries

Excess heat recovery

One of the main ways in which the HRE 2050 scenario creates synergies between heating and cooling and other energy sectors, is by using excess heat from industrial processes for the district heating system. In the HRE 2050 scenario, the potential to operationally utilise excess heat from industry is bounded geographically, temporally, and by temperature. The level of district heating in the HRE 2050 scenario has been designed assuming excess heat can be used only to cover the baseload. That which exists currently must be spatially present within a 50 kilometre zone of the prospective district heating system, and be within the needed temperature level for direct application. These boundaries are intended to create the distinction between the theoretical excess heat potential (i.e. all heat which is lost in industrial processes) and the accessible heat potential, which is governed by the spatial allocation of how heat can be used in district heating systems.

The excess heat sources considered in the HRE 2050 scenario are comprised of a variety of different types, including waste-to-energy and industrial sources like chemical and steel manufacturing, which respectively amount to around 2% and 9% of the total district heating production. However, within a deeply decarbonised energy system where a variety of hydrogen and electrofuels are being produced, additional types of excess heat become available. In the HRE 2050 scenario, a 10% heat recovery share of fuel production also becomes a significant source of industrial excess heat (representing around 14% of the district heating production, assuming that they can be located within the 50 kilometre zones of prospective district heating areas. By using a wide variety of different types of excess heat sources (both on a national and on a local level), a resilience can be designed into the scenario, reducing the dependence on one specific type of industrial activity or plant in the region, and to a certain extent safeguarding the safety of supply.

The development of the HRE 2050 scenario included several sensitivity analyses where excess heat from industry was excluded. In these scenarios, district heating was still viable. However, scenarios without excess heat available to the district heating system typically have a slightly reduced market share since the relative efficiency of individual solution (particularly heat pumps) increased (see Figure 16). Due to this, the spatial availability of renewables (particularly large scale solar thermal) is also lower. These scenarios replace the excess heat from industry with a higher use of large scale heat pumps, slightly higher CHP levels, and a more than doubling of direct boiler usage. Therefore, while district heating is still a viable solution in cases where excess heat is not recovered, these systems overall are more expensive, have significantly more difficulties integrating variable intermittent renewable electricity sources, and require more biomass.

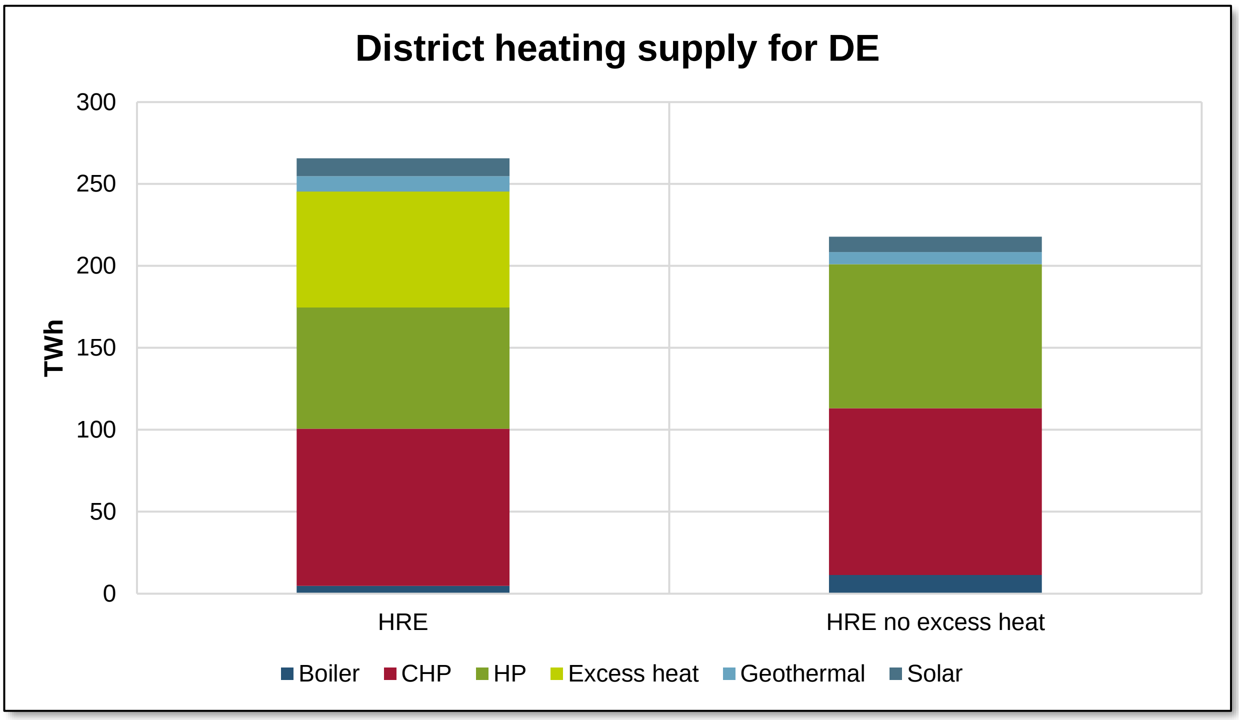


Figure 16. Viable district heating supply sources and quantities, in a sensitivity analysis where no excess heat from industries is available.

However, since excess heat is effectively the cheapest form of heat, any changes in the accessible potential do have an influence on the amount of district heating which can be implemented, by lowering the overall cost for heat. The limiting of the excess heat from existing industry and waste-to-energy plants to summer results in a very conservative approach. Sensitivity analyses suggest that the potential inclusion of levels of excess heat above the summer baseload level would result in a cheaper energy system. In addition, since only excess heat sources from industry with a high enough temperature to go directly into the district heating grid is considered, the option of using (urban) low temperature level sources is not considered in HRE4.. There are technical options to combine additional sources with large scale heat pumps to increase temperature and increase this share, particularly if they are already situated in urban areas. However, these results would require further geographic grounding to ensure that the different types of baseload heat are not crowing each other out of the same district heating systems.

The analysis and sensitivity analyses for excess heat show that since they are one of the cheapest forms of heat, their availability in the future to use for district heating is not only a factor in the primary energy efficiency of the wider energy system, but also for the local development of district heating and cooling systems. The planning process for new capacities, especially fuel production and waste to energy plants, should include a geographic and temporal analysis to ensure that they are placed where they can be effectively used by the district heating system. This emphasises the need to combine spatial and energy system modelling and shows that further research is needed to understand the role of non-baseload excess heat, especially in smaller district heating networks.

Renewable heat sources

The potential for renewables in the district heating supply mix is mostly geographically determined, based on the Pan-European Thermal Atlas. However, the methodology for allocating renewables is less robust than for the different sources of excess. Geothermal potentials are especially hard to quantify spatially in terms of how much would be accessible for use based on the extent of the district heating penetration (see Deliverable 2.3 [34]). Because of this, fairly conservative assumptions were used in the allocation analysis for geothermal. The potential in Europe for geothermal using this methodology is rather limited, representing only around 4% of the district heating supply. Operationally, it is used as a baseload supply (with some being redirected into storage during the summer), with very little temporal changes throughout the year. In addition, all the available geothermal potential that exists is economically viable, indicating that if the potential is there, the option of geothermal may be relevant even in larger systems where other types of baseload heat supply may be present. This means that where possible, geothermal energy in district heating presents a good solution to increase the share of renewables, reduce CO_2, and lower the fuel consumption in a cost-effective manner.

Solar thermal plays a smaller role in Europe, making up around 1% of the district heating supply. However, compared to the potentially available solar thermal, this does not represent the full amount of large scale solar thermal that could be utilised on technical potential alone. In the HRE 2050 scenario, solar thermal in district heating is mainly envisaged in the smaller district heating systems, where there is no opportunity to use excess heat, cogeneration, or geothermal sources as an effective baseload production. This is primarily because of the temporal discordance with when heat is demanded and required storage, and the competition between the other available baseload heat supply options (mainly excess heat from industries, and geothermal where available). Further research, which can make a more refined differentiation between the available heat sources for individual prospective district heating systems, is likely to show a different result, if it can represent at a more disaggregated level how much of the district heating demand cannot be connected to excess heat from (baseload) industries and geothermal. This is in line with other research, which concluded that the potential is normally between 3% and 10% of the heat production, and is mostly relevant as a source of sustainable heat where there is no possibility of using alternative (baseload) heat sources [57].

Large scale heat pumps and cogeneration

Large scale heat pumps play a very large role in the supply of the district heating in the HRE 2050 scenario. In total, they supply over 25% of the total district heating demand. This is because they can provide heat in a highly efficient manner, and provide a valuable link with the electricity sector through their use of (variable) renewable resources. Operationally, this means that they mostly function flexibly, in hours of the year when wind and solar electricity is abundant, and integrating it into the heating and cooling sector. This also allows for filling of the large thermal storages, allowing for even further use of the variable renewables. Based on this, large scale heat pumps have the potential to be an important technology in the heating and cooling sector in the long run, both in terms of scale and in terms of enabling variable renewable electricity utilisation. The deployment of large scale heat pumps need to become a key element of the (re-)development of district heating systems in Europe.

The applications modelled in HRE4 largely represent traditional applications of heat pumps in district heating systems, as they are common in some European countries today [58]. However, they are also modelled within the framework of a complete phase-out of hydrofluorocarbon (HFC) refrigerants, which means that the COP if the large scale heat pumps lies around 4. There may be technical potential to expand this, as a better understanding is generated of their applicability in unconventional heat sources, which could raise the COP significantly. This may one the one hand lead to a larger share of heat being produced by heat pumps, and a decreased capacity (accompanied by a decrease in capacity cost) required, see also [59]. Further research, particularly on the cost-effective role of storage in such scenarios, is necessary to understand better how radically increased efficiencies would work in the district heating sector.

The second link with the electricity sector is represented in the use of cogeneration, which produces around 38% of the redesigned district heating supply in Europe. While this is still a significant source of heat for district heating, this is both a lower share than the heat which is being produced in CHPs in 2015, and than it would be in a conventionally decarbonised scenario. This reduction in the HRE 2050 scenario is partially due to the integration of renewable and excess heat sources, but primarily due to the increased use of (large scale) heat pumps, which allow for more flexibility in the electricity system and reduce the overall demand for electricity. While the heat from cogeneration is considered a by-product, the fuels used in CHPs in HRE 2050 are mainly biomass and natural gas. This means that the reduced level of CHP also results in the reduced indirect combustion of fossil fuels and further decarbonises the wider energy system.

In terms of regulation, the heat from CHPs can be considered a by-product because these CHP units follow the electricity market, and the heat produced is considered secondary. The decarbonisation of the wider energy system, particularly the transport sector, relies largely on electrification so there is still a significant need on the electricity sectors part to produce electricity through combustion power plants. When heat storages have been filled and heat demand is low, electricity demand is typically fulfilled by power plants, showing that the CHPs are not operating to fulfil the heat demand, but are a way of using the heat as a by-product to electricity operation. In order to do this, it is both necessary to have a wider variety of heat sources in the district heating systems that can displace the cogeneration when electricity is abundant, but also to have a flexible electricity regulations. In this regard, the combination between cogeneration, heat pumps, and storage works extremely well in terms of the district heating system being able to respond to both high and low electricity availability hours and both high and low heat demand hours. In this way, the redesigned heating and cooling system, using cogeneration, allows for a high level of efficiency by using the by-product of electricity generation and provides a key link and synergy with the electricity sector.

This can also be seen from the sensitivity analyses which were done in the development of the HRE 2050 scenario, where cogeneration was reduced and then excluded from the heat and electricity supply mix (see Figure 17). As with the sensitivity analyses with excess heat, the potential for expansion of the district heating sector (and therefore the geographic accessibility to geothermal and peripheral solar thermal) is slightly reduced. However, the main changes in the supply of the district heating sector are in the use of heat pumps (for which the capacity is now using electricity, partially provided through condensation power plants, to produce heat) and the almost seven-fold increase of heat produced by heat-only boilers. In addition, the CHP capacity that was removed is almost fully transferred into condensation power plants, showing that both the regulation and the capacity of CHPs is much more driven by the needs of the electricity sector than of the district heating systems.

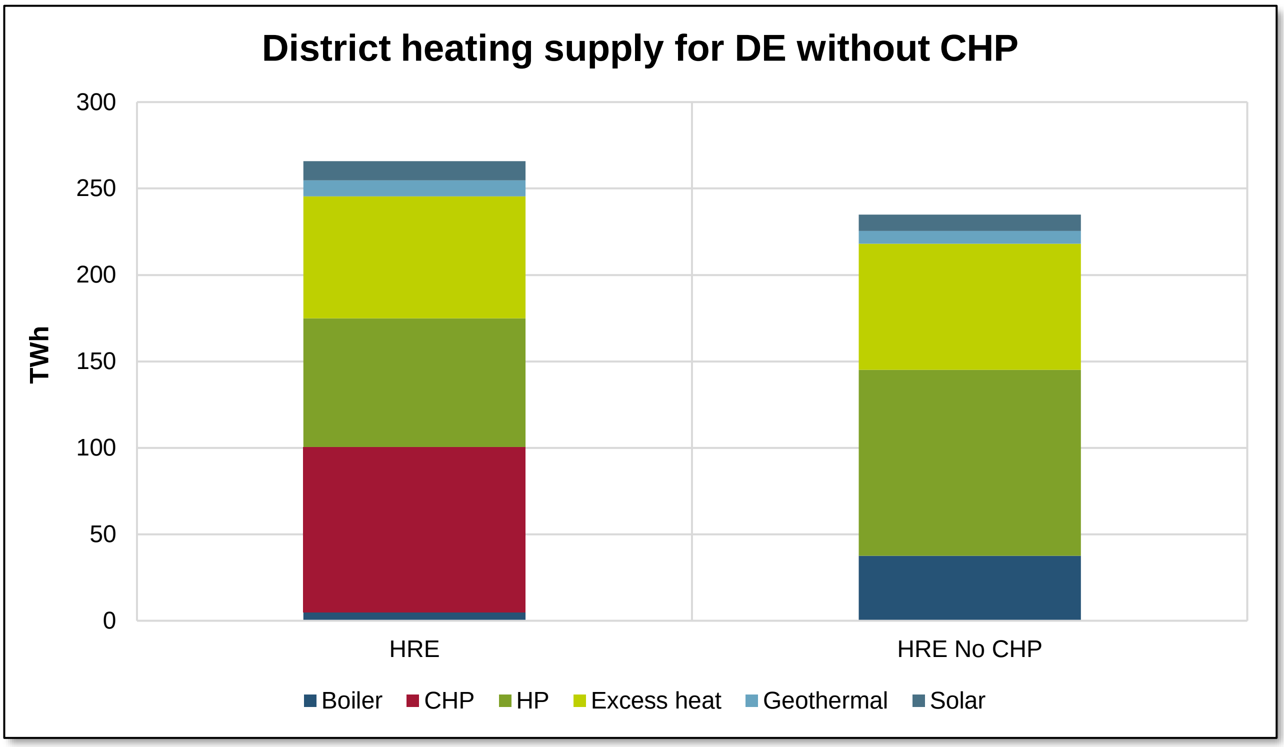


Figure 17. Viable district heating supply sources and quantities, in a sensitivity analysis where CHP is available.

While district heating remains economically viable without cogeneration, the whole energy system overall is more expensive, has significantly more difficulties integrating variable intermittent renewable electricity sources, requires more electric capacity and requires either more fossil fuels or an unsustainable level of biomass. Based on this, the role of cogeneration in future district heating systems needs to be understood as more deeply engrained in the electricity sector than it currently is. It also underwrites the role that district heating has in terms of the provision of energy efficiency, and the unique potential to use energy which would otherwise be wasted.

The HRE 2050 scenario shows a district heating sector looking towards 2050 which has a large variety of heat sources; uses both renewable, highly efficient, and excess sources of heat; and creates a strong link to the electricity sector, allowing for not only the decarbonisation of the district heating sector itself but also the further integration of renewable electricity into the wider energy system. As the supply and supply sources for district heating become more efficient and varied, the marginal costs of supplying heat fall, creating much more competition within the baseloads of district heating system markets, since the majority of these technologies are most socio-economically viable with high operating hours. For this reason, a better understanding of the exact shares of particularly excess heat and solar thermal energy would benefit from an approach that can both consider the spatial allocation of these sources, but also represent a better distinction between large, multi-source district heating systems and smaller district heating networks which are not likely to have more than two or three main heat sources.

Individual heating supply

Where network solutions are not viable and individual supply options are more cost-effective than district energy, heat pumps are used to supply the remaining heat demands. The results in from the savings and supply matrices showed that district heating expansions are preferable in most countries. However, not all heat supply is feasible to supply through district heating as the investments in pipes start growing exponentially and because energy losses associated with distributing the heating in rural areas becomes high once the heat density decreases. Hence, the heating outside of district heating areas has to be supplied in other ways.

In future deep decarbonised energy systems several alternatives exist in the form of bioenergy technologies, solar thermal in individual building, electric heating as well as heat pumps. Biomass boilers, electric heating, solar thermal, and heat pumps are considered, but heat pumps demonstrate the distinct advantage of efficiency and integration with the electricity sector. In addition, due to the decarbonisation of transport and (high-temperature) industry, bioenergy becomes increasingly scarce and its use in biomass boilers uneconomical from a system perspective.

While these heat pumps can in reality be combined with solar thermal and biomass boilers as part of the supply in some areas in Europe, in this study all individual heating is supplied by heat pumps as a modelling method due to the purpose of the analysis and their distinct advantage of efficiency and integration with the electricity sector. Due to reasons related to energy consumption, energy system efficiency, renewable resource availability and overall costs the energy supply mix is altered in the Heat Roadmap scenarios where a higher proportion of compression heat pumps are installed. Firstly, heat pumps deliver heating in an efficient manner by using electricity and excess heating from sources such as the air or the ground. The overall heat pump efficiency or COP is assumed to be in the range of 3.5 in the Heat Roadmap scenarios, significantly exceeding the efficiencies of fuel boilers and for electric heating. This reduces the primary energy demands and replaces fuels (which are either fossil fuels or scarce biomass resources) with electricity consumption from primarily variable renewable electricity sources.

Secondly, the introduction of heat pumps in the individual supply enhances the energy system efficiency by enabling an enhanced integration of variable renewable sources that would otherwise not be possible to integrate. Concretely, heat pumps can quickly absorb variable renewable energy that would otherwise be wasted, which is ideal when relying on large shares of variable resources. The implementation of heat pumps hence reduces the excess electricity generation and acts as an integration technology between the electricity and heating and cooling sectors.

Thirdly, the implementation of heat pumps reduces the need for fuel boilers, which in a high-renewable energy system would be supplied by bioenergy. However, as previously described, this resource is scarce and will be more valuable in the transport and industrial sectors where fewer renewable alternatives exist. Heat pumps can utilize variable renewable electricity generation supplemented by thermal electricity production in few hours of the year. The increasing electricity demand is however important to have in mind in relation to the pressure on electricity grids and whether grid enhancements will be necessary to handle the larger electricity demands, especially in peak hours during the winter periods.

Fourthly, it is crucial to assess the energy costs of the energy system from installing the different alternatives. In previous research it was found that heat pumps do not show significant economic benefits compared to the alternative technologies, but will result in overall system costs similar to biomass boilers with differences between the countries [7,60,61]. Heat pumps have higher investment costs and lower fuel costs compared to the alternatives.

In the Heat Roadmap scenario, individual heat pumps provide almost all the remaining heating demand in the 14 HRE4 countries, primarily in the rural and highly suburban areas, covering about half the heat market. Compared to 2015, this means both a reduction in the amount of heat produced on individual heating units, and an almost full replacement of the individual boilers, which are currently mostly fuelled by gas. This allows for a much higher level of efficiency, and a deeper level of decarbonisation through a deeper interconnection with the electricity sector.

The heat pumps considered in HRE 2050 are primarily ground-source heat pumps, air-to-air heat pumps, and air-to-water heat pumps with a high level of efficiency and the ability to produce both space heating and hot water. The high COPs of the individual heat pumps, which averages 3,5 overall, result in a very low energy consumption and minimises the consumption of biomass, significantly contributing to the decarbonisation of the remaining heat demand.

However, the increased demand of electricity for heat pumps is visible in increased electricity demand, but also in the peak electricity load. The importance of grid costs is analysed in [19]. For Europe, this amounts to an additional requirement of approximately 1% of the total electricity capacity. In terms of electricity grid infrastructure, the expansion requires approximately €14,4 billion worth of additional grid capacity. These are non-negligible amounts, and illustrate the need for high COPs and the problems that are faced within a full heat electrification scenario, but overall the main costs associated with supplying heat at the individual building level is the investment required for the heat pumps themselves with the assumptions used here.

The electricity that is used for heat pumps generally reflects the supply mix of the electricity sector, and includes a high level of variable renewables; shares of biomass combustion (in both cogeneration and condensing power plants), and a small amount of remaining fossil fuels. However, heat pumps are the primary way of supplying highly efficient and decarbonised heating in areas where district heating networks are not cost-effective, and contribute both to the overall efficiency and the decarbonisation of the energy system in Heat Roadmap Europe.

In the process of developing the savings and supply matrices discussed under in the section on Energy savings in the Heat Roadmaps, sensitivity scenarios were developed which have no district energy and which are fully electrified. In all the Heat Roadmap Europe countries, this leads both to a higher energy system cost and less efficient systems. This is because a full electrification of the heating and cooling sector leads to both a higher level of pressure (and associated cost) for the electricity grid, but also a higher requirement of electricity capacity in order to be able to cover the (winter hour) peak demands. For a country like Germany, the further strengthening of the grid would necessitate an investment of around €2,3 billion, which represents approximately an additional 1% of the total energy system cost. However, the main cost difference is driven by the need to install further a further 50 GW peak capacity (which is mostly in the form of condensing power plants). Even though the individual scale heat pumps are very efficient, the size of the heating and cooling sector means that without alternative sources of heat, the demands on the electricity system are significant and more expensive under a full electrification scenario.

Cooling supply

Cooling is considered in HRE 2050 in a similar way as heating; through spatial analysis of the demands and resources, and scenario development considering both district and individual supply options. However, as described the cooling sector is more diverse and cooling is mostly demanded by the industry and services sector, meaning that both determining the spatial demands and the nature of centralised and decentralised supply are slightly different.

District cooling is implemented in 20% of the urban areas in Europe, resulting in an overall market share of less than 5% of the cooling market (see Figure 18). However, the spatial analysis and energy system modelling that lead to this result are not as methodologically robust as those for the heating market. This is likely to be an underestimation, since the spatial dimensions of top-down cooling network modelling is not as well developed as for district heating infrastructures. In terms of operational simulation, district cooling is supplied equally through sorption cooling (using excess heat from the district heating system) and centralised chillers. The potential to explore the role of using direct sea- and lake water (where geographically available) and higher levels of cold water thermal storage requires further investigation to be able to fully understand the potential and role that district solutions for cooling could play.

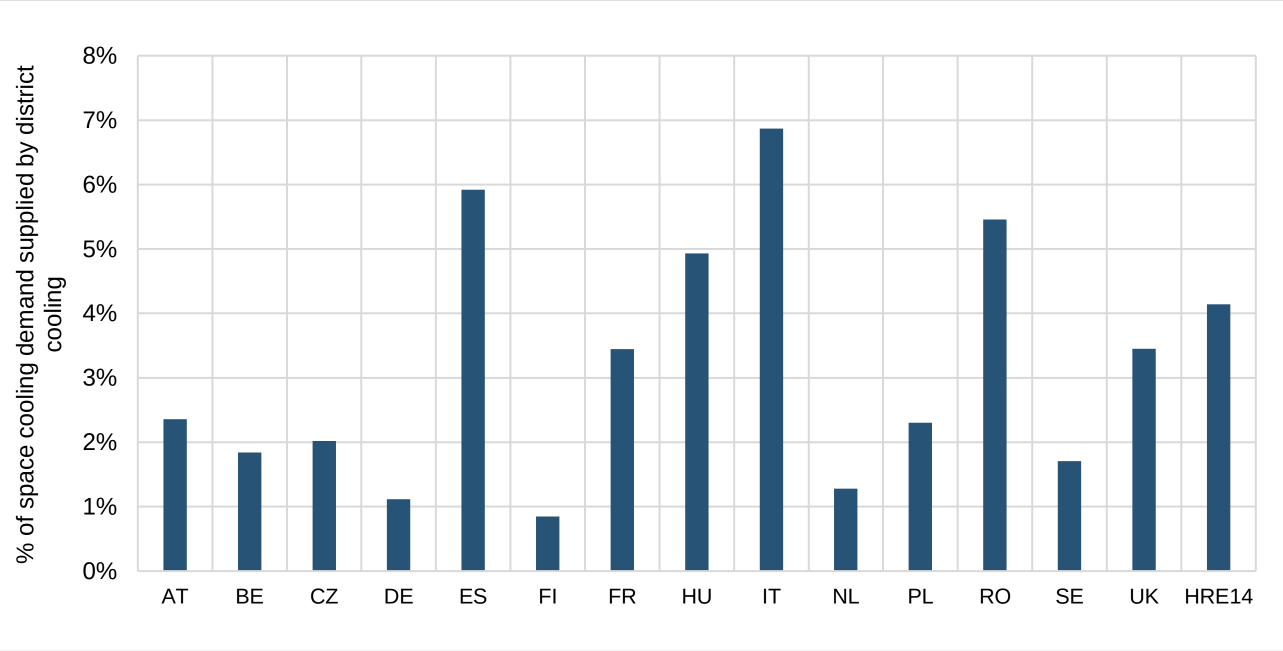


Figure 18. Share of district cooling in the Heat Roadmap Europe 2050 scenarios.

The individual cooling demand is supplied using mostly (small) split units, large split units, and chillers of varying sizes. Cooling is one of the fastest growing of the thermal sectors, but supply options can be highly efficient, with COPs ambitiously expected to be around 6,6 in 2050. This high efficiency, combined with the relatively smaller demands than for the cooling sector, is the main reason that even as the cooling sector expands, the impact on the wider energy system is relatively limited.

Integrating more renewable electricity

One of the key objectives of HRE4 is to understand the effects of a deeper interconnection of the heating and cooling sector with the other parts of the energy system, in particular creating synergies with the electricity sector that result in a better use of the resources that are available. In particular, the way that the electricity sector is redesigned is highly complementary to the design of the heating and cooling system; both to balance the operation, and to ensure that the synergies that are created through the heating and cooling sector are realised.

In order to do this, the transport and (non-heat) industry sectors are taken over from a conventionally decarbonised scenario, in order to account for the electricity and fuel demands of these sectors. Since these sectors do not form the main subject of analysis in the Heat Roadmap, they are not analysed in depth but they are taken into consideration in order to ensure the results could contribute to a fully decarbonised energy system. This is particularly important with regard to the electricity demand which comes from the electrification of transport, the production of hydrogen and electrofuels (to replace fossil fuels where direct electrification is not possible) and strategic use of bioenergy. By including these into the energy system, and considering the effect of the measures taken in HRE 2050 on a European energy system level, an analysis can be made on the synergies between decarbonising the heating and cooling sector and the electricity sector.

Compared to a conventionally decarbonised energy system, the increased level of energy efficiency in the heating and cooling sector also means less demand for the electrification of the heating and cooling sector (see Figure 19). The overall electricity production in both the conventionally decarbonised and Heat Roadmap scenario are much higher, since there is a very high level of electrification in the transport and industry sectors, and power is being used for electrofuel production. However, the overall need for electricity production in HRE 2050 compared to the conventionally decarbonised energy system is reduced by over 3%, simply because electricity demand for heating and cooling is replaced by district solutions, which can integrate more types of energy sources. Of this decrease in electricity production, the majority is in condensing power plants. Proportionally, this means that the variable electricity which is being produced in the Heat Roadmap scenario is being integrated at a higher level, indicating a higher level of flexibility within the system.

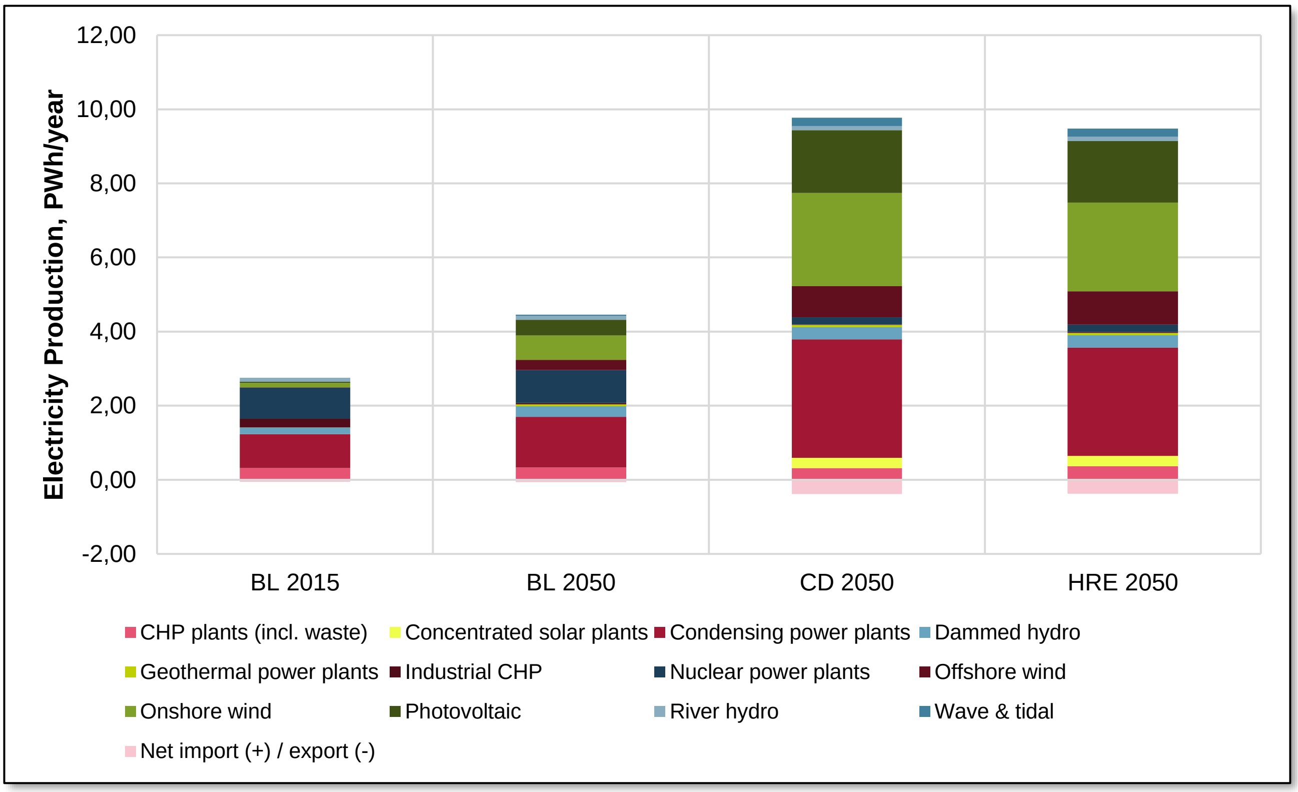


Figure 19. Electricity production currently, in the 2050 baseline scenario, in the conventionally decarbonised scenario and the Heat Roadmap scenario.

In terms of electricity production, RES represents 63% of the electricity produced, while thermal plants including combined heat and power, condensing power plants and industrial CHP produce 35%. The final 2% come from nuclear. The main electricity producing technologies in the HRE 2050 scenario are condensing power plants and onshore wind, producing about 31% and 25%, respectively. Photovoltaic produces an additional 17%, while offshore wind produces 9%. The remaining technologies each produce between 1% and 4% (see Figure 19).

The condensing power plants are the main consumers of biomass in the Heat Roadmap Europe scenario, and show that a while redesign of the heating and cooling sector does contribute to the deep decarbonisation and efficiency of the energy system, further measures (better linking the transport, fuel production and other energy sectors) could contribute to an even more efficient energy system. However, the redesign of the heating and cooling system which was in focus here uses principles in line with the Smart Energy System approach. This already allows for a more efficient power sector, better integration of variable renewables, and a much deeper level of decarbonisation.

Quantification of the impact of increased energy efficiency

The resulting Heat Roadmap for the HRE14 countries represents a technically feasible, economically viable alternative which shows how the heating and cooling sector could provide a large contribution to the deep decarbonisation of the European energy system. The approach is based on the combination of energy efficiency on the demand and the supply side of the heating and cooling sector, as a way to achieve a higher level of every savings in the system overall. Savings for both heating and cooling demand are considered simultaneous to an efficient supply of heating and cooling through heat pumps, efficient chillers, and district heating and cooling, and combined with a high level of system integration and variable renewable sources.

Decarbonisation

The HRE 2050 scenario shows that deeper decarbonisation, moving towards a nearly zero carbon emission energy system, is possible. Within the context of the HRE4 project, 'deep decarbonisation' is taken to mean a moving towards a 95% reduction in CO_2 emissions by 2050, compared to 1990 levels. The conventionally decarbonised energy system only represents an 80% decrease compared to 1990 (in line with the current long-term goal of between 80% and 95% [62]), while the Heat Roadmaps aim for a level which is more in line with deep decarbonisation and eventual nearly zero carbon energy systems.

HRE 2050 reduces energy-related emissions by 49% compared to conventional decarbonisation, and the overall emissions by almost 86% compared to 1990 levels (see Figure 20). This level of decarbonisation is especially remarkable since in the Heat Roadmap scenario the transport and non-heating/cooling industry sectors were taken as given from a conventionally decarbonised scenario, and changes were only made primarily in the heating, cooling, and to a lesser degree the electricity sector. With further integration of the sectors, higher levels of decarbonisation can be expected.

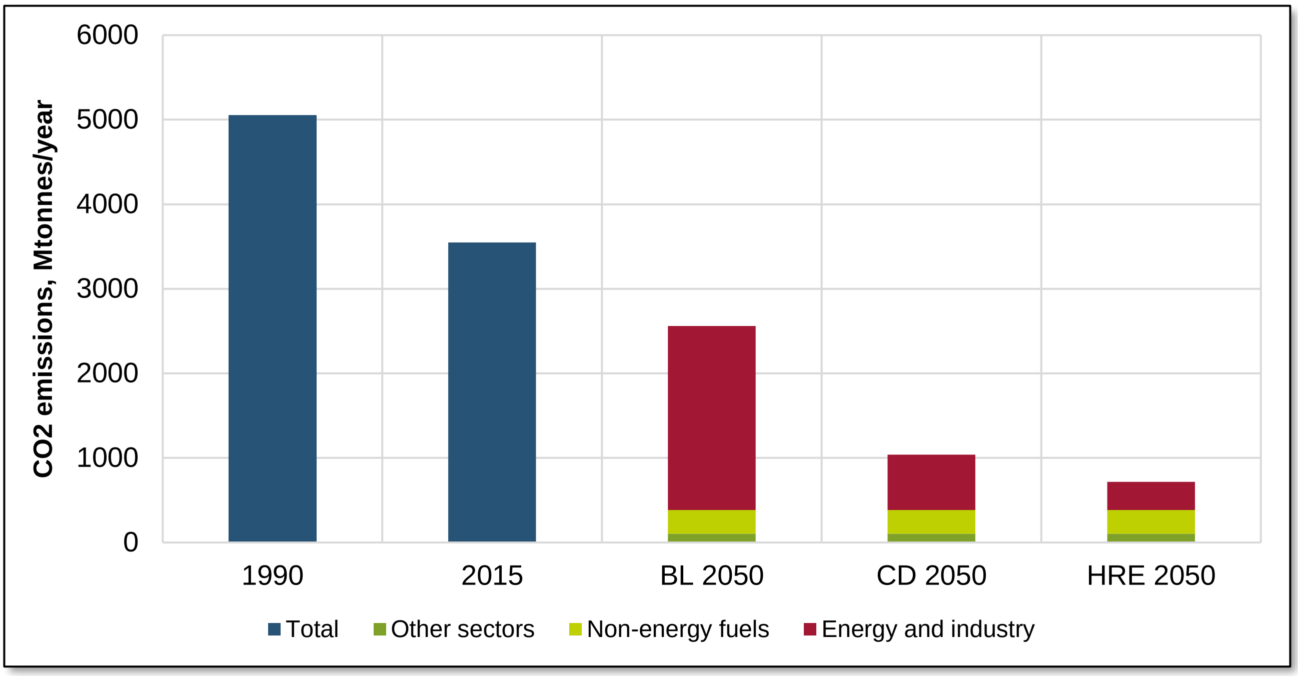


Figure 20. CO2 emissions for the HRE14 including 1990 [8] *(the base year for the Paris Agreement), currently, in the 2050 baseline scenario, in the conventionally decarbonised scenario and the Heat Roadmap scenario.*

Efficiency

In terms of primary energy supply, the HRE 2050 scenario uses approximately 12% less energy than a conventionally decarbonised scenario. This is mostly due to the vast reduction of natural gas, since the amounts of biomass and the main renewables are relatively comparable (Figure 21). While most of this gas is being used in the electricity sector, its use can be displaced through higher levels of efficiency in the heating and cooling sector.

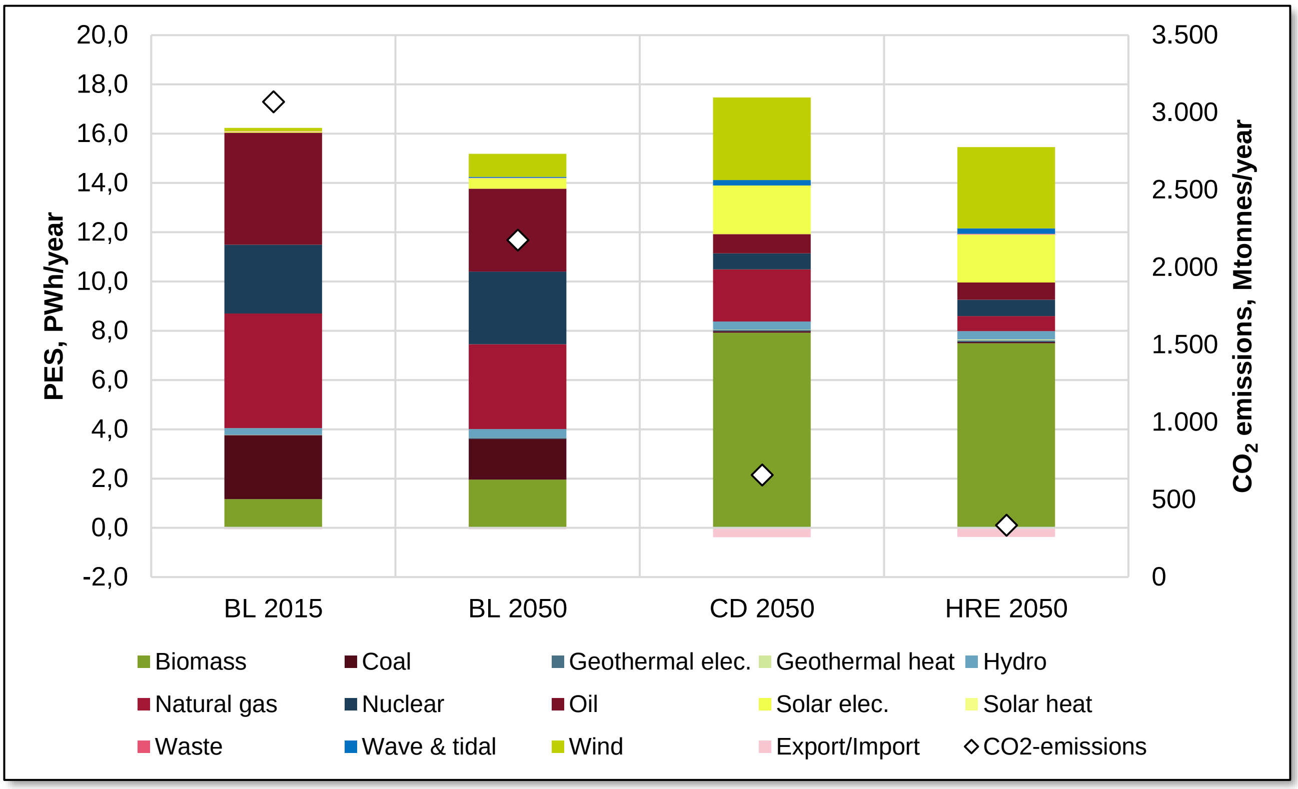


Figure 21. Primary energy supply currently, in the 2050 baseline scenario, in the conventionally decarbonised scenario and the Heat Roadmap scenario.

This primary energy reduction is partially brought through heat savings measures, and partially by efficiency in the demand side through the integration of excess heat sources, use of efficient supply technologies, and the better integration of the heating and cooling sector with the electricity sector. When split between the two, of this decrease in energy needs almost 30% is driven by the end user savings with the remaining 70% by the improved heating and cooling supply system. This underlines the importance of focussing not only on heat and cold savings, but also the need energy efficiency on both sides, in order to have a more cost-effective and deeply decarbonised energy system

Energy system costs

The HRE 2050 scenario achieves a deeper level of decarbonisation and a higher efficiency at a reduced cost, compared to a conventionally decarbonised scenario. The annual cost of achieving the energy system simulated in the HRE 2050 scenario is around 6% lower than a decarbonised energy system, equalling cost savings of around €67,4 billion annually (see Figure 22). While investments increase slightly, this reduction is costs is made through a shift away from using fuels and in that a significant reduction of fuel costs.

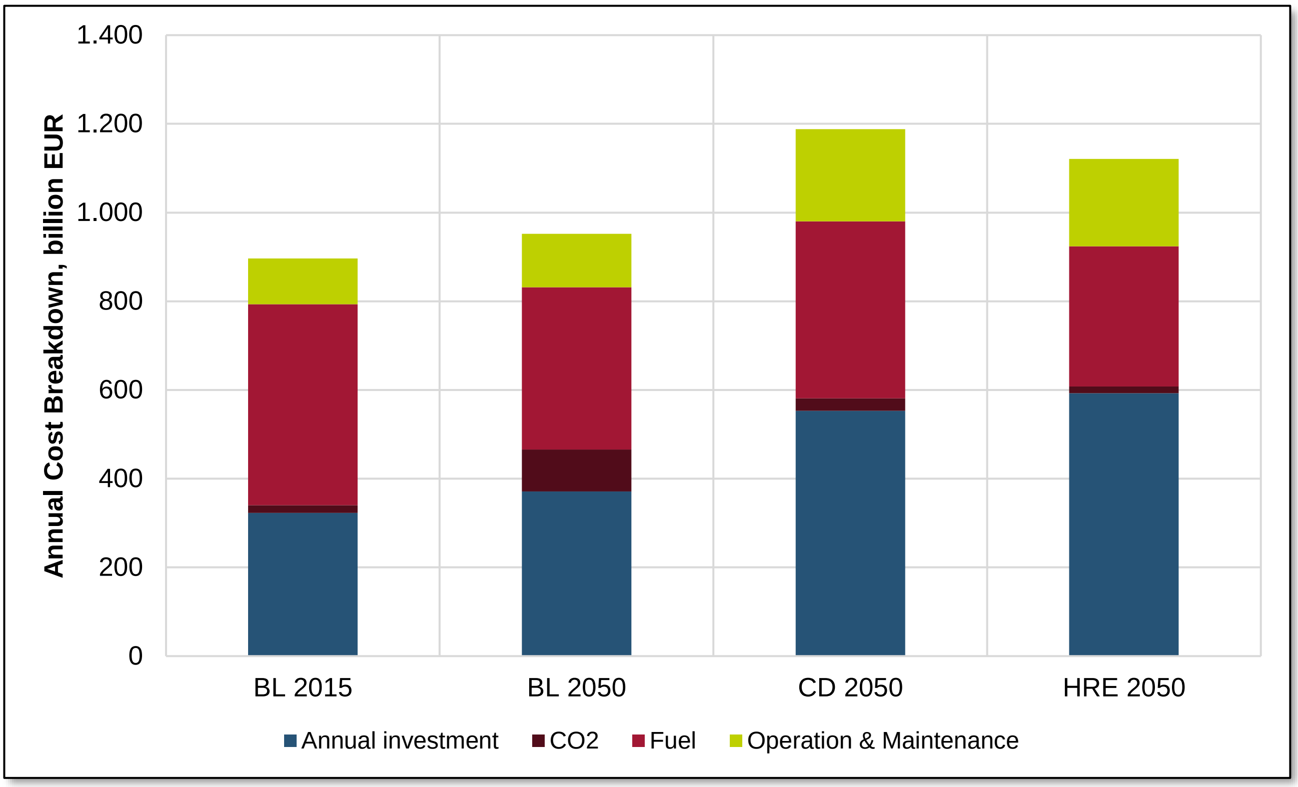


Figure 22. Annual socio-economic costs for the heating, cooling, electricity, industry, and transport sector.

There are some changes in terms of investments that are required in the HRE 2050 scenario, compared to today and a conventionally decarbonised energy system. The overwhelming category of investments needed across the HRE14 countries is in heat demand reduction measures, which make up about 66% of the investments required in the heating sector. The scale of these investments needed shows how ambition of the policies regarding heat savings, but also the need for a much stronger focus and enhanced approach towards policy implementation and realisation on a European level.

These costs are annualised and include the replacement of existing technologies. In terms of the investment in the energy system outside of the built environment, the highest levels of new investment are needed in the electricity sector, in order to facilitate the transition towards variable renewables and the partial electrification of other sectors. There are however also some changes to the investments necessary in the heating and cooling sector.

The energy system costs increase from the BL 2050 to the CD 2050, which is caused by changes in the annual investment costs and the operation and maintenance costs. These changes mainly come from an increase in the production capacities of renewable electricity but also for production of hydrogen and synthetic fuel. It has not been a focus to reduce these costs in this project, but previous research has shown that it is possible to do using a smart energy system approach [3,63].

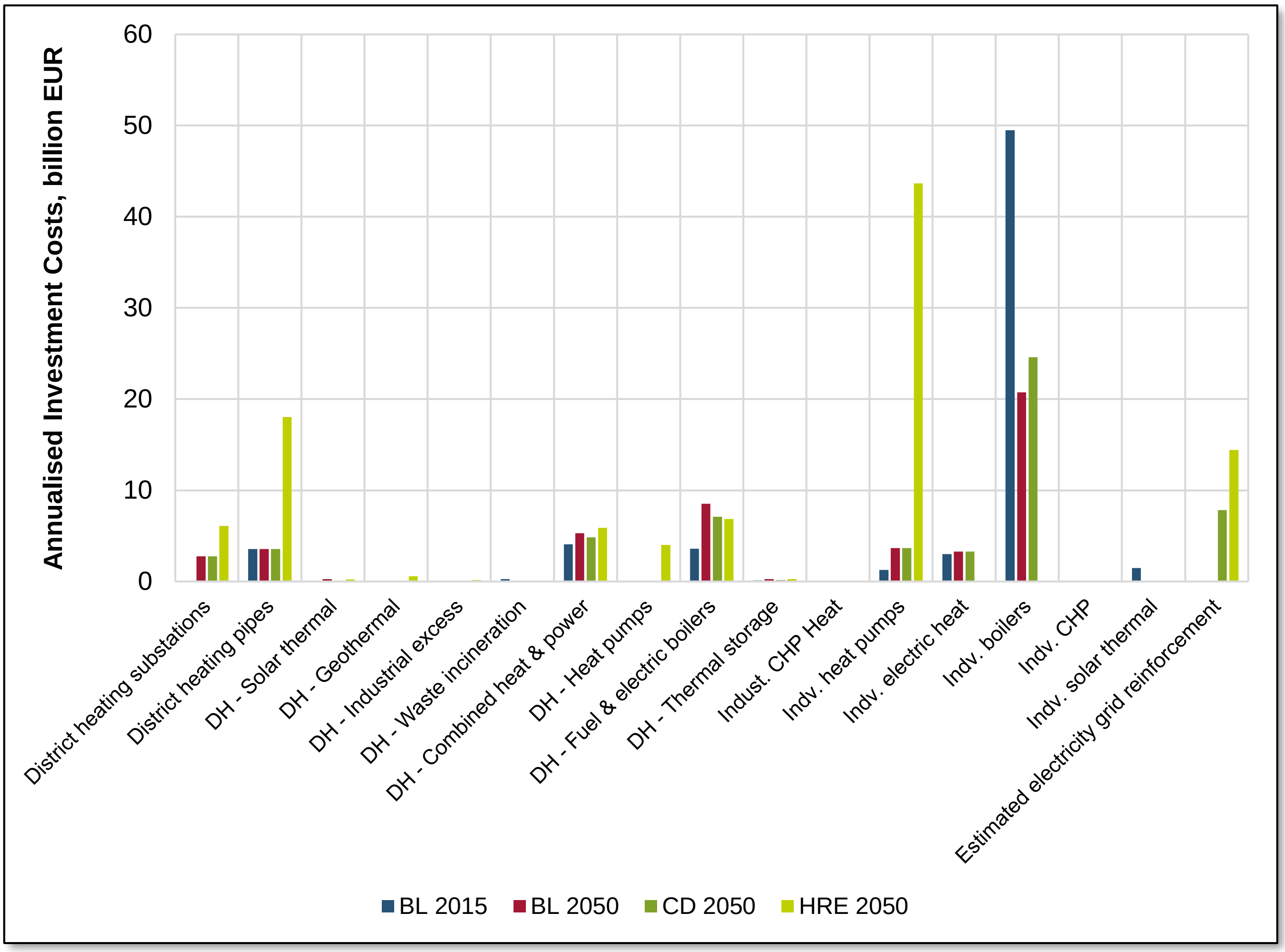


Figure 23. Annual costs for the heating sector technologies in the various scenarios.

After the heat savings measures, the most relevant new and growing investments for the HRE14 countries are individual heat pumps, heat pumps for district heating, and investments in district heating infrastructure (see Figure 23). Of these, the investment in individual heat pumps is most significant, representing about 15% of the investments necessary in the heating sector. As for savings, these investments often need to be made at the household or business level, so require a different approach and policies that focus on achieving explicit changes in peoples' investment choices.

The redesign of the district energy systems requires investments, but overall the investments in the distribution and transmission infrastructure only represent 6% of the investments necessary in the heating sector. In total (including supply technologies, substations, transmission and distribution) the district heating system only comprises 14% of the investments that are necessary. These investments are collective infrastructures, which have high up-front costs and require a policy support in order to ensure collaborative business and procurement models, but finally only represent a small fraction of the annualised investments needed in the heating and cooling sector.

In terms of economy, the energy system in the HRE 2050 scenario reduces the costs of the overall energy system while decarbonising it to a much higher degree. This is primarily achieved by reducing the fuel costs of the energy system and increasing the levels of investment for energy efficiency measures and technologies in the heating and cooling sector. Given the higher proportion of investments in the HRE 2050 scenario – especially in the built environment – it seems likely that this would both be a driver for local employment, and for an improved balance of payments. While this has not been analysed in detail, it is clear that the scenario presented in HRE 2050 has the potential to reduce the cost of energy for consumers, assuming that gains are redistributed.

Biomass

No explicit efforts made to reduce biomass in the HRE 2050 scenario; the levels used are equal to those developed in a constrained optimisation model of a conventionally decarbonised energy system [51]. Within a deeply decarbonised energy system, bioenergy is mostly used in condensing power plants in a proportion of 75%, with smaller shares in cogeneration (10%) industrial activities (9%), biofuel production (6%) and the rest in district heating boilers.

However, the final usage is likely to be higher than what could be considered precautionary [6,61,64]. A previous review of the sustainable bioenergy potential in Europe (EU28) ranged from 9 EJ/year to about 40 EJ/year, with an average of around 20 EJ/year [64]. In the HRE 2050 scenario, the use is almost 30 EJ/year which is likely to be too high, so future research should consider how this can be reduced. Further research should focus on how the redesign of other sectors can contribute to both the deep decarbonisation and the sustainable use of biomass. In addition, further analysis on how the heating and cooling sector could reduce the use of bioenergy in a nearly zero carbon emissions energy system could contribute to preventing an over-use or overreliance on scarce and potentially unsustainable bioenergy.

References

[1] Connolly D, Lund H, Mathiesen B V., Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. doi:http://dx.doi.org/10.1016/j.enpol.2013.10.035.

[2] Eurostat. Energy statistics - Energy production and imports n.d. https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports (accessed September 30, 2018).

[3] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53.

[4] Harmsen R, van Zuijlen B, Manz P, Fleiter T, Elsland R, Reiter U, et al. Report on cost-curves for built environment and industrial energy efficiency options. Heat Roadmap Europe Deliverable 4.2 & 4.3; 2018.

[5] Connolly D, Mathiesen B V, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe: First pre-study for EU27 2012.

[6] Connolly D, Mathiesen B V, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe: Second pre-study 2013.

[7] Connolly D, Hansen K, Drysdale D, Lund H, Mathiesen BV, Werner S, et al. Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States (Heat Roadmap Europe 3). Copenhagen: 2015.

[8] European Commission. Greenhouse gas emission statistics - emission inventories 2018. http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics_-_emission_inventories#Trends_in_greenhouse_gas_emissions (accessed June 1, 2018).

[9] European Commission. Report from the Commission to the European Parliament and the Council. vol. 24. 2017. doi:10.1002/ejoc.201200111.

[10] Eurostat. Europe 2020 indicators - climate change and energy 2018. https://ec.europa.eu/eurostat/statistics-explained/index.php/Europe_2020_indicators_-_climate_change_and_energy (accessed June 15, 2018).

[11] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy 2012;47:284–93. doi:10.1016/j.energy.2012.09.030.

[12] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:3–14. doi:10.5278.

[13] Mathiesen B V, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renew Power Gener 2009;3:190–204.

[14] Mathiesen BV, Drysdale D, Lund H, Paardekooper S, Ridjan I, Connolly D, et al. Future Green Buildings - A key to Cost-Effective Sustainable Energy Systems. Department of Development and Planning, Aalborg University; 2016.

[15] Dittmann F, Riviere P, Stabat P. Space cooling Technology in Europe. Heat Roadmap Europe Deliverable 3.2; 2017.

[16] Hansen K, Connolly D, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 2016;115:1663–71. doi:10.1016/j.energy.2016.06.033.

[17] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050 - Technical data and methods. 2015.

[18] Connolly D, Mathiesen BV, Lund H. Smart Energy Europe: From a Heat Roadmap to an Energy System Roadmap. Aalborg Universitet; 2015.

[19] Connolly D, Hansen K, Drysdale D, Lund H, Mathiesen BV, Werner S, et al. Croatia: Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States. STRATEGO; 2015.

[20] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. doi:10.1016/J.ENPOL.2013.10.035.

[21] European Comission. 2050 Energy Strategy 2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy (accessed June 14, 2018).

[22] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:https://doi.org/10.1016/j.energy.2017.05.123.

[23] Wouter N, Castelló PR, González IH, Stiff G. Energy Tools Manual for Lead-Users. Heat Roadmap Europe Deliverable 5.2; 2017.

[24] Aalborg University. EnergyPLAN Cost Database. 2015.

[25] Guddat MGA, Sørensen SS, Trier D, Paardekooper S. Review of the cost variation in energy plants across the 14 MSs. Heat Roadmap Europe Deliverable 6.2; 2017.

[26] Persson U, Möller B, Wiechers E, Grundahl L. Map of the heat synergy regions and the cost to expand district heating and cooling in all 14 MS. Heat Roadmap Europe Deliverable 2.2; 2017.

[27] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17.

doi:http://dx.doi.org/10.1016/j.energy.2013.10.041.

[28] Lund H, Mathiesen B V. The role of Carbon Capture and Storage in a future sustainable energy system. Energy 2012;44:469–76.

[29] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Emissions from land-use change. Science (80-) 2008;423:1238–40.

[30] Joskow PL, Parsons JE. The Future of Nuclear Power After Fukushima. Econ Energy Environ Policy 2012;1. doi:10.5547/2160-5890.1.2.7.

[31] Adamantiades A, Kessides I. Nuclear power for sustainable development: Current status and future prospects. Energy Policy 2009;37:5149–66. doi:10.1016/j.enpol.2009.07.052.

[32] Kahouli S. Effects of technological learning and uranium price on nuclear cost: Preliminary insights from a multiple factors learning curve and uranium market modeling. Energy Econ 2011;33:840–52. doi:10.1016/j.eneco.2011.02.016.

[33] Peta4 – Heat Roadmap Europe 2017. https://hre.aau.dk/resource-center/peta4/ (accessed October 1, 2018).

[34] Persson U. Methodologies and assumptions used in the mapping. Heat Roadmap Europe Deliverable 2.3; 2017.

[35] Fraunhofer ISI. FORECAST | eLOAD 2018. https://www.forecast-model.eu/forecast-en/index.php (accessed October 1, 2018).

[36] Fleiter T, Elsland R, Herbst A, Manz P, Popovski E, Rehfeldt M, et al. Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050. Heat Roadmap Europe Deliverable 3.3 & 3.4; 2017.

[37] Fleiter T, Stif G, Reiter U. FORECAST Guide for Lead-Users. Heat Roadmap Europe Deliverable 3.5; 2017.

[38] Fleiter T, Elsland R, Rehfeldt M, Steinbach J, Reiter U, Catenazzi G, et al. Profile of heating and cooling demand in 2015. Heat Roadmap Europe Deliverable 3.1; 2017.

[39] Connolly D, Paardekooper S, Hansen K, Thellufsen JZ, Nijs W, Ruiz P, et al. The Heat Roadmap Europe methodology of combining 4 modelling tools. Heat Roadmap Europe Deliverable 5.1; 2017.

[40] European Comission. The JRC-EU-TIMES model 2017. https://ec.europa.eu/jrc/en/scientific-tool/jrc-eu-times-model-assessing-long-term-role-energy-technologies (accessed October 1, 2018).

[41] Department of Development and Planning Aalborg University. EnergyPLAN | Advanced energy systems analysis computer model n.d. https://www.energyplan.eu/ (accessed October 3, 2018).

[42] Nijs W, González IH, Paardekooper S. Methodology report for comparing the JRC-

EU-TIMES and EnergyPLAN scenarios. Heat Roadmap Europe Deliverable 6.3; 2018.

[43] Nijs W, Castelló PR, González IH. Business-as-usual reference scenarios. Heat Roadmap Europe Deliverable 5.2; 2017.

[44] ENTSO-E. ENTSO-E Transparency Platform n.d. https://transparency.entsoe.eu/ (accessed October 3, 2018).

[45] Meteonorm. Meteonorm: Irradiation data for every place on Earth n.d. https://www.meteonorm.com/ (accessed October 3, 2018).

[46] Andresen GB, Søndergaard AA, Greiner M. Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis. Energy 2015;93:1074–88. doi:10.1016/J.ENERGY.2015.09.071.

[47] Victoria M, Andresen GB. Using validated reanalysis data to investigate the impact of the PV system configurations at high penetration levels in European countries 2018.

[48] Connolly D, Drysdale D, Hansen K, Novosel T. Stratego. Creating Hourly Profiles to Model both Demand and Supply. WP 2. Background Report 2. Copenhagen, Danmark: 2015. doi:IEE/13/650.

[49] MATSim. MATSim Multi-Agent Transport Simulation n.d. https://matsim.org/ (accessed October 3, 2018).

[50] Capros P, De vita A, Tasios N, Siskos P, Kannavou M, Petropoulos A, et al. EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050. European Commission; 2016.

[51] Nijs W, González IH, Paardekooper S. Methodology report for comparing the JRC-EU-TIMES and EnergyPLAN scenarios. Heat Roadmap Europe Deliverable 6.3; 2018.

[52] Bettgenhäuser K, Pouwels W, Boermans T. IEE EHP Stratego Report - Quantifying the Cost of Heat Savings in EU Member States - Backgrpund Report 3a. Ecofys; 2015.

[53] Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 2016. doi:10.1016/j.energy.2016.06.033.

[54] Werner S. European space cooling demands. Energy 2015;110:148–56. doi:10.1016/j.energy.2015.11.028.

[55] Jakubcionis M, Carlsson J. Estimation of European Union residential sector space cooling potential. Energy Policy 2017;101:225–35. doi:10.1016/j.enpol.2016.11.047.

[56] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. doi:10.1016/J.ENERGY.2017.04.045.

[57] Hansen K, Vad Mathiesen B. Comprehensive assessment of the role and potential for solar thermal in future energy systems. Sol Energy 2018;169:144–52. doi:10.1016/J.SOLENER.2018.04.039.

[58] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 2017;10:578. doi:10.3390/en10040578.

[59] Lund R, Ilic DD, Trygg L. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. J Clean Prod 2016;139:219–29. doi:10.1016/j.jclepro.2016.07.135.

[60] Lund H, Möller B, Mathiesen B V, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. doi:10.1016/j.energy.2009.11.023.

[61] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012. doi:10.1016/j.energy.2012.07.063.

[62] European Commission. EU Climate Action 2018. https://ec.europa.eu/clima/index_en (accessed June 11, 2018).

[63] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[64] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. doi:10.1016/j.rser.2016.02.025.