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Article

EU-28 Residential Heat Supply and Consumption: Historical Development and Status

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Abstract: EU is moving towards a climate neutrality goal in 2050 with heating of buildings posing a major challenge. This paper provides a deep understanding of the historical development, path dependency and current status of the EU-28 residential heat sectors to inform strategy and policy makers and to open up this black box. Data is combined for buildings, installed technologies, fuel consumption and energy supply for Member States from 1990 to 2015, to analyse the importance of large-scale infrastructures and supply chains. Primary energy supply for residential heating is mainly based on fossil fuels; 70% in 2015 with 69% imported. The building level technologies are dominated by non-condensing boilers and stoves. Primary and final energy consumption decreased in spite of an increase in the total occupied living area in most countries. Path-dependency effects are found in the residential heat supply in EU. The analysis show path-dependent trajectories are present in most Member States, especially regarding natural gas infrastructure. The period shows many options for decarbonisation are not used to the full potential, e.g., energy efficiency in buildings, district heating, heat pumps. Past experiences should be considered when developing new decarbonisation strategies in Member States and on the EU level.

Keywords: residential heat supply; heat; decarbonisation; EU-28; supply chain; energy efficiency; data quality; path dependency

1. Introduction

To fulfil the targets set in the Paris Agreement [1], The European Union (EU) have set ambitious targets for the energy transition towards 2030 [2] and 2050 [3], focusing on increasing renewable energy (RE) penetration, energy efficiency (EE) and lowering greenhouse gas emissions. Heating and cooling for residential, service and industry accounts for ~50% of the EU's primary energy supply (PES) [4,5].

Due to its physical properties, heating cannot be distributed, sold or exchanged over long distances, contrary to the international electricity and gas systems that characterize contemporary EU energy supply. This results in a local and contextualized situation for the EU-28 heat markets, still with significant unknowns. Compared to the electricity and the gas sectors, heating remains largely a black box with large unknowns to researchers and policy makers.

In order to address these knowledge gaps, heat transitions have received considerable attention both from the European Commission [6] and several Horizon 2020 research projects [7–10], presenting possible pathways towards RE based heat supply. Recent studies [11–13] contributed with open-source datasets of the EU-28 heating and cooling sectors for 2015, which also proved important in the realization of this study. A body of literature address policies for promoting renewable heating [14–16], for residential EE [17–19] as well as assessing the balance between heat supply and heat savings [20,21]. Future renewable and energy efficient heating and energy supply can be composed of multiple technologies such as waste heat, combined heat and power (CHP), heat pumps, geothermal, which can be utilized through district heating (DH) networks combined with the use of individual heat pumps in areas with low heat consumption densities in addition to significant heat savings in all buildings [22–24].

While these perspectives are valuable, they lack a consideration of the historical development of heating infrastructures, end-use technologies and the infrastructural systems that distribute the energy supply. Residential heating today is either supplied from collective infrastructures such as gas or DH grids, or in the form of solid or liquid fuels that are easy to transport without dedicated infrastructures, to be consumed in individual boilers and stoves. Not only are the household installations important, but the supply chain networks that the heat delivery depends on are as well. Technological change can be inhibited by existing infrastructures due to path dependency effects, such as economies of scale, network effects or knowledge and preferences of users and decisions makers [25]. Technological systems can be subject to increasing returns of scale and sunk costs contributing to a lock-in effect into incumbent technological choices [26]. The aim of this paper is to expand the knowledge about the current state of residential heating and the development trajectory in the EU-28 to facilitate and inform further transitions.

Historical accounts of the development of heat supply have been presented for DH supply in the EU and worldwide [27] and country specific approaches include Austria [28] and a more general energy system approach for Denmark [29] as well as technology and country specific accounts such as the Polish heat pump market [30]. Taking a historical perspective of the development of residential heating in Sweden and The UK, Gross and Hanna conclude that:

> *"To overcome lock-in to carbon-intensive heating, policymakers seeking to achieve carbon targets should draw on a historical perspective of how to support path-dependent change in heat transitions"* [31]

This paper adds to this understanding by describing the historical technological development of the EU-28 residential heating sectors, describing development trajectories, the current state-of-the-art and highlighting instances of path-dependency and transitions. We present an assessment of the current status and development of the EU-28 residential heat sectors from 1990 to 2015, to add to the knowledge of the development of EU residential heating. To our knowledge, no such studies have been carried out before, and we therefore add to the energy system transition debate by combining historical path-dependent perspectives with a discussion of future potential developments. This study establishes a broad understanding of residential heat supply by analysing PES, distribution infrastructures, end-use technologies, energy import shares and final energy consumption (FEC) as well as the heat consumption intensity per occupied living area in EU member states (MS). This allows to analyse the development of the residential heat sector as well as to provide an important input to understanding the departing point of the renewable heating transition in the current situation. Based on this analysis we provide general heat planning and development guidelines for countries largely supplied by individual heating, with extensive coverage of gas heating and for countries with high shares of district heating supply. The paper show that decarbonisation and renewable heating strategies should consider technological contexts and historical path-dependency from which future solutions will depart and likely struggle with. This should be considered by researchers, policy makers and decision takers on local, national and international policy scales, dealing with the decarbonisation of energy systems.

2. The Residential Heat Supply Chain

To assess the status of the EU-28 heating sectors, it is important to differentiate between different types of heating infrastructures. While biomass boilers, gas boilers and DH substations in themselves are different technologies, they also rely on vastly different supply chains. The technological network effect are important sources of path-dependency, as the supply chain elements must be compatible with the overall system [25,32]. While biomass boilers utilize fuel from different sites such as forests or wood processing industries, DH or gas relies on specific infrastructures to deliver the energy to the building [33]. Individual boilers are fuel specific and cannot easily be repurposed to use other fuels. Natural gas networks can be adjusted to integrate moderate amounts of biogas or hydrogen gasses into natural gas supply. For example, IRENA estimate that, depending upon the state of the gas grids, up to 10–20% hydrogen can be mixed with natural gas supply [34], but with potential impacts on end-use devices. DH grids are fuel agnostic, and the distribution grids can be used with several different supply types [33]. Switching to a renewable DH supply can depend on a decrease in distribution temperatures, affecting DH networks and building level installations [35]. All residential heat supply technologies are as such affected by certain types of technological lock-in due to the supply chains of installed technologies and infrastructures.

Building upon this understanding of path-dependency from technological supply chains [25,36] and drawing upon energy system literature describing a holistic approach to assessing energy systems from production to demand [37], this paper propose that the residential heat supply chain can be understood through five distinct focal points that informed the research design of this paper:

1. Primary energy supply and CO_2 emissions
2. Heat distribution infrastructures
3. Final energy consumption for residential heating and end-use heating technologies
4. Heat consumption intensity per living area
5. Useful energy demand

2.1. Primary Energy Supply and CO_2 Emissions

PES is a measure for the energy sources used to deliver heating, including conversion, transmission and distribution losses. PES estimate the total energy supply that enters the energy supply chain, and this measure allows a comparison of the energy amounts consumed by different heating technologies. For example, CHP plants utilize otherwise wasted heat from electricity production and distribute this to heat consumers. In order to compare this to heat production from a gas boiler located in the household, PES is a useful measure.

PES also focus on the primary fuels and not energy carriers or energy delivery. This means in practice that PES account for the fuels used to produce energy carriers such as DH or electricity. CO_2 emissions can be assessed based on PES as this accounts for the full energy amount used and thus the total CO_2 emissions released because of the heat consumption.

2.2. Heat Distribution Infrastructures

The different types of distribution infrastructures can be assessed with the concept of tightly or loosely coupled systems [38]. Here, a simple distinction between large-scale collective or individual heat supply is made. Materially tightly coupled heating infrastructures have specific infrastructures for energy delivery to the household and thus constitute large-scale collective supply infrastructures. Electricity, gas and DH grids fall in this category. Loosely coupled systems depend upon other infrastructures to deliver their services and characterize the individual heat supply technologies. Residential heating using oil, biomass or coal boilers relies on diverse distribution networks to deliver the energy carrier at the households for energy consumption. The different types of heating and their categories are presented in Table 1 below.

Table 1. Heat distribution infrastructure categories.

Heat Supply Type	Type of Infrastructure
District heating Gas Electricity	Large-scale collective infrastructure
Oil Biomass Coal	Individual heat supply

2.3. Final Energy Consumption for Residential Heating and End-Use Heating Technologies

FEC is the amount of energy delivered at the place of consumption, to be used in end-use technologies. End-use heat production technologies are the technologies used to produce heat energy, either directly from fuels such as household boilers using gas, oil, coal or biomass, or from electricity using electric radiators or heat pumps. While most heat production technologies are located at the place of consumption, DH is different. With DH supply the heat production happens before the distribution step, and not after [33].

2.4. Heat Consumption Intensity per Living Area

Heat consumption intensity is a measure for the amount of residential heat consumption per residential area heated. It describes the relative energy consumption compared to the living area that is being used, and is a measure for the average heat consumption per living area in a country. Several accounting measures for residential living area exists, which will be outlined in the materials and methods section below.

2.5. Useful Energy Demand

The useful energy demand is the need for residential heat that is met by the infrastructural supply chain system. This is difficult to assess as it is usually not measured and depends upon building stock quality, efficiency of building end-use technologies, heat distribution systems within the building, energy billing, heat control systems and heat consumption practices by the consumers and more. Van den Brom et al. estimate around 50% of the heat demand to depend upon the residents and their practices and 50% to depend upon building characteristics [39].

3. Methods and Empirical Data

Departing from the supply chain perspective presented above, this paper investigates the EU-28 residential heat sectors as systems that are connected from the production to consumption of energy. This was studied by investigating quantitative data sources available for residential heating across the EU-28 to compare longitudinal and cross-national developments. This approach allowed investigating the development of the current heat supply of the MSs and how they compare. By choosing a research design based upon existing databases, this paper investigates the extent of current available knowledge of the EU-28 residential heat consumption and the state-of-the-art of the sector. Most empirical data on residential heat consumption measures FEC, the energy amount consumed. The research design departs from this statistic as it is widely available and often reported by national statistical agencies. Based on this, PES, distribution infrastructures and FEC per residential living area can be derived with additional datasets. This research design has two main purposes. First, to bring residential heating forward by providing new knowledge of the development and current status. Second, to highlight knowledge gaps that black-boxes residential heat consumption, thus making it difficult for analysts and policy makers to address.

3.1. Primary Data Sources

The most comprehensive source of historical residential heat consumption data for the EU-28 found is the Odyssee-Mure (OM) database [40], an EE database collected in the OM research project with 30 partners and coordinated by the French Environment and Energy Management Agency (ADEME), with the database being managed by Enerdata. The OM database includes yearly residential heat consumption data including fuel supply collected from national energy agencies.

The climate corrected FEC for EU-28 residential heat consumption from OM is 2625 TWh in 2015 and deviates 8% from Pezzuto et al. [12] and Heat Roadmap Europe 4 [41] result which both are around ~2850 TWh. It is difficult to validate this data quality, but in their study of the 2015 space heating (SH) and domestic hot water (DHW) market in Europe, Pezzuto et al. [11] categorize their results as within 6% of PES to be *close* and find differences as large as 47% for PES compared to other studies. The primary quantitative data sources used in this study are presented in Table 2 below.

Table 2. Primary data sources.

Content of Dataset	Reference	Data Discrepancies in Datasets	Timeframe Covered
Residential heating technologies	[11]		2015
Final Energy Consumption for heating	[40]	Missing data	1990–2015
Occupied living area	[40] [42]	Missing data Discrepancy between quantifications	1990–2015
Heating degree-days	[43]	Missing data	1990–2015
District heating and electricity fuel supply	[44]	Missing data	1990–2015
Electricity and district heating production units (CHP, power plants or heat-only)	[45]		1990–2015
Energy conversion losses and district heating distribution losses	[46,47]	14 countries included in the dataset (90% of EU-28 heat demand)	Constant
CO_2 emission factors	[48]		Constant
Energy dependency	[49]	Only covers fossil fuels e.g., not imported biomass	1990–2015

3.2. Data Handling and Flow

The analysis is based on a combination of the data sources presented in Table 1 above. Figure 1 below illustrate their connection for creating the analyses presented in the paper. Final energy for heat consumption [32] is first climate adjusted [33] using heating degree days (HDD) [43] to estimate consumption in a standard year. The FEC is adjusted using the average HDD per country between 2000 and 2015.

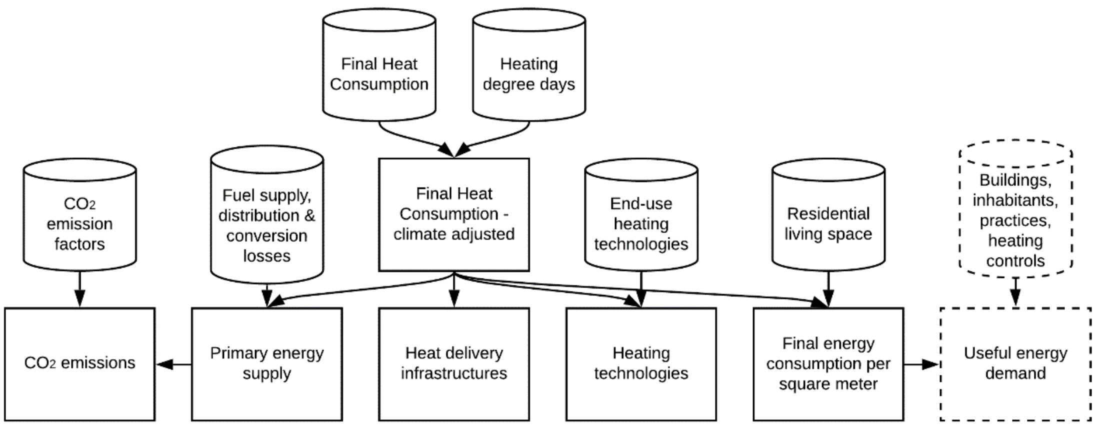


Figure 1. Representation of the data structure and relation between datasets used for the analysis in this paper. Useful energy demand is in a dashed box as this could not be estimated for this paper due to missing data.

To calculate PES, the primary fuels used in DH and electricity production must be estimated. This is done using Equation (1). *FEC* denote the measured final energy consumption. Distribution efficiency is denoted with η_{dist} and is calculated as 1–distribution losses. Production efficiency is accounted for using η_{prod}, and is calculated as 1–production losses. The primary fuels are estimated by finding the fuel supply share for each primary fuel, denoted α_{fn} for each primary fuel.

$$PES = FEC \cdot \left(\frac{1}{\eta_{dist}}\right) \cdot \left(\frac{1}{\eta_{prod}}\right) \cdot \begin{pmatrix} \alpha_{f1} \\ \alpha_{f2} \\ \ldots \\ \alpha_{fn} \end{pmatrix} \tag{1}$$

Energy losses from CHP plants can be attributed using different methods. This paper uses the energy content method, where losses are distributed based on the fractions of electrical and thermal output from CHP plants [50]. The principle for the share of losses attributed to the heat production from CHP plants is as follows:

$$l_Q = \frac{Q}{(E+Q)} \tag{2}$$

$$l_E = \frac{E}{(E+Q)} \tag{3}$$

where l_Q and l_E denote, respectively, the fraction of energy losses allocated to the heat production and electricity production, and Q and E, denote, respectively, the net heat and electricity production share.

Based on the PES, total CO_2 emissions and average CO_2 emission intensities expressed as gCO_2/kWh can be derived using emission factors of CO_2 per energy content [48]. Nuclear electricity is assumed produced with an efficiency of 33% according to IEA standards [47]. Losses from natural gas transmission and distribution are estimated by the Danish Energy Agency to be around 0.005% - 0.03% for natural gas distribution networks on a European scale [51]. These losses are practically insignificant and not included in this paper.

CO_2 emissions from combustion of biomass are uncertain and difficult to ascertain [52]. IPCC guidelines attributes CO_2 emissions from combustion of biomass to the land use, land-use change and forestry (LULUCF) sector [48], and as such they are typically not included in estimations of energy sector CO_2 emissions to avoid double counting in national and international statistics. It is although uncertain when and to what extent CO_2 emissions are reabsorbed in the LULUCF sector [53]. To assess the development of biomass consumption for residential heating, this paper quantifies the direct CO_2 emissions in relation to residential heating, as it is uncertain to which degree these emissions are offset in the LULUCF sector.

Heat delivery infrastructures are categorized based on the supply chain perspective presented above. This paper differentiates between heat supply based on large-scale infrastructures or individual heating. The categorization of heat delivery infrastructures are as presented in Table 1 above. For each MS the share of individual and large-scale collective heating was investigated from FEC for heating. This gives an indication of which countries have managed to supply heating through collective infrastructures and which countries primarily have relied on individual heating units.

For the end-use residential heating technologies, only data for 2015 is available and therefore a historical analysis cannot be made. Nevertheless, it allows for a detailed account of the current technological situation in the EU-28 households, and of the FEC for heating by each technology.

To assess the residential heat consumption intensity, a measure of the residential living area is needed. Detailed historical statistics for the residential occupied or heated living area in the EU-28 is not available in detail. The European Building Stock Database (EUBD) provides one resource for total useful residential living area, but does not provide information about occupied area [42]. It is difficult to estimate how much of the useful living area is occupied, actually used or heated. The OM database contains the number of total and occupied residential dwellings and average number of square meters per country and year. This provides an assessment of the occupied living area per MS. Other sources include Pezzuto et al. [12] for a detailed account of building age for 2016 and the Entranze research project which provides building stock statistics for 2008 [54]. Different methodologies for data collection and assessment makes these databases difficult to compare while maintaining data quality, and this paper therefore uses the OM database due to maintaining data consistency.

From FEC and the occupied living area, the average residential heat consumption intensity measured in kWh/m^2 can be derived. As this is MS averages, there will certainly be residences in the MSs with higher or lower heat consumption intensities. Ideally, the assessment of residential heat consumption intensity would include an assessment of building stock quality, end-use technology efficiency and renovations made. Reliable historical data of the EU-28 has not been available for this study, and is therefore not included here. This is discussed further in Section 5 below.

3.3. Data Error Handling

Most of the datasets used for this paper had missing data or included data points, which were irregular. Residential heat consumption data was lacking for Romania (2012–2015), Greece (2015), and Belgium (2014–2015), which was estimated until 2015 by using the last year of available data.

Missing data in the residential occupied living area was estimated using linear interpolation, as the living area is assumed to have had a steady development from 1990 to 2015.

For The UK and Poland, total and occupied living area was reported as the same value in the OM database. As a 100% occupancy rate is regarded as unfeasible and likely a data error, the occupied living area was adjusted with an average European occupancy rate calculated as the yearly ratio between European occupied living area and European total living area. This ratio was found to be between 85% and 87% from 1990 and 2015.

The HDD data for Sweden had a significant drop for 1994, which was due to missing data for some regions on a NUTS2 level [55]. The Swedish 1994 HDD were estimated using the average Swedish HDD adjusted with a 1994 factor from the remaining regions.

Both Denmark and Latvia missed data about energy consumption for DHW. For Denmark, no energy consumption for DHW was reported. This was estimated using a DHW share of FEC for residential heating of 15.95% from [12]. Latvia missed data about energy consumption for DHW before 2001. This was estimated using an average DHW share of FEC for residential heating of 19.2% for Latvia from the period 2001–2015. Finally, the average dwelling size in Belgium was lacking from the OM database, which was estimated using data from Pezzutto et al. [12].

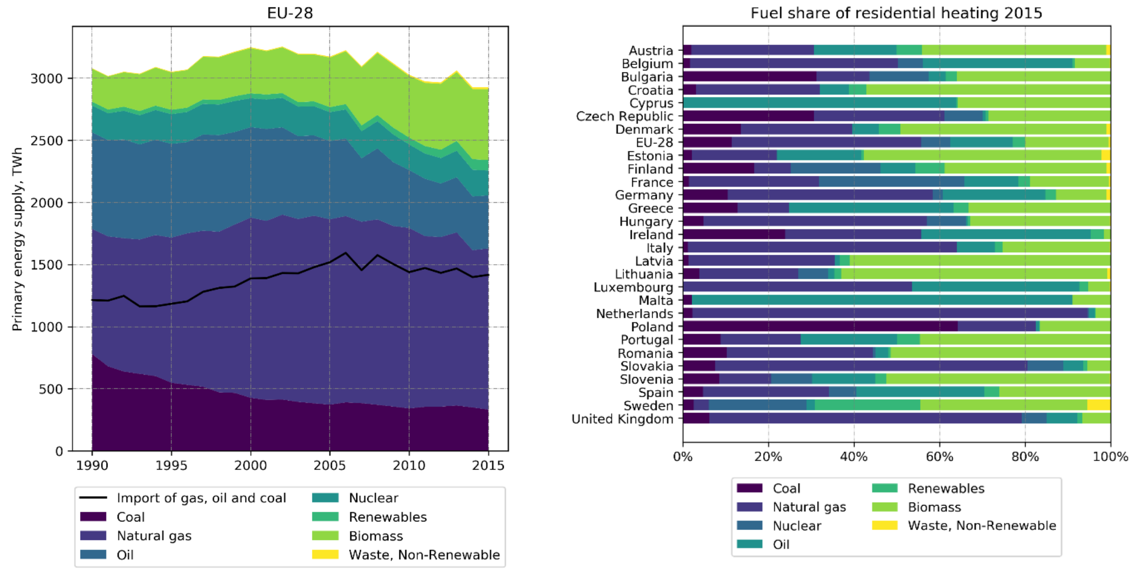
3.4. Software

All data processing and calculation was handled using the Python programming language [56] in Jupyter Notebooks [57]. Visualizations were made using the Matplotlib library [58].

4. Results

4.1. Primary Energy Supply for Residential Heating Consumption in the EU-28

The climate adjusted EU-28 PES for residential heating has remained around 3000 TWh/year from 1990 to 2015, as shown on Figure 2a. PES increased from 1990 levels at 3080 TWh to its highest in 2002 at 3255 TWh, before decreasing to 2927 TWh in 2015. The 25-year period remained within +5% and −6% of the mean PES consumption for the period of 3108 TWh, with the lowest consumption years in the period after 2010.



(**a**) (**b**)

Figure 2. (**a**) Development of primary energy supply for residential heating consumption from 1990 to 2015 in the EU-28 with the respective imports into the EU-28 of gas, oil and coal for residential heating. Results are climate adjusted. (**b**) Primary energy fuel share for residential heating in 2015 of the EU-28 member states.

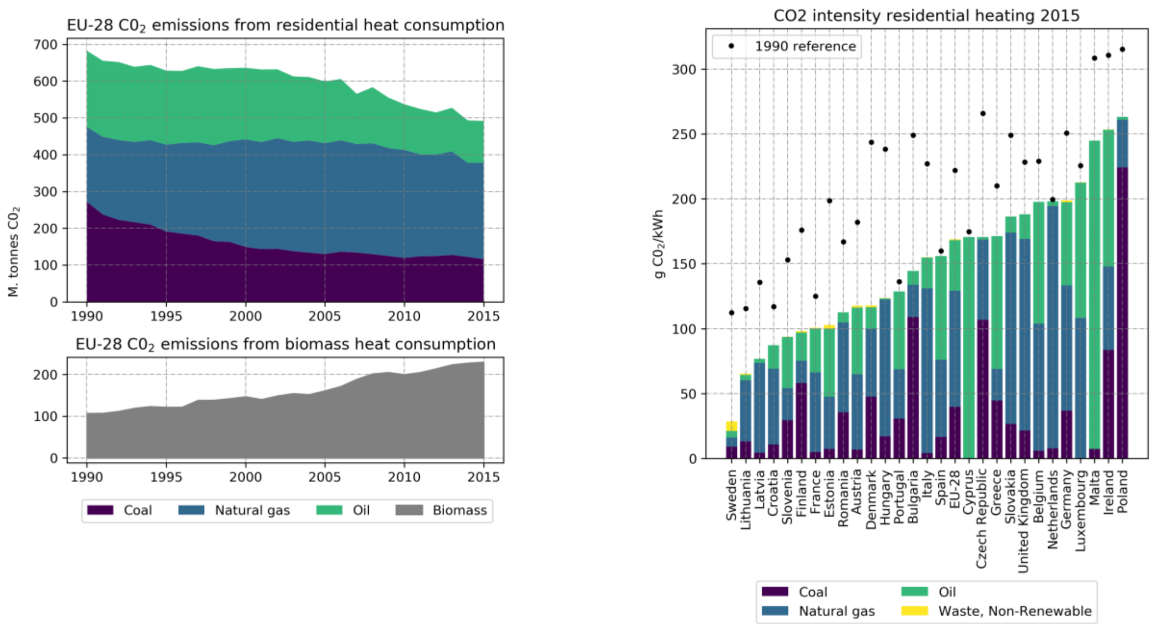
Natural gas is the single most used primary fuel for heating in the EU-28 increased from 1990 to 2015 to 1297 TWh accounting for 44% of the PES for residential heating. Natural gas PES increased from 1007 TWh in 1990 to its highest level in 2004 of 1510 TWh. 14% of the natural gas consumption was used in DH supply with the remaining 86% used in individual boilers. Coal PES more than halved during the period from 780 TWh in 1990 to 333 TWh in 2015, with two-thirds used in DH systems and one-third used directly for heating in boilers. The three countries with the highest coal consumption for residential heating in 2015 was Poland with 135 TWh, Germany with 62 TWh and the UK with 23 TWh, accounting for, respectively 41%, 19% and 7%, totalling 2/3 of the coal PES for residential heating in the EU-28. Nuclear PES for residential heating through electric heating or using heat pumps accounted for 216 TWh in 1990, peaking in 1999 at 249 TWh following a decrease to 200 TWh in 2015. In 2015, France alone accounted for 159 TWh of the nuclear PES used for residential heating, amounting to 79% of the EU-28 nuclear PES for residential heating. Oil PES decreased from 777 TWh in 1990 to 427 TWh in 2015, with Germany using 140 TWh of oil for residential heating in 2015. 95% of oil for residential heating was used in individual heating. Renewables, without biomass, are the single smallest supply source for residential heating in the EU-28, increased the PES with a factor 2.75 from 30 TWh in 1990 to 85 TWh in 2015. Sweden accounted in 2015 for 23% of the renewables in the EU-28 PES, with Germany and France following at 17% and 15% respectively. All renewables are used in either DH systems or with electric heating. Biomass saw a doubling in PES, going from 265 TWh in 1990 to 570 TWh in 2015 with 95% used in individual stoves. The top consumers in 2015 were France, Italy and Germany accounting for 15%, 14%, and 12% of the total EU-28 biomass PES respectively. Natural gas, biomass and renewable PES all increased during the period from 1990 to 2015, while coal, oil and nuclear PES decreased.

EU-28 energy imports of natural gas, oil and coal for residential heating increased from 1215 TWh in 1990 to 1417 TWh in 2015, an increase of 14%. The imports peaked in 2008 with 1576 TWh and decreased since then. In 2015, 69% of the fossil fuels for residential heating was imported from outside EU, more specifically 69% of natural gas, 42% of coal and 89% of oil was imported.

Figure 2b show the fuel share of PES for residential heating in 2015 for the EU-28 MSs. It shows a diverse fuel mix across the MSs, meaning that the PES for residential heating is difficult to compare between countries. A few countries have very uniform PES heat supply, such as The Netherlands, Slovakia and The UK where natural gas accounts for 92%, 74% and 73% of the PES for residential heating respectively. Cyprus used 64% oil and 36% biomass while residential heat on Malta was 89% based on oil. 64% of the PES for residential heating in Poland was in 2015 based on coal. Contrary to the countries with a high use of a single fuel are the countries that are using several different fuels. Only four countries have three fuels that each supply more than 20%, which are The Czech Republic (29% biomass, 30% coal and 31% natural gas), Ireland (24% coal, 32% natural gas and 40% oil), Spain (26% biomass, 29% natural gas and 30% oil) and Sweden (39% biomass, 24% nuclear and 25% renewables). While natural gas is the single most used fuel in the EU-28 for residential heating in terms of total PES, biomass is most used in terms of highest share per country. In 12 MSs (Austria, Bulgaria, Croatia, Denmark, Estonia, Finland, Latvia, Lithuania, Portugal, Romania, Slovenia, Sweden) biomass is the most used fuel, before natural gas with 9 MSs (Belgium, Czech Republic, Germany, Hungary, Italy, Luxembourg, Netherlands, Slovakia, United Kingdom).

4.2. CO_2 *Emissions from Residential Heating in the EU-28*

EU-28 CO_2 emissions from residential heating decreased from 1990 to 2015, primarily as a result of a shift away from coal and oil towards natural gas and biomass, as presented in Figure 3a below. The results of this analysis show a decrease from 683 M. Tonnes CO_2 emissions in 1990 to 494 M. Tonnes CO_2 emissions in 2015, a decrease of 28%. Natural gas accounts for the majority of the CO_2 emissions from residential heating at 53% in 2015, with oil and coal at 23% each.



(**a**) (**b**)

Figure 3. (**a**) Historical development of CO_2 emission from residential heating PES from 1990 to 2015 for the EU-28 MSs. CO_2 emissions from non-renewable waste incineration are not included in the figure as they only account for ~3 ‰ of EU-28 CO_2 emissions. Biomass includes only direct emissions and not for example uptake in the LULUCF sector or from direct and indirect land-use change. (**b**) Average g CO_2 per kWh heat used per MS in 2015 with 1990 as a reference level. Results are ranked from lowest average CO_2 intensity to highest in 2015.

The direct CO_2 emissions from biomass consumption are estimated to have more than doubled, from 107 M. Tonnes CO_2 in 1990 to 230 M. Tonnes CO_2 in 2015. If including all CO_2 emissions from biomass consumption, they would negate a large amount of the CO_2 emission reduction achieved in the EU-28 residential sectors from heating. As direct biomass emissions is the second largest source of

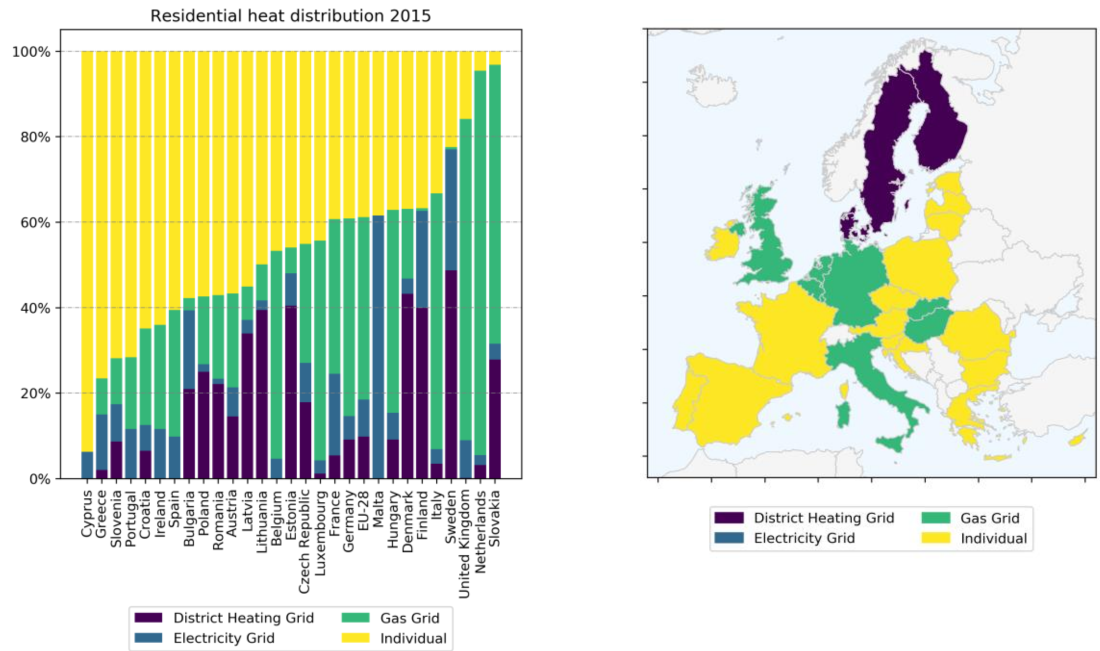
CO_2 emissions from residential heat consumption, it is important to consider the sustainability of this consumption and to which degree sustainable biomass is used for heating purposes.

Figure 3b shows that most MSs have seen a reduction in the average CO_2 intensity per kWh consumed for heating. In average, the CO_2 intensity decreased with 55 gCO_2/kWh among the EU-28 MSs from 1990 to 2015.

The results show Sweden to have the lowest average CO_2 intensity at 29 gCO_2/kWh due to a high concentration of biomass, nuclear and renewables in their heating sector. This was reduced from 112 gCO_2/kWh in 1990 due to a decrease in oil and coal consumption. Poland and Ireland have the highest CO_2 intensity among the EU-28 MSs due to the high consumption of coal and oil for heating. Poland and Ireland had a CO_2 intensity of 263 gCO_2/kWh and 253 gCO_2/kWh respectively in 2015. Denmark has achieved the highest reduction measured in gCO_2/kWh, from 244 gCO_2/kWh in 1990 to 118 gCO_2/kWh in 2015 also by reducing oil and coal consumption and switching to a high degree of biomass consumption. Portugal, Spain, Cyprus and The Netherlands have achieved very little or no reductions in the CO_2 emissions intensity from residential heating.

4.3. Residential Heat Delivery Infrastructures

Figure 4a illustrates the share of residential heating that is consumed via individual types of residential heating or from one of the large-scale collective infrastructures: DH, gas grids or electricity grids. It shows the range of diversity there is from countries with mostly individual based residential heating to countries that are primarily based on collective infrastructures. While 94% of the FEC is supplied by individual heating units in Cyprus, only 3% of the FEC is supplied by individual heating in Slovakia.



(**a**) (**b**)

Figure 4. (**a**) Share of residential heat consumption from individual heating or delivered via district heat networks, gas grids or electricity grids per MS. (**b**) Geographical representation of the most used heat delivery infrastructure or individual heating per MS.

Figure 4b shows the most used heat delivery method per country. 3 countries, Denmark, Finland and Sweden has expanded DH to be the single most used type of residential heating. 8 countries have deployed gas networks to the extent that gas delivers the highest amount of final energy for residential heating.

These are Belgium, Germany, Hungary, Italy, Luxembourg, Netherlands, Slovakia and The United Kingdom. In The Czech Republic, natural gas is the most used primary energy source, but individual heating is the most used residential heating type. This is due to primary natural gas consumption being split between direct use in gas grids and in district heating production.

Individual heating is the most used type of residential heating in 16 MSs in the EU-28. Malta is the only MS where electricity is the most used type of heating.

This illustrates which MSs have done active heat planning to expand supply infrastructures and in which MSs where residential heating primarily has been an individual concern. In the primarily individually heated countries, there seems to have been little coordinated effort to expand collective infrastructures in the residential heating sector. The MSs with high amounts of collective infrastructures seems to have actively promoted certain types of large-scale infrastructures.

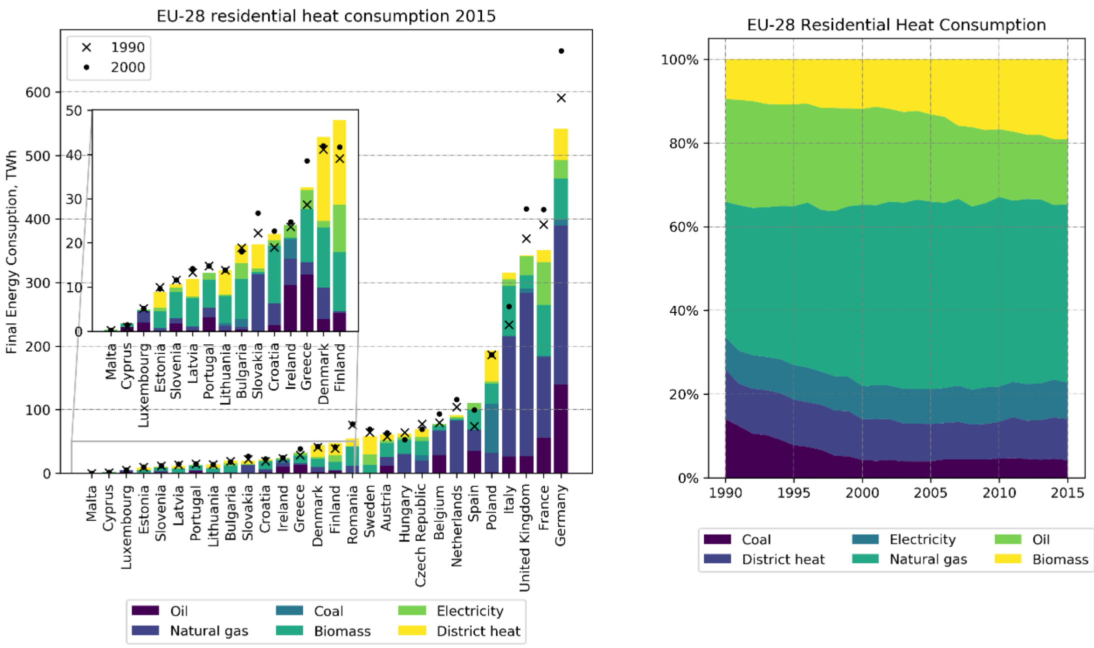
The MSs with high DH shares, Finland and Denmark have relatively low estimated average CO_2 emissions from residential heating, with Sweden having the lowest average CO_2 emission from residential heating of the analysis. Denmark, Finland and Sweden were all able to make significant decreases in the CO_2 emission from residential heat consumption from 1990 to 2015, showcasing the ability of shifting fuel supply in DH systems.

But collective heating infrastructures are not synonymous with low-carbon intensity for residential heating. Of the MSs primarily using natural gas for heating, 6 out of 8 (The Netherlands, The UK, Slovakia, Luxembourg, Belgium and Germany) have higher average CO_2 emissions from residential heating than the EU-28 average. Lithuania, Latvia, Croatia and Slovenia all have low average CO_2 emissions from residential heating due to high amounts of biomass in their heat supply. France is also below 100 gCO_2/kWh due to biomass and the high amount of nuclear power in the French electricity supply.

4.4. Residential Final Heat Consumption and End-Use Technologies in the EU-28

Among the EU-28 MSs a large diversity in heat delivery methods and the scale of consumption can be observed. Figure 5a show the residential heat consumption for each MS in 2015 and the contribution from each end-use technology. The FEC for residential heating in the EU-28 was 2625 TWh in 2015. Germany is the highest consumer of final energy for residential heating in the EU-28 at 543 TWh in 2015, followed by France, UK and Italy who consumed 351 TWh, 342 TWh and 316 TWh in 2015 respectively. Germany, France, UK and Italy together consumed 60% of the FEC for residential heat consumption in the EU-28 in 2015. Residential heat consumption increased from 1990 to 2000 in Germany, France, Netherlands and UK, but decreased from 2000 until 2015.

Italy and Spain have increased the residential heat consumption from 1990 until 2015. Figure 5b illustrate the development of the share for each heat delivery technology of the total residential FEC in the EU-28. In 1990, natural gas accounted of 33% of FEC for residential heat in the EU-28, which expanded to 43% in 2015. Both oil and coal FEC decreased from 25% and 14% to 16% and 4% respectively during the period from 1990 to 2015. Biomass, as the only individual type of residential heating increased from 10% to 19%. DH decreased slightly during the period from 12% to 10% and electric heating increased slightly from 8% to 9% of FEC. On an EU-28 level, Figure 5b illustrate that the residential heat supply display path-dependent characteristics. No large shifts or changes in FEC for residential heating has been observed from 1990–2015, while gradual fuel changes away from oil and coal are evident.



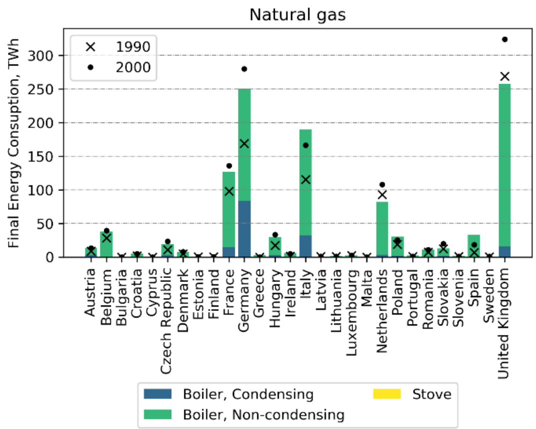
(**a**) (**b**)

Figure 5. (**a**) Final energy consumption for residential heat consumption in the EU-28 in 2015. MSs with residential heat consumption lower than 50 TWh are enlarged in the inset. The residential heat consumption from 1990 and 2000 is included to show the development of final energy consumption for residential heating. (**b**) Development of final energy consumption share for residential heating in the EU-28 from 1990–2015.

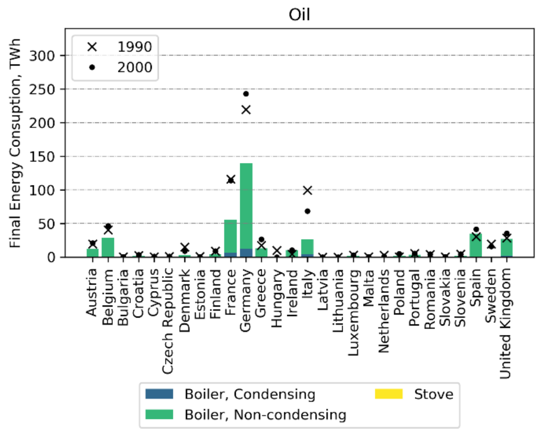
The FEC of end-use technologies that delivered the residential heat consumption in 2015 are presented in Figure 6 below. It shows overall that the end-use residential heating technologies in the EU-28 MSs are not state-of-the-art technologies. The majority of end-use natural gas and oil equipment are non-condensing boilers and most individual heat consumption from biomass is from stoves. According to the data, residential heat consumption from coal is only from non-condensing boilers. Electric heating is primarily supplied by electric radiators, with Sweden being the MS with most individual heat pumps, supplying around 39% of the Swedish residential heat consumption met by electricity. The largest consumer of electricity for residential heating, France, only supply about 1% of the residential heat consumption with heat pumps. The majority of DH is produced in CHP plants.

Overall, and with a few exceptions, the FEC for residential heating displayed path-dependent traits. Many MSs FEC per fuel in 2015 was close to the 1990 and 2000 levels, and as such does not display large shifts in residential heating consumption.

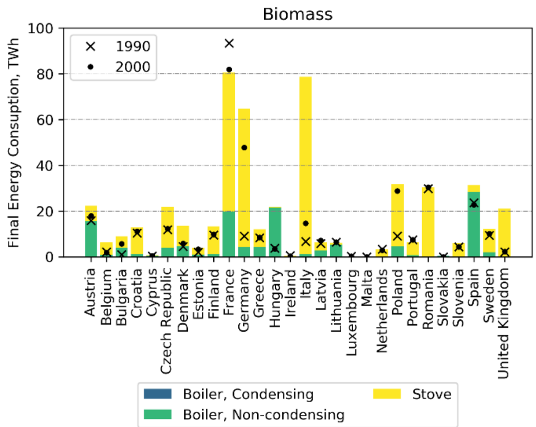
In absolute terms, the majority of natural gas FEC for residential heating was consumed in five countries: The UK (269 TWh), Germany (169 TWh), Italy (115 TWh), France (98 TWh) and The Netherlands (93 TWh) making up 84% of the EU-28 FEC of natural gas for heating in 2015. While Natural gas FEC decreased in The UK and The Netherlands from 1990 to 2015, in France and Germany it increased from 1990 to 2000 but then decreased again to 2015. In Italy, the natural gas consumption increased from 1990 to 2015. Germany and France were the two top consumers of oil for residential heating, with a consumption of 220 TWh and 116 TWh respectively in 2015.



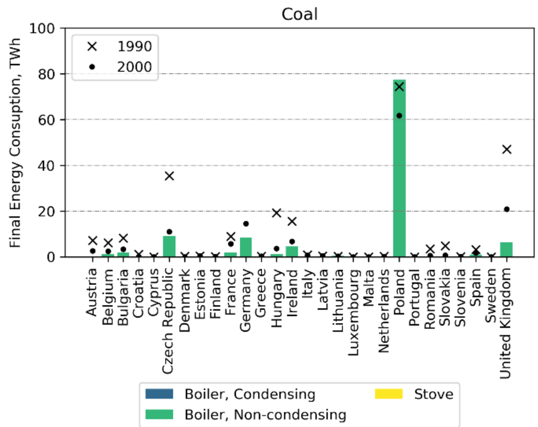
(**a**) Natural gas



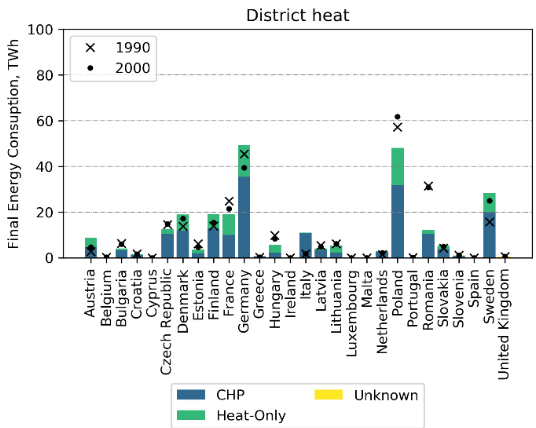
(**b**) Oil



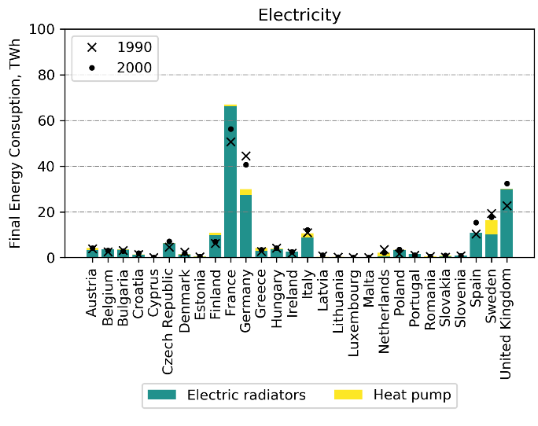
(**c**) Biomass



(**d**) Coal



(**e**) District heating



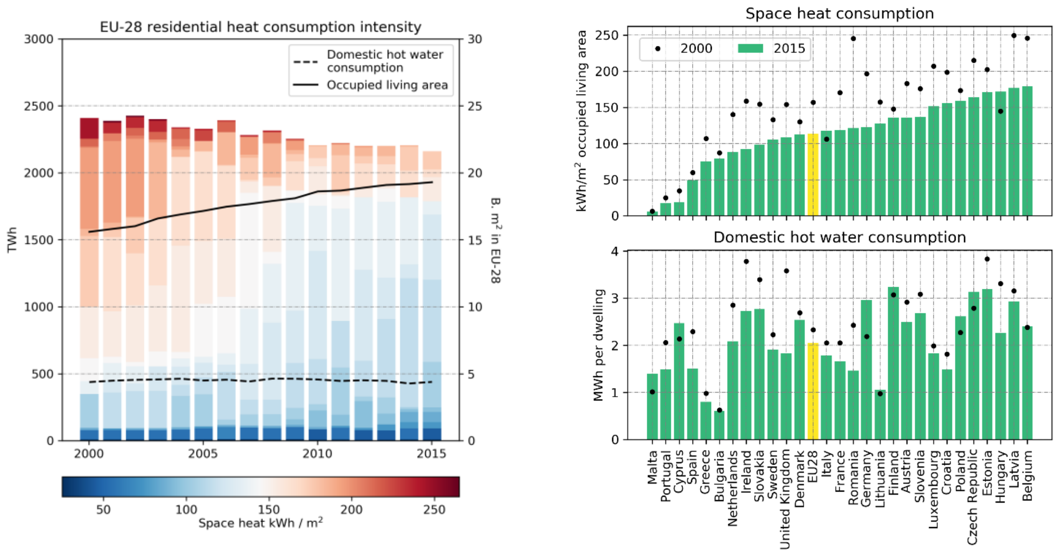
(**f**) Electricity

Figure 6. Final residential heat consumption for each EU-28 MS by type of end-use residential heat technology for (**a**) Natural gas, (**b**) Oil, (c) Biomass, (**d**) Coal, (**e**) District heating, and (**f**) Electricity. Note: (**a**) and (**b**) have a different x-axis scale than the remaining figures.

For biomass, France (93 TWh), Italy (79 TWh) and Germany (65 TWh) had the highest FEC among the EU-28 in 2015. The analysis show that Italy experienced a significant high growth in biomass consumption from 7 TWh in 1990, increasing more than 10-fold the FEC of biomass for residential heating. After these countries follow Austria, The Czech Republic, Hungary, Poland, Romania, Spain and The UK who all with a FEC of biomass above 20 TWh in 2015. Poland alone is the top consumer of coal for residential heating in the EU-28 with 77 TWh in 2015, 70% of the FEC of coal in 2015. Several other countries have managed to achieve large declines in FEC of coal for residential heating: Czech Republic, Ireland, Hungary, France and the UK all saw large declines in coal consumption. Germany and Poland had the highest DH FEC in the EU-28 with 49 TWh and 48 TWh respectively in 2015. Sweden follows with a DH FEC of 28 TWh, with Finland, France and Denmark all supplying 19 TWh of DH in 2015. Romania experienced a decline of 50% in the FEC for DH from 2000, the largest in the dataset for the large-scale collective heating infrastructures. Poland, Hungary, Czech Republic and France also decreased the FEC for DH during the 25 year period, while Austria, Denmark, Finland, Germany, Italy and Sweden expanded DH. As mentioned above, France was the highest consumer of electricity for heating at 67 TWh in 2015, with The UK and Germany both at 30 TWh.

4.5. Space Heat and Domestic Hot Water Consumption per Occupied Square Meter

Figure 7a show the development of residential SH consumption in the EU-28 split into shares of SH consumption intensity per MS average per occupied m^2 as well as the development of DHW consumption and total occupied living area in the EU-28. The EU-28 total residential SH consumption has decreased around 10% since 2000, from 2411 TWh to 2161 TWh in 2015, despite an increase in occupied living space as illustrated by Figure 7a. The EU-28 occupied living area increased 24% during the period, from 15.6 B. m^2 in 2000 to 19.3 B. m^2 in 2015. The DHW consumption remained steady just below 500 TWh per year during the period.



(**a**) (**b**)

Figure 7. (**a**) Development of EU-28 total residential heat consumption from 2000 to 2015 (left y-axis), split into MS average heat consumption intensity per m^2, and development of occupied residential living area (right y-axis). (**b**) Residential space heat consumption per occupied living area and domestic hot water consumption per dwelling for each MS in 2015 with a reference value for year 2000. MSs are sorted based on space heat consumption per occupied living area in 2015.

MS with high average SH consumption per occupied living area, above 250 kWh/m^2, overall decreased their SH consumption intensity per occupied living area to the range between 150 and 200 kWh/m^2.

The residential SH consumption intensities in 2015 ranged from Malta at 6 kWh/m^2 to Belgium at 179 kWh/m^2 in 2015 as shown by Figure 7b. While this represents a significant difference between the residential heat consumption intensities in the EU-28, there is also a number of MSs within a close range. Ireland, Slovakia, Sweden, United Kingdom, Denmark, Italy, France, Romania, Germany, Lithuania, Finland and Austria were all within ±20% of the EU-28 average residential SH consumption intensity at 113 kWh/m^2 in 2015, representing 70% of the total EU-28 residential SH consumption. MSs with higher residential SH consumption per occupied m^2 than 20% of the EU average could look into their building stock quality, residential housing renovations, control systems and heat billing, as these aspects could influence the higher SH consumption.

Figure 7b also illustrates that the average MS residential SH consumption decreased since 2000. Latvia had the highest average SH consumption per occupied m^2 in 2000 at 250 kWh/m^2, followed by Belgium and Romania both at 246 kWh/m^2. Latvia decreased the average SH consumption per occupied m^2 to 177 kWh/m^2 and Belgium decreased to 179 kWh/m^2 in 2015. Romania has made a significant improvement to 121 kWh/m^2 in 2015, cutting the average SH consumption per occupied m^2 in half compared to 2000 levels. The average MS decrease during the 15 years was 36 kWh/m^2, and in 2015, no MSs had average residential heat consumption intensities above 200 kWh/m^2. Italy and Hungary increased as the only MSs the residential SH consumption, but decreased in DHW consumption during the same period. Malta, Cyprus, Germany, Finland, Poland and the Czech Republic all increased their DHW consumption, while Bulgaria, Lithuania and Belgium remained at the same level in 2015 as in 2000.

5. Lacking Knowledge about Residential Heat Consumption and the Building Stock Quality

This paper has assessed the EU-28 residential heat consumption supply chain from PES to heat demand. Data for FEC was available for all EU-28 countries, with some instances of missing data. This allowed the estimation of PEC and distribution infrastructures. When assessing the parts of the supply chain within the building stock as the end-use technologies, energy demand, building age, renovations and quality, significant empirical knowledge gaps arise. These topics have received considerable attention from research efforts see e.g., [11,51], with the purpose of creating a detailed single year dataset or cost-curves describing renovation costs of existing building stock for forecasting and modelling work [41,59].

The actual knowledge about the current building stock and its historical development is scarce and with inconsistencies among dataset. Data about the historical development and quality of the EU-28 building stock makes it difficult to assess the building level efficiency regarding residential heat consumption. Increasing data collection about residential heat consumption is a task spread across several actors and multiple layers of government. While local governments and municipalities are important in the work with utilities, building developers and renovators, national governments must provide sufficient incentives and regulative frameworks to support data collection about residential heat consumption. The EU is already implementing such measures, in, for example, the EED [60] that promotes increased consumption based billing relying on measuring actual consumption.

In order to facilitate policy design for decarbonising residential heat supply, reliable and detailed data is important for decision makers, planners and researchers. Further research into the historical development and current status of the EU-28 building stock, heating demands and the connection with heating infrastructures forms part of moving towards low-carbon heat provision.

6. Discussion and Conclusions

The EU-28 residential heat supply show considerable need for a transition towards a decarbonized and efficient supply. Taking up 16% of EU-28 total PES at 17,875 TWh in 2015 [61], residential heating is an important subsector of the energy sector to decarbonise. 70% of PES for residential heating is fossil based, most end-use technologies are not state-of-the-art units and fossil fuel imports for heat consumption have increased since 1990.

Overall, large-scale collective heating systems using gas expanded from 1990 to 2015, while collective DH and electricity systems slightly decreased. The combined FEC for residential heating from collective heating infrastructures increased from 52% to 61% from 1990 to 2015. The only individual heating type that increased in market share was biomass, with an increase from 10% to 19% of the EU-28 FEC for residential heating between 1990 and 2015. While biomass is currently accounted for as CO_2 neutral and seen as a part of a RE supply for heating, it is still important to conserve and prioritize limited biomass resources for other energy uses in the overall energy system decarbonisation process [62].

Overall, the MSs residential heat supply display path-dependency and largely continue with established heat supply. Especially natural gas supply has been gradually expanded. Poland displayed a significant amount of lock-in from coal consumption, being by far the top consumer for residential heat and with no decline during the 25 year period. DH supply display a significant amount of lock-in, with almost all countries remaining at fairly stable levels, but with an overall EU wide decrease. Notable exceptions to the path-dependency effects exists, such as Italy, where individual biomass consumption increased 10 fold from 1990 to 2015, or Romania as an example of a country where DH infrastructure was rolled back by more than 50% since 2000. Ireland and The Czech Republic managed to make significant decreases in their coal consumption for residential heating. France, Germany, Italy and Sweden, among others, decreased oil consumption for heating.

The decline in coal and oil and shift to biomass indicate that incremental changes, such as changing fuels while maintaining the overall supply chain, is easier to accomplish and more widely used, than more disruptive changes such as changing from individual to collective supply.

The large-scale collective residential heating infrastructures display a coordinated planning effort from the MSs that have promoted these and which have resulted in large shares of residential heat consumption in certain countries.

The conclusions from this paper points specifically towards two use-cases. One, further research should continue to investigate path-dependency in residential heat supply and analyse more sources of lock-in and transition than was included in this study, such as institutional, political, domestic resources, behaviour or economic factors [25,32]. Empirical accounts of which factors produce path-dependency for residential heat supply could be important contributions to shifting towards renewables in residential heating. Second, by highlighting the path-dependent properties of existing infrastructures in residential heating, we highlight a topic that, to the best of our knowledge, is lacking from today's decarbonisation strategies for heating: the type of residential heating infrastructure and supply chains in the individual MSs will influence future developments towards decarbonized heat supply. To promote residential heating transitions in the individual MSs, this paper provides additional country specific figures of PES and FEC, in addition to those presented in this paper (Supplementary Materials).

There is both potentials for incremental upgrades in terms of replacing existing technologies with more efficient ones, but also for more radical changes such as new supply chains or collective infrastructures. Several studies show the potential for switching towards DH in high heat-density areas and to electric heating supplied by efficient heat pumps in low heat density areas [22,63]. Currently DH and electric heating account only for 10% and 8% respectively of the FEC for residential heating. Electric heating as a primary strategy for Europe can increase the strain on the electricity grids significantly as the magnitude of the heat demands compared to the current electricity demands is in the order of magnitude of a factor 2 to 4, and with a distribution over the year concentrated in the winter [4]. While individual heat pumps can decrease the peak demands and save expansion of electricity distributions grids and peak power plants [22], such strategies can be combined with more energy efficient buildings and DH [64,65].

Decarbonisation strategies should include two important points regardless of the infrastructural context. First, all residential heat decarbonisation strategies should be considered in relation to a long-term 100% RE system, to ensure that they comply with e.g., EU 2050 targets [3] and to avoid sub-optimization between energy sectors [24]. Second, all strategies need to include EE improvements both for energy supply and consumption while considering integration of RE [21,64].

MSs with DH infrastructures can leverage these to exploit heat sources such as geothermal, waste heat from industry, power production or large-scale heat pumps [22,23,64]. This will allow fuel supply changes to be made largely using existing infrastructures. A main challenge for existing DH systems is to lower supply temperatures to increase the efficiency of the network and give access to low-temperature heat sources [35,63].

MSs largely relying on gas grids should consider how these infrastructures fit into a future RE system. The historical trend from 1990–2015 has been to expand the use of natural gas in residential heating, and many MSs are currently locked into a largely gas fuelled supply regime. Gas grids could be repurposed either to supply flexible power plants [66], or for transporting green gases (biomethane, e-methane and hydrogen) for industrial purposes and transport as a part of the RE transition [67]. The potential for increasing the production of biogas to cover the natural gas use in industry, residential heating and power plants is though limited [68] and hydrogen is not proven to be a viable large-scale option for the heating sector.

MSs with high concentrations of individual heating should consider how to replace existing heating units and analyse potentials for collective heating systems. The EU's EED's article 14 on comprehensive assessments already mandate that such analyses be carried out [60]. Considerations of heat demand location and densities for evaluating the potential of collective and individual heat supply systems is crucial [65,69]. While the replacement of millions of individual boilers and stoves across the EU is a large strategic and governance task, transitions towards new fuel supply is possible in the residential sector as seen in the decrease of oil and coal for residential heating. While fuel shifts historically have been observed, it has been more difficult to find examples of radical supply chain shifts to collective large-scale infrastructures. Across the EU MSs, supplying 50% of FEC for heating with district heating and 50% with heat pumps in areas with low heat densities, combined with heat savings around 30–50% of projected heat demands have been shown as a cost-efficient approach [65,70,71]. This paper has shown that overall FEC for residential heating has decreased on an EU-28 scale, but the pace needs to increase to reach advised levels of heat savings.

Current rates of transition do need to increase to achieve a decarbonised residential heat supply in 2050, and the path dependency observed in EU-28 residential heat supply must be addressed. Overall, this paper has highlighted the scale of the transitions the residential heating sector faces towards decarbonized heating and the lock-in of different types of residential heating. While this paper has focused on the EU-28 MSs residential heat supply, the general arguments in this paper are likely also applicable to countries outside the EU. Being sensitive to historical infrastructural developments and their potential lock-in effects is important in many contexts of decarbonisation and countries aiming at developing low-carbon heat supply should be aware of their current technological situation.

It will entail ambitious policy design, strategies and investments to encourage shifting the current residential heat supply to new configurations. The analysis highlights the diversity of the EU-28 heat sectors in terms of PES, CO_2 emissions, distribution infrastructures, and end-use technologies and efficiency. The EU-28 MSs heat sectors have developed along different pathways to the current situations, resulting in diverse technological contexts. This is a crucial element to take into consideration when making strategies for heat transitions on an EU scale.

Supplementary Materials: Country specific figures for residential heating PES and FEC are available online at http://www.mdpi.com/1996-1073/13/8/1894/s1.

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Abbreviations

Combined heat and power	CHP
District heating	DH
Domestic hot water	DHW
Energy efficiency	EE
The European Union	EU
Final energy consumption	FEC
Member State	MS
Odyssee-Mure	OM
Primary energy supply	PES
Renewable energy	RE
Space heating	SH

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