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The decarbonisation of the EU heating sector through electrification: A parametric analysis

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ABSTRACT

In this paper, we examine the electrification of the heating sector as a decarbonisation strategy, discuss its effectiveness, and preliminary assess its impact on the European power system. For this purpose, we perform a complete description of the EU heating sector compliant with official statistics and decompose the EU power demand in different uses to define and assess different levels of heat electrification. We find that heat electrification is an effective decarbonisation option, which can reduce the total energy related emissions by up to 17%, if paired with simultaneous expansion of low-carbon energy. Due to the relative sizes of heat and power demands, we find that most national power systems could cope with higher heat-electrification rates. Specifically, an additional heat pump capacity in the order of 1.1–1.6 TW_{th} can be deployed based on the existing firm power capacity, which would correspond to a heat pump share of 29–45% in space heating. Based on their current power capacity, 12 Member States are prepared for even full electrification scenarios, whereas three Member States could get their power system stressed if 40–60% of all fossil-fuelled technologies are substituted. Flexible electric demand is identified as a key enabler of larger heat electrification shares.

1. Introduction

The heating and cooling sector, responsible for half of the EU's final energy consumption (European Commission, 2016; JRC, 2018), has been recognised as a priority to achieve decarbonisation targets set for the energy sector. In Fig. 1, we show the breakdown of the final energy consumption across all Member States (MSs). A total of 22% is attributed to the space heating needs in the residential and tertiary sectors, which makes the 'sector integration' with the power system a promising strategy to reduce greenhouse gas emissions. Among others, it allows reducing fossil fuel consumption by substituting fossil-fuelled boilers with more efficient electric-driven technologies, benefiting from a rapid decarbonisation of the power system, faster than other sectors.

This rapid decarbonisation of the power system can be observed by the fast reduction of the fossil fuel intensity indicator in recent years, which is defined as the energy content of fossil fuels (excluding uranium for nuclear) needed to produce one unit of electricity. Fig. 2 shows the evolution for the EU 28 countries from 1990 to 2017 sorted by their corresponding values for 2016. The overall picture across the EU is diverse. Still, the mean fuel intensity is falling from 1.27 to 1.06 $kWh_{fossil}/kWh_{electric}$ for the period 2010–2017. Countries, such as Sweden, France or Slovakia have already achieved a fairly clean power system while others, such as Denmark, Ireland and Greece, are experiencing a steep transition towards it.

The European Commission identified electrification as one of the seven key trends that are likely to shape the power system in the future (Commission Expert Group, 2017). Within the heating and cooling sector, a great potential lies for reducing its carbon intensity by switching to electricity as energy carrier. Even without active carbon policies in place, electrification can lower CO_2-emissions and improve local air quality by reducing the emissions of pollutants (EPRI, 2018).

1.1. Electrifying the heating sector: challenges and opportunities

Power-to-heat technologies, such as heat pumps, can benefit from the increasing decarbonisation of the national electricity mixes across the EU. Running on clean electricity, heat pumps would not only reduce emissions associated with the heating sector, but also increase the efficiency of the energy system. This results from the high performance that this technology, using either ground or air source reservoirs, can provide delivering a thermal output several times greater than the required electric input.

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A further advantage of the electrification of the heating sector is the utilization of a highly developed transmission infrastructure. On top of that, the fast deployment of decentralized electricity generation in the EU, based mainly on renewable sources, increases the security of supply not only for the power sector but also for the heating one if power-to-heat technologies are in place.

In the literature, the electrification of the heat sector, as a cost effective measure to decarbonize the energy system, is becoming more and more relevant (Bloess et al., 2018). Heat pumps — a mature and highly efficient technology — are key to reduce emissions in the heating-and-cooling sector and, thus, preferable to other sector coupling technologies (IWES/IBP, 2017; Raghavan et al., 2017; Schaber et al., 2013). While being economically viable on a macroeconomic scale, the high upfront investment costs hinder the deployment of heat pumps at small scale in many EU countries (Barnes and Bhagavathy, 2020; Karytsas, 2018). Realigning building codes, subsidies and taxes helps create a level playing field with gas boilers and other fossil based heating solutions (Bruckner and Kondziella, 2019; Hannon, 2015).

Furthermore, the flexibility of electric heating applications plays an important role in balancing power demand and supply, and may – in combination with other sector coupling technologies from the transport and chemical sectors – render electricity storage redundant, even in a highly decarbonised system (Böttger et al., 2015; Brown et al., 2018).

On a grid level, electrification creates new consumers who put the local infrastructures to the test. However, it has been shown that even large penetration levels of electric vehicles and heat pumps are manageable if appropriate operation strategies are implemented (de Boer-Meulman et al., 2010; Shao et al., 2013). In areas with distributed generation, heat pumps can even relieve the pressure on the grid if their demand response potential is used (Felten et al., 2018).

The electrification of heat is, however, highly dependent on an energy-efficient building stock. Heat pumps are most efficient when they supply heat at low temperatures. Their efficiency decreases in buildings that are not well insulated, since those demand higher supply temperatures. This has been identified as one of the key risks in focussing on a one-sided deployment of heat pumps for the decarbonisation of the heating sector and sparked a controversial discussion on the right strategy (Chaudry et al., 2015). Some studies argue that it is advantageous to decarbonize heating fuels through power-to-X technologies rather than investing in the cost-intensive renovation of the building stock (Bründlinger et al., 2018; Ecke et al., 2017; Filippidou and Jimenez Navarro, 2019). Others see positive economic effects in the renovation of the building stock and highlight the risk of potential lock-ins from a strategy that counts on a high penetration of synthetic fuels - a technology which is currently far from being competitive (Mellwig et al., 2018). Regarding the macro effects of heat-pump deployment on the power system, there are two sides to the same coin: On the one hand, there are strong signs, in most EU MSs, that heat demand exceeds electricity demand in both peak and aggregated annual demand values. Extensive electrification can place a heavy burden on the power system and, thus, require significant capacity expansion (Connolly, 2017). Furthermore, rising demand might produce additional CO_2 emissions in the power sector (depending on the electricity mix at hand) (Sandvall et al., 2017). On the other hand, heat pumps are a source of flexibility to the power system, which facilitates the management of the electricity supply to meet demand in a system with high shares of variable renewable electricity sources, thereby reducing curtailment and fossil fuel consumption (Bloess et al., 2018).

The effect on generation capacity levels cannot be seen as proportional to the heat-pump uptake. We must rather distinguish according to the penetration level. At low penetration rates, in combination with thermal storage, heat pumps were found to lead to little or no additional required capacities to satisfy the additional demand because they can operate in off-peak times due to their flexibility (Baeten et al., 2017). Additional storage units are, however, no precondition for a flexible dispatch since the thermal inertia of buildings can be used as a low-cost option for load shifting without impacting the comfort of the inhabitants (Heinen et al., 2017).

High penetration levels generate a demand for electricity that cannot be satisfied by just 'filling in the gaps'. This additional demand can generate new peaks that lead to increased capacity requirements, and, thus, to additional investments in power generation. Flexible operation still remains important to reduce the volatility of heat-related electricity demand (IWES/IBP, 2017; Ruhnau, 2017). The study carried out by (Watson et al., 2019), however, found that the peak demand from domestic heat was much lower in reality than what previous research suggested, when analysing smart meter data from 6000 households in the UK.

The appearance of strong winds in fall and winter correlates with the heating period in central and northern European countries, which makes heat pumps and wind power a great match in this geographical area (Hedegaard et al., 2012; Heinen et al., 2017; Vorushylo et al., 2018). Heat pumps can therefore help reduce renewable surpluses and enable further integration of wind power in systems with already a high penetration level (Hedegaard et al., 2012). Whether a flexible dispatch in combination with real-time pricing is economically profitable for the consumer, however, highly depends on the electricity pricing regime (Felten and Weber, 2018; Hedegaard et al., 2017; Oldewurtel et al., 2010). The partial integration of heating into the power sector to build a more efficient overall system can only succeed, if the two sectors are designed together.

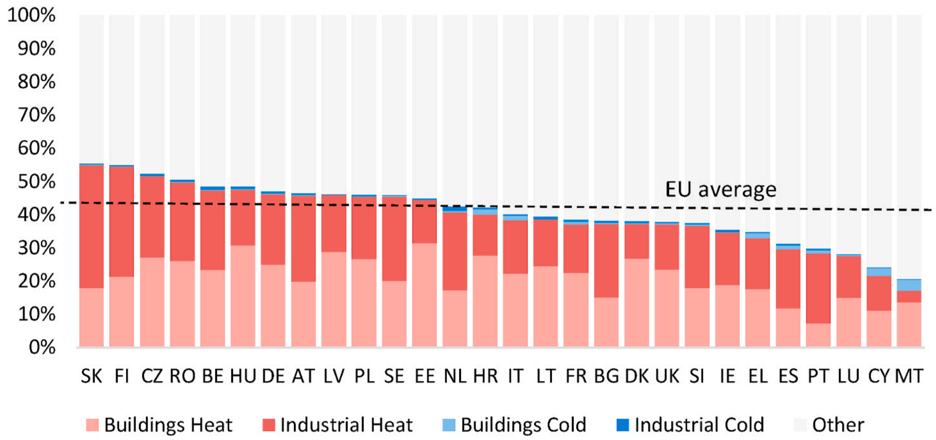


Fig. 1. Share of final energy consumption for heating and cooling services across the EU in 2015. The dotted line represents the EU average, 42% of the final energy demand, which goes to heating and cooling services. Data source: JRC IDEES Database (JRC, 2018).

1.2. Scope of this work

The scope of this work is to contribute to the ongoing discussion by assessing the impact and the effectiveness of the electrification of the heating sector in Europe as a promising decarbonisation pathway. As shown in this section, there are plenty of sources discussing the subject. However, there are not many quantifying the implications of such a development, with a scope covering the whole EU. In this work, we provide a detailed analysis on the individual heat sector of each MS with a special focus on their adequacy for being electrified. The analysis includes environmental aspects, technology deployment prospects and economic implications for end-users.

Furthermore, we quantify how electrification can help individual MSs reduce CO_2 emissions, evaluating the costs and necessary boundary conditions for effective climate mitigation. In addition, we assess what level of electrification can safely be achieved without threatening the security of supply. To that end, we generate and investigate scenarios assuming different degrees of electrification.

Previous works on this particular topic mentioned in the literature review, often relied on a bottom-up approach, upscaling profiles based on a collection of household consumption data (Hedegaard et al., 2012; Vorushylo et al., 2018) or thermodynamic building models (Felten and Weber, 2018; Heinen et al., 2017) to construct the demand profiles. Instead, we disaggregate the electricity demand on a national level and isolate the heat-related profiles while remaining consistent with official national statistics. This top-down-approach allows us to investigate the matter at a larger scale providing a better understanding of the effects that the new electricity demand profiles will have on the macro scale. Last, we assess these scenarios not only from a system adequacy perspective but also from an economic one.

Our results are of a high relevance for EU policy makers, as they give a detailed perspective on the conditions for each MS. We furthermore highlight the challenges in the power sector with a focus on the security of supply and outline elements for successful mitigation strategies through heat-pump deployment.

2. Analysis of the European heating sector

In this section, we describe in detail the heating sector in Europe based on the JRC IDEES database (Mantzos et al., 2017) — built on EUROSTAT's energy balances, followed by a disaggregation using official data and other widely accepted sources by solving a constraint-satisfaction problem. The result is a detailed description of all sectors in the energy system with regard to fuel consumption, technologies and more. Since it follows the release cycles for Eurostat, the last year available is 2015.

2.1. Fuel consumption for heating in the built environment

In Fig. 3, we present the total EU fuel consumption for space heating (right) and a country-specific breakdown (left) in 2015. Currently, heating in the EU relies, over 40%, on low-carbon technologies – including district and electric heating, as well as renewable fuels, namely biomass. Two northern European countries boast the highest shares for cleaner heating technologies: Sweden gets almost 95% of space heat in buildings coming from district-heating networks, electricity and renewables, while Finland claims the second place with roughly 90%.

Correspondingly, trends based on geographic locations become clearer: District heating is particularly dominant in northern European MSs, while renewables – due to large biomass shares– are leading in the east. As a result, the Baltic countries, which combine both, exhibit a share of around 80% of low carbon heating fuels. The heat supply in central and western countries is largely based on gas.

Electricity as a fuel is most popular in southern European countries, where direct-electric heating is still widely spread, as well as some northern European countries, where heat pumps are more established in the heating market. In relation with the total electricity demand, electricity consumption on a country level does not even exceed 10% in the most heat-pump-reliant countries, Sweden and Finland. Fig. 4 shows the share of electricity consumed for heating and cooling compared to the total electricity demand. Up until today, direct-electric heating puts a greater load on the system in every EU country. In most of them, the share of electricity consumption attributed to heat pumps is well below 5%, and more or less at the same level as air conditioning if considered on a European level.

2.2. Heat pumps in EU buildings

Heat pumps are expected to be a major player in future heat markets, which can mainly be attributed to the following reasons: They do not emit CO_2 when generating heat from green electricity, and their efficiency has risen sharply. This development is already observed in the historic data: Fig. 5 compares the average useful-heat production per unit of primary-energy input. The calculations are based on general and technological specific efficiencies from IDEES, and power-system efficiencies for each individual MS (EUROSTAT, 2018). We can see that even taking into account the current conversion processes in the power sector, newly installed heat pumps in the residential sector have been more efficient than the average new heating appliance since 2005.

2.2.1. Carbon emissions

In this section, we present a comparative overview of the historical carbon intensity for two heating options: heat pumps — the focus of our study — and gas boilers — the most common competitor in the heat sector with a market share of 41%, and the decentralized fossil heating option with the lowest specific CO_2 emissions (JRC, 2018).

When it comes to attributing carbon-emission factors the two following methods can be employed: the average (power mix) method where the emission factor is the average of the whole power mix and the marginal method where each additional electricity demand requires an update of the emission factors associated to the newly installed capacity. The reason for the latter is that the additional power demand will increase the carbon intensity as less-clean generators will be utilized

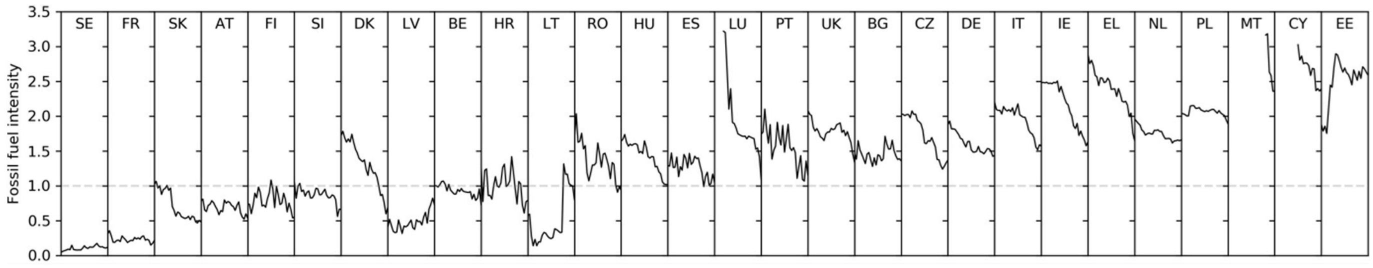


Fig. 2. Evolution of fossil fuel intensity for all EU MSs (1990–2017). MSs are sorted by the value of last year (2017). Data source: Eurostat Tables nrg_110a, modified power system efficiency definition (eta).

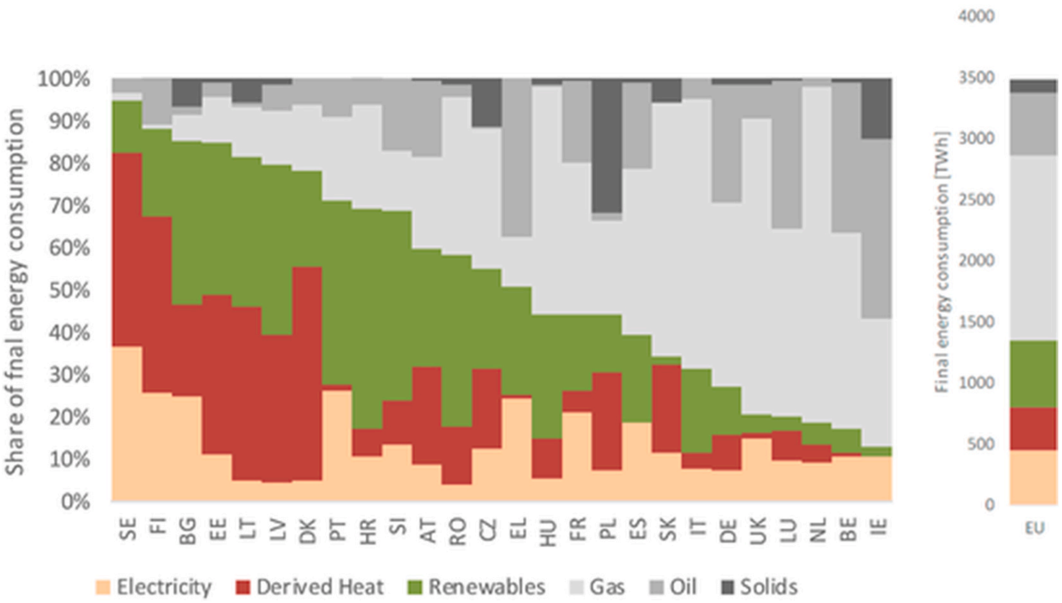


Fig. 3. Fuel consumption for space heating and domestic hot water in the residential and the tertiary sector in 2015. Derived heat describes heat delivered by heating networks. Data source: JRC IDEES Database (JRC, 2018).

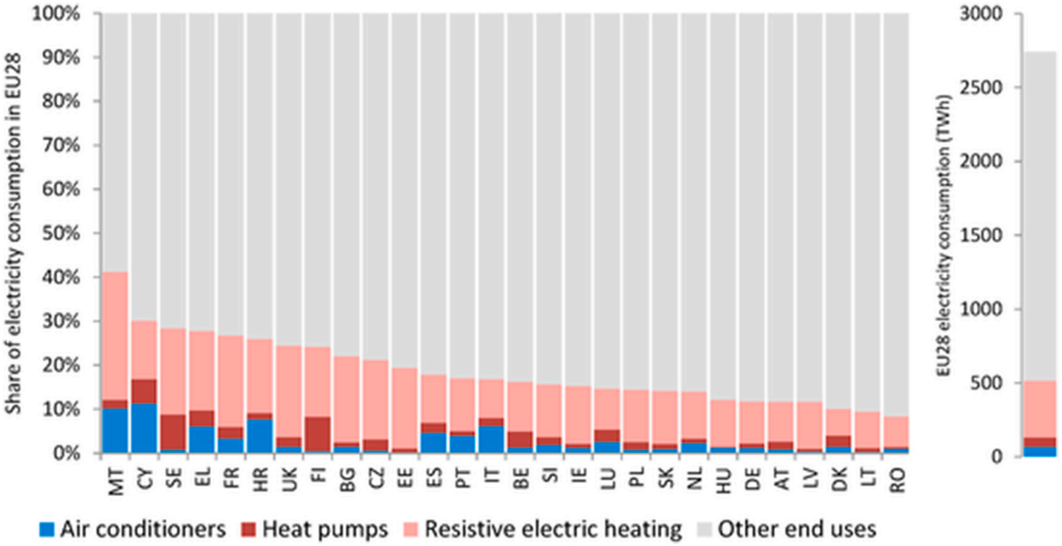


Fig. 4. Space Heating and space cooling share of electricity demand in 2015. Data source: JRC IDEES Database (JRC, 2018).

depending on the merit-order of any given power system (Regett et al., 2018).

In this section as we evaluate the historical carbon intensity of heat pumps, we use the average method. In section 4.2, we carry out a detailed analysis of the effects of future heat-pump deployment on the total energy-related emissions using the marginal method.

Following the above, Fig. 6 shows the carbon footprint of one MWh_{th} provided by heat pumps using the average method. In terms of CO_2 intensity, we can see a clear trend in all MSs towards heat pumps beating gas boilers, if not already the case. In countries with a strongly decarbonized power mix, such as Sweden and France, which rely heavily on nuclear power, heat pumps are much cleaner than gas boilers. Looking at the whole of Europe, in more than half of the MSs, heat pumps are already less carbon intensive. Even in countries with a carbon-intense power mix, heat pumps are not far from parity. We can see that heat pumps are on track to be less carbon intensive than gas boilers across all MSs, since the decarbonisation of their power system is continuing.

2.2.2. *Heat pump deployment*

Fig. 7 displays the share of households per MS, which are heated by a heat pump, including a projection based on the development over the period 2011–2015. This timeframe is selected, since the pace of heat pump deployment increased at that time in several MSs. The projection must be seen as an indicator of how fast each country is deploying heat pumps, and not as a precise forecast. While it ignores several constraints and assumes a linear progression, it gives a good impression of the pace, at which heat pumps are being deployed in the majority of EU countries. Fig. 8 then compares the end-consumer costs of heat provided by a heat pump and a gas heater, calculated based on household prices published by EUROSTAT.

The heat-pump-deployment trend is most promising in Sweden and Finland, aiming at shares beyond 40% for 2030. Both countries were early adopters of a carbon tax, and currently have the highest rates implemented in the EU: In Sweden, the tax is set at 110 EUR/tCO_2 (Government Offices of Sweden, 2020), while Finish consumers have to

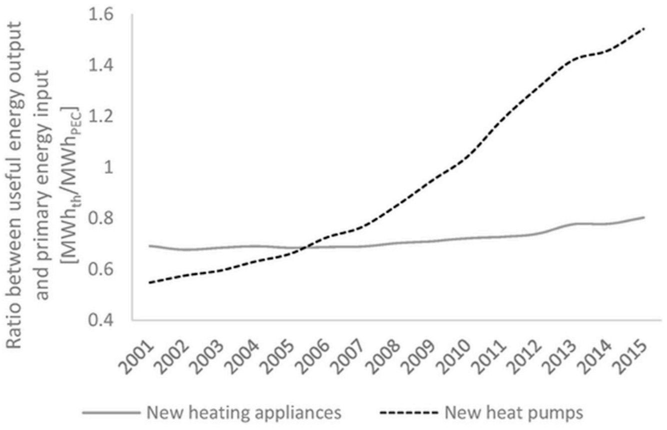


Fig. 5. Performance with regard to primary energy consumption of heat pumps in comparison to the average new heating appliance in the EU's residential sector. Data source: JRC IDEES Database (JRC, 2018).

pay a charge set at 54 EUR/tCO_2 for carbon emissions due to household heating (World Bank Group, 2020). The development in Sweden, the European front-runner in residential heat-pump deployment, appears to be strongly motivated by the energy prices, as heat from a Swedish gas boiler is roughly 5 ct/kWh more expensive than from a heat pump.

An increased uptake of heat-pumps can be seen in several countries, as soon as cost parity is reached: France, Slovenia, Spain, Greece and Austria, are on track to achieve notable shares between 10 and 30%. Cost parity alone, however, is not sufficient to explain completely the differences in heat pump deployment: While Belgium is projected to reach roughly 15% by 2030, even though gas appears to be cheaper, Bulgaria, Latvia and Lithuania have reached cost parity, yet only see a slow, or even no heat-pump deployment. Certain aspects not considered here can explain this. For one, additional subsidies are not considered here. On the other hand, we only compare the heating costs of heat pumps with those of gas boilers. In Eastern Europe, domestic biomass is dominant, and usually comes at a much lower cost, as it is regionally produced and widely available.

2.3. Power demand decomposition

To understand the implications of electrifying the heat sector, we, first, need to quantify today's electricity demand dedicated to heat. We decomposed the total power demand per country into three uses: space heating, space cooling and other uses. To do so, the analysis combined electricity and heat demands (ENTSOE, 2018; JRC, 2018), and temperatures profiles (De Felice and Kavvadias, 2019).

The total power demand is plotted against the temperature for different days of the week and hours of the day. The distribution of load in most cases is bimodal, which means that the sensitivity of the electric load to the temperature is different between day and night times and between weekdays and weekends (Fig. 9).

In order to decompose the electric load into heating and cooling loads within a country, among different hours of the day and among weekdays and weekends and holidays we use a variable-base degree-hour method, which is a generalisation of the traditional degree-day method. Then, we smooth and rescale the heat degree-hour time series to fit the total electricity consumption for heating. The steps were as follows:

1. Find hinge point base temperature for heat/cooling degree hours. This is the temperature beyond which the power demand will have a monotonic relation with the temperature. The point is found by checking the Spearman-rank correlation coefficients (which show the monotonicity of a data series) for each of the base temperatures used (Azevedo et al., 2015). The highest spearman factor was chosen. A very low spearman factor (below 0.2) or a high p-value (above 0.05) indicate no monotonic relationship among the variables. In that case, it is safe to assume that there is no dependency of the load on the temperature. This was conducted for day/night and weekday/weekend based on the results of a density clustering.

Fig. 6. Tons of CO_2-emissions per MWh useful heat provided by heat pumps (blue) in comparison to conventional gas boilers (orange) for reference. Note that Cyprus and Malta do not have a gas network. Data source: JRC IDEES Database, Tertiary sector (JRC, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

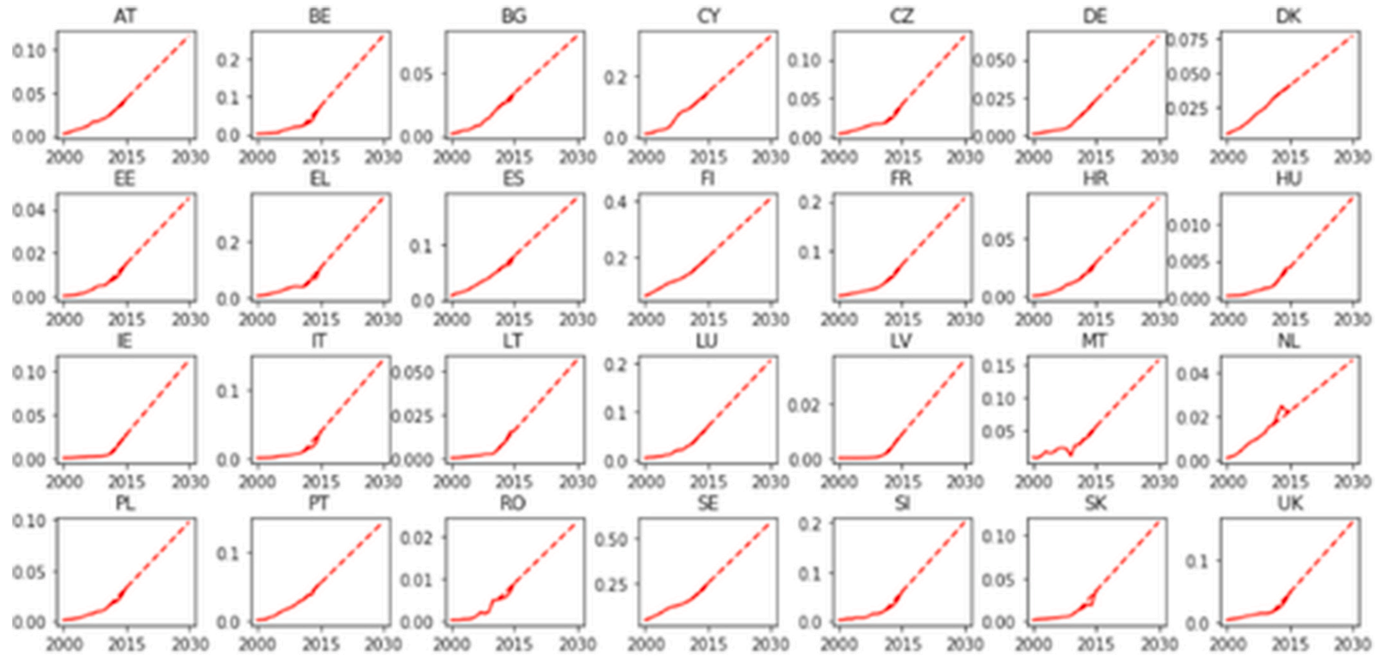


Fig. 7. Projection of the heat pump share in the EU space heating based on useful heat supplied. Historical development as solid line, projection based on the development 2011–2015 as a dotted line. Data source: JRC IDEES Database (JRC, 2018).

Fig. 8. Average end-consumer cost of 1 kWh_{th} in EUR. Comparison between heat pumps (blue) and gas boiler (orange). Missing gas prices are due to incomplete data in the EUROSTAT database. Data sources: EUROSTAT Tables nrg_pc_202 (Band DD) and nrg_pc_204 (Band D2); JRC IDEES Database (JRC, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Establish heat degree hours (HDH) and cooling degree hours (CDH) using the hinge points found above using the formulas:

$$CDH_t = MIN(T_t - hinge_c, 0)$$

$$HDH_t = MIN(hinge_h - T_t, 0)$$

where T_t is the temperature at time *t* and *hinge* the identified hinge point for heating or cooling for the type of the day (weekday/weekend) and type of period (day/night). If there is no hinge point then the *CDH* or *HDH* is zero for that time step. An exponential weighted moving average with a decay of 3 h was applied in the resulted time series in order to smoothen the series and simulate the dependency of the heating/cooling load to previous time steps. This is recommended to reduce unrealistic peaks and ramps of power demand that can be caused by fast changes in temperature and to simulate the building inertia and dependency on previous temperature values. Last, we normalise the two time series of the above step so that their sum is equal to one.

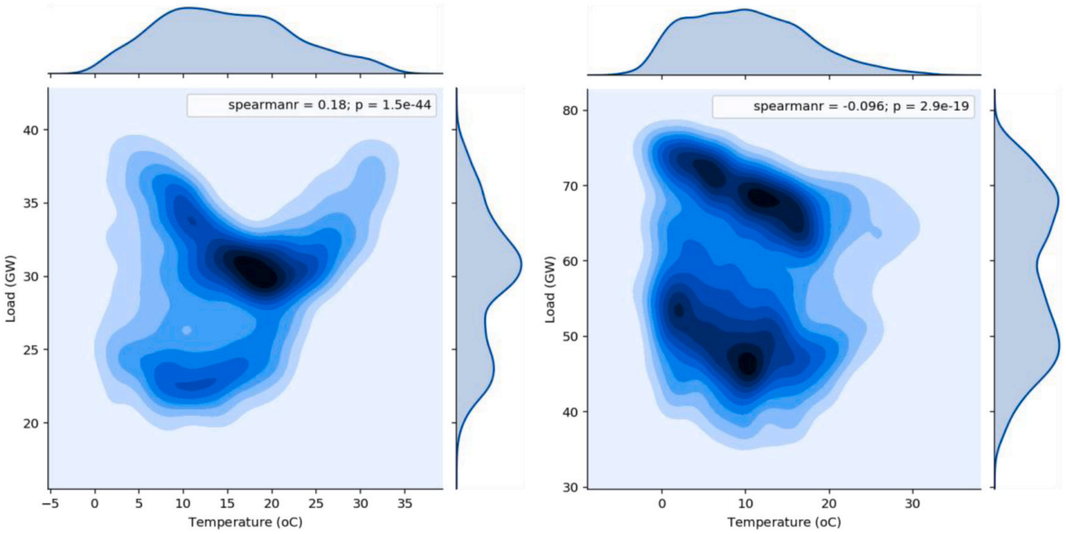


Fig. 9. Density scatterplots illustrating the relationship between load and temperature for Spain (left) and Germany (right). The marginal distributions of the two variables are also shown to indicate the bimodal nature of the load (day-night, weekend-weekday).

3. We define the following rescaling function,

$$scale(x_t; A, B, C) = A x_t^B + C$$

where, x_t the original normalized time series and *A, B, C* the rescaling parameters. The rescaling is done through a combination of stretching (*A*), shifting (*C*) and skewing (*B*).

The implied coefficient of performance (*COP*) time series is based on a Carnot factor by means of:

$$\mathrm{COP_t} = \eta_c (1 - \mathrm{T_{set}} / \mathrm{T_t})$$

where, η_c is the second law efficiency $\eta_c = 45\%$, T_t is the temperature at time *t*, and T_{set} a set-point Temperature. In this study a $T_{set} = 22$ °C is used. This equation is needed to simulate the variations of the heat-pump efficiency, which is affected negatively by the cold spells.

4. For the decomposition, the following equation needs to be satisfied:

$$L_t = Other_t + scale(CDH_t;\ A_c,\ B_c, C_c) + scale\ (HDH_t \cdot COP_t;\ A_h, B_h, C_h)$$

Based on this function, the decomposition should satisfy the following targets:

$$\sum_t scale(CDH_t; A_c, B_c, C_c) = target\ \ cooling\ \ load$$

$$\sum_t scale(HDH_t \cdot COP_t; A_h, B_h, C_h) = target\ \ heating\ \ load$$

$$HDH_t \cdot CDH_t = 0$$

The targets are taken from real shares of electricity for heating and cooling for all historical years based on (JRC, 2018). The last constraint assures that there is no simultaneous space heating and cooling. Since the above problem is highly non-linear and discontinuous it was formulated as a minimization problem using a combination of positive penalty factors and solved via a genetic algorithm. The python DEAP package was used.

The decomposition was performed at MS level. In all cases, the algorithm converged to the target within less than a minute. The result obtained is fully compliant with the national heating and power statistics from the above-mentioned sources.

For the sake of conciseness, we present the aggregate EU demand in Fig. 10. This figure includes the temperature-dependent components (electricity for space cooling and space heating) and the electricity used for other purposes.

Demand for heating and cooling follows the inter-annual weather variation. The deviation range of peak demand (i.e. the difference between maximum and minimum deviation) among different weather years varies from 2 to 10 percentage points depending on the region ((De Felice et al., 2020). The subsequent analysis in this work refers to 2015, which is selected as recent median weather year. A median year is sufficient for the parametric analysis done in this work, however more detailed adequacy planning should involve the effect of extreme weather events and detailed hourly dispatching.

3. Heat electrification scenarios

Despite all its potential benefits, the electrification of the heating

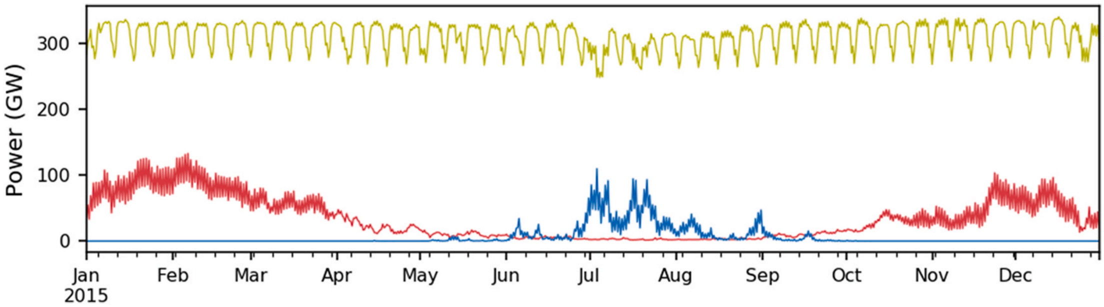


Fig. 10. Aggregate electricity demand for heating (red), cooling (blue) and other purposes (green) in 2016. NB: Lines are not plotted cumulatively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sector requires a thorough evaluation. A complete integration of the heating and power sectors would have major implications on the power system, which, among others, would need to deal with additional demand. Furthermore, the potential emissions cut will vary depending on which heating technologies are displaced: While replacing an oil or coal boiler with a heat pump might always make sense, due to their higher carbon intensity, the case is not as clear for gas boilers, as demonstrated in Fig. 6.

To investigate the optimal electrification levels, or at least those beneficial to the energy system, we have created scenarios that vary according to the level of electrification as well as the technologies selected to be replaced by heat pumps.

The baseline scenario (BLS), used as reference, is defined based on the European heat sector in 2015 described in the previous section. The EL20 – EL100 scenarios describe a step-wise replacement of *decentralized*-fossil and resistive-electric heaters with heat pumps. The number in the scenario name refers to the replacement rate of fossil-fuel-driven technologies, i.e. 100 implies that all decentralized fossil-fuel technologies are replaced with heat pumps. These technologies were chosen since they are the main sources of CO_2 emissions in the European building's heat sector.

In addition, we have created two more scenarios: the EL100BIO that assumes a displacement of biomass in the heat sector. We chose this scenario since there is only a limited biomass potential (European Environment Agency, 2013; JRC, 2015), but great competition from the industrial and the transport sector for available resources. In these sectors, there are applications, where low- and zero-carbon alternatives are much harder to find. They will need biomass to decarbonize, for example, high-temperature-heat applications or airline fuel, driving up biomass prices. Their willingness to pay for available biomass resources exceeds the one of the residential and the tertiary sector, where low-carbon alternatives are available at much lower costs. Sharply rising biomass prices could therefore lead to a mass migration towards other low-carbon heating options. Several eastern European countries rely heavily on biomass for space heating. The EL100BIO scenario can therefore highlight the risk of a large-scale displacement of biomass through heat pumps, due to the above-mentioned reasons.

Last, to quantify the maximum impact of electrification, the EL100ALL scenario describes a fully electrified heat sector in Europe. In comparison to the EL100BIO, we additionally assume that all the households connected to heating networks switched to heat pumps. This last scenario, albeit not realistic, serves as an upper limit and frames the analysis.

To generate the time series for these scenarios, we derive the useful heat covered by electricity based on the rules set above. We rescale the decomposed electricity demand of Section 2.2 in order to match the total useful heat demand, considering also the implied COP variation. Then we add the other two electricity demand components, electricity for cooling and electricity for other uses. All scenarios have been built at the national level and are then aggregated at EU level.

In Fig. 11, we present an overview of all scenarios. It depicts the total final energy consumption per fuel. The increase of electrification rates leads to a reduction of the total final energy demand — from almost 3500 TWh in the BLS down to, roughly, 2000 TWh in the EL100 — due to the higher efficiencies of the heat pumps. The EL100ALL shows the smallest consumption, ~ 1200 TWh. In Table 1, we provide an overview at national level, including the scenario each MS aims at in 2030, according to the projection in section 2.2.2. It lists the first scenario with a higher heat pump share than the projection. As we can see, all but five MS would not even reach the EL20 scenario, if their build out continued at the current pace.

Fig. 12 shows the heat-pump shares in heating on a MS level. As we can see, the shares vary drastically among MSs in the different scenarios. A couple of eastern and northern European countries see only low electrification rates up to the EL100 scenario, yet immense heat pump uptake above, when biomass and district heating is replaced.

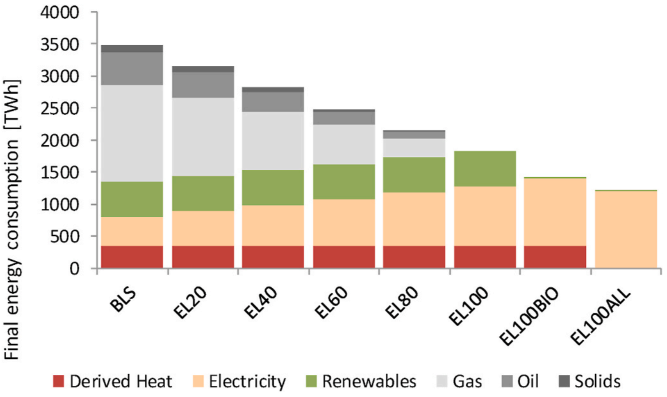


Fig. 11. Scenarios for the electrification of the heating services — space heating and domestic hot water — of the built environment on an EU level. Derived heat describes heat delivered by heating networks.

4. Results and discussion

In this section, we present the results obtained from our analysis. First, the discussion focuses on the reliability of the power sector for different demand alternatives. Then, we continue with the analysis in terms of carbon emissions. Last, benefits based on today's power-sector means are discussed.

4.1. Implications on power sector reliability

The electrification of the heat supply in the buildings sector has cross-sectoral implications as it results in additional electricity demand. The current power systems were not designed to accommodate this additional demand and investments in new generation capacity might occur with delay. Therefore, it is essential to anticipate demand surges by designing electrification pathways for the heating sector, which are accompanied by the necessary investments in the power sector.

In this section, we assess the security of the national power systems for the scenarios presented before, based on their current available capacities and different demand assumptions. We start considering a completely inflexible demand and assessing the future adequacy of the generation park based on the POTEnCIA Central Scenario (JRC, 2019a). Then, we assume that the thermal inertia of the building stock is used as thermal storage to make the demand flexible.

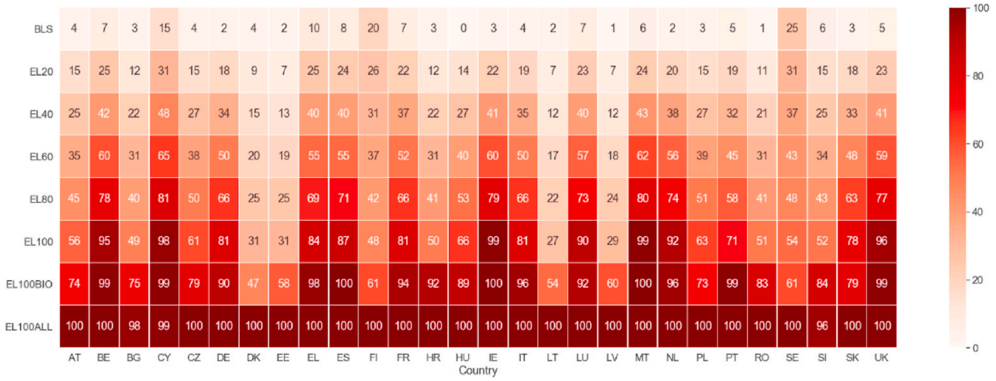
The heavy burden that electrification places on the power system can be seen in Fig. 13. It shows the load duration curves (LDCs) for the different scenarios. Additionally, the firm capacity level for the year 2016 is indicated, calculated based on (JRC, 2019b).

The seasonal profile of the heat demand leads to large increases of electricity demand along half of the year, especially in winter. The steeper profile of the LDC illustrates a highly variable energy demand, implying a small amount of hours with a very-high demand. Demand-side flexibility could reduce this number of hours, spreading out the peak demand more evenly.

In a preliminary analysis, we only consider firm capacity. Our assumption is conservative and simplifies by abstracting from outages of conventional power plants, capacities reserved for balancing services and unstable renewable generation (see Appendix C for a classification which technologies were included in the calculation of the firm capacities). The first two factors might lead to overestimate the available firm capacity. A large fraction of balancing reserves, however, could still contribute to the supply, as an imbalance in the spot market would not directly lead to load shedding, but rather only if the balancing market is unable to compensate it. On the other hand, by not taking into consideration variable renewable generation we underestimate the available capacity, which is more significant in countries with large renewable shares.

Table 1
Electricity demand for heating in different MSs and scenarios (TWh).

Fuel replaced	BLS	EL20	EL40	EL60	EL80	EL100	EL100BIO	EL100ALL	Projection trend 2030
	None	Fossil	Fossil	Fossil	Fossil	Fossil	Fossil and biomass	Fossil, biomass, district heating	
Electrification rate	13%	18%	24%	32%	42%	55%	77%	100%	
AT	6.6	8.2	9.8	11.3	12.9	14.4	19.8	28.2	EL20
BE	12.3	17.1	21.9	26.8	31.6	36.4	37.9	38.5	EL40
BG	5.8	5.5	5.2	4.8	4.5	4.1	6.0	7.6	EL20
CZ	11.2	12.6	14.1	15.6	17.0	18.4	23.7	30.2	EL20
DE	54.9	86.9	118.9	150.9	182.9	215.0	238.5	269.0	EL20
DK	2.7	3.2	3.8	4.4	5.0	5.6	8.7	19.2	EL20
EE	1.3	1.3	1.3	1.3	1.3	1.3	2.5	4.7	EL20
EL	11.1	11.3	11.7	12.0	12.3	12.7	14.6	15.8	EL40
ES	30.8	33.6	36.4	39.2	41.9	44.7	50.6	51.7	EL20
FI	18.6	17.9	17.2	16.5	15.9	15.2	20.2	35.2	EL80
FR	99.8	108.0	116.1	124.4	132.6	140.8	160.4	169.9	EL20
HR	2.8	3.0	3.3	3.6	3.8	4.0	7.0	7.5	EL20
HU	3.9	6.1	8.2	10.4	12.6	14.7	19.6	21.9	EL20
IE	3.5	4.8	6.0	7.3	8.5	9.8	9.9	10.3	EL20
IT	30.6	42.9	55.1	67.4	79.7	92.1	108.0	113.5	EL20
LT	0.9	0.9	1.0	1.2	1.3	1.4	3.0	5.4	EL20
LU	0.8	1.1	1.4	1.8	2.1	2.4	2.5	2.5	EL20
LV	0.7	0.9	1.1	1.2	1.4	1.5	3.3	5.5	EL20
NL	12.1	17.8	23.5	29.1	34.8	40.5	42.1	44.4	EL20
PL	17.5	23.6	29.7	35.9	42.0	48.0	56.0	77.1	EL20
PT	6.0	5.9	5.8	5.8	5.6	5.6	7.3	7.9	EL20
RO	3.2	4.9	6.7	8.5	10.3	12.1	19.9	24.1	EL20
SE	34.5	32.3	30.2	27.9	25.7	23.5	26.7	45.4	EL100BIO
SI	1.8	1.8	2.0	2.1	2.2	2.3	3.7	4.4	EL40
SK	3.2	4.1	4.9	5.8	6.5	7.4	7.5	9.8	EL20
UK	69.7	85.5	101.2	117.0	132.8	148.5	153.1	154.9	EL20
TOTAL	**446.3**	**541.6**	**636.6**	**731.8**	**827.2**	**922.4**	**1052.5**	**1204.6**	



	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO	SE	SI	SK	UK
BLS	4	7	3	15	4	2	4	2	10	8	20	7	3	0	3	4	2	7	1	6	2	3	5	1	25	6	3	5
EL20	15	25	12	31	15	18	9	7	25	24	26	22	12	14	22	19	7	23	7	24	20	15	19	11	31	15	18	23
EL40	25	42	22	48	27	34	15	13	40	40	31	37	22	27	41	35	12	40	12	43	38	27	32	21	37	25	33	41
EL60	35	60	31	65	38	50	20	19	55	55	37	52	31	40	60	50	17	57	18	62	56	39	45	31	43	34	48	59
EL80	45	78	40	81	50	66	25	25	69	71	42	66	41	53	79	66	22	73	24	80	74	51	58	41	48	43	63	77
EL100	56	95	49	98	61	81	31	31	84	87	48	81	50	66	99	81	27	90	29	99	92	63	71	51	54	52	78	96
EL100BIO	74	99	75	99	79	90	47	58	98	100	61	94	92	89	100	96	54	92	60	100	96	73	99	83	61	84	79	99
EL100ALL	100	100	98	99	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	96	100	100

Fig. 12. Heat-pump share of the thermal energy provided to the built environment according to each scenario.

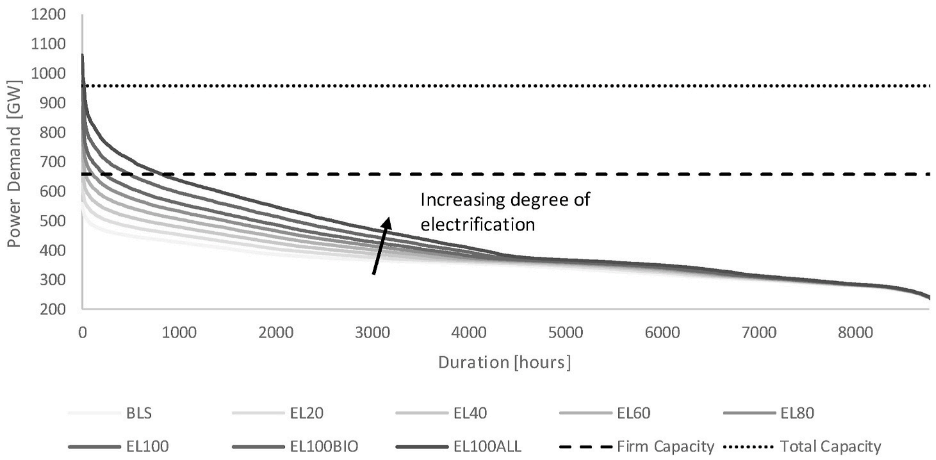


Fig. 13. Load duration curve for the different scenarios.

Comparing the LDCs with the firm capacity (no RES assumption), the EL60 scenario seems to be the most ambitious electrification scenario that can be secured by today's capacities.

At country level, the picture is much more diverse. Fig. 14 displays the number of hours during which the demand for electricity cannot be satisfied by firm capacities while Fig. 15 shows the corresponding share of annual demand exceeding the firm capacities both on a MS level. It is observed that even in the BLS scenario, some countries — Austria, Finland and Latvia— cannot meet the national demand with firm capacity exclusively. In these cases, demand is balanced by other flexibility options such as available renewable capacity or, ultimately, importing energy from neighbouring countries. This might indicate that these countries have a positive import balance today. As they already rely on their neighbours for supply, they might risk the system's stability if the stock of their, or their neighbours', heating appliances is further electrified without increasing the capacity of the power system.

It catches the eye that a group of 11 MSs appear to be very well prepared for a high degree of electrification. In the EL100 scenario, these countries have no, or no substantial, demand that exceeds the firm capacity level. In ten of these, the demand does not exceed the firm capacity for any single hour, while in the Czech Republic, this number is still in the single digits.

Striking is the regional composition of this ready-to-electrify group: It would seem only logical that countries with a warmer climate could cope better with far-reaching electrification. While this assumption holds for countries such as Spain, Greece, Portugal, Romania, Italy and Bulgaria, others — mainly Northern European countries — handle heat electrification just as well, despite their much colder climate. The low impact that electrification has on Sweden, Denmark, Estonia, Lithuania and the Czech Republic is because their heating system already consists of a large share of low-carbon heating technologies (compare Fig. 3). Lastly, Ireland has such a high firm-capacity level that they can handle electrification well. We can therefore summarize the three factors, which have been identified as beneficial for a high degree of electrification: A mild climate, a large share of low-carbon heat, and, unsurprisingly, a high level of installed firm capacity.

On the other hand, electrification takes a much larger toll on the system for some MSs leading to uncovered demand shares of between 2.8 and 7.8% observed over a cumulated timespan between two and four months, the major part of the heating season. These countries should carefully monitor the progress of electrification and react to anticipated demand growth at early stages investing in new capacities and, thus, avoiding threats of a shortfall.

Another group of countries, consisting mainly of eastern European countries, deals fairly well with the electrification of their fossil-heating stock. As soon as biomass boilers are substituted, however, uncovered demand surges. For these countries, the rise of biomass prices due to higher demands from other sectors could pose a risk to their power systems (see section 3).

Countries in the first group can even afford a full electrification of the heat supply for their building stocks. Small capacity additions would be necessary in some cases, when approaching a complete electrification, which would most likely not be achieved within the near future. Countries in the second or third group should focus on replacing only fossil-fuelled boilers. For these groups, a complete electrification would put an extreme burden on their power systems. Only if heat demand is reduced or additional power-generation capacities are installed, further electrification could be targeted.

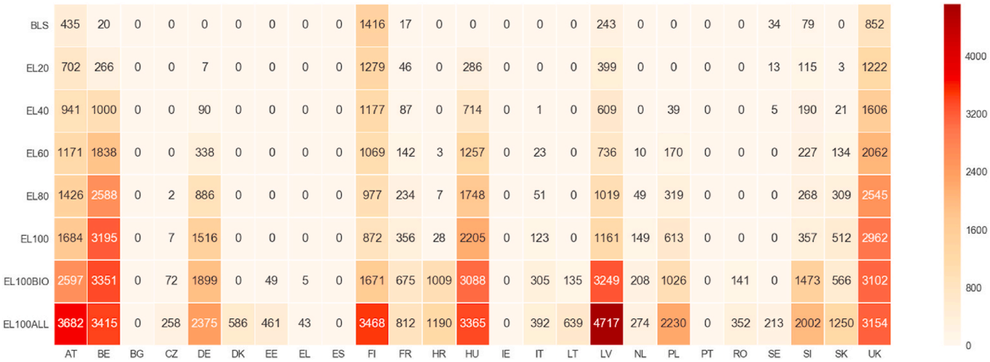
In the future, the threat of a capacity shortage could even increase. Fig. 16 shows the amount of energy, which is not covered by the firm capacities, based on the capacities from the POTEnCIA central scenario (JRC, 2019a). The calculation was performed on a country basis and was then aggregated to the EU27+UK level. Until 2030, the aggregate remains fairly constant, between 1.5 and 3%. In the longer run, however, it rises up to 9%, due to the decommissioning of firm capacities as part of the power-system transformation towards its decarbonisation. This indicates that, along its transformation, the likelihood of shortfalls increases, as the firm capacity level could shrink notably due a stronger reliance on variable renewable generation after 2030.

4.1.1. The effect of demand-response on reliability

Demand shifting has a further stabilizing effect on the system's reliability. Demand curves that can respond to price signals are usually flatter and consequently less stressful to the power system. In order to conceptualize the effects of a flexible demand we assume a simple method. We shift a predefined amount of monthly peak demand to off-peak hours. Fig. 17 shows the effect of shifting a predefined set of hours to the peak reduction.

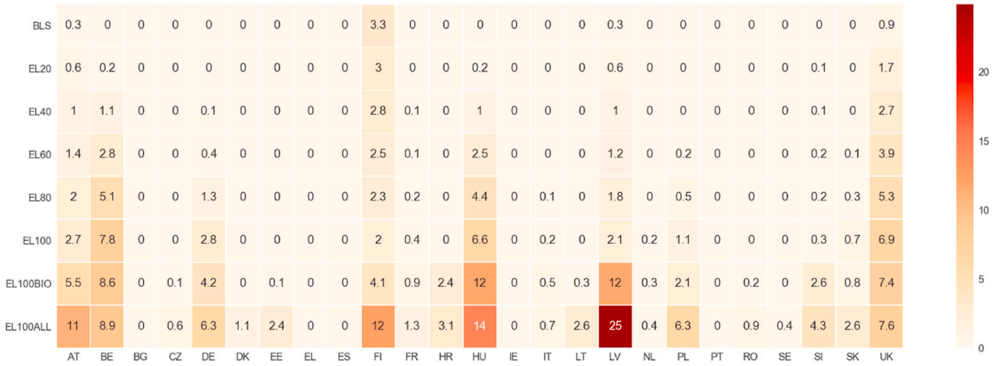
For the rest of the analysis, we select a value of 6% as the share of the monthly peak hours shifted to off-peak hours. This value is a trade-off between keeping the amount small but realistic and significantly lowering the peak. The storage capacity required under this assumption is roughly 3.2 TWh in the EL100ALL. We assume that all storage needs can be satisfied by using the thermal inertia of the building stock, which would amount to a storage capacity of 2.88 TWh.

According to (Kensby et al., 2015), 0.1 kWh/m^2 can be stored in buildings while keeping temperature deviations under 0.5 °C. Based on this, the storage capacity is estimated using the floor area calculated in (JRC, 2018). The approach seems appropriate for several reasons: Firstly, most countries will not reach a state as described in this scenario in the near future (compare Table 1), as it describes a rather extreme cases of heat pump deployment. Secondly, the building stock would change substantially until such a point was reached. Thirdly, we only present a rather rough estimate to describe the flexible integration of heat pumps. More detailed assessments are necessary to depict the thermal storage capacity of the building stock more accurately, yet it goes beyond the scope of this paper. Lastly, this storage potential could be further increased, if we assume that deviations larger than 0.5 °C



	AT	BE	BG	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LV	NL	PL	PT	RO	SE	SI	SK	UK
BLS	435	20	0	0	0	0	0	0	0	1416	17	0	0	0	0	0	243	0	0	0	0	34	79	0	852
EL20	702	266	0	0	7	0	0	0	0	1279	46	0	286	0	0	0	399	0	0	0	0	13	115	3	1222
EL40	941	1000	0	0	90	0	0	0	0	1177	87	0	714	0	1	0	609	0	39	0	0	5	190	21	1606
EL60	1171	1838	0	0	338	0	0	0	0	1069	142	3	1257	0	23	0	736	10	170	0	0	0	227	134	2062
EL80	1426	2588	0	2	886	0	0	0	0	977	234	7	1748	0	51	0	1019	49	319	0	0	0	268	309	2545
EL100	1684	3195	0	7	1516	0	0	0	0	872	356	28	2205	0	123	0	1161	149	613	0	0	0	357	512	2962
EL100BIO	2597	3351	0	72	1899	0	49	5	0	1671	675	1009	3088	0	305	135	3249	208	1026	0	141	0	1473	566	3102
EL100ALL	3682	3415	0	258	2375	586	461	43	0	3468	812	1190	3365	0	392	639	4717	274	2230	0	352	213	2002	1250	3154

Fig. 14. Number of hours during which the demand for electricity exceeds the firm capacity level, per MS and scenario. Luxembourg excluded due to its strong import dependency, which results in load always exceeding the firm capacities.



	AT	BE	BG	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LV	NL	PL	PT	RO	SE	SI	SK	UK
BLS	0.3	0	0	0	0	0	0	0	0	3.3	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0.9
EL20	0.6	0.2	0	0	0	0	0	0	0	3	0	0	0.2	0	0	0	0.6	0	0	0	0	0	0.1	0	1.7
EL40	1	1.1	0	0	0.1	0	0	0	0	2.8	0.1	0	1	0	0	0	1	0	0	0	0	0	0.1	0	2.7
EL60	1.4	2.8	0	0	0.4	0	0	0	0	2.5	0.1	0	2.5	0	0	0	1.2	0	0.2	0	0	0	0.2	0.1	3.9
EL80	2	5.1	0	0	1.3	0	0	0	0	2.3	0.2	0	4.4	0	0.1	0	1.8	0	0.5	0	0	0	0.2	0.3	5.3
EL100	2.7	7.8	0	0	2.8	0	0	0	0	2	0.4	0	6.6	0	0.2	0	2.1	0.2	1.1	0	0	0	0.3	0.7	6.9
EL100BIO	5.5	8.6	0	0.1	4.2	0	0.1	0	0	4.1	0.9	2.4	12	0	0.5	0.3	12	0.3	2.1	0	0.2	0	2.6	0.8	7.4
EL100ALL	11	8.9	0	0.6	6.3	1.1	2.4	0	0	12	1.3	3.1	14	0	0.7	2.6	25	0.4	6.3	0	0.9	0.4	4.3	2.6	7.6

Fig. 15. Percentage of annual demand exceeding the firm capacities, per MS and scenario. Luxembourg excluded due to its strong import dependency.

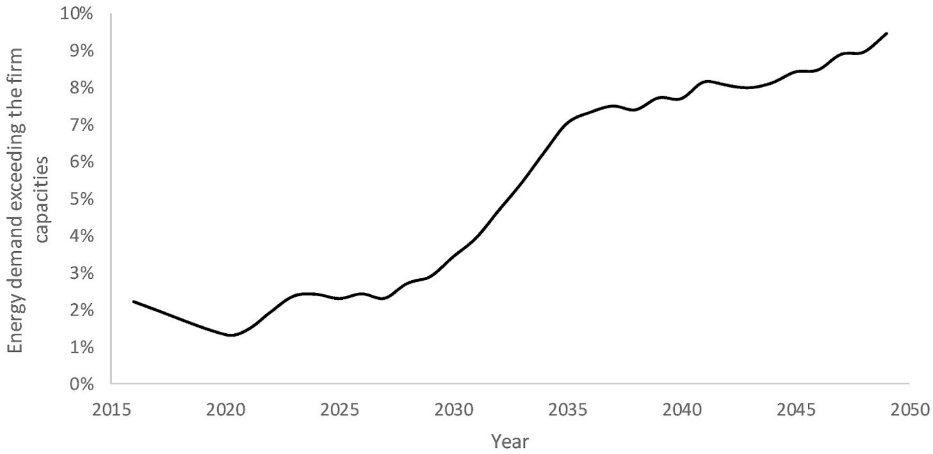


Fig. 16. Development of the energy above the firm capacities for the EL100 scenario for the EU27+UK. Future capacities (2020–2050) based on the POTEnCIA central scenario.

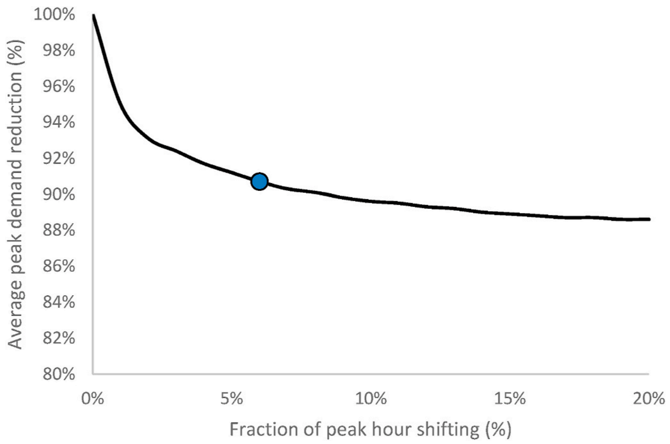


Fig. 17. Effectiveness of peak load shifting in reducing peak demand.

would be acceptable to the inhabitants.

Applying this, the amount of energy that cannot be served by firm capacity is reduced in almost all scenarios for all countries (Fig. 18 and Fig. 19). The number of countries with no significant uncovered demand increases to 12 in the E100_DR[1] scenario. In the presence of large amounts above the firm capacities, the uncovered demand decreases, but not the hours above the firm capacities. This suggests that demand exceeds the firm capacity not only at peak but also during off-peak hours.

4.2. Implications on carbon emissions

The calculation of the total emissions is based on emissions data from the IDEES database and the power sector efficiencies for each country (EUROSTAT, 2018).

In Fig. 20, we show the effects of heat-pump deployment on CO_2 emissions as the reduction of total energy-related emissions. The emissions for each scenario were calculated based on all emissions in the power sector, the decentralized heat sector, as well as in district heating. Emissions from CHP were attributed according to the shares of electricity/heat of the combined total production. As additional demand affects the electricity mix, we compare two different cases:

First, we assume that demand exceeding the BLS in each hour has to be satisfied with gas-fired power plants. Then we will investigate the effect if, additionally, low-carbon energy is made available to satisfy a share of the additional demand.

Gas plants usually have higher short-run marginal costs than other dispatchable generators, and would therefore likely be dispatched to accommodate additional demand, wherever there is still some avaiable capacity. Furthermore, as the lowest emitting fossil-fuelled generation technology, new investments in firm capacity would likely occur in gas-fired power plants. Since additional demand would likely be satisfied by a mix of combined-cycle and open-cycle gas turbines, we used the average CO_2 intensity of electricity from gas-fired units in the EU as a proxy (JRC, 2018). Despite its limitations, this approach is still valid to give an indication prior to a more detailed modelling – preferably using

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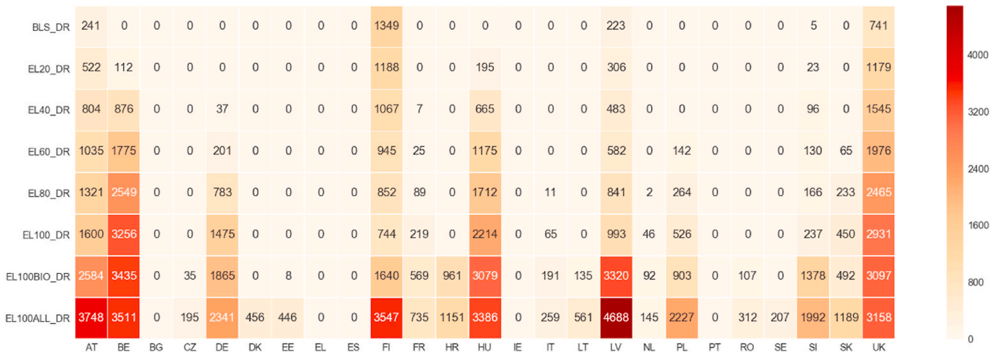
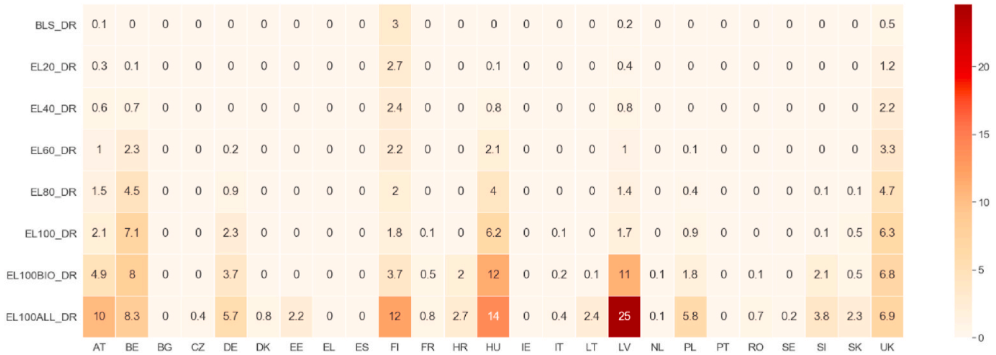
[1] Full electrification and demand response scenario.



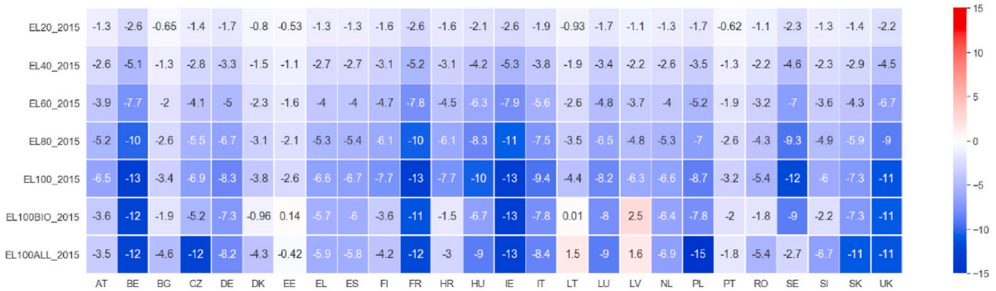
	AT	BE	BG	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LV	NL	PL	PT	RO	SE	SI	SK	UK
BLS_DR	241	0	0	0	0	0	0	0	0	1349	0	0	0	0	0	0	223	0	0	0	0	0	5	0	741
EL20_DR	522	112	0	0	0	0	0	0	0	1188	0	0	195	0	0	0	306	0	0	0	0	0	23	0	1179
EL40_DR	804	876	0	0	37	0	0	0	0	1067	7	0	665	0	0	0	483	0	0	0	0	0	96	0	1545
EL60_DR	1035	1775	0	0	201	0	0	0	0	945	25	0	1175	0	0	0	582	0	142	0	0	0	130	65	1976
EL80_DR	1321	2549	0	0	783	0	0	0	0	852	89	0	1712	0	11	0	841	2	264	0	0	0	166	233	2465
EL100_DR	1600	3256	0	0	1475	0	0	0	0	744	219	0	2214	0	65	0	993	46	526	0	0	0	237	450	2931
EL100BIO_DR	2584	3435	0	35	1865	0	8	0	0	1640	569	961	3079	0	191	135	3320	92	903	0	107	0	1378	492	3097
EL100ALL_DR	3748	3511	0	195	2341	456	446	0	0	3547	735	1151	3386	0	259	561	4688	145	2227	0	312	207	1992	1189	3158

Fig. 18. Number of hours during which the demand for electricity exceeds the firm capacity level with demand shifting taking place, per MS and scenario. Luxembourg excluded due to its strong import dependency, which results in load always exceeding the firm capacities.



	AT	BE	BG	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LV	NL	PL	PT	RO	SE	SI	SK	UK
BLS_DR	0.1	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0.5
EL20_DR	0.3	0.1	0	0	0	0	0	0	0	2.7	0	0	0.1	0	0	0	0.4	0	0	0	0	0	0	0	1.2
EL40_DR	0.6	0.7	0	0	0	0	0	0	0	2.4	0	0	0.8	0	0	0	0.8	0	0	0	0	0	0	0	2.2
EL60_DR	1	2.3	0	0	0.2	0	0	0	0	2.2	0	0	2.1	0	0	0	1	0	0.1	0	0	0	0	0	3.3
EL80_DR	1.5	4.5	0	0	0.9	0	0	0	0	2	0	0	4	0	0	0	1.4	0	0.4	0	0	0	0.1	0.1	4.7
EL100_DR	2.1	7.1	0	0	2.3	0	0	0	0	1.8	0.1	0	6.2	0	0.1	0	1.7	0	0.9	0	0	0	0.1	0.5	6.3
EL100BIO_DR	4.9	8	0	0	3.7	0	0	0	0	3.7	0.5	2	12	0	0.2	0.1	11	0.1	1.8	0	0.1	0	2.1	0.5	6.8
EL100ALL_DR	10	8.3	0	0.4	5.7	0.8	2.2	0	0	12	0.8	2.7	14	0	0.4	2.4	25	0.1	5.8	0	0.7	0.2	3.8	2.3	6.9

Fig. 19. Annual demand exceeding the firm capacities with demand shifting taking place, per MS and scenario. Luxembourg excluded due to its strong import dependency.



	AT	BE	BG	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	NL	PL	PT	RO	SE	SI	SK	UK
EL20_2015	-1.3	-2.6	-0.65	-1.4	-1.7	-0.8	-0.53	-1.3	-1.3	-1.6	-2.6	-1.6	-2.1	-2.6	-1.9	-0.93	-1.7	-1.1	-1.3	-1.7	-0.62	-1.1	-2.3	-1.3	-1.4	-2.2
EL40_2015	-2.6	-5.1	-1.3	-2.8	-3.3	-1.5	-1.1	-2.7	-2.7	-3.1	-5.2	-3.1	-4.2	-5.3	-3.8	-1.9	-3.4	-2.2	-2.6	-3.5	-1.3	-2.2	-4.6	-2.3	-2.9	-4.5
EL60_2015	-3.9	-7.7	-2	-4.1	-5	-2.3	-1.6	-4	-4	-4.7	-7.8	-4.5	-6.3	-7.9	-5.6	-2.6	-4.8	-3.7	-4	-5.2	-1.9	-3.2	-7	-3.6	-4.3	-6.7
EL80_2015	-5.2	-10	-2.6	-5.5	-6.7	-3.1	-2.1	-5.3	-5.4	-6.1	-10	-6.1	-8.3	-11	-7.5	-3.5	-6.5	-4.8	-5.3	-7	-2.6	-4.3	-9.3	-4.9	-5.9	-9
EL100_2015	-6.5	-13	-3.4	-6.9	-8.3	-3.8	-2.6	-6.6	-6.7	-7.7	-13	-7.7	-10	-13	-9.4	-4.4	-8.2	-6.3	-6.6	-8.7	-3.2	-5.4	-12	-6	-7.3	-11
EL100BIO_2015	-3.6	-12	-1.9	-5.2	-7.3	-0.96	0.14	-5.7	-6	-3.6	-11	-1.5	-6.7	-13	-7.8	0.01	-8	2.5	-6.4	-7.8	-2	-1.8	-9	-2.2	-7.3	-11
EL100ALL_2015	-3.5	-12	-4.6	-12	-8.2	-4.3	-0.42	-5.9	-5.8	-4.2	-12	-3	-9	-13	-8.4	1.5	-9	1.6	-6.9	-15	-1.8	-5.4	-2.7	-6.7	-11	-11

Fig. 20. Total change in energy related CO_2 emissions (%) (JRC, 2018), if additional electricity demand (compared to BLS) was satisfied by gas-fired power plants.

an hourly dispatch simulation – which is required to determine the correct marginal emission factors.

In case gas-fired power plants supply the additional demand, we see that the total energy-related emissions of all sectors are reduced by 1.5% on average for every 20% of fossil-fuelled heaters replaced in the buildings sector. The mean emissions reduction for displacing all decentralized fossil-fuelled heaters is 7.5%.

Several countries can reduce their energy related emissions by 10–15% through heat pump deployment alone. These are countries with a large share of decentralized fossil-fuelled heating. All countries see a decline in emissions up to the EL100 scenario. While a replacement of biomass does not reap any climate benefits, some eastern European countries, such as Poland and Slovakia, see a further decline in emissions when district heating is replaced by heat pumps. The situation is different in some Baltic and Scandinavian countries: In Lithuania, Latvia and Sweden, emissions reductions decline, or might even turn into a net increase when district heating is replaced. This reflects the level to which heating networks in these countries depend on fossil fuels or biomass and heat pumps.

As the EU strives for climate neutrality by 2050 (European Commission, 2019), it is likely that additional demand triggers the expansion of generation capacities with a low carbon footprint, for example, if governments decide to expand renewable auction volumes in return. For this reason, we show the reduction in emissions if the additional demand is not only satisfied by gas, but by a mix of carbon-neutral electricity and gas. Fig. 21, shows the emissions reduction for different shares of carbon neutral generation.

According to our analysis, up to 8% of the EUs emissions could additionally be reduced if heat pump demand is met by carbon-neutral electricity. This would reduce the total EU27+UK emissions by 17% in the extreme case of complete electrification, and a carbon-neutral supply of the additional demand (for example through a combination of renewables, and nuclear, biomass or hydrogen).

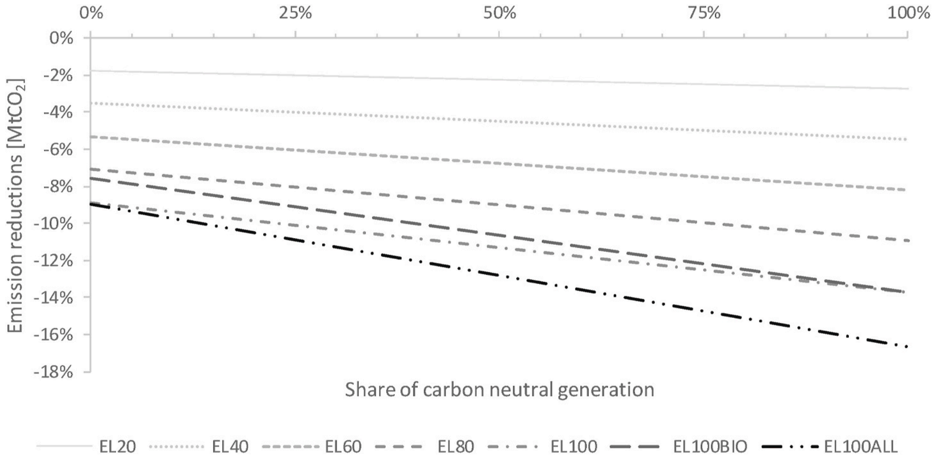


Fig. 21. Emissions reductions for each scenario in dependence of the renewable share that satisfies the additional demand. Indicated as share of total EU27+UK emissions today.

4.3. Costs and benefits of electrification

In this section, we examine to what degree each MS can electrify their heating stock, without exceeding the capacity of the existing power system. The overview can be seen in Table 2, which includes the benefits and costs, as well as the installed capacities for the currently feasible scenario. This is the most ambitious electrification scenario where peak demand is still covered by the firm capacities. The costs and emissions reductions are displayed relative to a case in which the same amount of heating systems was replaced by gas boilers.

The capacities were calculated based on the heat-pumps' country-specific capacity factors, which can be derived from the generated profiles. The heat-pump and gas-boiler cost assumptions are based on (JRC and Planenergi Fond, 2017), which gives an overview of realized costs for heat pumps in different MSs. We assumed costs of 1000 EUR/kW for small-scale heat pumps, which are deployed in single-family houses, and 800 EUR/kW for large heat pumps installed in multi-family houses and the tertiary sector. These assumptions are on the conservative end of the cost-spectrum. The split between the residential and the tertiary sector was calculated based on (JRC, 2018) for each MS, while the split between single- and multi-family house in the residential sector was taken from (Fleitler et al., 2016). Costs for temperature regulation in the demand-response scenarios have been taken from (Schäuble et al., 2020). For the gas scenarios, we assume one gas boiler for each household at a cost of 4000 EUR per boiler based on (JRC and Planenergi Fond, 2017). The number of gas boilers in the tertiary

Table 2
Electrification potential and cost under the conservative assumption that load needs to be completely covered by today's power system firm capacities.

	Inflexible demand					Demand response				
	Currently feasible scenario	Capacity [GWth]	Differential costs [bn. EUR]	Differential emissions [MtCO2]	Abatement Cost [EUR/tCO2]	Currently feasible scenario	Capacity [GWth]	Differential costs [bn. EUR]	Differential emissions [MtCO2]	Abatement Cost [EUR/tCO2]
AT	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
BE	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
BG	EL100ALL	36.0	0.0	−4.9	−10.0	EL100ALL	36.0	0.1	−4.9	11.4
CZ	EL100	53.7	1.8	−6.2	283.6	EL100BIO	70.4	1.9	−7.5	257.1
DE	EL20	121.7	3.8	−11.1	344.0	EL40	243.1	8.4	−22.2	376.5
DK	EL100BIO	20.6	0.5	−2.0	254.6	EL100BIO	20.6	0.6	−2.0	289.7
EE	EL100	4.6	0.1	−0.6	171.1	EL100BIO	9.0	0.2	−0.8	221.0
EL	EL100ALL	78.8	1.4	−5.1	281.1	EL100ALL	78.8	1.6	−5.1	314.9
ES	EL100ALL	193.5	2.1	−19.7	107.1	EL100ALL	193.5	3.3	−19.7	166.7
FI	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
FR	EL20	68.1	1.6	−10.0	164.2	EL80	272.3	7.6	−40.1	190.4
HR	EL100	14.8	0.5	−1.4	372.5	EL100	14.8	0.5	−1.4	389.1
HU	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
IE	EL100ALL	20.6	0.2	−3.5	47.4	EL100ALL	20.6	0.2	−3.5	63.5
IT	EL60	202.3	7.4	−21.1	351.4	EL80	269.7	11.0	−28.2	389.9
LT	EL100	4.7	0.1	−0.4	285.1	EL100	4.7	0.1	−0.4	312.1
LU	EL100ALL	7.4	0.2	−1.0	239.4	EL100ALL	7.4	0.3	−1.0	261.2
LV	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
NL	EL80	89.6	4.1	−9.8	420.4	EL100	111.9	5.7	−12.3	461.3
PL	EL40	66.7	1.7	−5.5	300.4	EL40	66.7	1.8	−5.5	326.7
PT	EL100ALL	30.7	−0.3	−3.0	−99.9	EL100ALL	30.7	0.0	−3.0	−3.5
RO	EL100	47.5	2.0	−4.1	481.3	EL100	47.5	2.0	−4.1	498.7
SE	EL100BIO	42.8	0.3	−5.4	53.7	EL100BIO	42.8	0.4	−5.4	78.6
SI	None	0.0	0.0	0.0	–	EL60	4.2	0.1	−0.5	181.1
SK	EL40	9.3	0.4	−1.0	362.4	EL60	14.0	0.6	−1.5	397.2
UK	None	0.0	0.0	0.0	–	None	0.0	0.0	0.0	–
EU27 + UK		1113.3	27.9	−115.9	232.1		1558.6	46.4	−169.0	259.2

sector were determined in a way that the average surface area covered by one gas boiler is the same as in the residential sector. The equipment costs are annuitized based on an interest rate of 5% and a lifetime of 20 years for both technologies. As we assume electrification within the means of today, additional demand from heat pumps is satisfied with gas-fired power plants, assuming gas costs of 20 EUR/MWh$_{th}$ for both technologies.

The results show that seven MSs (six with demand shifting) have the BLS as the currently feasible scenario. Assuming that each MS achieves the BLS as feasible scenario would lead to an installed heat pump capacity of 1.1 TW$_{th}$, and an annual emission reduction of 115 MtCO$_2$ compared to the gas scenario, at an additional cost of EUR 27.9 bn per year. Basic load shifting measures, employing the thermal inertia of the buildings, could increase installable capacity to 1.6 TW$_{th}$ and reduce carbon emissions by 169 MtCO$_2$ at additional cost of EUR 40 bn per year.

It can be observed that abatement costs are high in several countries. This happens as the additional electricity fed to the heat pumps is generated by the marginal units, which are assumed to be gas-fired, revealing the caveat of such policy: Heat electrification has to be accompanied by simultaneous power sector decarbonisation. Otherwise the abatement will be very expensive in the short term. In the long term, however, these technologies do not lock in a specific carbon-intensive primary fuel, so they will lead to benefits even if the decarbonisation of the power sector will come at a later stage.

Additional low-carbon electricity would lower the abatement costs rapidly for two reasons: since more electricity going to heat pumps will be generated by clean sources, it will result in a higher emissions benefit. The second reason is that the levelized cost of electricity (LCOE) for wind, which according to (IRENA, 2020) will be roughly 50 EUR/MWh, is comparable to the marginal production cost of combined-cycle gas-fired power plants (not even considering the costs for EU Emission Trading System certificates). Therefore, additional wind generation would not increase the total cost, as the cost of producing the electricity from gas is as expensive as building and operating specifically designated wind turbines. This, of course, assumes that the energy of these wind turbines is not curtailed when the heat demand is low, which would increase the LCOE.

Finally we see negative abatement cost, which are typical for energy efficiency measures (IEA, 2011), where we get a simultaneous cost and energy benefit. This occurs in countries with a large share of direct-electric heating. As a result, the electricity demand declines in the currently feasible scenario, resulting in a reduction of operating costs as well as a reduction in emissions.

5. Conclusion and policy implications

In this paper, we have created scenarios for the European heat sector, supplying the built environment, based on different degrees of electrification. For each MS, heating and cooling profiles were isolated by decomposing the electricity demand based on its temperature dependency using heating and cooling degree hours. These profiles, which comply with official statistics, were used to produce electricity demand curves for the different scenarios proposed. Based on these demand curves, the impact of heat pump deployment on generation adequacy and associated CO$_2$-emissions was assessed and put into context.

Our analysis shows that an additional heat pump capacity of 1.1 TW$_{th}$ can be installed in the EU27+UK with the current capacity of the power system. This would cover 32% of space-heating demand in buildings. The conditions for the heat-pump uptake are, however, quite diverse. Today's firm capacities, and up to 2030, appear sufficient for large heat pump penetrations in several MSs. Their resilience can be explained by two factors: warm climates — leading to low heating demands — and an already-clean heat sector.

Some countries show too-low levels of firm capacity already today for relying on heat pumps for large-scale climate mitigation. This could even become an EU-wide trend after 2030, as firm capacities could exit the market due to a stronger reliance on variable renewables. MSs should ensure the security of supply, possibly by implementing additional capacity reliability mechanisms, if not already in place. Countries relying on capacity auctions should monitor the state of heat-pump deployment closely, and proactively increase the tendered amount of capacity according to the expected additional heat-pump demand. Countries relying on a strategic reserve should ensure that this "safety net" is adequately dimensioned. Furthermore, they should have monitoring processes in place to assess whether the investments in generation capacity materialize as soon as a capacity shortage threatens.

Basic demand shifting measures, such as those relying on the thermal inertia of the building stock, drastically increase the heat-pump capacity that can be installed — from 1.1 to 1.6 TW$_{th}$. This increase, which would allow heat pumps to cover 45% of the space heating demand, highlights the importance of incentivizing a flexible dispatch. Regulators should ensure that this flexibility is available to the market. To do so, one option is for transmission-system operators to contract heat pump capacity, acquiring a large portfolio of interruptible loads available when the system runs tight. Another option is to enable smaller consumers to react to price signals from the wholesale market. This would require the rollout of smart-meters and the implementation of real-time metered electricity tariffs for households and other small consumers.

Regarding carbon emissions, our results highlight that the deployment of heat pumps and renewables should go hand in hand to maximise its contribution to climate-change mitigation. Large emissions savings, in the order of 2–14% of the total energy-related emissions of each MS, can already be achieved when gas-fired power plants satisfy the additional electricity demand. Heat-pump deployment is therefore already an effective mitigation measure in itself, which reduces the emissions compared to a stronger reliance on gas in buildings. This form of abatement is, however, costly in many MSs, mostly in the range of between 200 and 300 EUR/tCO$_2$.

As long as renewable electricity capacity keeps getting deployed, these costs will decrease, as the emissions reduction increases while costs remain at a similar level. Heat pump deployment today enables further abatement in the future, as the decarbonisation of the power system continues. If additional carbon-neutral electricity satisfies the heat-pump demand, total emissions reductions in the magnitude of up to 16% of the total EU emissions (compared to today) can be achieved. Thus, we recommend that countries monitor the additional demand from new electrical consumers, such as heat pumps, and increase the tendered volumes at renewable auctions accordingly.

The rate at which heat pumps are currently deployed among the EU MSs appears insufficient in most cases to reap large emission reductions. Most MSs would not even reach a 20% penetration level in their building-heat sector by 2030 if this rate remained constant. We have noted that the two MSs with the highest carbon tax see the highest penetration rates of heat pumps today, being on track for further large emission-savings by 2030. While there are several other factors, which influence the market share of heat pumps, the data indicates that end-consumer costs for heat are a strong influence on heat-pump deployment. Countries with a low uptake might therefore consider implementing a carbon tax, as it increases the heat costs from fossil-fuelled competitors, as well as decreasing electricity related levies and taxes. This can be done simultaneously, as implemented in Germany where the revenue generated through a carbon trading system will be used to reduce the electricity price (Government of Germany, 2019). Connecting reduced grid charges with the participation in demand-side management programs could be a way to incentivize heat-pump deployment and their flexible integration at the same time.

Further work will focus on the power system. In this work, to assess the impact of heat electrification, we assumed that gas-fired power plants, or a combination of gas with renewables, satisfy additional electricity demand. The next step is to consider the feedback with the power system, to get a more detailed picture of the emissions that additional heat pump demand causes, including also extreme weather events. This includes the impact of the power system’s ongoing decarbonisation on carbon emissions, which will likely further increase the climate benefit from electrification.

CRediT authorship contribution statement

Georg Thomaßen: Data curation, Methodology, Visualization, Writing - original draft. **Konstantinos Kavvadias:** Conceptualization, Methodology, Software, Supervision, Writing - review & editing. **Juan Pablo Jiménez Navarro:** Writing - review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Gas demand

Table 3
Additional gas demand in the gas scenarios compared to the electrification scenarios in TWh. XX standing for the respective gas scenario or electrification scenario (EL)

	XX20	XX40	XX60	XX80	XX100	XX100BIO	XX100ALL
AT	−1.5	−0.5	0.5	1.3	2.3	6.2	9.9
BE	−2.9	0.4	3.8	7.1	10.5	12.0	11.3
BG	−0.8	−1.1	−1.2	−1.5	−1.6	3.6	7.1
CZ	−0.7	1.3	3.5	5.7	7.9	17.8	26.5
DE	14.7	40.9	66.9	92.9	118.9	138.9	157.2
DK	−1.2	−0.8	−0.3	0.0	0.4	4.0	19.1
EE	0.0	0.0	0.1	0.2	0.3	1.6	2.9
EL	−4.3	−4.8	−5.3	−5.8	−6.3	−4.1	−6.0
ES	−5.9	−0.7	4.3	9.4	14.4	24.2	22.0
FI	−12.6	−12.5	−12.4	−12.5	−12.3	−9.9	−1.4
FR	−16.6	−9.0	−1.5	6.0	13.5	47.7	56.4
HR	−0.1	0.2	0.5	0.8	1.2	4.8	5.9
HU	2.1	4.4	6.8	9.1	11.4	17.8	21.4
IE	1.8	4.3	6.6	9.1	11.5	11.8	11.1
IT	9.0	29.1	49.3	69.4	89.4	110.5	114.1
LT	0.0	0.1	0.1	0.3	0.4	1.8	5.4
LU	0.0	0.4	0.6	0.9	1.3	1.3	1.9
LV	0.1	0.2	0.5	0.7	1.0	3.2	6.5
NL	3.2	8.7	14.2	19.5	24.9	27.1	29.2
PL	2.0	8.9	15.7	22.7	29.6	38.2	62.1
PT	−1.9	−2.6	−3.4	−4.0	−4.9	−3.4	−4.7
RO	1.7	3.9	6.0	8.0	10.2	17.2	22.0
SE	−22.0	−23.1	−24.0	−25.1	−26.1	−24.0	−7.3
SI	−0.2	0.0	0.3	0.6	0.7	2.7	3.3
SK	0.4	1.4	2.4	3.5	4.5	4.7	8.5
UK	8.2	30.5	52.9	75.2	97.5	104.6	106.8
EU	−27.7	79.7	186.8	293.6	400.6	560.3	690.9

Appendix B. Descriptive load statistics

Table 4
Peak load demand for each scenario and MS in MW

	BLS	EL20	EL40	EL60	EL80	EL100	EL100BIO	EL100ALL
AT	12,866	13,704	14,498	15,292	16,130	16,924	19,702	24,068
BE	14,478	17,031	19,598	22,165	24,732	27,299	28,061	28,382
BG	9012	8790	8568	8291	8069	7791	9123	10,239
CZ	13,060	13,868	14,723	15,530	16,338	17,145	20,137	23,890
DE	85,299	101,539	117,740	133,981	150,221	166,462	178,401	193,878
DK	6331	6497	6712	6961	7244	7528	8912	13,737
EE	1920	1920	1920	1920	1920	1920	2764	4322
EL	11,082	11,213	11,377	11,541	11,705	11,869	12,787	13,344
ES	40,897	42,583	44,228	45,914	47,559	49,314	53,084	53,769
FI	21,710	21,264	20,819	20,373	19,991	19,545	22,728	32,150
FR	94,583	97,335	100,165	103,370	106,575	109,779	117,426	121,108
HR	3381	3522	3663	3852	3993	4135	6020	6303
HU	7027	8223	9391	10,577	11,882	13,139	16,040	17,442
IE	4849	5143	5433	5743	6058	6392	6429	6522
IT	56,103	61,965	69,064	76,164	83,263	90,450	100,121	103,401
LT	2291	2347	2402	2514	2569	2625	3642	5218
LU	1118	1269	1441	1656	1828	2000	2043	2043
LV	1543	1672	1801	1865	1994	2059	3348	4960
NL	19,284	21,973	24,658	27,342	30,063	32,747	33,535	34,609

(*continued on next page*)

Table 4 (*continued*)

	BLS	EL20	EL40	EL60	EL80	EL100	EL100BIO	EL100ALL
PL	26,196	29,449	33,280	37,163	40,994	44,825	49,872	63,569
PT	8166	8149	8115	8098	8065	8048	8699	9078
RO	9101	10,291	11,481	12,671	13,918	15,108	20,360	23,241
SE	35,672	34,512	33,351	32,140	30,980	29,819	31,535	41,475
SI	2538	2585	2679	2727	2774	2868	3672	4050
SK	5048	5525	6003	6481	6910	7388	7483	8773
UK	71,567	75,341	79,115	82,987	87,888	92,821	94,262	94,803

Table 5
Ratio between peak load and minimum load for each scenario

	BLS	EL20	EL40	EL60	EL80	EL100	EL100BIO	EL100ALL
AT	2.78	2.93	3.07	3.22	3.38	3.52	4.03	4.83
BE	2.29	2.57	2.93	3.28	3.64	3.98	4.08	4.13
BG	3.34	3.27	3.20	3.11	3.04	2.95	3.38	3.73
CZ	2.96	3.09	3.23	3.41	3.58	3.75	4.37	5.14
DE	2.43	2.81	3.21	3.60	4.01	4.44	4.75	5.16
DK	2.88	2.92	2.99	3.07	3.16	3.28	3.85	5.78
EE	4.01	4.01	4.01	4.01	4.01	4.01	5.60	8.72
EL	3.17	3.18	3.20	3.21	3.23	3.24	3.45	3.58
ES	2.18	2.20	2.24	2.30	2.37	2.43	2.59	2.62
FI	4.00	3.93	3.86	3.79	3.72	3.65	4.17	5.60
FR	3.16	3.22	3.28	3.36	3.44	3.53	3.72	3.83
HR	2.87	2.95	3.04	3.15	3.23	3.31	4.64	4.85
HU	2.24	2.62	2.99	3.36	3.78	4.18	5.10	5.54
IE	2.73	2.80	2.87	2.97	3.12	3.27	3.28	3.33
IT	2.90	3.01	3.33	3.64	3.95	4.29	4.75	4.91
LT	2.82	2.88	2.95	3.07	3.13	3.20	4.41	6.32
LU	2.86	3.22	3.62	4.11	4.52	4.93	5.03	5.03
LV	3.47	3.74	4.00	4.14	4.40	4.53	7.17	10.62
NL	2.11	2.36	2.61	2.89	3.16	3.43	3.51	3.62
PL	2.53	2.79	3.10	3.40	3.68	3.96	4.36	5.49
PT	2.38	2.39	2.40	2.40	2.41	2.42	2.41	2.48
RO	2.41	2.70	2.99	3.28	3.58	3.85	5.08	5.72
SE	4.16	4.04	3.93	3.80	3.69	3.56	3.74	4.73
SI	2.69	2.71	2.77	2.80	2.82	2.91	3.68	4.05
SK	2.21	2.40	2.61	2.81	3.00	3.20	3.24	3.79
UK	3.20	3.35	3.49	3.64	3.83	4.02	4.07	4.09

Appendix C. Firm capacity technologies considerations

Table 6
Considerations on firm capacities

Technology	Firm capacity	Considerations
Renewables (wind, solar)	N	
Wind	N	Wind risks the heat supply in years when wind lulls and cold weather coincide (Huneke et al., 2017.
Solar	N	Solar cannot contribute to satisfy the yearly heating peak demand in Europe, which occurs in December or January after 16.00
Run-of-river plants	N	Even though more stable than the production from wind and solar, they are still subject to seasonal variations.
Thermal plants	Y	
Hydro dams	Y	We assume, as a simplification, that storage operators anticipate the yearly peak demand, as it is the time period with the highest prices, and adjust their schedules accordingly.
Pumped-storage	Y	See Hydro dams.
Extraction-condensing CHP	Y	Included at full capacity.
Backpressure CHP	N	Operation follows a heat load.

Disclaimer

The views expressed in this paper are purely those of the writers and may not under any circumstances be regarded as stating an official position of the European Commission.

References

Azevedo, J.A., Chapman, L., Muller, C.L., 2015. Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK. Meteorol. Appl. 22, 789–796. https://doi.org/10.1002/met.1525.

Baeten, B., Rogiers, F., Helsen, L., 2017. Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response. Appl. Energy 195, 184–195. https://doi.org/10.1016/j.apenergy.2017.03.055.

Barnes, J., Bhagavathy, S.M., 2020. The economics of heat pumps and the (un)intended consequences of government policy. Energy Pol. 138, 111198. https://doi.org/10.1016/j.enpol.2019.111198.

Bloess, A., Schill, W.P., Zerrahn, A., 2018. Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl. Energy 212, 1611–1626. https://doi.org/10.1016/j.apenergy.2017.12.073.

Böttger, D., Götz, M., Theofilidi, M., Bruckner, T., 2015. Control power provision with power-to-heat plants in systems with high shares of renewable energy sources - an illustrative analysis for Germany based on the use of electric boilers in district heating grids. Energy 82, 157–167. https://doi.org/10.1016/j.energy.2015.01.022.

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M., 2018. Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system. Energy 160, 720–739. https://doi.org/10.1016/J.ENERGY.2018.06.222.

Bruckner, T., Kondziella, H., 2019. Die nächste Stufe der Energiewende. WISO-Diskurs.

Bründlinger, T., König, J.E., Frank, O., Gründig, D., 2018. Integrierte Energiewende.

Chaudry, M., Abeysekera, M., Hosseini, S.H.R., Jenkins, N., Wu, J., 2015. Uncertainties in decarbonising heat in the UK. Energy Pol. 87, 623–640. https://doi.org/10.1016/j.enpol.2015.07.019.

Commission Expert Group, 2017. Towards a Sustainable and Integrated Europe - Report of the Commission Expert Group on Electricity Interconnection Targets.

Connolly, D., 2017. Heat Roadmap Europe: quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy 139, 580–593. https://doi.org/10.1016/j.energy.2017.07.037.

de Boer-Meulman, P., van der Burgt, J.J.A., Hafkamp, P.J.M., Hunik, R., Kokmeijer, E., Kolokathis, C., Nieuwenhout, F., Özdemir, Ö., Ross, R., Schoots, K., Sikkema, F.D., 2010. Effect of scenarios and alternatives for electric vehicles and heat pump implementation on grid reliability , sustainability and socio-economy. Management 94.

De Felice, M., Kavvadias, K., 2019. ERA-NUTS: time-series based on C3S ERA5 for European regions (Version 1980-2018) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.2650191.

De Felice, M., Busch, S., Kanellopoulos, K., Kavvadias, K., Hidalgo Gonzalez, I., 2020. Power System Flexibility in a Variable Climate. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18183-5. https://doi.org/10.2760/75312.

Ecke, J., Klein, S., Werner Klein, S., Steinert, T., 2017. Klimaschutz durch Sektorenkopplung : Optionen, Szenarien. Kosten 49, 0–56.

EPRI, 2018. U.S. National Electrification Assessment.

European Commission, 2019. The European green deal. Commun. from Comm. to Eur. Parliam. Eur. Counc. Counc. Eur. Econ. Soc. Comm. Comm. Reg. 53, 1689–1699. https://doi.org/10.1017/CBO9781107415324.004.

European Commission, 2016. An EU Strategy on Heating and Cooling. COM(2016) 51 final. Brussels.

European Environment Agency, 2013. EU Bioenergy Potential from a Resource-Efficiency Perspective.

EUROSTAT, 2018. ETA-timeseries 1990-2016 [WWW Document]. URL. https://ec.europa.eu/eurostat/documents/38154/4956088/ETA_time_series-1990-2016.xlsx/d2cb41a2-2158-4410-8dd9-6a86aca77e5d.

Felten, B., Raasch, J., Weber, C., 2018. Photovoltaics and heat pumps - limitations of local pricing mechanisms. Energy Econ. 71, 383–402. https://doi.org/10.1016/j.eneco.2017.12.032.

Felten, B., Weber, C., 2018. The value(s) of flexible heat pumps – assessment of technical and economic conditions. Appl. Energy 228, 1292–1319. https://doi.org/10.1016/j.apenergy.2018.06.031.

Filippidou, F., Jimenez Navarro, J., 2019. Achieving the cost-effective energy transformation of Europe's buildings. https://doi.org/10.2760/278207.

Fleitler, T., Steinbach, J., Ragwith, M., et al., 2016. Mapping and analyses for the current and future (2020 - 2030) heating/cooling fuel development (fossil/renewables). Work Packag 1.

Government of Germany, 2019. Eckpunkte für das Klimaschutzprogramm 2030 1–23.

Government Offices of Sweden, 2020. Sweden's carbon tax [WWW Document]. URL. https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/ (accessed 4.26.20).

Hannon, M.J., 2015. Raising the temperature of the UK heat pump market: learning lessons from Finland. Energy Pol. 85, 369–375. https://doi.org/10.1016/j.enpol.2015.06.016.

Hedegaard, K., Mathiesen, B.V., Lund, H., Heiselberg, P., 2012. Wind power integration using individual heat pumps - analysis of different heat storage options. Energy 47, 284–293. https://doi.org/10.1016/j.energy.2012.09.030.

Hedegaard, R.E., Pedersen, T.H., Petersen, S., 2017. Multi-market demand response using economic model predictive control of space heating in residential buildings. Energy Build. 150, 253–261. https://doi.org/10.1016/j.enbuild.2017.05.059.

Heinen, S., Turner, W., Cradden, L., McDermott, F., O'Malley, M., 2017. Electrification of residential space heating considering coincidental weather events and building thermal inertia: a system-wide planning analysis. Energy 127, 136–154. https://doi.org/10.1016/j.energy.2017.03.102.

Huneke, F, Perez Linkenheil, C, Niggemeier, M., 2017. Kalte Dunkelflaute - Robustheit des Stromsystems bei Extremwetter. Greenpeace Energy eG.

IEA, 2011. Summing up the Parts: Combining Policy Instruments for Least-Cost Climate Mitigation Strategies.

IRENA, 2020. Renewable Power Generation Costs in 2019.

IWES/IBP, F., 2017. Heat Transition 2030. Agora Energiewende.

JRC, 2019a. The POTEnCIA. Central scenario. An EU energy outlook to 2050, JRC science for policy report. https://doi.org/10.2760/78212.

JRC, 2019b. The operation of the European power system in 2016. https://doi.org/10.2760/434010.

JRC, 2018. JRC-IDEES - Integrated Database of the European Energy System (2000-2015).

JRC, 2015. The JRC-EU-TIMES model . Bioenergy potentials for EU and neighbouring countries. https://doi.org/10.2790/39014.

JRC, Planenergi Fond, 2017. Techno-economic projections until 2050 for smaller heating and cooling technologies in the residential and tertiary sectors in the EU External study performed by Planenergi Fond for the Joint Research Centre. https://doi.org/10.2760/110433.

Karytsas, S., 2018. An empirical analysis on awareness and intention adoption of residential ground source heat pump systems in Greece. Energy Pol. 123, 167–179. https://doi.org/10.1016/j.enpol.2018.08.001.

Kensby, J., Trüschel, A., Dalenbäck, J.O., 2015. Potential of residential buildings as thermal energy storage in district heating systems - results from a pilot test. Appl. Energy 137, 773–781. https://doi.org/10.1016/j.apenergy.2014.07.026.

Mantzos, L., Wiesenthal, T., Matei, N.A., Tchung-Ming, S., Rozsai, M., 2017. JRC-IDEES : integrated database of the European energy sector. https://doi.org/10.2760/182725.

Mellwig, P., Pehnt, M., von Oehsen, A., Blömer, S., 2018. Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung.

Oldewurtel, F., Ulbig, a., Parisio, a., Andersson, G., Morari, M., 2010. Reducing peak electricity demand in building climate control using real-time pricing and model predictive control. Decis. Control (CDC). In: 2010 49th IEEE Conf, pp. 1927–1932. https://doi.org/10.1109/CDC.2010.5717458.

Raghavan, S.V., Wei, M., Kammen, D.M., 2017. Scenarios to decarbonize residential water heating in California. Energy Pol. 109, 441–451. https://doi.org/10.1016/j.enpol.2017.07.002.

Regett, A., Baing, F., Conrad, J., Fattler, S., Kranner, C., 2018. Emission assessment of electricity: mix vs. Marginal power plant method. Int. Conf. Eur. Energy Mark. EEM 2018–June. https://doi.org/10.1109/EEM.2018.8469940.

Ruhnau, O., 2017. Modellierung von Power-to-Heat zur Bestimmung der Auswirkungen auf die Strommarktintegration fluktuierender Erneuerbarer Energien.

Sandvall, A.F., Ahlgren, E.O., Ekvall, T., 2017. Low-energy buildings heat supply–Modelling of energy systems and carbon emissions impacts. Energy Pol. 111, 371–382. https://doi.org/10.1016/j.enpol.2017.09.007.

Schaber, K., Steinke, F., Hamacher, T., 2013. Managing temporary oversupply from renewables efficiently: electricity storage versus energy sector coupling in Germany. Int. Energy Work 2013, 1–22.

Schäuble, D., Marian, A., Cremonese, L., 2020. Conditions for a cost-effective application of smart thermostat systems in residential buildings. Appl. Energy 262, 114526. https://doi.org/10.1016/j.apenergy.2020.114526.

Shao, N., You, S., Segerberg, H., Lyngby, D.K.K., 2013. Integration of 100% heat pumps and electric vehicles in the low voltage distribution network: a Danish case story. Proc. 3rd Int. Conf. Microgeneration Relat. Technol.

Vorushylo, I., Keatley, P., Nikhilkumar Shah, N., Green, R., Hewitt, N., 2018. How heat pumps and thermal energy storage can be used to manage wind power: a study of Ireland. Energy 539–549. https://doi.org/10.1016/j.energy.2018.03.001.

Watson, S.D., Lomas, K.J., Buswell, R.A., 2019. Decarbonising domestic heating_ what is the peak GB demand?.pdf. Energy Pol. 126, 533–544. https://doi.org/10.1016/J.ENPOL.2018.11.001.

World Bank Group, 2020. Carbon pricing dashboard [WWW Document]. URL. https://carbonpricingdashboard.worldbank.org/map_data.