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ORIGINAL ARTICLE

Heat Roadmap Europe: strategic heating transition typology as a basis for policy recommendations

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Abstract In order to support European-wide transition of heating systems, it is useful to categorise the types of transitions that are necessary. Coherent actions are needed at (supra-)national level to support transition aligned with the energy efficiency first principle and long-term development of a smart energy system. Owing to the decentralised nature of heating, transition must also reflect particular local circumstances. This article uses commonalities between countries to create a representative typology, which can suggest appropriate policies for transition. Following the energy efficiency first principle, transition should include supply-side and demand-side efficiency to ensure coherency and efficient use of resources. Their comparative analysis supports implementing the energy efficiency first principle locally, and a more coherent European strategy for the heating sector. Methodologically, 14 national heating strategies are considered which include current and future energy system developments, demand- and supply side energy efficiency, hectare-level thermal mapping and energy system analysis. Four heat sector types are proposed and discussed. These are (1) extant heat planning traditions, aiming for more efficiency and integration; (2) extant heating infrastructure, aiming to refurbish and upgrade both building stock and existing heating infrastructure; (3) existing gas infrastructure, requiring radical transition; (4) and those without strong historic heat planning traditions.

Keywords Strategic energy planning · Energy efficiency · Heat infrastructure · District heating · Smart energy systems

This article is part of the Topical Collection on Making the Energy Efficiency First Principle Operational

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Introduction

While heating represents approximately half the European Union's (EU) energy supply, the EU has lacked a coherent approach for its decarbonisation. This is partially explained by the fact that while heat is an important sector, it is also complex and locally determined. The challenges of reducing demands, particularly in residential heating and practices, are significant (Drysdale et al., 2019; Gram-Hanssen, 2013). Heating is also highly integrated in the built environment, gas and electricity sectors, and achieving energy efficiency gains in supply requires even further integration and complexity (Lund et al., 2012).

This complexity is reflected in the development of policy at European level. Prior to 2016, policy related to heating was disparately housed under the Energy

Performance of Buildings Directive (EPBD, concerning thermal quality of buildings), Renewable Energy Directive (RED, concerning renewable heat), Energy Services Directive/Energy Efficiency Directive (EED, concerning efficiency in industry and cogeneration), and Ecodesign Directives (efficiency of heat/cold generating equipment) (European Commission, 2016). This mirrors the complexity and fragmentation, with parallel focus on supply- and demand-side, observed in literature.

The 2016 'Strategy on Heating and Cooling' was published with the purpose of strengthening and renewing these instruments with greater coherence (ibid). This included anchoring the energy efficiency first (EEF) principle from an integrated perspective on energy efficiency in heating, recognising the role of energy savings to reduce demand, but also efficient supply infrastructures and sources to reduce primary energy, in the Energy Union of 2018 (Regulation 2018/1999).

A second specificity to effective transition has been the local character of heat and heating systems, given the difficulty of transporting heat over long distances. This means it lacks the obvious cross-border nature that the EU gas and electricity markets have, and which provides strong levers for EU coordination. As a result, the initiative has remained at the member state (MS) level with large differences between countries' selected pathways. Different historic policy frameworks, stakeholders, and market dynamics have often resulted in strong path dependency (Gross & Hanna, 2019; Bertelsen, Mathiesen and Paardekooper, 2021) little radical change recently (Bertelsen & Mathiesen, 2020). This is problematic, since it results in potential gains not being implemented and slows the overall decarbonisation of the EU energy system.

Objectives

This paper aims to bridge the gap between a generic EU level approach and highly localised approaches. The development of representative typologies enables initial transferability of methodologies and knowledge in imperfect information/data-scarce situations, while respecting local characteristics and specificities. It does so by identifying similarities between countries based on current and long-term perspectives, to propose policies. To achieve strategic policies on a wide scale that can support the transitions needed towards decarbonisation, scenario development, simulation and strategy designs based on quantification can be used to identify policy objectives and support policy development (Lund, Arler, Østergaard et al., 2017). The strategies and scenarios here, using the EEF principle, can form a basis for concrete development of policies and measures to support transition.

A comparative analysis of the current heating sector and strategic 'Roadmaps' outlining the transitions necessary towards 2050 allows for the identification of the different types of strategic planning objectives and decisions. The typology is based on the technical and physical characteristics and potentials of the heating and energy system, and considers both demand- and supply-side considerations to implement the EEF principle.

The focus of the heat strategies laid out in this paper is primarily on the development of the built environment and heating infrastructures, which implicitly disregards particular aspects of rural heating. The paper also has a relative focus on investigating the form of district heating (DH) in national heat strategies, since this presents the largest development compared to how heat planning has been addressed traditionally, at an EU level. However, the authors are aware that there is increasing development in the analysis of stand-alone solutions (for example, in Petrovic & Karlsson, 2016) and require strategic decisions about how to supply heat in areas where infrastructure solutions are not feasible.

The heating sector considers residential, service, and industrial demands, which were all considered for the development of the heating strategies. However, the focus for this paper is on demands in the built environment, and in particular heating and domestic hot water use in the residential sector. This is because the differences between countries were most obvious here, and policies most required to ensure socio-economically viable solutions are implemented.

Describing heating

Policy development for heating and cooling has been accompanied by increasing academic attention for the role of heat and heat planning in decarbonisation. At the EU level, this has included reviews of the heating sectors (Bertelsen & Mathiesen, 2020) and the built environment (Zangheri, et al., 2018), as well as historical analysis of transitions in heating and cooling (Bertelsen, Mathiesen and Paardekooper, 2021; Gross

& Hanna, 2019). Parallel, research has developed various strategies for decarbonisation, including considering DH (for example Colmenar-Santos et al, 2016; Connolly et al., 2014; Kozarcanin, et al., 2020).

At country and local levels, a more diverse body of knowledge is forming which in many cases specifically combines energy efficiency and energy supply approaches, across a range of countries. Literature and (energy) planning practices are developing more refined approaches, methodologies, data, and policy recommendations to support and implement effective heating and cooling strategies (e.g. comprehensive assessment methodologies from the EED) — often with the inclusion of DH. In many cases, these studies have implicitly addressed the transferability of learnings, by seeing certain places as 'representative' with regard to DH (technology) development.

Many of these representations from local and national cases become regional; e.g. Eastern Europe/ Central and Eastern European Countries (Cirman, Mandic, Zoric 2013); South-East Europe (Dominikovic et al., 2016; Rutz, et al., 2019), cold-climate and warm-climate countries (Kozarcanin. et al., 2020), Mediterranean (Lizana, et al., 2017) or Nordic (Helin, Syri, Zakeri, 2018; Sandberg, Sneum, Trømborg, 2018). Some papers take a political economy approach, considering "formerly planned economies" (Werner, 2017); "post-communist" (Tirado Herrere and Urge-Vorsatz, 2012); "coordinated market economies" (Hawkey & Webb, 2014); and "liberal market economies" (ibid). Grey literature (including the European DH industry association) specifically distinguishes technology markets, as "mature", "con solidation";"refurbishment";"expansion" and "new development" (Euroheat & Power, 2019; Werner, 2010).

When looking at another perspective of the heating sector in the form of energy performance of buildings, similar representations are observed; geographical (including specifically Scandinavia) (Bartiaux et al., 2011), climatic conditions (Zangheri et al., 2018) but also political economies, for example "post-Socialist" representations (Cirman, Mandic, Zoric 2013). However, it is to be strongly noted that the useful typologies when assessing building stocks and renovations are usually disaggregated to the age, size, and type of building, rather than a characterisation of the stock overall between countries, since this much better captures the variance within the stock and facilitates more granular analysis, which can then be used to develop cross-country analysis (Filogamo, Peri, Rizzo, Giaccone, 2014; Loga, Stein, Diefenbach 2016).

Several observations arise from this literature, which clearly highlights the interest in transferable knowledge for heating. First, the former communist/ socialist/planned economies of Eastern Europe are regularly and fairly intuitively cohorted together, but other aggregations are not as obvious. The second is that these proxies and characterisations often arise in order to generalise and contextualise case studies, and be able to apply knowledge gained broader and meaningfully. The third is that the literature on the heating sector reflects its diversity, with the focus often on either decarbonisation and/or efficiency of the built environment on the demand-side, or the heat supply infrastructure/system on the supply-side. This underlines the need to analyse integrated heating strategies, following the EEF principle, for a coherent energy system perspective.

This paper approaches transferability by deductively analysing 14 countries with the intent of determining a useful typology that can inform and facilitate the transfer of policy for integrated heating strategies. The paper hypothesises and posits that commonalities and differences exist in the (physical and technical) heating sector and in heating strategies for decarbonisation — and the policy recommendations that results from them. This then allows for categorisation. This type of abstraction, by the authors knowledge the first of its kind, can help inform planners and decision-makers as well as researchers where tailored strategies do not (yet) exist or data is scarce — but where the characteristics are similar so policy recommendations are likely to be productive.

This article does not aim to categorise all the social, economic, political, institutional, and ideological contexts of different countries' heating regimes, but does aim to draw some similarities in the development and outlook for the heating sector. This is delimited to the current (physical) state, strategies, and scenarios looking towards the future, since this is where rich and aligned data exists for comparative analysis. By creating types that can function as sub-groups, the recommendations can be tailored more specifically and allow for more context-specific policy suggestions which then have a larger change of being successfully transferred and implemented. This study shows that while heat strategies need to be local and specific, shared characteristics result in common ground in terms of the transition strategies.

Structure

Following this introduction is a methodological overview. This includes both detailing of the different data considered and an in-depth description of the 'Heat Roadmap' strategies that play a large role in informing the operationalising of the EEF principle. Following this is a discussion of how the typology is developed, putting forward the emergence of the different country types. The final section details the 4 different country types and relevant policy recommendations, before presenting the conclusions.

Methodology

The development of the typology proposed in this paper takes its point of departure in a comparative analysis of comprehensive heating strategies, which specifically focus on implementing the EEF principle. With this regard, the comparative angle covers energy demands, and in particular the state of the built environment, energy supply infrastructures, and energy sources. It includes the perspective of the status quo, what current policy can achieve, and how strategic implementation of the EEF principle (through Heat Roadmaps) could deliver. These then form the basis of an emerging typology through an exploratory comparative analysis.

Data used

The development of the typology and basis for policy recommendations are several datasets, scenarios, and strategies. These cover the current status of the heating sector; the projected expectations towards 2050 given current policies, energy system scenarios looking towards implementing the Paris Agreement by 2050, and accompanying strategies (see Table 1).

The 2015 Baseline information is a slightly broad interpretation of current, but it serves as the most detailed perspective on a baseline that is specifically

Table 1 Summary of sources used to describe and analytically compare the current heat sector, future trends under current policies, and strategic heating transitions

Abbreviation	Information used	Reference
2015 Baseline (BL)	- Current heating infrastructures, share of DH and sources	- *Profile of heating and cooling demand in 2015* (Fleiter, Elsland, Rehfeldt et al., 2017b)
	- Current shares of gas, other stand-alone heating sources	- *Data annex to Profile of heating and cooling demand in 2015* (Fleiter, Elsland, Rehfeldt et al., 2017c)
	- Energy performance of buildings: minimum standards and average performance	- *Space Cooling Technology in Europe*. (Dittmann, Rivière, Stabat et al., 2016.)
	- Heat/cool demands	
2050 Baseline (BL)	- Expected heating infrastructures, share of DH and sources	- *Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050 (*Fleiter, et al., 2017a)
	- Expected shares of gas, other stand-alone heating sources	- *Report on cost-curves for built environment and industrial energy efficiency options.* (Harmsen et al., 2018)
	- Expected minimum standards and performance	- *Baseline scenario of the total energy system up to 2050: JRC-EU-TIMES model outputs for the 14 MS and the EU.* (Nijs, Ruiz Castelló, and Hidalgo González, 2017)
	- Energy savings in terms of delivered heat	
2050 Roadmap scenarios and Heat Roadmaps	- Recommended heating infrastructures	- *Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Heat Roadmap Europe. (*Paardekooper et al, et al, 2018a)
	- Recommended heating sources	- *Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Heat Roadmap Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, Netherlands, Poland, Romania, Spain, Sweden, United Kingdom.* (Paardekooper et al, 2018b-o)
	- Recommended energy savings in terms of heat	- Heat Roadmap Europe 4 Energy models for 14 EU MSs (Paardekooper et al, 2018p)
	- Investments needed	
	- Analysis of starting points, transitions required	

geared towards creating a clear profile of what the starting point is for the heating sector and the built environment, on an EU level. While aligned to Eurostat, the references in Table 1 are used over more generic Eurostat or IEA data since they are more detailed than the statistics available in typical energy balances in the heating and cooling technologies as well as in different sectors. Additionally, these data include detailed information on building stock, type, state, and the performance of the built environment broken down by roof, wall, basement, and window performance. Overall, this means that the data is detailed enough to allow an in-depth understanding of the heating sector — but is also comparable across different countries.

The 2050 Baseline provides a scenario to understand how the heating and cooling sector would develop, and where that will lead, given no additional policies on climate, energy, and heating. This allows for a background on what is needed to drive change, versus what developments are likely to already be addressed by extant mechanisms and policies. It is based on projection modelling using FORECAST and the JRC-EU-TIMES models. Similar to the 2015 datasets, the 2050 Baseline provides a set of information at a granular level about the projection of the heating and cooling sectors looking towards 2050 within the frame of the energy and climate policies of the EU, which can be compared European-wide. While these scenarios are based on the policies which were decided by end 2016, their relevance is still high since there have not been many radical shifts since the setting of 2030 targets. It should however be noted that this does not include the (intended and proposed) policies in the National Energy and Climate Plans and Long-Term Renovation Plans developed by member states.

Heat Roadmaps

This paper relies strongly on 14 country strategies termed Heat Roadmaps, from which the typology emerged. The ontology, methodological approach (including model descriptions), and specific results of the Heat Roadmaps themselves are described in more detail in (Paardekooper et al., et al., 2018a; Paardekooper et al., 2018b-o).

These Heat Roadmaps are modelled scenarios for potential development pathways for the heat sectors to be in line with the Paris Agreement. This includes full decarbonisation of the heating sector, and an energy system decarbonisation of 86% compared to 1990. They represent an alternative vision towards decarbonisation, through a re-designed heating and cooling sector that explores the potential of increased efficiency and integration, for example through concrete application of the EEF principle for the heating sector.

The 2050 Roadmaps are alternative scenarios that have been developed, where the heating and cooling sectors have been re-designed in line with several approaches:

- Energy efficiency on both the demand and the supply side, in line with the EEF principle, to determine the effect of demand reductions and also allow for the option of currently unused (excess and renewable) heat to be used for heating;
- The use of local resources and currently available technologies, to ensure scenarios that rely on proven technologies and avoid reliance on imports.
- Integration with the electricity and transport sectors, to support the full decarbonisation of the energy system. This includes a specific regard for the synergies between different energy infrastructures (including heat, electricity, and gas).

These alternative Roadmaps scenarios have been produced using hectare-level geographic data for heat demand in order to understand the spatial dimension of heating, account for specific infrastructure costs, and determine proximity and potential of (local) heat sources such as excess heat and geo-/solar thermal for district energy at hectare level (Möller et al., 2019). Intertemporal energy system modelling was carried out with the JRC-EU-TIMES model, to show the transitions between 2015 and 2050 for all sectors; EnergyPLAN was used for high-resolution intra-annual simulation of the 2015 and 2050 scenarios for all sectors, to be able to better reflect the dynamics of a high-renewables energy system (Paardekooper et al., et al., 2018a). The scenarios are assessed by considering together the multiple criteria of minimising cost, CO_2 emissions, fuel (and in particular imports), and prioritising proven technologies.

These Heat Roadmap scenarios represent a quantified vision of what can be achieved towards efficiency in the heating sector. Because they are developed within the context of the wider energy system, they take into account the needs of, for example, the transport and industry sectors as deep decarbonisation takes place. Because they are developed using tools that recognise the synergies that (local) district energy can present towards higher efficiency and decarbonisation, they recognise the role that local heating solutions can play towards achieving this goal (Lund et al., 2021). This approach also support the operationalising of the EEF principle, since it explicitly integrates the supply-side and demand-side of heat, as part of the analysis and development of heating strategies and relevant policy frameworks.

The strategies in the Heat Roadmaps are a result of the combined understanding of the current situation, a baseline counterfact, and the alternative Heat Roadmap (technical) scenarios (Fig. 1). This is then also the basis for the typology development. The analysis of the EEF principle takes place by looking at three dimensions separately, to recognise both the role of energy demand reductions and more efficient supply options in the principle. These are then discussed within the perspectives of now and alternative futures, to adequately identify policy gaps and suggest how there is potential for faster or deeper efficiency and decarbonisation gains. To support the development of policy recommendations, emphasis is placed on the second and third elements outlined in Fig. 1.

Approach to typology development

The identification of the typology follows comparative approach of the dimensions described in Fig. 1. The research design is based on the observation of the countries' data and strategies in order to notice and identify differences and similarities. This means that the process is highly exploratory and includes qualitative and quantitative elements. This includes analysis of all sources discussed in Table 1 and historiographic contextualisation through literature, meaning that the typology is a result of many factors and criteria, rather than distinctly allocated ranges or cut-offs. Data exploration techniques included (manual) ranking, correlation searches, and various visualisations, in order to discern (a) which factors presented relevant differences between countries, and (b) what types of groupings emerged, based on dimensions and aspects relevant to decarbonisation and energy efficiency first principle. A selection of

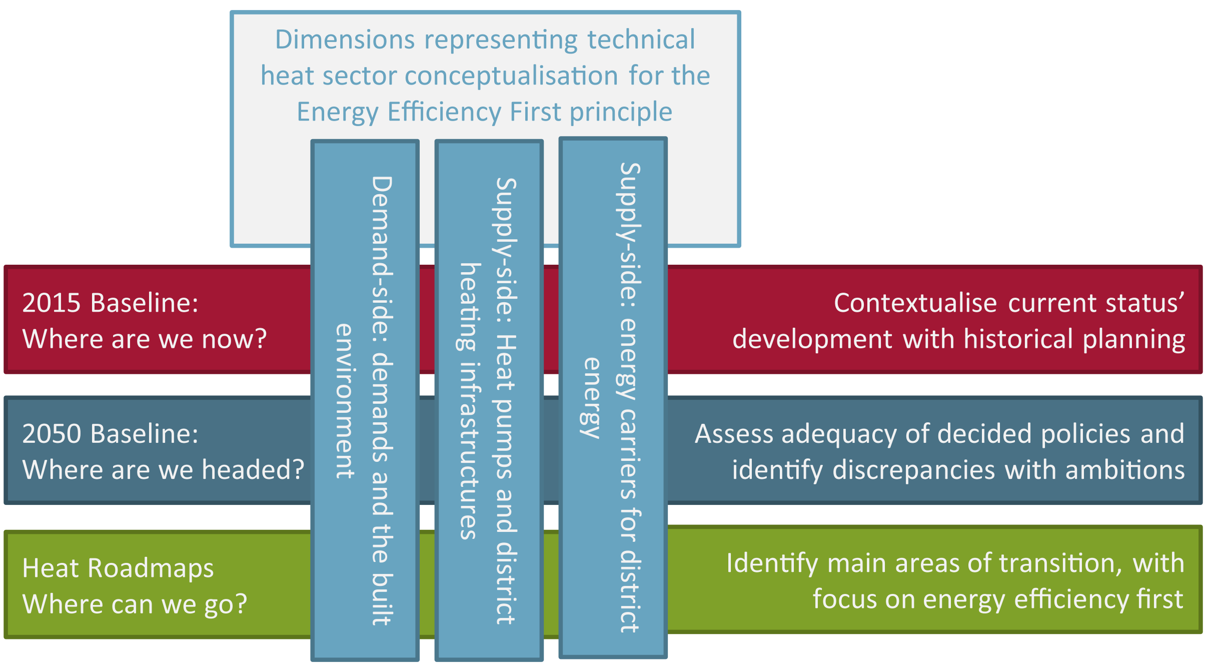

Fig. 1 Overview of how the different dimensions and time perspectives are used to describe both the (physical and technical) state and support policy for energy efficiency and decarbonisation strategies

these is presented in the sections below to motivate the typology factors. Data on the (physical and technical) state and potentials was complemented by literature on the historiographical development of countries' heating and cooling sectors. From this exploratory process, several groupings emerge, which are then classed together and described to form the typologies, based on the defined characteristics.

The choices and coherence for these groups are, per definition, a scaled assessment. In addition, the explicit decision to compare (future-looking) strategies that use the energy efficiency first principle mean that the groups inherently include regard to current and future scenarios, energy demands (particularly the built environment) and energy supply. The advantage of comparing datasets and strategies based on one methodology is that the differences are not a result of varying methodologies; however, the strategies are still shaped by the applied methodology. Normative choices in the strategies — notably to use only proven technologies, to actively explore the potential of DH, and to support the decarbonisation of the wider energy — of course also shape the different variables along which the assessment is made.

Typology development

Based on the combination of characteristics and strategies of the 14 countries considered, several groupings emerge through the comparative process to form types. Several key exploratory perspectives that construct the typology are presented below.

Current supply technologies and infrastructures

Figure 2 plots the 14 countries considered in terms of the 2015 renewable energy share in heating and cooling and the market share of DH. Factors such as bioenergy availability and the decarbonisation of the electricity when used for heating and cooling are also drivers of renewable energy in heating/cooling, so the diagram does not denote direct causation. Nonetheless, the plot provides a good starting point to group countries in terms of their heat infrastructure and effective decarbonisation.

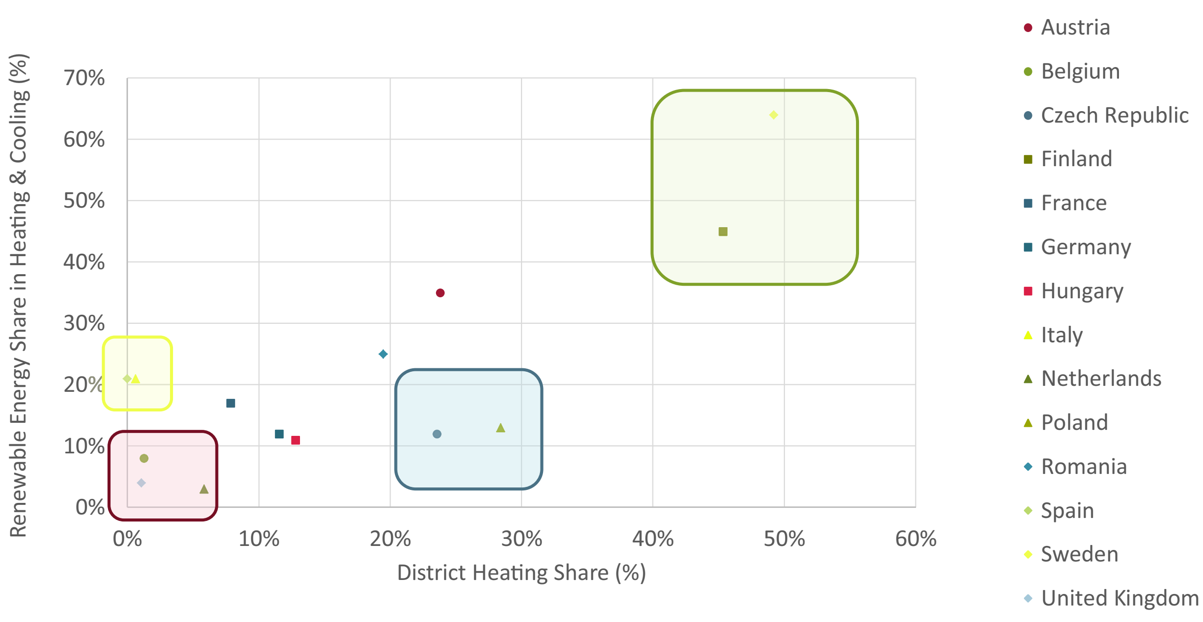

Fig. 2 DH market share and renewable energy share in heating and cooling, 2015, for 14 MS considered, with groupings indicated for high shares of both (green, at far right); medium shares of DH but low shares of renewables (blue, at bottom centre), low shares of both (red, at bottom left) and low shares of DH but medium shares of renewables (yellow, above left). Based on Fleiter et al. (2017b)

The first grouping emerges where there are simultaneous high shares of DH and high shares of renewable energy in 2015 (represented in green, comprising Finland and Sweden). Of the countries with medium market shares of DH, those with a relatively low share of renewable energy raise interest, since the extant infrastructure has clearly not been accompanied by high shares of decarbonisation (represented in blue, comprising the Czech Republic and Poland). This is particularly the case since these have quite significant biomass potentials, which may drive the higher share of renewable energy. The third grouping is the countries where there is very little DH and a very little renewable energy in the heating and cooling sector, mostly due to high shares of gas (represented in red, including the Netherlands, the UK, and Belgium). The fourth groupings of interest are the two outliers, which have next to no DH, but higher shares of renewable energy in heating and cooling than the red grouping (represented in yellow, comprising of Italy and Spain). In between these latter, three groups sit Germany, France, and Hungary, which are quite mixed in their heating and cooling sector and do not show an obvious similarity in this perspective.

Figure 3 gives further insight to the current heating infrastructures of the red group, by visualising the extent to which residential heat is supplied by gas. The range of the (final) residential energy market share for gas in the EU28 is between 0 and 84%. From this map, it is clear that there are several countries (specifically the Netherlands and the UK) where gas dominates, and some where it is quasi-non-existent. This strengthens particularly the red grouping from Fig. 2. In most countries, urban and rural differences mean it is more a question of to what extent heat is supplied by gas. This also reveals the local nature of heating, since in most of these countries, it can also differ on a city-by-city basis.

Recommended technologies and infrastructures

Parallel to current infrastructures and sources, characterising the transition in the heating sector that countries need to make considers identifying the difference between the current infrastructures and the recommended level of infrastructure in the Heat Roadmaps (Fig. 4). Assessing this discrepancy helps give insight into the scale of transition, and further supports the grouping of different types.

Similar groupings emerge as those which are identifiable from the current infrastructure. Sweden and Finland (green) effectively have a current market share for DH and the techno-economic analysis shows it is viable and recommended for the future. The second grouping (circled in blue) differs from that based on the renewable share, and here, more accurately represents countries which have a significant share of DH currently, and in most cases the potential to expand. However, this group is evidentially not as close in similarity as the others in this regard, and will be more strongly consolidated in Sect. 2.1.2. The third group (yellow) shows the widest gap between realised and potential DH infrastructure, with very little extant and an extremely high techno-economic potential. The final group (red) shows a similar pattern, but with less high overall potential. Again, there are several remaining countries for which there is no obvious fit.

State of the built environment and energy savings

Transition in heating should consider not only heat infrastructure but also the state of the built environment (Drysdale, Mathiesen, Paardekooper, 2019; Hansen et al., 2016). Following the EEF principle, this allows for a consideration of the amount and the type of heat required simultaneously and supports the idea of maximising energy efficiency. To typify this, Fig. 5 shows a comparison between the amount of savings in delivered space heating demands between now and 2050 using the Baseline that results from the implementation of policy already decided — and the level of savings that the Heat Roadmap strategies considered to be techno-economically preferable in that same period.

It is firstly worth noting that the Baseline 2050 is aligned to the EU Reference Scenario of 2016, it includes only agreed upon measures as of 2016. This includes adherence to the Clean Energy Package measures as proposed in March 2018, but not intended further measures (Nijs, Ruiz Castelló, and Hidalgo González, 2017; Paardekooper, et al., , et al., 2018a). Finally, it is useful to note that the metric is delivered energy (as opposed to final energy, where heat pumps are expected to make large savings).

The similarity between the countries in blue (Poland, the Czech Republic, Romania, and Hungary) is the highest in this category, with extremely

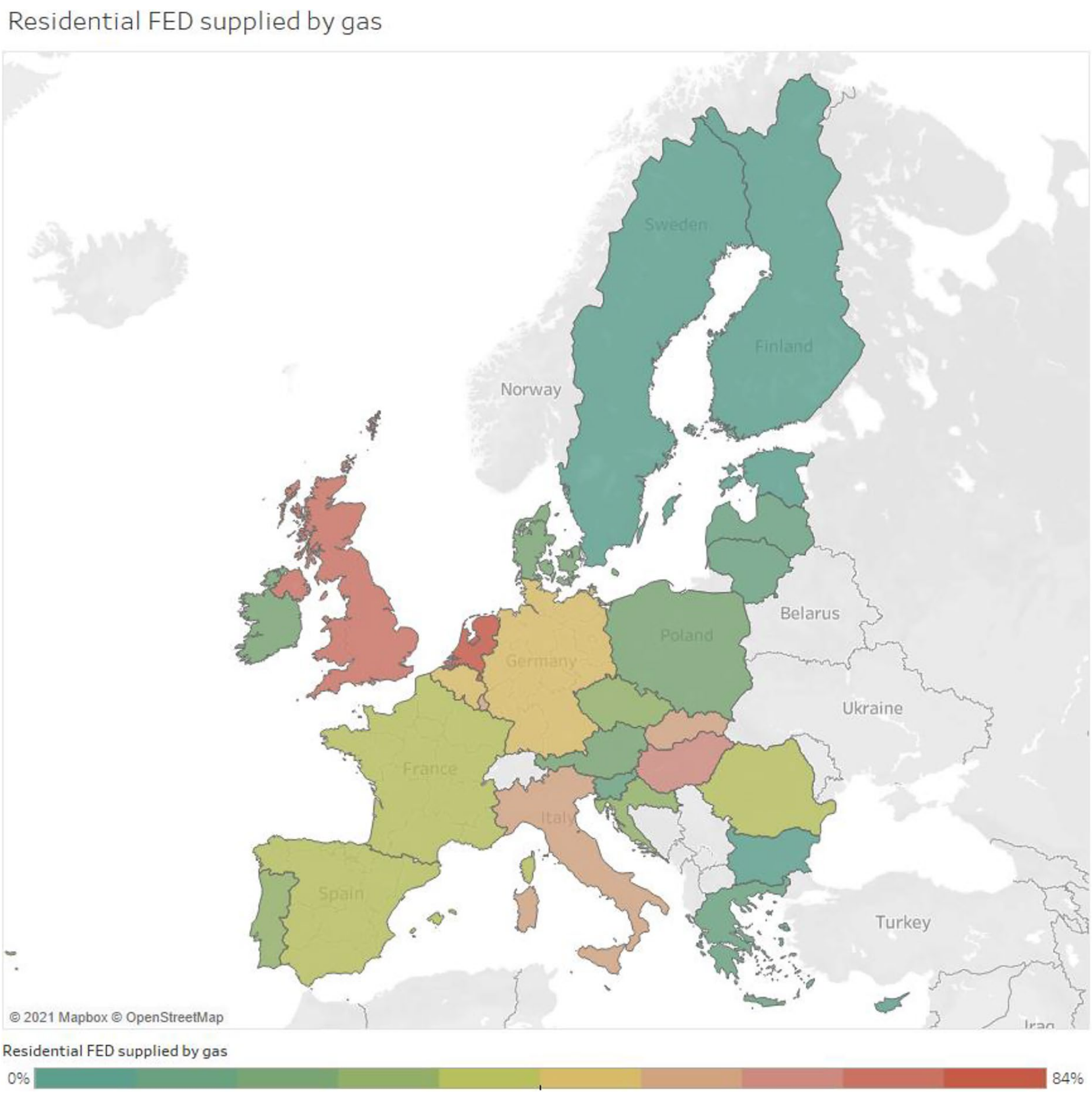

Fig. 3 Spatial representation of (final) residential heat demand supplied by natural gas in the EU in 2015. Based on Fleiter et al. (2017b) and Paardekooper et al. (2018a)

high potentials (in all four cases, the highest modelled potentials) being found to be cost-optimal, and far above current ambitions. When the countries are ranked based on differential between current policies and socio-economically viable potential, they represent the highest 4. The singularly high differential between potential and agreed policy also consolidates them as a type.

For the other groupings, alignment can be observed also here; while the current policy initiatives do not achieve the techno-economic optimal level in Sweden and Finland (green), it is approached. Italy and Spain (yellow) show some of the lowest determined savings, while the potential recommended is higher but not extremely so. The countries with both significant current policy initiatives but also significant expected

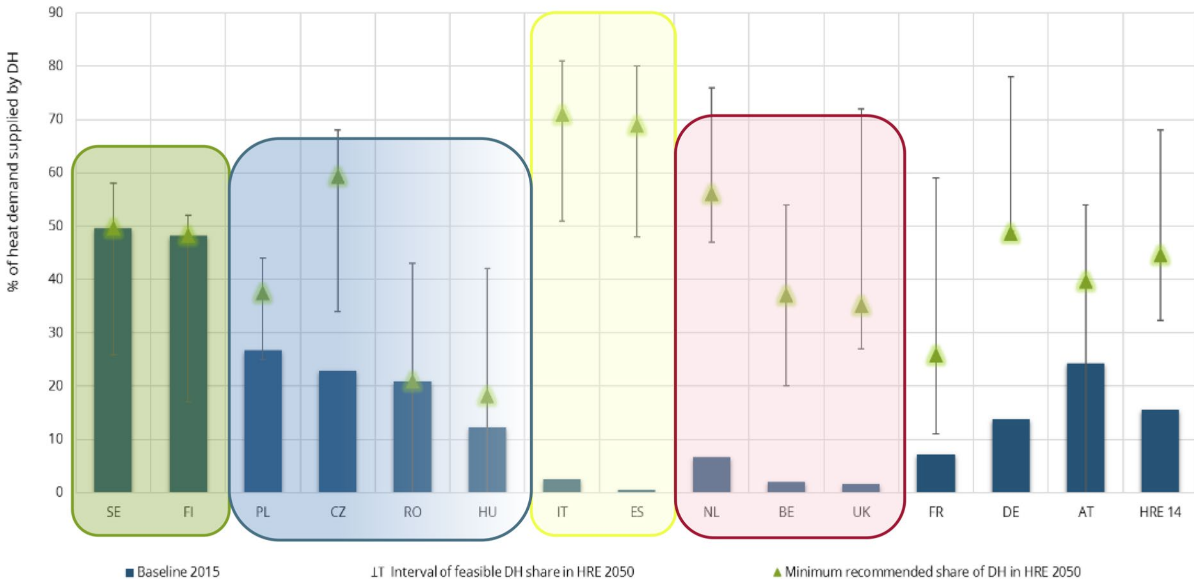

Fig. 4 Share of DH in 2015 and share recommended in the Heat Roadmaps developed for 14 EU MS, with groupings indicated for little infrastructure expansion needed (green, at far left); significant current shares with potential to expand (blue, second left), extremely rare and high potentials (yellow, second right) and scarce with large potentials to expand (red, right). Ranges represent a 0.5% cost change to the (whole energy) system. Based on Paardekooper et al. (2018a)

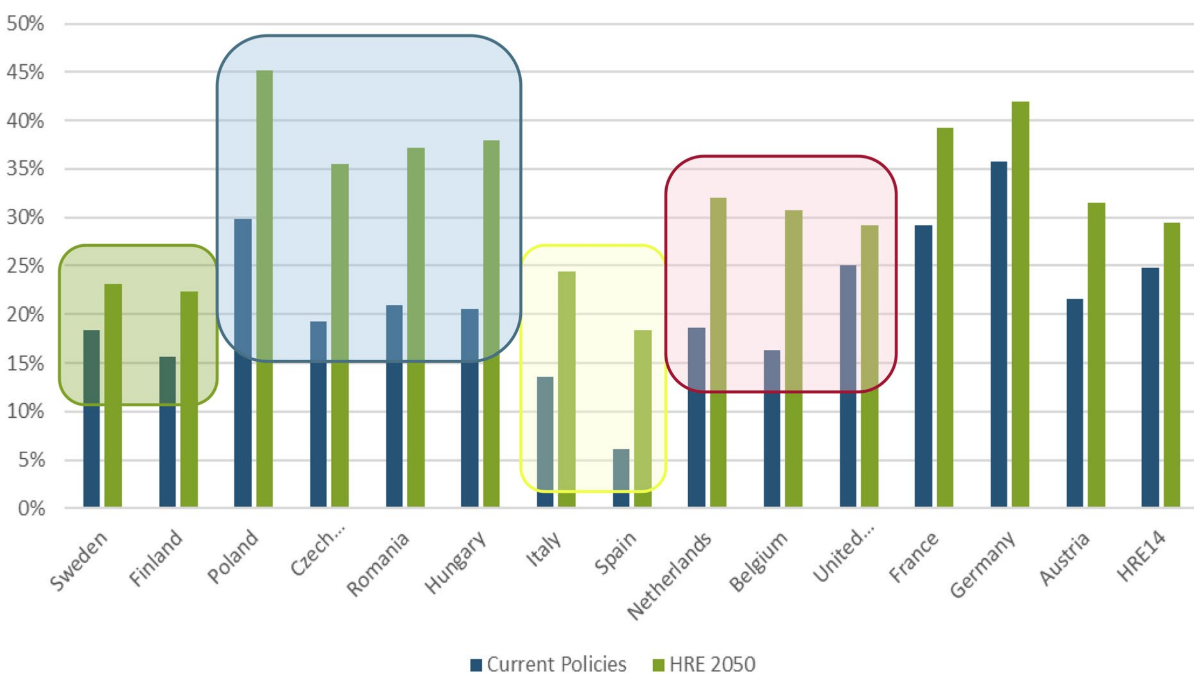

Fig. 5 Delivered heat savings between 2015 and 2050 foreseen in policies decided in 2016 and in the Heat Roadmaps for 14 EU MSs, with groupings indicated for approaching recommended level (green, at far left); high potentials with large discrepancies (blue, second left), low potentials and moderate discrepancies (yellow, second right) and moderate discrepancies with moderate potentials (red, right). Uncertainties and optimisation planes are presented in Paardekooper et al., (2018b-o). Based on Paardekooper et al. (et al. (2018a)

savings can be identified here (in red, represented by the Netherlands, Belgium and the United Kingdom). Again, there are several key countries which are difficult to allocate.

Results and discussion

A comparative analysis shows that categorisation is possible, based on the physical characteristics of the current heating sector, scenario's developed towards 2050, and strategies which consider a redesign of the heating and cooling sector to decarbonise in line with the EEF principle. This allows for the identification of some distinct groups of countries, which show meaningful enough commonalities to also present typical policy recommendations. Not all countries can be clearly categorised: certain present 'in between' results — most notably France and Germany — but using the characterisations described in the methodology, it is possible to distinguish 4 clear groups of countries as types. These are summarised in Table 2 and discussed in depth in the subsequent sections.

Germany, France, and Austria cannot confidently and exclusively be placed within one type or another. Their levels of renewable energy in heating are all fairly mixed (Fig. 2), which is further supported by there being in many cases a clear mix of DH, renewables in biomass, some heat pump maturity, and solar thermal (Fleiter et al., 2017b). Gas shares exist, but nationally do not dominate (Fig. 3); the discrepancies between current and recommended levels of DH are also not clearly similar to any particular group, since there are medium market shares of heat already existing and the potentials vary (Fig. 4). Finally, France, Germany, and Austria all have relatively low discrepancies between their currently determined and their recommended level of delivered heat savings; but these levels are also relatively high (Fig. 5). This supports the idea that local approaches are required in complement, especially in more diverse countries.

It is probable that with a further regional breakdown, Germany would be a mix between more gas based and depreciating DH, requiring refurbishment. Since heating mostly consists of long-term infrastructures, historical divergences in planning can still be very prominent today, and this is mostly based on the strong "district heating promotion before reunification" in the former German Democratic Republic, and the effect of building construction policy and practices (Michelsen & Madlener, 2012). For example, the EU-wide buildings categorisation tool Tabula specifically categorises former GDR buildings between 1949 and 1983, as a way to integrate their characteristics into the assessment of the energy performance of buildings (see Loga, Stein, Diefenbach 2016). Such historical divergences in heating policies and culture are partially infrastructure based but are at the same time perpetuated after their end; Michelsen and Madlener conclude that the former divide influences homeowners' choices when it comes to adopting more or less efficient and renewable domestic heating systems (2012).

France also shows a mixed assessment, which is likely partially due to climatological variations across the country, but also because there is a strong mix of both gas/oil and electricity (Bertelsen & Mathiesen, 2020). The gas-dominated areas may resemble the gas type countries on a smaller scale; gas networks were similarly expanded in certain French cities after the discovery of domestic gas resources and replacing coal gas in the 1950s and 1960s. Simultaneously, electricity is used to quite a large extent, particularly in the south, where it is also sometimes combined with cooling. These regional differences, particularly in large countries, underwrite the point that the organisation of heating is often still local. While this paper focusses on the national level, this recognises that that certain municipalities/regions may be exceptional to area and resulting policy recommendations should be moderated.

Active heat planning countries

The first identified type that emerges is those with extant heat planning traditions, aiming to move toward integrated, smart energy systems and clean, high efficiency DH systems. In this study, they are exemplified by Sweden and Finland, but this can of course be used to describe countries like Denmark and parts of Germany. These countries are overall characterised by already existing strong policies on building requirements and high market shares of DH and heat pumps, where policy should be aimed towards implementing the EEF principle to support parity between heat demand reduction and supply, and efficient integration of the heating sector with the increasingly decarbonised energy system.

Table 2 Overview of the identified types in the typology and the countries to which they apply, and the main policy recommendations resulting from each of the elements of the physical and technical characteristics of the heating system considered

Type name	Countries	Demand-side: delivered energy savings	Supply-side: DH market share	Supply side: DH sources
Active heat planning countries	Finland[a], Sweden[a], Denmark[b]	Current policy supports transition objectives. Recommendation focus on implementation	Current DH market shares are within range to support transition objectives. Recommendation is to maintain	Current system includes large shares of boilers and high temperatures. Main recommendation is to move towards more diverse and efficient supply
Refurbishment heating countries	Poland[a], Hungary[a], Romania[b], Czech Republic[b], Slovakia[b] (parts of Germany[b])	Current policy designed for high level of savings. Main recommendation to reach even higher levels	Current market shares are high, but stagnant. Recommendation is to ensure consolidation and facilitate (re-)expansion where possible	Current system includes large shares of boilers and very high temperatures. Recommendations is to align phase out with introduction of efficient and diverse supply
Gas infrastructure countries	Netherlands[a], United Kingdom[a], Belgium[b], (parts of France[b]), (parts of Germany[b])	Currently policy supports savings. Recommendation to support higher levels	Current shares are low, main recommendation is to support radical switch of heating infrastructure	Ensure newly established DH sources align with EEF principle
Countries without strong heat planning traditions	Spain[a], Italy[a], (parts of France[b])	Currently binding policy support some savings. Recommendation is to consolidate some further potential	Current low shares, main recommendation is to enact remarkably high potential	Ensure newly established DH sources align with EEF principle, given high baseload potentials

[a]Countries that were modelled in detail in the Heat Roadmap Europe project and for which strategies were developed, with presented results in the discussion. [b]Countries that were modelled in detail in the Heat Roadmap Europe project and for which strategies were developed

Key characteristics

The current high DH shares, and varied sources, indicate established systematic planning for developing the infrastructure. Market shares for electric heat pumps (particularly Sweden) are also a result of ongoing discussions on the optimal use of fuels, electricity production, and efficient integration of heating and electricity that stems from the OPEC crises (Dzebo & Nykvist, 2017; Johansson, 2021). Similar motivations initiated Danish energy planning (Bertelsen, Mathiesen, and Paardekooper, 2021). Strong planning traditions have allowed the systemic consideration and eventual development of heating infrastructures, with a variety of heat supply sources.

Planned policy for reducing heat demands in buildings is largely in line with socio-economic potentials. The scenarios looking towards 2050 for these countries show that Sweden and Finland have low further renovation potentials than already determined policy, despite their higher specific demands. This is mostly the result of the already (and historically) existing high standards in buildings, resulting in, relatively, the building stock having some of the lowest average U-values, and some of the most stringent future minimum standards (Fleiter et al., 2017a; Harmsen et al., 2018).

In terms of the market shares for supplying heat, the scenarios recommend around 50% of the heat to be supplied by DH. This is a similar or not much higher market share for DH as exists now and is rooted in a deliberate and guided expansion in the latter decades of the twentieth century, under the auspices of active and often explicitly interventionist energy policy and direction (Roberts & Geels, 2019).

Policy recommendations

Since policy supporting energy performance of buildings is already relatively ambitious, policy development should be aimed primarily at achieving and implementing the stated ambitions and policies rather than drastically raising them. Since the baseline already aims at demand reductions of around 15%, on top of the already high existing performance, this is likely to be more difficult to achieve than for other countries, where the more straightforward options for savings have not yet been capitalised upon. It will require policy to balance and accumulate between ambitious low energy new builds, but particularly building elements in and rates of renovation/retrofit (Drysdale et al., 2019). As a result, increasingly higher ambitions are hard to achieve and not necessarily useful; focus should be on implementing the current ambitions with regard to EEF in buildings.

Energy policy focusing on the supply of DH should mostly focus on maintaining (high) levels of DH market share, and ensuring expansion where necessary. Simultaneously, less heat will be required as buildings reduce demand. Coordination is required to ensure that renovations and efficiency improvements enable lowering of temperatures and losses (Lund, et al., 2014). By allowing for lowering temperatures in DH networks, implementing the EEF principle can be supported as both absolute efficiency gains can be made in terms of reduced losses, but also a wider variety of (flexible) heat source introductions can be facilitated.

In terms of the supply for DH, there are some distinct transitions (shown in Fig. 6) that could facilitate efficiency and cost-effective decarbonisation that require policy support. Firstly, a changing role of cogeneration (CHP) is envisioned (Lund and Mathiesen, 2015). While it is currently the backbone of many DH systems, looking forward, the strategies see it partially phased out and becoming primarily operated in response to the electricity market, rather than the heat market. This flexibility should be used as a means to the end of a more decarbonised energy system. Since a deeply decarbonised energy system is expected to use and integrate a high level of (variable) electricity, policy should incentivise the use of excess heat from power production only at times where electricity is needed within the power sector. Finally, CHP should be fuelled by renewables. This type of operation leads to a much lower capacity of required CHP, and as such, a redesigned heat sector sees a significant phase-out of CHP capacity.

In addition, there is a large role for heat pumps to play in DH systems (Fig. 6). Sweden is quite exceptional in that they already have a high share of heat pumps in DH, resulting from a direct need in the 1980s to integrate excess (night) electricity from nuclear power plants (David, et al, 2017). However, this also means that these old installations will have to be replaced with newer ones, likely with different refrigerants. So while there is experience, the challenge of deploying new (flexible) heat pump

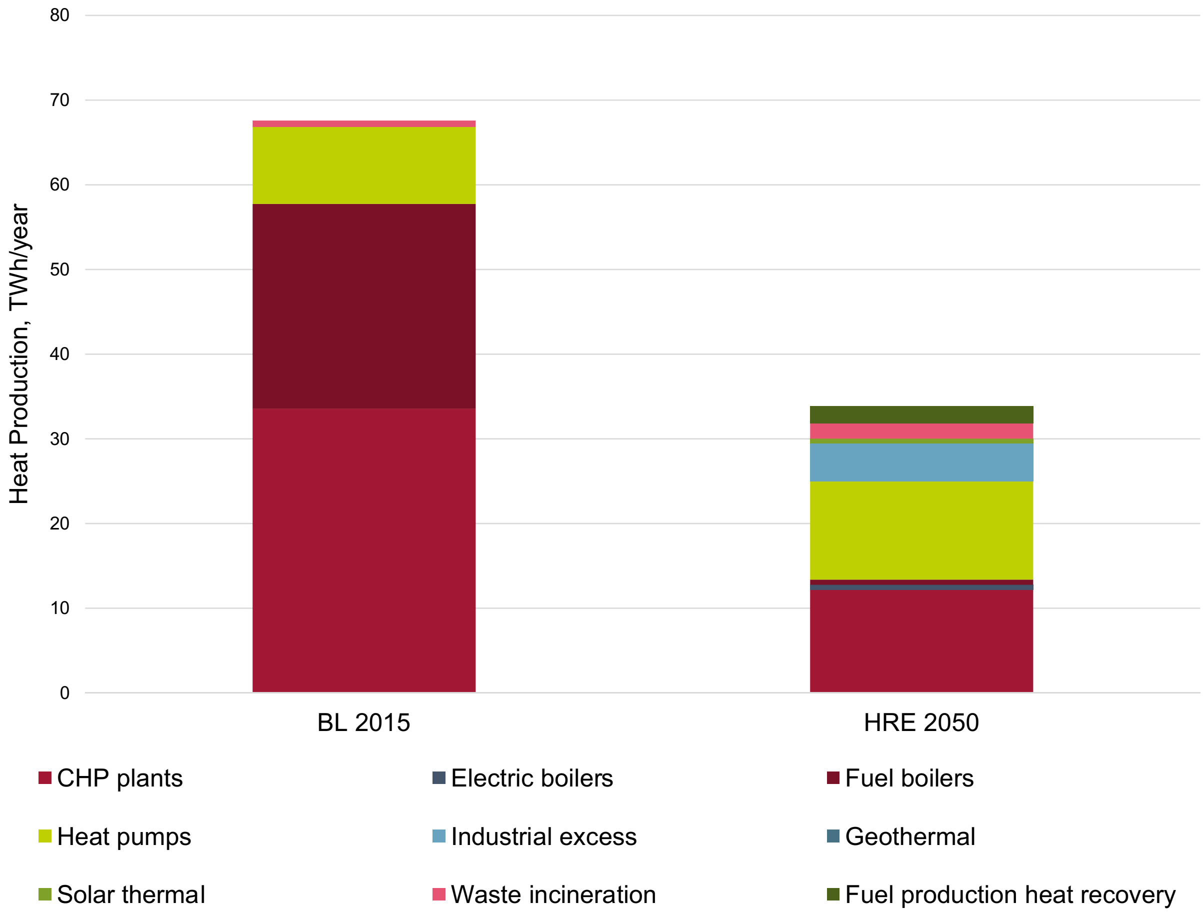

Fig. 6 DH supply for Sweden in 2015 and in the Heat Roadmap scenario 2050, showing both a decreasing absolute heat supply (due to energy savings and efficiency gains in residential, service and industry sectors) and more diverse supply technologies. Based on Paardekooper et al., (2018n)

capacity remains. Combining low-temperature excess heat sources with heat pumps allows for better performance, and lower required capacities.

Thirdly, other heat production methods such as excess heat from industry rise. While excess heat from industry varies in temperature and quantity, direct utilisation has the potential to expand significantly and its recovery is a major part of operationalising the EEF principle. This is also the case for future fuel production through electrolysis, which should be strategically placed to allow for heat recovery. As a result of these three developments, boilers become almost insignificant in terms of heat production, with capacity existing primarily for security of supply.

To underwrite these transitions, policy recommendations must consider that a shift in the temperature level of the DH system is important, since this shift represents the interplay between the demand and supply side, and enables the further implementation of the EEF principle. This requires a coordinated transition in built environment, increasing efficiency of several production units, enabling many new sources of heat, and the infrastructure itself. The transition in these countries with a heat planning tradition is less radical than in the other countries, but instead requires an ongoing, coordinated action across the board to ensure that heating actively evolves and fully implements the EEF principle.

Refurbishment heating countries

The second type is those countries with extant, but depreciating heating infrastructure and buildings that are in need of radical refurbishment. In line with the EEF principle, refurbishment, energy savings, and efficiency measures are needed both in terms of (supply) infrastructure, but also in terms of energy demands in buildings and processes. They are here specifically represented by Poland and Hungary, but the type can also be used to describe large parts of the Czech Republic, Romania, but also parts of Germany, and to an extent parts of South-Eastern Europe. This type basically aligns with what is identified as 'former planned economies' in Werner (2017). These countries have high potential for energy savings. There are also existing shares of DH, but recent decades have left these countries with a varied DH market shares, sometimes stagnating or declining. Urban–rural dynamics also mean that the potential for DH is more varied between countries within this type than the others (Persson, Wiechers, Möller, 2019). Policies for these countries are characterised by a high necessity to refurbish and upgrade both the existing building stock and existing heating infrastructure through operationalising the EEF principle, to ensure modernisation of the heating sector.

Key characteristics

In many cases, these countries have significant market shares for DH as a result of historic government-led development; however, these systems can typically be described as 2nd generation at best, and the share of efficient or renewable heat sources is low. In many cases, this market share has been declining (Euroheat & Power, 2019), and projections towards 2050 based, without further policy, see in most cases a further shift away from DH (Fleiter et al., 2017a). Contrarily, the scenarios looking towards 2050 in the heat strategies recommend similar market shares for DH, or where relatively large industrial excess heat potentials exist, as in the Czech Republic, there is even potential to expand.

These countries are not only characterised by inefficient heating infrastructure but also where refurbishment to the building stocks would capture the remaining, high, energy savings potential. Notwithstanding, radical efforts made, large inefficiencies in the building stock remain. Current policies lead to a trajectory of significant savings in delivered space heating demands (typically on top of significant savings already made in the past decades). However, the scenarios show that a doubling of saving rates, through both more and deeper renovations, would be cost-effective. Indeed, in many of the countries within the refurbishment type, the potential could be even higher than identified here, if more innovative measures were also considered (Paardekooper et al., 2018d,h,k,l). This marked potential strongly shapes the type and its subsequent recommendations.

Policy recommendations

A key focus for heating policy in the countries where radical refurbishment is required is to continue focussing on the energy performance of buildings. In many countries, significant gains have already been made over the last few decades. Partially due to this, the current averages of the U-values for the countries with particular refurbishment needs in the heat sectors are not wildly out of line with EU averages. Contrastingly, some future minimum standards are conspicuously out of line with EU averages, and adjustments to this would provide an obvious first avenue for new builds. For the existing building stock, achieving high levels of energy renovations requires a mix of policies, but continuing the development of effective awareness raising, know-how (both technical, but also to ensure successful financial incentive programmes), and financial instruments to ensure that energy savings are carried out in accordance with the energy system-wide application of the EEF principle.

The challenge regarding the transitions required in the heating infrastructure for these countries is that while DH as an infrastructure should stay, it also needs radical reform which borders on a sense of re-invention. This effectively means a replacement of most of the infrastructure that currently exists and a focus on reconnections to reverse the trend of increasing stand-alone solutions. This specifically includes modernising DH on the one hand, but also (re-) expanding connection rates and DH systems where appropriate, as a form of efficient and clean heating.

Similarly, policy must work hard to support a transition in the supply of DH, since new, clean sources are necessary, as shown in Fig. 7. From a coordination perspective, a shift towards high-efficiency DH

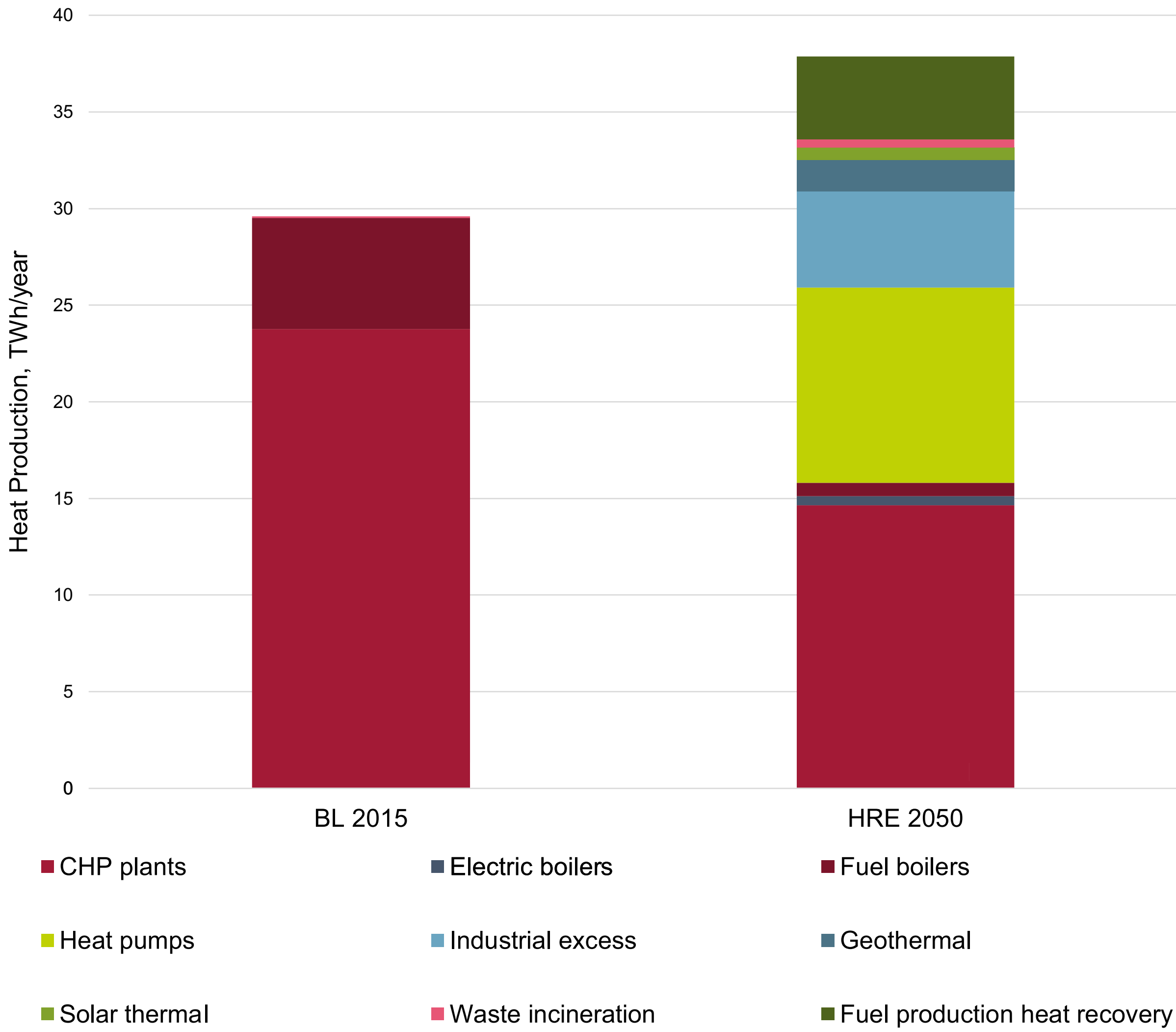

Fig. 7 DH supply for the Czech Republic in 2015 and in the Heat Roadmap scenario 2050, showing the phase-out of fuel boilers and inefficient co-generation to establishing more diverse and efficient supply technologies. Based on Paardekooper et al., (2018d)

requires better infrastructure to reduce losses and allow for different heat sources to be integrated, in direct combination with building improvements (Lund, Østergaard, Chang et al. 2018). A concerted phase-out of reliance on (fossil fuel) boilers and inefficient cogeneration, and towards a more diverse mix of industrial excess heat, large-scale heat pumps, and a mix of renewables is required, and should be supported and mandated. This requires strategic market design to properly (re)allocate benefits and incentives. While CHP capacity and boilers will still be needed in the future, as in the countries with an active tradition of heat planning, these must provide (a) efficiency and flexibility in their ramp rate, (b) primarily functioning in operation of the electricity market, rather than as traditional heat plants, to ensure the heat recovered is waste heat from power production, and (c) based on renewables.

The counterpart to these phase-outs is the introduction of new, efficient heat supply sources, with a focus on the large-scale heat pumps and the recovery of excess heat from various sources. The scale of the transition for the separate technologies required on the heat supply side is shown in Fig. 7, and the role of policy will be both to facilitate the cost-effective phase-out of existing supply and ensure that new supply plants can fit within the frame of a high-efficiency network.

The underlying objective for the heat infrastructure then is to move, rapidly but progressively, towards modern networks, with regard to technical reliability (including through hot water supply), but also with regard to ameliorating customer relations, adjusting finance mechanisms, and continuing to develop consumer trust to ensure (re-) establishing appropriate market shares. This presents some challenges that are not unsurmountable, but require comprehensive addressing. Appropriate policies, to counter the depreciation of the existing heat infrastructure networks, should support a radical transition — but a transition that is still expected to occur over several decades, with pieces of existing networks being renovated and expanded, as supply sources are substituted. This should occur at a relatively high pace with radical change in different parts of the system — but is still as a gradual process of system change, since the infrastructure is already in place, and market shares are already substantial.

The EEF principle, and its application in planning, is particularly pertinent since the improvements on the supply-side both enable and are dependent on the demand-side, and vice versa. The combination of the increased energy performance of buildings and the simultaneous transition of the DH — which in many cases is dependent on lowering of network temperatures — has been extensively described in terms of their synergies (Lund, et al., 2014, 2018). However, there is also an ascending need to ensure that policy (and particularly, incentivisation actions) use an integrated approach, and plan renovation and expansion of both DH systems and buildings in concordance with each other (Delmastro et al., 2017; Cenian, Dzierzgowski, Pietrzykowski, 2019; Paiho, et al., 2019). This should be the case both for the alignment of standards, for example with regard to internal distribution systems and area-based renovation strategies based on the EEF principle.

Concluding, the countries which have in the past established significant shares of DH, but which have require radical refurbishment continue to have a large potential and need to make heat demand savings, and further renovate the existing building stock. In addition, they face a more radical reform need of the DH sector than in those with active heat planning strategies, also to ensure that market shares continue to stay high. Key to the strategies and resulting policies is the implementation of the EEF principle to support co-evolution of the built environment and the supply infrastructures, to modernise and support overarching cost-effective decarbonisation of the energy system.

Gas infrastructure countries

The third type represents those with existing heating planning traditions in the form of gas infrastructure, which will require radical transition to decarbonise. The EEF principle here can both guide changes needed in terms of energy demands and alternative supply infrastructures. There, they are here represented by the Netherlands and UK, but also encompass Belgium, and likely parts of France, Germany, and Italy. At a local level, this may be relevant to many cities across the EU where gas networks are dominant and other heat infrastructure is not (well) developed. The gas type typically has a high share of heating through natural gas, as a result of wide-spread natural gas based infrastructure, meaning that policy recommendations are largely about shifting strongly from gas infrastructure to new, more complex, and more interconnected infrastructure in the form of DH in urban areas.

Key characteristics

Similar to the first transition type, these current high shares of gas heating result directly from previously established systematic planning for developing the infrastructure. The existing gas infrastructure in these countries is typically the result of a strong government-led roll out, often in conjugation with the discovery of domestic gas resources (e.g. Pearson and Araposthasis, 2017 and Verbong & Schippers, 2000 for the UK and Netherlands respectively). However, the scenarios looking towards 2050 for these countries show that strategic heat planning required in these countries takes the form of radically changing heat infrastructure.

Regarding the energy performance of buildings, the gas countries not only have committed some ambition to future minimum standards and energy savings but also have a current performance that is better than average. This means that while higher ambitions are also recommended for some countries in this category (specifically the Netherlands, whose ambitions are not as high as the others of this category), the focus of the built environment should also strongly be on achieving the current ambitions, with particular regard to renovating existing buildings.

The most radical transition required is a shift away from gas infrastructure for heating, and towards district energy solutions in urban areas. This is required to be able to introduce renewables and efficiency into the heat supply, in line with the EEF principle. The scenarios recommend market shares between 35 and 55%, and a full elimination of direct use of gas for heating buildings. The challenge here, thus, is not so much the establishment of a DH share, although this too is required, but a shift away from a naturally monopolistic and entrenched gas infrastructure.

This result is explained because the energy systems modelling that underpins the scenarios takes its point of departure in the energy system transition — including industry, transport, and electricity sectors. This means that (valuable) future green gas and hydrogen resources are not easily available for the heat sector, since they are mostly allocated to these sectors. A high share of DH is to be expected, since the efficacy of both gas and DH infrastructures is partially driven by density; so a country with a high historical potential for gas infrastructure is likely to have a high future potential for DH.

Policy recommendations

Energy policy for heat in these countries needs to effectively be energy policy to replace gas with different infrastructures, by using the EEF principle to determine efficient supply options to complement energy demand savings. This is difficult due to the highly imbedded nature of the gas infrastructure; not only physically, where long-term investments have been made over the years, but also in terms of interests, knowledge, organisations, and planning practices.

The first step for this is a clear policy perspective on the role of gas for heating, or, based on the Heat Roadmap scenarios, rather the lack thereof. Increasingly, there have been public attempts to frame a transition towards green gas or hydrogen as a viable option for the heating sector in these countries (for example, Dodds, et al., 2015). This is problematic. There is very little research based on energy system modelling — both through optimisation and simulation approaches — that show that the quantities of gas and hydrogen needed in this case would not result in highly suboptimal solutions from a thermodynamic perspective and an energy systems analysis perspective (Korberg, Skov and Mathiesen, 2020; Mathiesen, Lund, Connolly, 2012). This congrues with the research done in Denmark, which also has (domestic) gas reserves and hydrogen potentials, but does not forsee a large role for them in the heating sector (Mortensen, et al., 2020). Similarly, the scenarios developed for these countries and their Heat Roadmaps do utilise substantial amounts of hydrogen for transport, industry, and power, but show that the widespread application of DH (combined with better energy performance of buildings and heat pumps where network connections are not viable) should be the policy preference.

Because of this, policy that supports green gas and hydrogen development must be very clear about the potential to continue evolving domestic industrial processes, to maintain transport options, and to work in line with the large amounts of power capacity required in an already electrified world. However, support and development of green fuels and hydrogen must be with the clear understanding that there are other — better — options for heating, that are more in line with the EEF principle.

Secondly, planning and policies towards heat have to shift radically, with a conscious decision to move away from gas. Strong measures, which can include timed phase-outs or coordinated zoning away from gas may be required, but must be designed to also offer viable alternatives. These countries do already have a tradition of thermal demand management, which can be used. Further, these countries already have infrastructure planning traditions, with national support having being used to develop networks in the past, albeit of a different kind. The switch away from gas to DH represents different types of pipes, but similar policy issues as the development of gas several decades ago — rapid transmission and distribution network establishment; spatially coordinated connection policies and incentives, and equipment exchanges (for a historioriography of the Dutch gas roll-out, see Verbong & Schippers, 2000). The recommendation is to initiate deliberately switching away from gas towards DH and electrification, with regard for the spatial density. However, because the institutions and planning frameworks have been developed over time and experience towards gas systems, developing DH networks may be challenging.

The supply-side of the DH system is then expected to radically increase — and thus change — as the systems are built, so the focus should primarily be on developing a network that can connect many new and different resources as they become required, by keeping temperatures relatively low. The supply for DH is expected to be very diverse, so policy should aim at stimulating many types of heat to be considered (including excess heat from power production, industry, and in the development of new industries such as fuel production).

Underpinning these transitions is the recognition that the ongoing use of gas in heating — while currently highly dominant in the heating sector and deeply embedded in the planning practice — is not a viable option for the future for climate and geopolitical reasons, and a conscious transition needs to be achieved to ensure cost-effective decarbonisation of the heating and energy sectors in line with the EEF principle.

Countries without strong heat planning traditions

The final type that can be identified within the country strategies is those where widespread heat planning traditions are not historically present. This shows in strong transition potentials. Here, these are represented most strongly by Italy and Spain, but transferability may be possible to parts of France, Portugal, and several other Mediterranean countries. These countries are typically considered to have 'warm' climates, reflected in higher cooling demands, but still with significant heating demands. Because the climate can be mild and strong policy to address heating decarbonisation has typically been lacking, these countries do not (yet) have a strong energy performance of buildings, and the prevalence of stand-alone solutions for heating is high, even though there are large potentials for network solutions. Policy should aim towards developing EEF principle planning practices as part of energy system planning, to allow for capitalisation of the high potentials for efficiency and renewable energy that exists.

Key characteristics

While typically considered 'warm' countries from a European perspective, these countries are characterised by a more balanced share between space heating, hot water, and cooling demands. Cooling is not explicitly considered in this paper, but has high potential to be considered in conjunction with heating. However, this does not mean heat planning is not required, or less relevant, since infrastructure solutions have the potential to both decarbonise and reach comfort affordably. Figure 8 shows the magnitude of the heating sector, particularly with regard to space heating, domestic hot water, and process heating, which remain sizeable demands in the energy system. This is expected to remain true looking towards 2050, with total heat demands in all countries (including Spain as the most extreme case) exceeding cooling demands.

In terms of heat infrastructure, the scenarios show that the cost-effective potential market share of DH in this type is among the highest in EU. This is partially the result of dense urban planning, which supports network solutions. The high potential is also supported by the high utilisation rate of the DH and supply technologies; particularly stable and excess heat options. This is because the seasonal load differential is less high, given that winter space heating and year-round hot water demands are more balanced.

Regarding the potential for energy savings there is some variability within this type, but the overall energy performance of buildings is not very strong — often due to lacking standards and historical requirements. The baseline development in delivered energy, given currently (binding) policy in these countries, is not expected to lead to radical heat demand savings. Simultaneously, while further savings are cost-beneficial, the overall potential is not as high as for the other types, so the focus needs to be, in concordance with the EEF principle, on both heat demand reduction and efficient, sustainable heat supply in order to decarbonise cost-effectively.

Policy recommendations

For this type, the establishment of heating and cooling governance and planning practices within the framework of energy planning should be prioritised for policy development. This should incorporate EEF

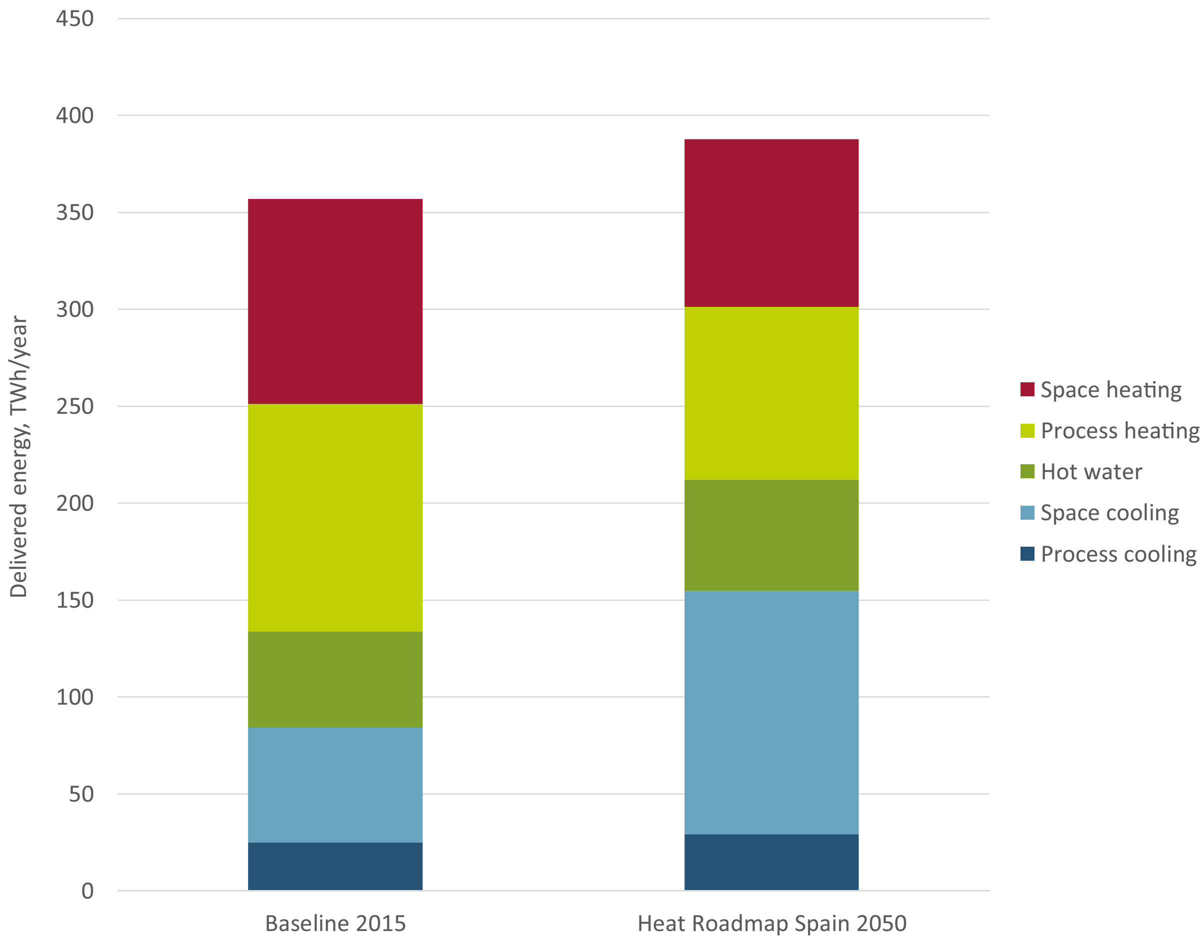

Fig. 8 Development of delivered thermal energy demands for Spain between the Heat Roadmap scenario and 2015. Based on Paardekooper et al., (2018f)

principles to ensure energy demand savings and the efficient recovery and use of resources for heat supply. In terms of the energy performance of buildings, it is necessary to balance the cost-effectiveness of implementing further renovations and minimum standards. However, raising ambitions results in a more cost-effective energy system and should be actively pursued. Addressing the energy demands in the built environment should also then provide a starting point on policy development to stimulate the decarbonisation of the heating and cooling sector.

The scenarios for these countries identify high potentials for DH infrastructure when compared to alternatives such as electrification, green gas options, and bioenergy. This includes explicit spatial planning for both demand and supply-side establishment, expansion, and consolidation of DH. The high potential is partially the case because of the beneficial ratio between the summer and winter loads, which means that infrastructure capacity is well used, but also means that relatively constant and marginally cheap heat sources like excess heat from industry, solar thermal, geothermal, and waste-to-energy, can be responsible for a much of the DH supply without the need for seasonal storage, compared to the other types. This mechanism is also observed elsewhere in heat loads for decentral heating (Kozarcanin, et al., 2020). The ability to take advantage of this is one of the main drivers behind the high cost-effectiveness of DH in these countries. Policies aiming to support the EEF principle and development of DH could benefit from an explicit alignment to industrial policy and industrial zoning, to ensure that networks can continue expanding into areas of high demand density while being able to use these efficient and renewable heat resources.

Because the cost-effective level of DH is relatively high, the impact that the combination of CHP and large-scale heat pumps can make is significant, particularly with regard to the inherent interrelation with the electricity sector. As in the other types, policies that can support the development of flexible CHP and large-scale heat pumps are required, in particular with regard to where new plants are placed (to ensure future connection to networks), as well as the active incentivisation of efficient heat pumps. Examples of these technologies, methodologies, and practices do exist, as well as succesful attempts to explore quantified overall market potentials (for example, Denarie, Calderoni, and Muschera, 2017; Lizana, et al., 2017). This means policy does not necessarily have to focus on supporting proof of concept or technology, but rather facilitating and catalysing replication.

Given the very low shares of district energy in this type's countries today, achieving this will require a highly organised introduction of long-term infrastructure, guided by the EEF principle, at a relatively fast pace. In this way, the development of a significant share of DH, coming from very little, is relatively similar to that of the gas countries, but without an extant framework that is geared towards gas. This on the one hand means that it may be easier to establish EEF principles and fossil-fuel free visions and ambitions. However, it also means policies and planning instruments for infrastructure development cannot build too heavily on the policies and mechanisms already developed for the implementation of gas infrastructure.

Conclusions

In many cases, radical change must be made to achieve decarbonisation. For heating, this means implementing far-reaching infrastructures, heat supply changes, and interventions in millions of buildings; urgently rolling out these transitions in a complex and decentralised sector requires focussed decision making on policy direction and implementation.

This study considers strategies which reflect the role of the EEF principle, to avoid overlooking the potential of energy savings. This includes on the one hand reductions in heating demands, but also a strong potential to (re-)use energy sources and integrate renewable sources through appropriate infrastructures. The use of district heating in heating transition strategies results in faster and cost-effective decarbonisation and reflects the need for an integrated perspective that supports implementation of the EEF principle.

This decarbonisation of the European heating sector, within the context of an increasingly decarbonised and sustainable energy system, will require active transition planning and implementation at a local level, and strong support and direction from the national and EU level. However, the focus of how to implement the EEF principle differs. In order to support an EU-wide transition of local heating systems, it is necessary to be able to categorise the types of transitions that are required and develop appropriate policy recommendations.

Given its fragmented nature, the approaches, methodologies, datasets, policy learning, and transferability concerning the heating sector have typically been reliant on inductive case study generalisations. This study explicitly sets out to deductively identify comparable heat sector typologies, based on a cross-country comparative analysis of data, methodologies, scenarios, and strategies that comprise the 14 largest countries in the EU.

Considering the (physical) current and future heat sectors, alongside strategies for these 14 countries, 4 distinct types can be identified. The 4 identified types are those with a heat planning tradition, aiming to move toward more integrated and clean, high-efficiency systems; those aiming to refurbish and upgrade both the building stock and the existing heating infrastructure; those which have a developed heating sector in the form of gas infrastructure, but which will require radical transition to decarbonise; and those without strong heat planning traditions, where the heating demand (and subsequently need for transition) is underrated, even though the potential for heat infrastructures and energy efficiency is large.

By using the approach presented in this paper, the transferability of knowledge, data, and planning approaches is facilitated, making it easier for areas where there is currently imperfect knowledge on how to implement the EEF principles and achieve the heating transition to develop initial policy recommendations and serve as a starting point. It supports EU policy towards heating to become more sophisticated and less generic, as policy recommendations can be more specifically directed towards different types of heating transitions. This can facilitate a level of analysis that lies between the current fragmented EU approach and the fragmented MS approach.

This study shows that while heat strategies need to be local and specific, shared characteristics result in common ground in terms of the transition strategies. This serves not only as a basis to equip the more widespread implementation of strategies to achieve heating transitions locally but also to develop a more coherent EU strategy for transforming the heating sector in line with the EEF principle.

This typologies presented here is based in a comparative analysis of the (physical) state and strategies and scenarios looking towards the future, since this is where clear data exists. A logical next step to complement this work could be a formal qualitative comparative insight on how to typify institutional frameworks and planning practices, which also comprise the heat sector as a planning object and area of transition. Such further research would go a long way towards developing typologies that can not only form the basis for policy objective recommendations but also strategic design of appropriate policy instruments.

A second avenue of further investigation would be to assess concrete plans and policy packages, (for example, at MS level the National Energy and Climate Plans, and ongoing National long-term strategies) for comparison with either the Heat Roadmaps or the typology at local level. This type of comparison and exchange on the direction and implementation of strategies to achieve energy efficiency and heating transitions locally could also guide the agenda for research to contribute to effective heating and cooling strategy development and EEF principle implementation.

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Author contribution Conceptualization: SP and HL. Methodology: SP. Formal analysis and investigation: SP. Data curation: SP. Writing—original draft preparation: SP. Writing—review and editing: SP, HL, JZT, NB, and BVM. Supervision: HL and JZT. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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