Electrifying the heating sector in Europe: The impact on the power sector

Konstantinos Kavvadias[a], Georg Thomassen[b], Matija Pavičević[c], Sylvain Quoilin[c]

[a] European Commission, Joint Research Center (JRC), Petten, Netherlands,
konstantinos.kavvadias@ec.europa.eu
[b] University of Leipzig, Faculty of Economics and Management Science, Leipzig, Germany
[c] KU Leuven, Faculty of Engineering Technology, Leuven, Belgium

Abstract:

The heating and cooling sector represents half of the energy consumption in the EU, being supplied 75% by fossil fuels. Buildings, including residential and services sectors, currently represent the largest share of final energy consumption in the EU – 40% of the total final energy demand. Since the heat sector has strong interconnections with others it is difficult to study separately. This study is focusing on the integration of the heat and power sector and their compatibility with the decarbonization targets. More specifically we study an extreme scenario assuming a massive turn to electric-driven heating. Firstly, a novel demand decomposition technique is applied to specify how much power is spent for heating. Based on that, we create new demand load scenarios which are used into a detailed unit commitment and economic dispatch simulation of the whole EU power system. Results show that the electrification of heat will cause an increase in winter peak from 20% to 70% higher than today and significant amounts of energy not served. The need of firm capacity additions and flexibility measures is examined in detail.

Keywords:

Space heating, Heat pump, Unit commitment and power dispatch, Dispa-SET, EU28.

1. Introduction

The heating and cooling sector has been recognised as a priority to achieve decarbonisation targets set for the European energy sector. It accounts almost for half of the EU energy consumption. Heating and cooling are consumed in three main sectors, namely residential, tertiary and industry, with the residential (mainly households buildings) representing the highest share. The residential sector accounted for 45% of final energy heating and cooling consumption in 2012, followed by industry's share of 37% and services' of 18% [1]. In general the heating and cooling sector is characterised by low efficiencies, and large amounts of waste heat [2].

Within the heating and cooling sector, there is a great potential for reducing its carbon intensity by switching to electricity as an energy carrier. Even without active carbon policy, electrification can lower CO2-emissions and improve local air quality by reducing the emissions of pollutants [3]. It allows for the reduction of fossil fuel consumption by substituting fossil-fuelled with more efficient electric-driven technologies, benefiting from the rapid decarbonisation of the power system.

While the shares of green energy in the electricity mixes of EU member states continue to grow, heat pumps can rely on this development to provide clean heating services at a high efficiency: Using ground or air as ambient reservoirs, the thermal energy provided by heat pumps is several times higher than their electrical input.

A further advantage of electric heating is its utilization of a highly developed transmission infrastructure. Electricity is easier to transfer and to distribute than liquid fuels. And since the production chain of electricity is increasingly domestic in the European Union – due to the expansion of renewable energies – the security of heat supply increases and import dependencies are reduced, enhancing the overall energy security. This is of particular interest in times where the uncertainties in foreign relations are continuously growing.

In the literature, the role of electrifying heat as a cost effective measure to decarbonise the energy system is becoming more and more relevant [4]. As the lowest hanging fruit, heat pumps are key to reducing emissions in the heating and cooling sector and preferable to other sector coupling technologies [5]–[7]. While being economically viable on a macroeconomic scale, the business case for heat pumps with regard to the end consumer still has to be developed in many EU member states. Realigning building codes, subsidies and taxes helps to create a level playing fields with gas boilers and other fossil based heating solutions [8]. Especially their high investment costs are seen as a great barrier to higher installation rates [9].

Their flexibility plays an important role in balancing power demand and supply, and may – in combination with other sector coupling technologies from transport and the chemical sector – render electricity storage redundant, even in a highly decarbonized system [10].

The electrification of heat is, however, highly dependent on an energy efficient building stock. The low supply temperatures of heat pumps make them much less efficient in buildings that are not well insulated, resulting in lower performance of the heating system. This has been identified as one of the key risks in focussing on a one-sided deployment of heat pumps for the decarbonization of the heating sector and sparked a controversial discussion on the right strategy [11]. 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 [12], [13]. Others see cost advantages and 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 competitive [14].

On a grid level, electrification creates new consumers which put the local infrastructures to the test. It has, however, been shown that even large penetration levels of battery electric vehicles and heat pumps are manageable if appropriate charging/operation strategies are implemented [15], [16]. In areas with distributed generation, heat pumps can even relieve the grid, if their demand response potential is utilized [17]. Moreover the amount of electricity demand from a heat electrification scenario is minimal compared to a transport electrification scenario.

Regarding the macro effects of heat pump deployment on the power system, there are two sides to the same coin: On the one hand, electricity consumption rises, which can create a need for capacity expansions and might produce additional CO_2-emissions in the power sector (depending on the electricity mix at hand) [18]. As there are strong signs in most EU Member States that heat demand exceeds electricity demand in both peak and annual demand, extensive electrification can place a heavy burden on the power system and requires significant capacity expansion [19]. On the other hand, heat pumps are a source of flexibility to the power system, which facilitate the reconciliation of electricity supply and demand in a system with high shares of variable renewable electricity sources, thereby reducing curtailment and fossil fuel consumption [20].

The effect on generation capacity levels cannot be seen as proportional to the heat pump deployment and should be distinguished according to the penetration level. At low penetration rates, in combination with thermal storage, heat pumps can lead to little or no additional required capacities to satisfy the additional demand. They can satisfy their needs in off peak times due to their flexibility [21]. Separate, additional storage units are, however, no precondition for a flexible dispatch, since the thermal inertia of buildings can be used as a no-cost option for load shifting without impacting the comfort of the inhabitants [22].

High penetration levels generate a demand for electricity which cannot be satisfied by just "filling in the gaps". This additional demand can generate new peaks and/or boost existing peaks, which leads to increased capacity requirements and requires additional investment in power generation capacities. Flexible operation still remains important to reduce the volatility of heat related electricity demand [5], [23]. Watson et al. [24], 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 UK households.

The scope of this work is to describe the European heat sector, quantify its link with the power sector and explore how it will be affected under a full heat electrification scenario.

2. Power and heat sector data

2.1 Description of the EU building sector heat demand

The heating and cooling sector represents half of the energy consumption in the EU, being supplied 75% by fossil fuels [2]. Buildings, including residential and services sectors, currently account for 40% of the total final energy consumption in the EU [25]. The residential sector, alone, is responsible for 54% of heating and cooling consumption, followed by services - 21% and industry - 24% (final energy - 2015 data) (Figure 1). Therefore, the built environment has been identified as a key pillar in the European energy policy to achieve a climate neutral Europe by 2050.

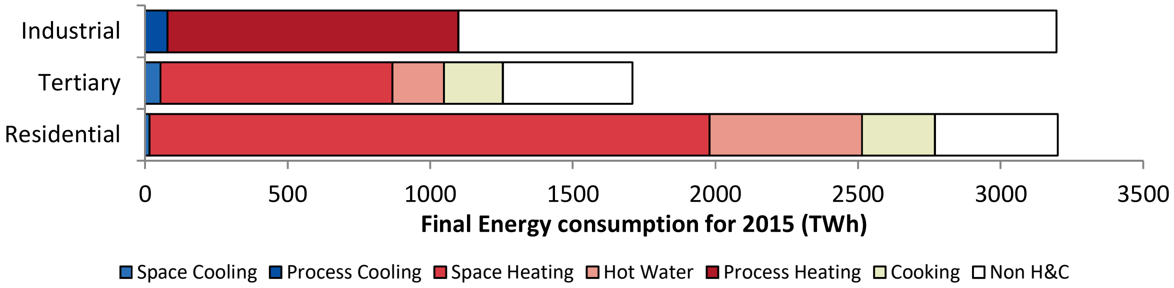

Figure 1 Shares of final energy demand per end-uses and Member States Data source: [26].

Figure 2 shows a comprehensive view of space heating, hot water and space cooling with their relative energy demands and their current fuel breakdown. Figure 3 presents the space heating needs in 2015 as well as their fuel breakdown at country level. Currently, heating in the EU relies by over 40% on low carbon technologies – such as district and electric heating, as well as renewable fuels, namely biomass. Two northern European countries stand out with the highest shares for cleaner heating technologies: Sweden gets almost 95% of the space heat in buildings from non fossil fuels, while Finland claims the second place with roughly 90%.

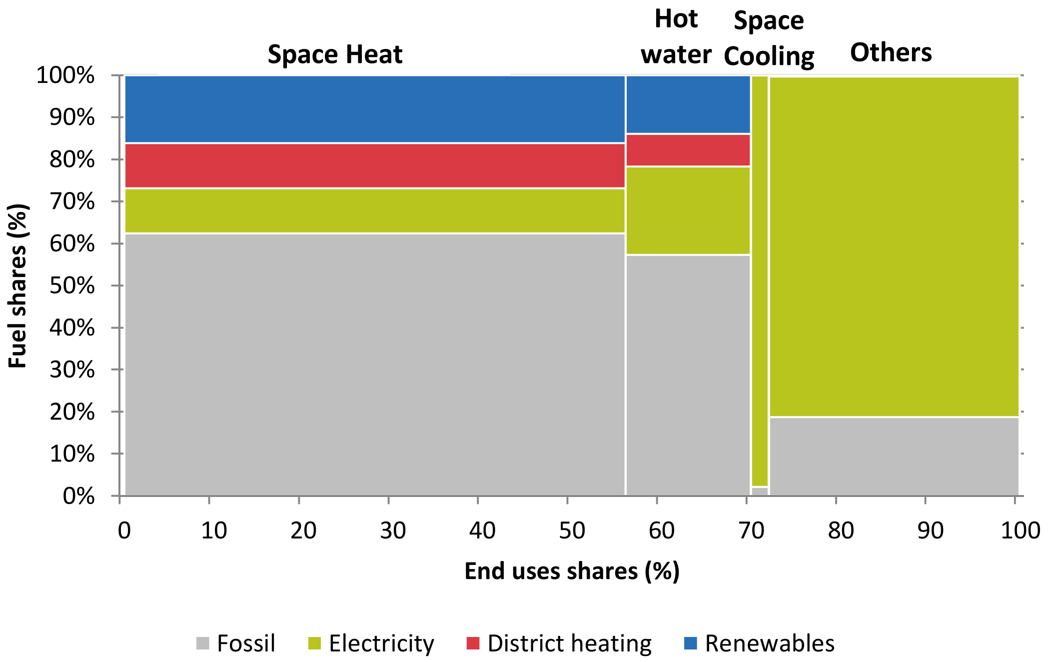

Figure 2 A comprehensive view of useful energy composition of the built environment for different end uses in the EU. Data source: JRC-IDEES database [26]

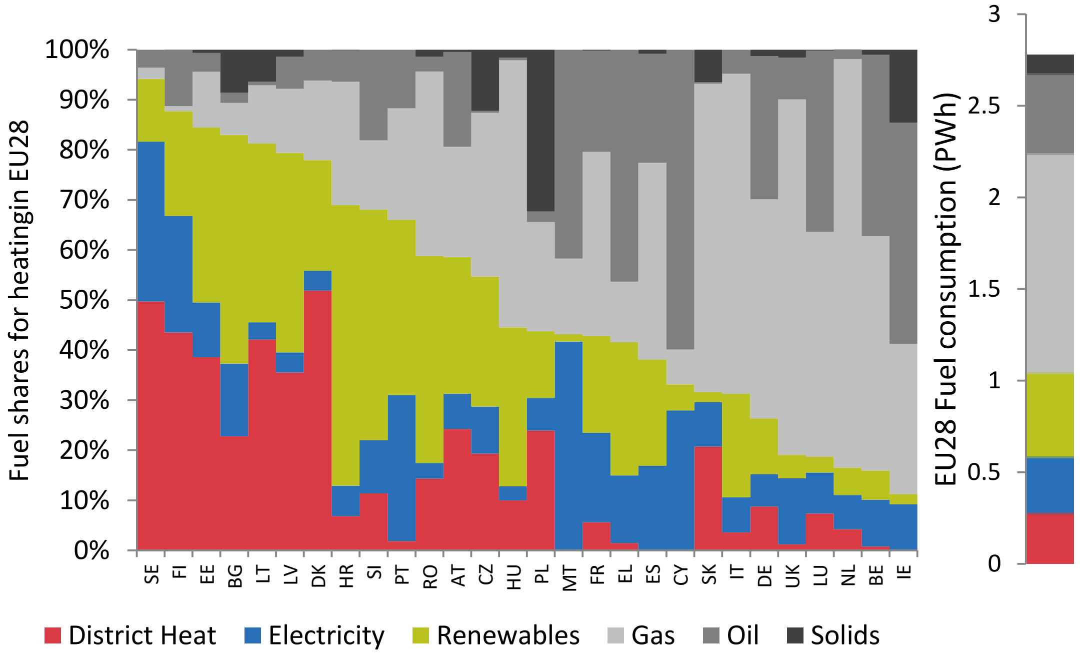

Figure 3 Fuel consumption for space heating in 2015. Member states are sorted by the amount of fossil fuels they are consuming

2.2. Power sector efficiency

A new indicator called fossil fuel intensity is defined in an attempt to show a measure of the decarbonisation of the power system and its readiness to a clean electrified economy. The fossil fuel intensity of the power system, is defined as the amount of fossil fuels (excluding uranium for nuclear) needed to be 'combusted' in order to produce 1 kWh of electricity. Figure 4 shows its evolution for the EU 28 countries from 1990 – 2017 sorted by their corresponding values for 2017. The overall picture across the EU 28 is diverse but overall the average fossil fuel intensity is falling from an average of 1.27 to 1.06 $\text{kWh}_{\text{fossil}}/\text{kWh}_{\text{electric}}$ for the period 2010 — 2017. Many countries have already achieved a fairly clean power system while others are experiencing a steep transition towards it.

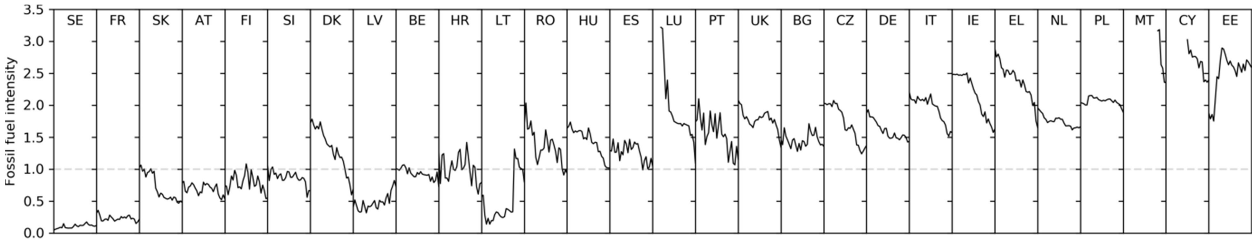

Figure 4 Fossil fuel intensity of power system for different countries and years (1990 – 2017). Countries are sorted from the lowest current value to the highest (The lower the better). Data source: Eurostat Tables nrg_110a, modified power system efficiency definition (eta)

2.3 Power demand decomposition

The total power demand of a country at a national level was decomposed into three uses: electricity for space heating, electricity for space cooling and electricity of other uses. The decomposition of electricity demand to different uses is needed to analyse different heat related scenarios such as the effect of electrification of heat on the power demand curves. The following sources were used for this analysis:

- Electricity demand data from ENTSOE power portal as retrieved and pre-processed by Open Power System Data [27]
- Weighted average Temperature based on ERA5 [28] aggregated at a MS level [29]
- Public Holidays from various public sources
- Share of electricity for space heating from JRC IDEES [26]

Power demand is plotted against 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 during the day is different compared to night time or weekdays and weekends.

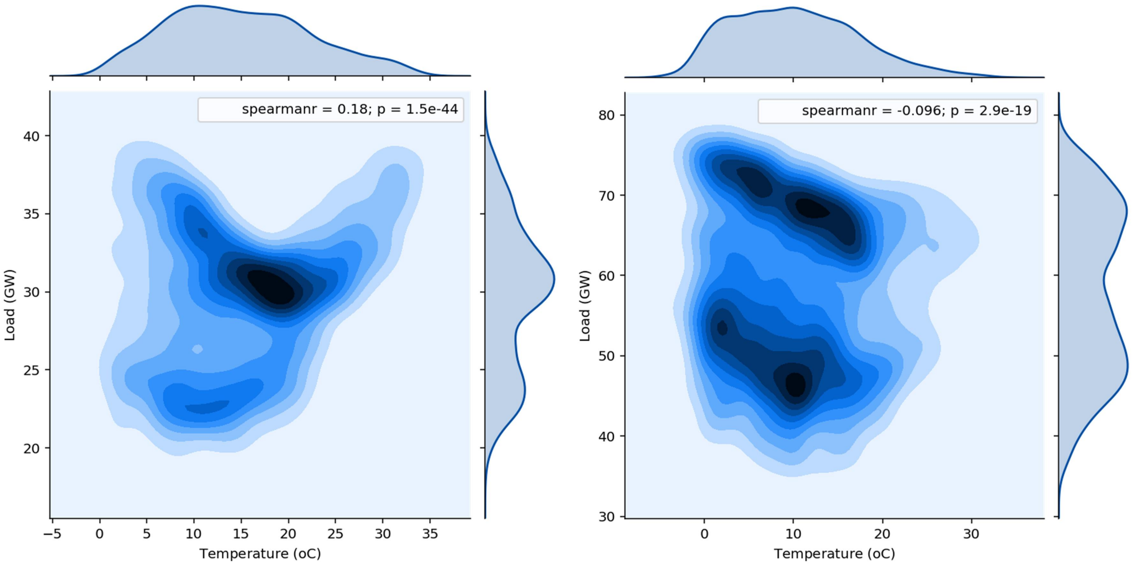

Figure 5 Density scatterplots illustrating the relationship between load and temperature for Spain (left) and Germany (right). The marginal distributions of the two variables are also shown to indicate the bimodal nature of the load (day-night, weekend-weekday).

In order to decompose the electric load into heating and cooling within a country, among different hours of the day and among weekdays and weekends and holidays we use a variable-base degreehour method which is a generalization of the traditional degree-day method. The following steps were followed:

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. This 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 [30]. 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 with the temperature. This was conducted for day and night, weekday/weekend based on the results of a density clustering.
2. Establish heat degree hours (HDH) and cooling degree hours (CDH) using the hinge points found above using the formulas:

$$\mathrm{CDH_t} = \mathrm{MIN}(\mathrm{L_t} - \mathrm{hinge_c}, 0) \tag{1}$$

$$\mathrm{HDH_t} = \mathrm{MIN}(\mathrm{hinge_h} - \mathrm{L_t}, 0) \tag{2}$$

   Where L_t is the load at time t and *hinge* the identified hinge point for heating or cooling for the type of the day (weekday/weekend) and type of time period (day/night). If there is no hinge point then the CDH or HDH is zero for that timestep. Exponential weighted moving average with a decay of 3 hours was used in order to adjust the series. 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.
3. The two timeseries of the above step are normalized so that the sum is 1. The following rescaling function is defined:

$$scale(x_t; A, B, C) = Ax_t^B + C \tag{3}$$

   where, x_t the original normalized timeseries and A,B,C the rescaling parameters. The rescaling is done through a combination of stretching (A), shifting (C) and skewing (B).
4. For the decomposition the following equation needs to be satisfied:

$$L_t = Other_t + scale(CDH_t; A_c, B_c, C_c) + scale\ (HDH_t; A_h, B_h, C_h) \tag{4}$$

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

$$\sum_t scale(CDH_t; A_c, B_c, C_c) = target\ cooling\ load \tag{5}$$

$$\sum_t scale(HDH_t; A_h, B_h, C_h) = target\ heating\ load \tag{6}$$

$$HDH_t \cdot CDH_t = 0 \tag{7}$$

   The targets are taken from real shares of electricity for heating and cooling for all historical years based on the JRC IDEES [26]. database. 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[1].

The decomposition was done at a Member State level. The values for A, B and C for both the heating and cooling component result to the desired decomposed elements. In all cases the algorithm converged to the target within less than a minute. At the end, the result 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 Figure 6. This figure includes the temperature dependent components (electricity for space cooling and space heating) and the electricity used for other purposes.

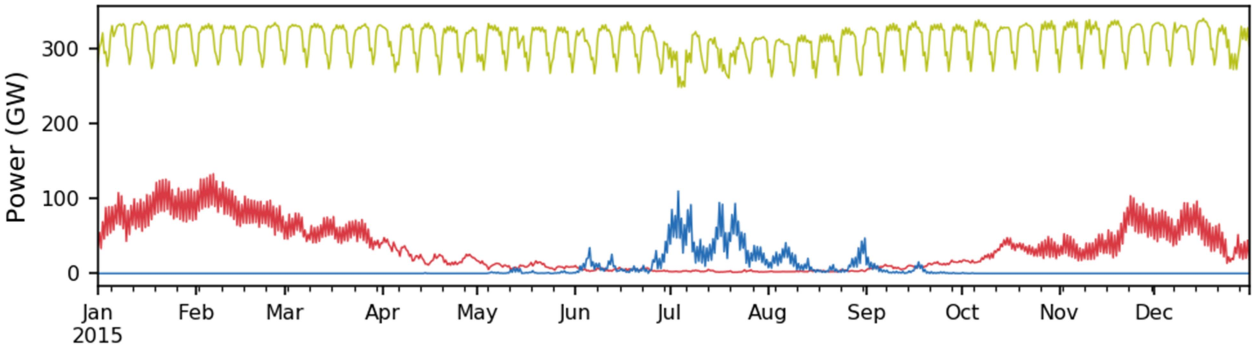

Figure 6 Aggregate electricity demand for heating (red) cooling (blue) and other purposes (green) in 2016. NB: Lines are not plotted cumulatively

2.4 Power demand scenarios

Figure 7 shows the electricity that is spent for heating as part of the overall electricity demand for the base case and a full electrified case. Based on these scenarios and the decomposition done in previous section, we rescale the part of electricity that is used for heating according to the electrification rate. Consequently, the load duration curve of the power demand scenarios is modified as shown in Figure 8. This Figure shows also intermediate scenarios with 20, 40, 60, 80, 100% of electrification. It is observed that mainly the peak changes but not the baseload, due to the fact that the increase in demand of the heating occurs mainly during winter.

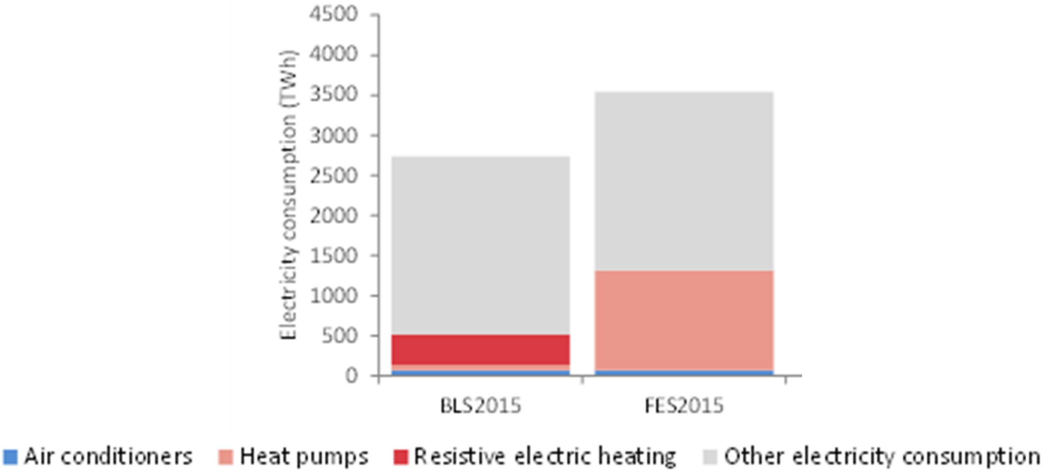

Figure 7 Scenario for the development of electricity demand

---

[1] The python DEAP package was used

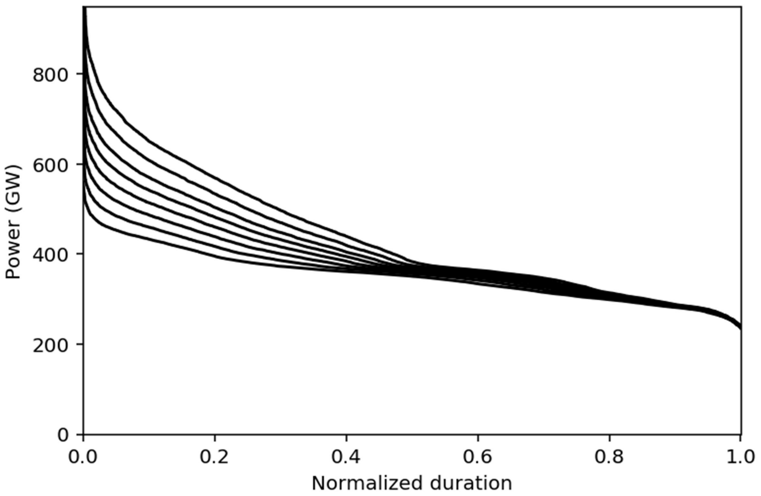

Figure 8 Load duration curve of EU28 from current demand (bottom curve) to full electrification (top curve)

3. Model description

A is an existing unit commitment and dispatch model, the open-source model Dispa-SET v2.3. (http://www.dispaset.eu) was used to simulate the power system under the developed electrification scenario. This new version includes some special features to be able to simulate the European power system in detailed but computational efficient way.

Dispa-SET has been documented in multiple successive reports [31-33]. The aim of the model is to represent with a high level of detail the short-term operation of large-scale power systems, solving the unit commitment problem. To that aim, it is considered that the system is managed by a central operator with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network. The main model features can be summarized as follows: minimum and maximum power for each unit, power plant ramping limits, reserves up and down, minimum up/down times, load shedding, curtailment, pumped-hydro storage, non-dispatchable units (e.g. wind turbines, run-of-river, etc.), start-up costs and ramping costs.

The new features include the new mixed integer clustering formulation, in which all units of a similar technology, fuel and zone are clustered. A typical unit is defined by averaging the characteristics of all units belonging to the cluster. This formulation divides the simulation time by a factor higher than 10 and allows extending the geographical scope of Dispa-SET. The total number of units is conserved, allowing a proper representation of constraints such as start-up costs, minimum up/down times or minimum stable load values. This is the main innovation compared to other models that represent country level aggregated fleets which ignore constraints such as thermal units, start-ups and shutdowns with associated costs and constraints.

The costs can be broken down as: fixed costs, variable costs, start-up and shut-down costs, ramp-up and ramp-down costs, shed load costs and transmission costs. The variable production costs are determined by fuel and emission prices corrected by the efficiency and the emission rate of the unit. The start-up and shut-down costs are positive variables, active when the commitment status between two consecutive time periods is modified.

Simulations were run in a cluster node with the following characteristics: 2x Intel Xeon E5-2690 v4, 2.60GHz, 14-core processors (in total 28 cores), 256GB of DDR4-2400MHz ECC memory. Each simulation took from 3 to 10 hours to complete.

4. Results and discussion

Figure 9 shows how the heat demand sector gets cleaner and decarbonized by replacing fossil fuel driven heating with heat pumps. For each country the heating mix and the power mix, efficiency and emission factors were used. The "cleaner" the power sector and the more gas dependent the heat sector, the more enhanced the impact would be.

Looking at the power sector, a full electrification scenario would induce a lot of stress on the European power system. 2.90% of the total amount of load would not be able to be served. The picture at individual member states is even more severe, with almost 20% of load being shed in the UK and more than 10% of load losses in Italy, Hungary, the Netherlands, Belgium and Slovenia.

The operating costs in the power sector more than double due to electrification, from 31 Bn. EUR in the base scenario scenario to 66 billion EUR in the full electrification scenario. Since all heating services are provided either through CHP plants or heat pumps, the operating costs for the heating sector drops to zero, compared to 69 billion EUR in the baseline. This means that, even though costs in the power sector rise, there is an overall annual cost saving of 34 billion EUR. Since this scenario is not able to satisfy the EU standards of supply security, additional investment would be required, which could also affect the operating costs.

Similarly, emissions would rise in the power sector under full electrification, which would be overcompensated by the displacement of fossil fuels in the heating sector. Emissions in the full electrification scenario drop to 1260 $MtCO_2$ (from 1320 MtCO2 in the baseline scenario). At the same time, emissions in the power sector rise from 510 $MtCO_2$ to 1260 $MtCO_2$.

The amount of generation (peak and total) per technology is presented comparative in Figure 10 in the form of load duration curves. We observe a big increase on gas generation especially on the more flexible technologies that can deal with the heat demand peaks.

Figure 9: Comparison of current case and a full electrification scenario. Bubble size are proportional to the useful energy demand of each country

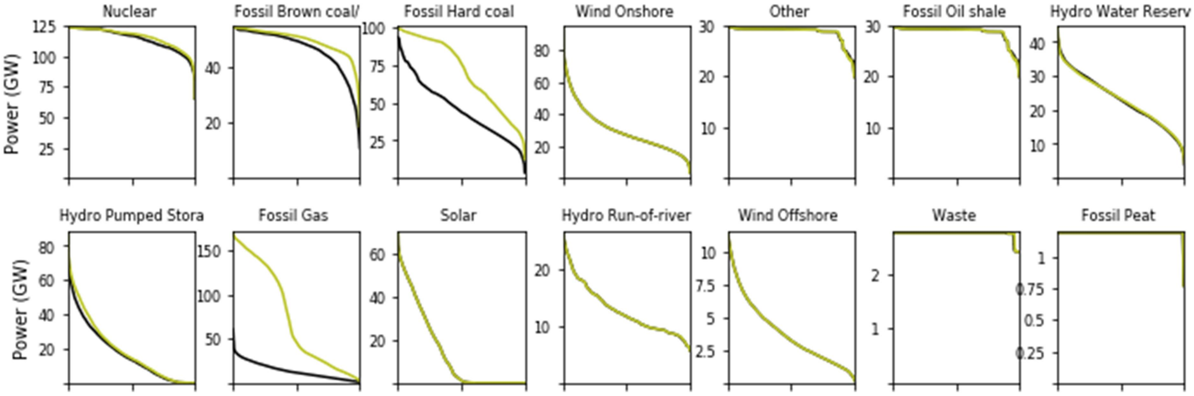

Figure 10 Power plant generation per technology for the base in black and the full electrification scenario in green in the form of load duration curves.

5. Conclusions

A description of heating demand and the share of electricity for heating was analysed and different scenarios were constructed. If heating sector was fully electrified, heat pumps would make up 35% of final electricity consumption or 1,248 TWh. The overall consumption rises by 800 TWh or 29% when compared to the base case. Electrifying the heating sector will imply an increase in winter peak from 20% to 70% higher than today. The biggest changes would be noticed in Germany, Italy and UK. Power sector is not able to cope with the increased peak demand. 3% of the total load would not be able to be served, while some countries have up to 18% lost load. Overall emissions of power and heating sector drop by only 5% because the power mix of some countries is not clean and efficient enough yet so it may even increase the emissions in some cases. This is most notable in Italy, Spain and the Netherlands, while countries such as France and the UK profit most from the electrification of heating. While there are countries with more drastic changes in CO_2-emissions, most countries see little or no change compared to the base case. Despite these challenges there are 34 billion EUR overall cost savings. Firm power capacity additions are needed in all cases since load shaping measures are not enough to cover the whole demand. Future work will include the optimal capacity expansions that can make the power system resilient enough under such developments.

References

[1] M. Ragwitz, A. Herbst, S. Hirzel, M. Ragwitz, M. Rehfeldt, M. Reuter, and J. Steinbach, "Service contract regarding a study on 'Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)' ENER/C2/2014-641," 2016.

[2] European Commission, "An EU Strategy on Heating and Cooling. COM(2016) 51 final," vol. 1. 2016.

[3] EPRI, "U.S. National Electrification Assessment," no. April, 2018.

[4] A. Bloess, W.-P. Schill, and A. Zerrahn, "Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials," *Appl. Energy*, vol. 212, pp. 1611–1626, Feb. 2018.

[5] F. IWES/IBP, "Heat Transition 2030," *Agora Energiewende*, 2017.

[6] K. Schaber, F. Steinke, and T. Hamacher, "Managing Temporary Oversupply from Renewables Efficiently: Electricity Storage Versus Energy Sector Coupling in Germany," *Int. Energy Work. 2013*, pp. 1–22, 2013.

[7] S. V. Raghavan, M. Wei, and D. M. Kammen, "Scenarios to decarbonize residential water heating in California," *Energy Policy*, vol. 109, no. May, pp. 441–451, 2017.

[8] M. J. Hannon, “Raising the temperature of the UK heat pump market: Learning lessons from Finland,” *Energy Policy*, vol. 85, pp. 369–375, 2015.

[9] S. Karytsas, “An empirical analysis on awareness and intention adoption of residential ground source heat pump systems in Greece,” *Energy Policy*, vol. 123, no. March, pp. 167–179, 2018.

[10] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, “Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system,” 2018.

[11] M. Chaudry, M. Abeysekera, S. H. R. Hosseini, N. Jenkins, and J. Wu, “Uncertainties in decarbonising heat in the UK,” *Energy Policy*, vol. 87, pp. 623–640, 2015.

[12] dena, “Integrierte Energiewende,” 2018.

[13] J. Ecke, S. Klein, S. Werner Klein, and T. Steinert, “Klimaschutz durch Sektorenkopplung : Optionen, Szenarien, Kosten,” vol. 49, no. 0, pp. 0–56, 2017.

[14] F. I. und C. ifeu, “Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung,” 2018.

[15] N. Shao, S. You, H. Segerberg, and D. K. K. Lyngby, “Integration of 100 % heat pumps and electric vehicles in the low voltage distribution network : a Danish case study,” *3 Microgen*, 2013.

[16] P. de Boer-Meulman, J. J. A. van der Burgt, P. J. M. Hafkamp, R. Hunik, E. Kokmeijer, C. Kolokathis, F. Nieuwenhout, Ö. Özdemir, R. Ross, K. Schoots, and F. D. Sikkema, “Effect of scenarios and alternatives for electric vehicles and heat pump implementation on grid reliability , sustainability and socio-economy,” *Management*, no. 10, p. 94, 2010.

[17] B. Felten, J. Raasch, and C. Weber, “Photovoltaics and heat pumps - Limitations of local pricing mechanisms,” *Energy Econ.*, vol. 71, pp. 383–402, 2018.

[18] A. F. Sandvall, E. O. Ahlgren, and T. Ekvall, “Low-energy buildings heat supply–Modelling of energy systems and carbon emissions impacts,” *Energy Policy*, vol. 111, no. January, pp. 371–382, 2017.

[19] D. Connolly, “Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries,” *Energy*, vol. 139, pp. 580–593, 2017.

[20] A. Bloess, W. P. Schill, and A. Zerrahn, “Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials,” *Appl. Energy*, vol. 212, no. August 2017, pp. 1611–1626, 2018.

[21] B. Baeten, F. Rogiers, and L. Helsen, “Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response,” *Appl. Energy*, vol. 195, pp. 184–195, 2017.

[22] S. Heinen, W. Turner, L. Cradden, F. McDermott, and M. O’Malley, “Electrification of residential space heating considering coincidental weather events and building thermal inertia: A system-wide planning analysis,” *Energy*, vol. 127, pp. 136–154, 2017.

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

[24] S. D. Watson, K. J. Lomas, and R. A. Buswell, “Decarbonising domestic heating_ What is the peak GB demand?.pdf,” *Energy Policy*, vol. 126, no. August 2018, pp. 533–544, 2019.

[25] European Commission, “A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy,” Brussels, 2018.

[26] L. Mantzos, T. Wiesenthal, N. A. Matei, S. Tchung-Ming, and M. Rozsai, “JRC-IDEES : Integrated Database of the European Energy Sector,” 2017.

[27] Open Power System Data, “Data Package Time series,” *Version 2018-06-30*, 2018. [Online]. Available: https://doi.org/10.25832/time_series/2018-06-30.

[28] Copernicus Climate Change Service (C3S), "ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate," 2017.

[29] M. De Felice, "Country averages of Copernicus ERA5 hourly meteorological variables [Data set]," *Zenodo*, 2018. [Online]. Available: http://doi.org/10.5281/zenodo.1489915%0A.

[30] J. A. Azevedo, L. Chapman, and C. L. Muller, "Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK," *Meteorol. Appl.*, vol. 22, no. 4, pp. 789–796, Oct. 2015.

[31] Hidalgo González, I., Quoilin, S., & Zucker, A. *Dispa-SET 2.0: unit commitment and power dispatch model* (EUR 27015 EN). Petten, Netherlands: European Commission. 2014

[32] Quoilin, S., Hidalgo Gonzalez, I., & Zucker, A. *Modelling Future EU Power Systems Under High Shares of Renewables: The Dispa-SET 2.1 open-source model.* Publications Office of the European Union. 2017

[33] Kavvadias, K., Hidalgo Gonzalez, I., Zucker, A., & Quoilin, S. *Integrated modelling of future EU power and heat systems - The Dispa-SET v2.2 open-source model* (EUR 29085 EN). Luxembourg: European Commission. 2018