# Towards the electrification of buildings heating - real heat pumps electricity mixes based on high resolution operational profiles

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**Abstract**

The energy transition driven by the need of a deep decarbonization to limit the world temperature rise requires coordinated actions across the whole energy sector. Among other measures, the strong development of renewable energy sources in the power sector is gaining momentum in different parts of the world. The possibility of producing low-carbon electricity leads to a renovated interest in increasing electricity penetration in final sectors, especially in transport and buildings heating. However, a large share of renewable electricity comes from non-dispatchable sources, notably wind and solar PV, and their daily and seasonal variability needs to be matched with the demand profiles of those sectors. In particular, the charge of electric vehicles shows a relatively constant demand on a seasonal basis while attention must be paid on the daily operational logic to fully exploit available power from solar and/or wind. On the other hand, the operation of heat pumps for building heating shows a strong seasonality that may be an issue in countries that have a larger renewable production during summer. This research work is focusing on this specific issue, with the aim of improving the common practice of evaluating energy consumption and emissions on an annual basis, thanks to a detailed analysis based on hourly time-step, both for the electricity generation mix and for the heat pumps demand. To increase the significance of the results, different countries across Europe have been analyzed and compared.

*Keywords:* heat pumps, renewable energy sources, electricity, power mix, decarbonization

## 1. Introduction

The electricity sector has shown the fastest growth rate in global final energy consumption, increasing its penetration from 15% in 2000 to 19% (around 22,000 TWh)

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in 2017 [1]. The worldwide boost of Renewable Energy Sources (RES) will increase the presence of clean but non-programmable electricity in the grid, with the need of flexibility solutions to ensure grid stability. The European Union (EU) is among the regions with the strong decarbonization policies, with the Clean Energy Package for all Europeans [2], the new legislative package which set new and ambitious targets for 2030 to respect the Paris Agreement: 32% of RES share in final consumption and -40% $CO_2$ emissions are among the targets described in the package. However, these targets will probably soon increase, as different EU countries are implementing dedicated regulations to reach net-zero emissions by 2050.

Electrification of final sectors is increasingly seen as an opportunity to replace part of the fossil fuel usage with renewable energy and to balance the variability of power generation from RES through additional flexible power demand [3], as described in [4], where the integration between thermal and electrical grids result in energetic, environmental and economic advantages. In particular, the heating [5] and transport [6] sectors are the ones getting major attention for electrification, and this trend may have a strong role in determining the future consumption profiles [7]. Their electrification can also be driven by the need of increasing the self consumption of local generated electricity in photovoltaic systems, which is an important trend in many countries worldwide [8]. Other authors highlight the potential role of heat pumps (HPs) in managing variable renewable power, especially when coupled with energy storage systems [9].

Renewable energy accounted for 19.5% of the total energy used for heating and cooling in 2017 in the EU, marking an increase of 9.1 percentage points from 2004. This increase can be ascribed to an increased usage of direct heat renewable sources (like geothermal, solar energy or bio-energy) but also to the increased deployment of HPs [10]. The growing trends of HP technology is highlighted by the *European Heat Pump Association* (EHPA) [11] at the EU level and, in general, by the *International Energy Agency* (IEA) [12]. Despite a global HPs sales increase of 10% in the last year, power-driven HPs still supply less than 3% of heating demand in the building sector worldwide (slightly less than 10% in EU) [13] even if its theoretical potential could reach over 90% of global water and space heating [14].

In fact, the EU is fostering the diffusion of HPs in different directives and documents [15] [16], where they are indicated as an important driver to increase the RES share in final energy consumption. For example, the usage of HP could improve the energy efficiency of users heating devices or power plants [17] and could enable the connection between electrical and district heating grids [18], towards the so called *"4th Generation of District Heating Networks"* [19], creating an integrated smart energy system [20]. Moreover, *Electricity-to-heat* storage systems are proposed among the most effective ways of storing the excess of electricity production as deeply investigated by [21] and in [22], where *Electricity-to-heat* storage systems are compared with batteries and electrical vehicles storage.

Both electricity consumption and production show seasonal, weekly and daily variations, and because production units have to adapt their energy output following the users' needs, this leads to have a wide variation of the actual power generation mix on both seasonal and daily basis [23]. Therefore, both the Primary Energy Factor (PEF) of the electricity generation and the $CO_2$ emission factor (EF) show significant variation ranges, depending on the energy sources available for each country as shown in [24] for PEF and in [25] for EF. The use of average annual values for PEFs and $CO_2$ emission factors, which is the standard approach in energy scenarios modeling as in [26], could lead to over- or underestimation of the impacts of the electricity sector in all the related sector such as building application [27] or for electric mobility [6]. As a consequence, this bias could lead to a non-optimal utilization of the carbon-free electricity that may be available, making the switch to electrical devices less profitable from the environmental point of view. To fully exploit the carbon-free potentiality of RES, it is thus not only important to increase their absolute share in the energy mix, but also to use their energy production when available. Using RES electricity when it is produced can lead to different advantages as lower energy costs, grid stability, increase the RES utilization [28] and lower $CO_2$ emissions [21], and a detailed time-step evaluation is needed to develop a correct simulation of the real system operation.

The importance of considering high temporal detail for $CO_2$ emissions is underlined in other literature works, including [6, 25, 29]. In [6], the authors developed a methodology for calculating the hourly average $CO_2$ intensity of the electricity mix for Norway, highlighting that a refined analysis needs to be taken into account especially for countries with high RES penetration, where generation variability and import/export can highly affect the electricity emission factors. In [29], instead, the focus is on the impact of electrical mobility performance of the variable electricity mix, while in [25] the variability of emission factors in New Zealand is discussed. Other works use the hourly EF approach to design heating control systems to minimize the $CO_2$ emissions [30] or to quantify the potential of innovative demand response predictive control systems [31] for the same purposes. In [32] the authors investigate the effects of demand response techniques for electrical appliances highlighting an inverse correlation between energy consumption reduction and $CO_2$ emissions. However, while these papers present different evaluations based on an hourly assessment of EFs, there are no studies in the literature aiming at comparing the difference between national average values and hourly average values.

The objective of this paper is the assessment of the impact of the final results when considering hourly behaviour in comparison with annual average values, both for electricity mix and heat pump demand. The heat pumps energy consumption, during winter time, will be compared with the national energy production on hourly basis in order to catch the RES production variations and to highlight how the consumption pattern of electrical heat pumps influence their emission factor. The evaluation of different energy production portfolios across some European countries will strengthen the results, giving a better insight on the potential of HPs in decarbonizing the heating sector by the use of electricity from RES. This comparison is based on a data analysis of the operational conditions of multiple HPs from historical monitoring information, in comparison with the power generation mix of ten different European countries (Austria, France, Germany, Switzerland, Italy, Netherlands, United Kingdom, Ireland, Denmark, Poland) to evaluate the variability of the hourly performance parameters in comparison with annual average values.

## 2. Methodology

The aim of the study is to evaluate the effect of different electricity mixes in powering a heat pump that can show a comparable profile in different European regions. This analysis is based on the real operation data of existing heat pumps, to assess to what extent their variable profiles may have an impact on their actual electricity generation mix, which is calculated as a weighted average based on their operation. This section will present the main assumptions and procedures that have been used in the analysis of HPs operation, in the evaluation of the power generation hourly data and in the definition of proper comparison indicators.

### *2.1. Heat pumps' operation*

The HPs considered in this study are obtained by two distinct data sets, which ensure a larger significance by providing various profiles and operation logics based on historical data from real plants. The first database has been provided by an Italian company that monitors different HP systems installed in Northern Italy [33]. It is based on the operation of four water-to-water geothermal (close loop) vapor compression heat pumps, of which two of them are for residential use (named as C7 and C8 in the following charts) and the other two are used for accommodation facilities (C9, C10). The HPs are equipped with scroll compressors and electrical valves coupled with inverters, to regulate the power output and increase the efficiency. The units C7 and C8 are working with the refrigerant R407C and coupled with a radiant floor heating system, working with a nominal flow temperature of around 35°C . C9 and C10 are operated with the refrigerant R410A, and they are coupled with fan-coils heating system, resulting in a nominal flow temperature of 45°C. In particular, all the monitored plants are located in Italy at different latitudes (in Central and Northern Italy) and present different electrical rated powers as can be seen in Figure 1. The data has been provided for the years 2018/2019 with a very narrow time resolution (each minute), but the analysis has been carried out by aggregating the values on hourly basis on the entire heating season (October - April). The data availability was quite accurate, with the main issue being related to a limited number of missing data. However, since the data were provided per each minute, we decided to fill the occasional lacking values taking the previous data observation, since no particular variation can usually happen in such a limited time interval. The choice of hourly values is consistent with the available information for power generation mix in most countries, although in some cases values are available each 15 minutes.

In Figure 1 the hourly average electrical profiles are displayed for the different months. While the analysis has been performed on an hourly basis, the average monthly profiles are useful to represent the strong variability related to different climate conditions over the year. It can be seen that C7 and C8 present the typical residential profile, with the morning and evening peaks of consumption, although with a different relative importance. Conversely, the other two users present a more constant consumption typical of hotel and accommodation facilities. Moreover, for all HP systems the power consumption increase in the coldest months such as December, January, and February, as commonly happens in Northern Italy.

The second data collection has been retrieved from an external source, the *London Datastore* [34] which is an open data-sharing portal about London. The two archives [35] are provided from two different UK suppliers and consist of electrical and thermal data (including absorbed power, frequency, reactive power, water temperature, outdoor temperature, etc.). Since one of the two data collection does not provide the required time windows to compare the results with the previous one, only one of the two available datasets has been taken into account. In this case, the data are recorded with a 15-minutes timestamp between the last days of December 2011 to the first days of March 2014. In order to compare the profiles and the consumption with the previous data

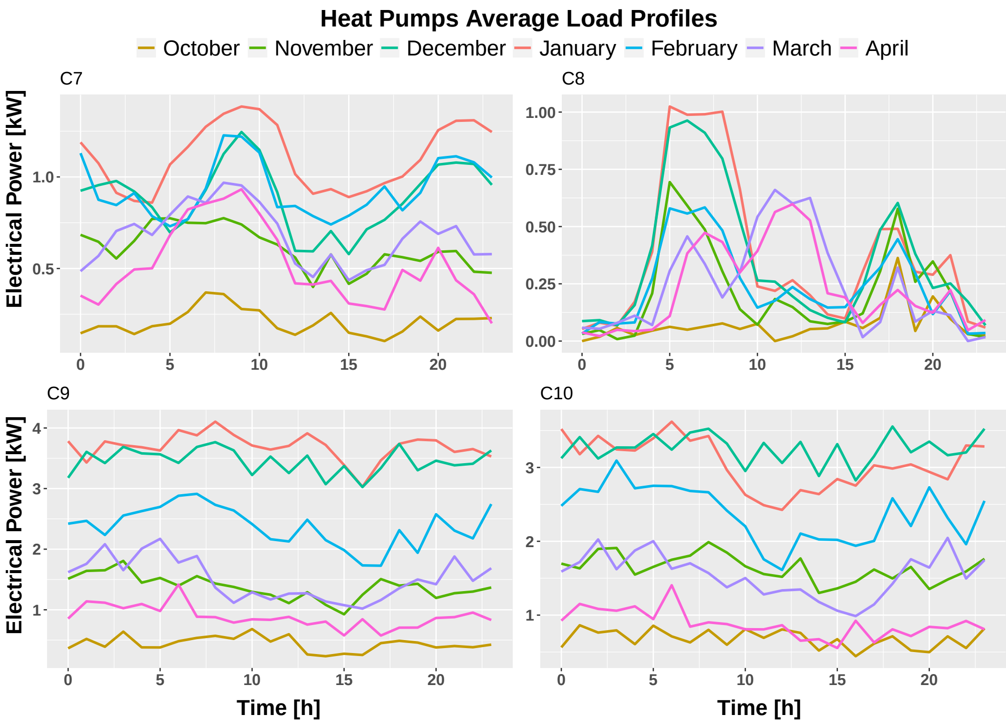


Figure 1: Average hourly electrical load profiles for GSI heat pumps

collection over an entire heating season, the data from October 2012 to April 2013 have been considered. One of the limitations of the analysis is the unavailability of more recent data, which does not allow a comparison on the very same time frame. However, we believe that this approximation is acceptable for the purpose of this paper, since multiple real operational profiles are still providing a valuable source for evaluating the effect of the variability in comparison with the usual profiles that are derived from software simulation tools. Unfortunately, no further information (such as technical data and/or heat pump typologies) about the heat pumps systems are available. Nevertheless, for the purpose of this work the availability of real electricity demand profiles of different units is an important feature to compare the results of hourly and annual analyses.

Since the London government requires a certain standard quality of the datasets that are uploaded on the page, the data were rather complete and just minor adjustments were needed. Again, the hourly average has been considered in the analysis, and the average hourly profiles per each month are reported in Figure 2.

Unfortunately, there is very little information on the characteristics of the HP systems, and the type of user is unknown. Nevertheless, some plots show typical residential profiles, especially for C1, C2 and C5. The different country location is also noticeable by the fact that the monthly distribution is slightly different than for the Italian systems. Again, the comparison of profiles from two countries, although operating with different external conditions, ensure a wider variability range for the assessment of the potential differences with average annual values.

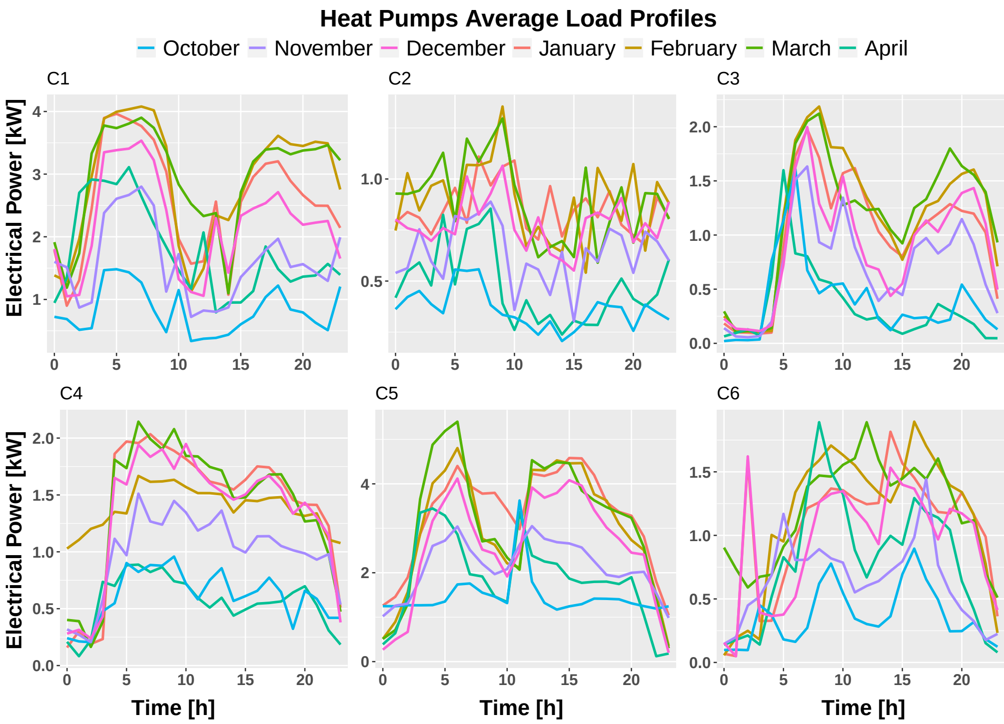


Figure 2: Average hourly electrical load profiles for UK heat pumps

*2.2. Power generation data*

In parallel with detailed information on the HP power demand, which are usually difficult to retrieve, operational data of power generation is usually available at national level and for each bidding zone of the electricity market. In this study the analysis has been limited to the country level, which is usually used in energy systems modelling to evaluate the generation mix. Further focuses can also be performed with a higher spatial detail, to increase the accuracy of the estimation of the use of local resources.

The generation mix data for each country has been retrieved by the ENTSO-E Transparency Platform [36]. The platform makes the production data available at least with hourly detail for different European countries. This study is focused on ten European countries: Austria, Denmark, France, Germany, Ireland, Italy, Netherlands, Poland, Switzerland, and the United Kingdom. These countries have been chosen to consider relatively comparable weather conditions (at least in some regions of them), but at the same time to evaluate the effect of very different electricity mixes.

The actual generation by energy source has been collected for the year 2018. We have chosen to consider the actual production rather than the planned day-ahead production to evaluate the real energy mix that is available at any given time. The data has been aggregated into a limited number of energy sources: biomass, coal, gas, geothermal, hydro, nuclear, oil, solar, waste, wind and other. The main objective of this simplification has been the definition of meaningful electricity mixes, to be qualitatively compared among each other. The void data points are presented as "NA" values. Since no detailed information were available, we decided to replace the NA with zero being aware that this can lead to under-estimate the potential of some energy sources.

The quality of the data available on the ENTSO-E platform has been criticized [37], due to the fact that it lacks of completeness and consistency. The authors perform a quality data analysis based on statistics, comparisons and direct interviews for the 2015-2016 data collection. In particular, concerning the *Aggregated Generation per Type* data, that are being used in this work, a lack of consistency has been specifically highlighted. For example, the combined cycle gas turbines are aggregated in "Other" instead of "Natural Gas" class for some countries, without any given explanation. This, of course, can lead to major deviations in countries with high penetration of this technology, for example, Italy as also noticeable in figure 4, where Italy presents a quite large portion of "Other" energy source. As far as completeness is concerned, some countries such as Germany and Austria have almost zero voids in the dataset while others present quite large missing data. Figure 3, obtained by [37], presents the results obtained by the authors. The table in Figure 3 presents the completeness of *Aggregated Generation per Type* data for different countries calculated as share of missing values per different technologies. 0.0% (green cells) mean no missing values while 100% (red cells) mean the opposite. The white cells filled with "n/e" indicate that no generation from that technology is expected in the country. Nevertheless, the authors report an improvement of data quality in the last two years, and for this reason only 2018 data have been used in this research.

| | Biomass | Fossil Gas | Fossil Hard coal | Hydro Pumped Storage | Hydro Run-of-river and poundage | Hydro Water Reservoir | Nuclear | Solar | Wind Onshore | Other |
|---|---|---|---|---|---|---|---|---|---|---|
| AT | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | n/e | 0.3% | 0.3% | 0.0% |
| BE | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | n/e | 0.0% | 1.0% | 1.4% | 0.0% |
| BG | 0.3% | 100% | 100% | 0.1% | 100% | 0.0% | 0.3% | 0.1% | 0.4% | n/e |
| CY | n/e | n/e | n/e | n/e | n/e | n/e | n/e | 100% | 28.2% | n/e |
| CZ | 0.1% | 0.1% | 0.1% | 0.0% | 0.1% | 0.1% | 0.1% | 0.2% | 0.1% | 0.2% |
| DE | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% |
| DK | 0.0% | 0.0% | 0.0% | n/e | 32.4% | n/e | n/e | 0.0% | 0.0% | n/e |
| EE | 0.3% | 0.3% | n/e | n/e | 0.3% | n/e | n/e | 0.3% | 0.3% | 0.3% |
| ES | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% |
| FI | 0.3% | 0.3% | 0.3% | n/e | 0.3% | n/e | 0.3% | n/e | 0.3% | 0.3% |
| FR | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | n/e |
| GB | 100% | 0.0% | 0.0% | 0.8% | 0.8% | n/e | 0.8% | 0.0% | 0.0% | 0.2% |
| GR | n/e | 0.5% | n/e | n/e | n/e | n/e | n/e | 0.2% | 0.2% | n/e |
| HR | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| HU | 0.3% | 0.1% | n/e | n/e | 0.4% | 0.1% | 0.3% | n/e | 0.3% | 0.1% |
| IE | n/e | 15.2% | 15.2% | 15.2% | 15.2% | n/e | n/e | n/e | 35.6% | 15.2% |
| IT | 50.1% | 49.8% | 49.9% | 49.8% | 49.9% | 49.8% | n/e | 49.8% | 49.8% | 49.9% |
| LT | 4.7% | 4.7% | n/e | 4.7% | 4.7% | n/e | n/e | 4.7% | 4.7% | 4.7% |
| LU | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e |
| LV | 0.3% | 0.3% | n/e | n/e | 11.7% | 88.6% | n/e | n/e | 0.3% | 0.3% |
| MT | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e | n/e |
| NL | 1.4% | 0.0% | 35.4% | n/e | n/e | n/e | 9.0% | 3.8% | 1.0% | 9.7% |
| PL | 0.1% | 0.1% | 0.1% | 0.3% | 0.1% | 0.1% | n/e | n/e | 0.0% | n/e |
| PT | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | n/e | 0.0% | 0.0% | 0.0% |
| RO | 0.8% | 0.8% | 0.6% | 100% | 0.9% | 1.1% | 0.8% | 0.7% | 0.8% | 100% |
| SE | n/e | n/e | n/e | n/e | n/e | 1.0% | 1.0% | n/e | 0.5% | 1.0% |
| SI | 50.1% | 0.0% | n/e | 0.0% | 0.0% | n/e | 0.0% | 0.0% | 50.1% | n/e |
| SK | 1.9% | 1.9% | 2.0% | 1.9% | 1.9% | 1.9% | 1.9% | 1.9% | 1.9% | 2.0% |

Figure 3: Share of missing values for different countries for selected technologies [37]

In the end, the hourly data-set has been built by calculating the hourly average power per each source per each country. In Figure 4 average hourly electricity mixes over the day are presented, to highlight the differences among selected countries. Again, the calculations are performed on an hourly basis, which is however difficult to compare on a visual basis.

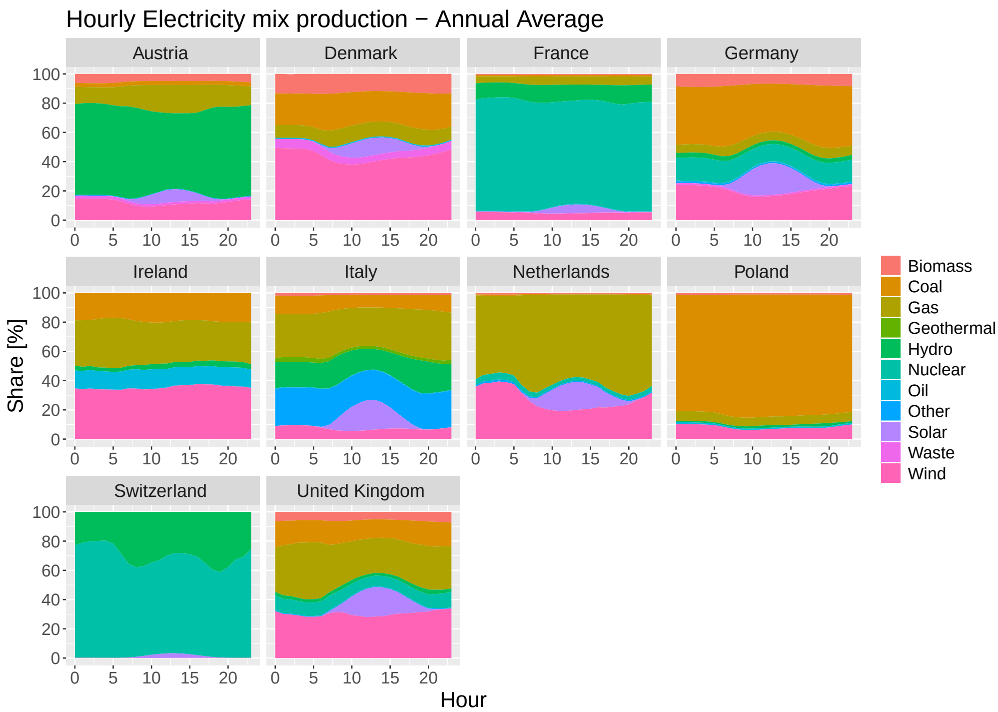


Figure 4: Hourly Production Profiles per Country - Annual Average

The selected countries present very different energy profiles. It is notable the solar contribution in Italy and Germany, and in general in the middle hours of the day. Other countries have a significant share of wind power, and while annual average profiles appear quite smooth, wind power is probably the most variable and non-predictable energy source. Switzerland and France present an important contribution from nuclear power: in the first one, the typical constant profile is integrated by the hydro generation during the day, while in France it seems to follow the demand by maintaining a stable share. The relative share has been presented in the plots, but it is important to remember that during the day the electricity generation show significant variations.

Finally, the effect of import and export has been neglected. While in some countries it may represent a significant share of the final demand, a precise quantification and allocation of all the energy sources involved in abroad generation systems is non-trivial.

### *2.3. Calculation of indicators*

The availability of hourly data for both energy generation and demand allows to calculate the hourly electricity mix throughout the year, together with the primary energy consumption and the $CO_2$ emissions associated with the electricity that is consumed by the HPs.

The most common indicator to quantify and compare different electricity mixes is the $CO_2$ emissions factor of the electricity generation. Usually this factor is calculated as an annual average, as:

$$EF_{annual,mean} = \frac{\sum_i EF_i \cdot E_i}{\sum_i E_i} \tag{1}$$

Where the average annual electricity emission factor ($EF_{annual,mean}$) is calculated as the sum of the product between the specific emission factors ($EF_i$) and the annual power generation ($E_i$) for each energy source, divided by the total power generation in the system.

The approach proposed in this work goes beyond the simple annual average, by defining a weighted average based on the effective electricity consumption profile of each single user. Therefore, the emission factor is calculated by defining an hourly emission factor for each j-th hour:

$$EF_{hourly,j} = \frac{\sum_i EF_{i,j} \cdot E_{i,j}}{\sum_i E_{i,j}} \tag{2}$$

to be used for a weighted average based on the electricity consumption of the heat pump in each j-th hour of the heating season ($E_{HP,j}$):

$$EF_{annual,weighted} = \frac{\sum_j EF_{hourly,j} \cdot E_{HP,j}}{\sum_j E_{HP,j}} \tag{3}$$

This weighted average is a more precise representation of the actual electricity mix related with the HP operation. This indicator will be compared with the annual average for different HP profiles and different countries to assess the range of variation of the results.

In order to calculate the emission factors for the different energy mixes and the HP systems, the Intergovernmental Panel on Climate Change (IPCC) [38] $CO_2$ factors have been considered. The carbon intensity of the different energy sources take into account the emissions related to the whole life cycle of the production plants, from construction to operation and decommissioning. Using life cycle factors allowed us to have a better comparison between the fossil and non-fossil energy sources since, as reported in table 1, also renewable sources, that are usually considered carbon neutral, have an impact (although limited in comparison with fossil sources).

The IPCC values are detailed at [39] and they are extracted from the *IPCC - 5th Assessment Report* [40] and, in particular, from the following two sections [41, 42]. The emission factors are expressed as $CO_2$-equivalent, i.e. taking into account also other gaseous compounds that have an impact on global warming.

## 3. Results

As described in the previous sections, the aim of the study is to evaluate the effect of different electricity mixes in the actual generation mix of the electricity consumption of

Table 1: $CO_2$ emission factors for the different energy sources

| **Energy Source** | **Emission Factor** $[gCO_2eq/kWh]$ |
|---|---|
| Biomass | 230 |
| Coal | 820 |
| Gas | 490 |
| Geothermal | 38 |
| Hydro | 24 |
| Nuclear | 12 |
| Oil | 650 |
| Other | 700 |
| Solar | 45 |
| Waste | 603 |
| Wind | 11 |

an heat pump. In particular, the real HP consumption mix will be compared with the annual production mix of each country, to evaluate to which extent an hourly analysis differs from an annual average, and if the additional requirements in terms of data are justified by the more accurate results that can be obtained.

The bar plots in figure 5 and 7 represent the shares of the national energy mix of Austria and Germany for each of the main energy sources, compared with the corresponding energy mixes weighted for each HP consumption profile. Moreover, each barplot reports the annual average emission factor for each electricity mix (in white at the bottom of each bar) in order to quickly catch the differences between the produced energy and the emissions related to HP consumption.

Additional data for the $CO_2$ emission factors are reported in Table 2, where the mean, maximum and minimum values are recapped for each country.

The plots highlight how the different load profiles produce different shares of energy consumption, due to the different power consumption in each hour of the day and over specific months. In particular, Austria, which relies heavily on hydro power, shows a deep seasonal variability highlighted also from the different EF values in Table 2. For all the different $C_n$ the emission factor is higher than the annual average, and it varies between +9.6% and +1.5%. This is mainly caused by the fact that the hydro power has a high variability during the year: in winter the resource is scarcer, while in spring is abundant as shown in figure 6, where April presents 70% of hydro power share in comparison with lower values for the rest of the winter period.Nevertheless, considering the weighted average values for the HP systems, since energy consumption for heating in April is generally very limited, its weight remains marginal in comparison with the annual generation mix. The mismatch between hydro production and HP energy consumption is compensated mainly with natural gas (Figure 5), increasing the EF of the different HPs profiles.

Conversely, the energy mix in Germany, which is characterized by a more diversified generation mix with a higher contribution from carbon-intensive sources, produces both positive and negative variations of the EF, between +2.4% and -2.9% depending on the specific HP system. The strongest negative variation corresponds to the HP profile C8,

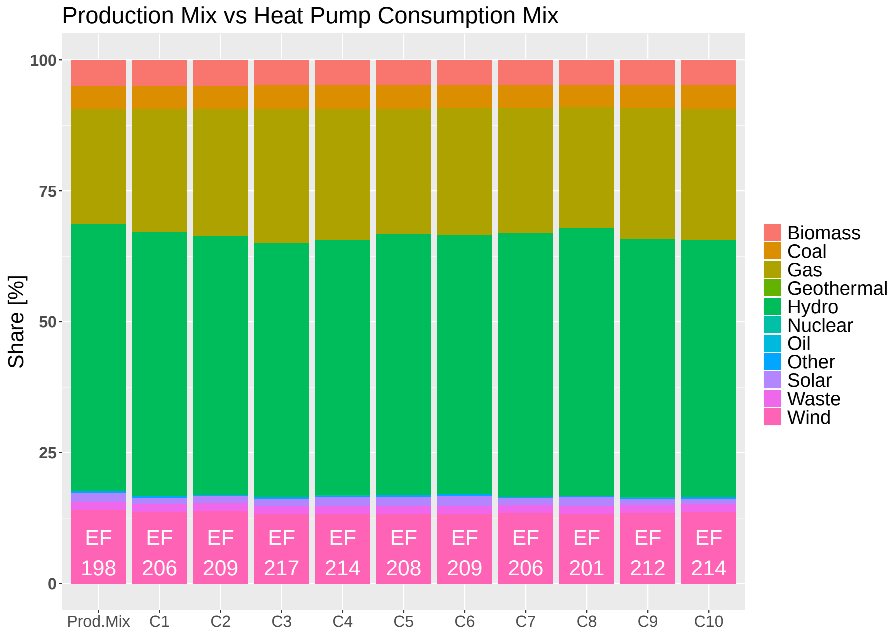


Figure 5: Austria - electricity production mix compared with the electricity consumption mix of the different HP systems

which is characterized by an electricity profiles that better exploit the central hours of the day, especially in spring (see Figure 1), where the generation from solar energy is higher. Moreover, Germany has a more diversified generation mix than Austria, presenting different energy integration possibilities: C7, C8, C9 and C10 present higher wind shares in comparison with the annual production mix, decreasing the overall HP fossil consumption with respect to the other six profiles.

Finally, in figure 8 it is shown the effect of the HP load profile C3 against all the countries taken into account in this study. This load profile has been chosen because it represents quite well the typical residential load profile where HPs is expected to play a key role toward the decarbonization, with both the morning and evening peaks. It is possible to notice that countries, characterized by a higher RES penetration, like Denmark and Austria, present a wide variability on EF. Instead, regions like Switzerland (CH) or United Kingdom (UK), present a much narrow difference due to a limited a production mix, in case of Switzerland, while a good match between consumption and production looking at the UK.

## 4. Discussion

The results presented above show that the calculation of weighted emission factors for the electricity consumed by heat pumps considering different demand profiles and generation mixes lead to different results when compared to a simple annual average value. This result confirms the added value of performing hourly analyses when data are

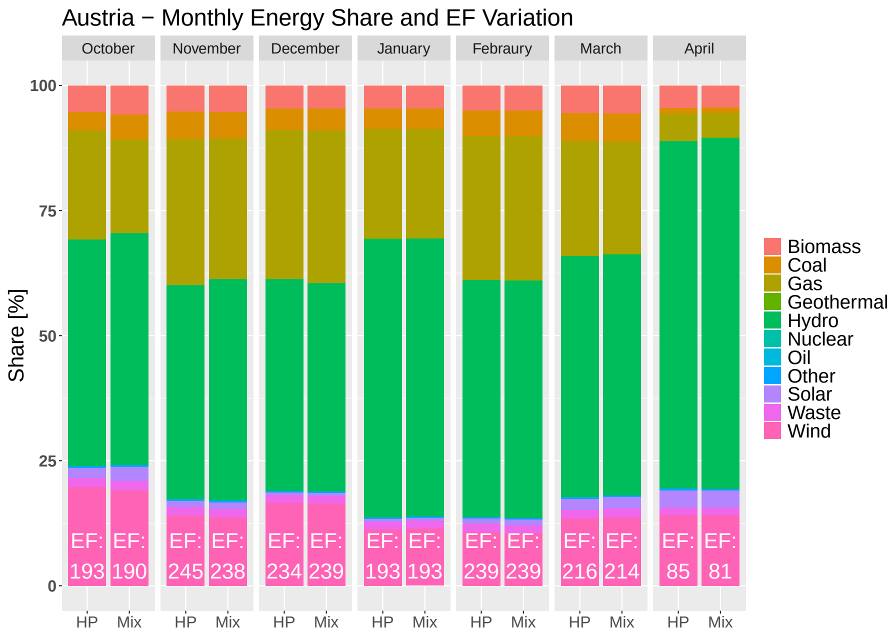


Figure 6: Austria - Monthly variation of the energy mix share and the HP consumption share

Table 2: Summary of the different EF and their variation for the HP systems

| Country | EF - Energy Mix | Mean Difference Absolute Value | Max EF Difference | Min EF Difference |
|---|---|---|---|---|
| | $[gCO_2eq/kWh]$ | [%] | [%] | [%] |
| Austria | 198 | 5,86% | + 9,6% | + 1,5% |
| Denmark | 348 | 4,51% | + 7,5% | + 1,7% |
| France | 67 | 2,54% | + 7,5% | - 3,0% |
| Germany | 420 | 1,52% | + 2,4% | - 2,9% |
| Ireland | 369 | 1,17% | + 1,4% | - 2,2% |
| Italy | 466 | 1,09% | + 1,7% | - 1,1% |
| Netherlands | 360 | 1,28% | + 3,3% | - 1,1% |
| Poland | 765 | 0,39% | + 0,8% | - 0,4% |
| Switzerland | 17 | 0.00% | 0,0% | 0,0% |
| United Kingdom | 326 | 0,58% | + 0,6% | - 2,5% |

available and reliable. However, the difference remains generally limited, with average mean absolute differences on a country basis lower than 5% (with the exception of Austria, with 5.9%). At the same time, the strongest effects appear in Austria and Denmark, both characterized by significant shares of energy generation from RES, suggesting that the expected increase in RES shares in future years in EU countries may increase the gap between hourly and annual evaluations. For specific HP profiles the difference can be as high as 9.6% or as low as -3.0%, but in the majority of the cases the emissions of HPs are underestimated when using annual emission factors. Considering additional demand

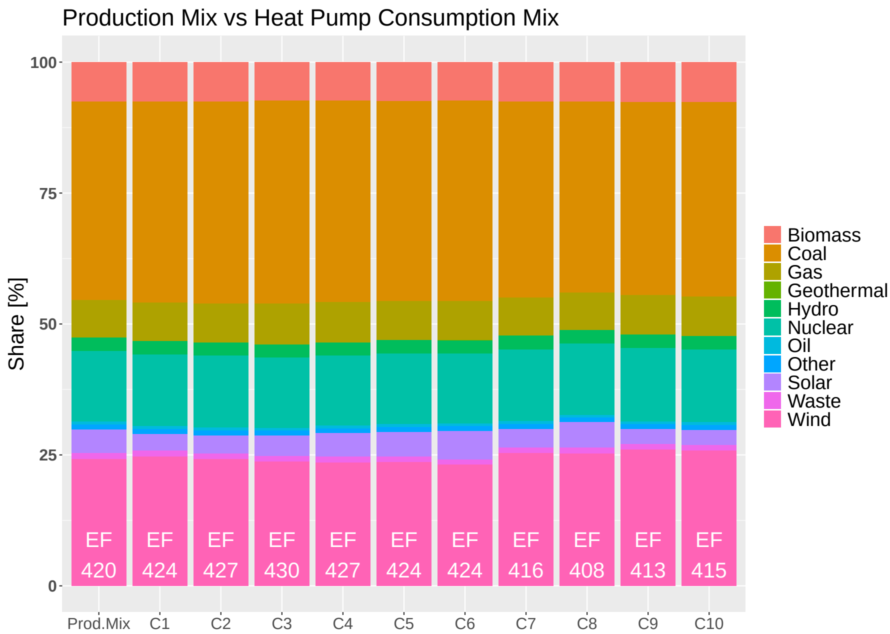


Figure 7: Germany - electricity mix compared with the electricity consumption mix of the different HP systems

profiles may increase this range, but we expect no major differences with the results of this study as long as the current generation profiles are maintained.

In fact, an important aspect to be highlighted is the current limited weight of variable RES in the electricity generation mixes, especially in winter. As highlighted by Figure 6, different behaviours could be expected if the same analysis have been conducted looking at summer time, where solar source has a strong share in some country mixes. The challenging decarbonization goals that are being set by different European countries will require significantly higher shares of integration, which will be also combined with various flexibility options (including storage, demand side response, sector coupling and networks interconnections). In this framework any evaluation on the increased electricity penetration in final users will need to be based on hourly simulations, to provide an accurate and timely evaluation of the emission savings that are obtained.

Moreover, the current analysis is performed on the underlying hypothesis that the HPs are already existing, and therefore they do not modify the current electricity mix of the grid. Conversely, if these results may be used to evaluate the planning of a large number of new appliances consuming electricity, their deployment would increase and possibly modify the shape of the power system demand profile. Additional analyses will be required to assess the potential rebound effects that they may cause on the generation mix, such as increasing the need of dispatching fossil-based generation to compensate the lack of electricity from RES. Again, this aspect highlights the importance of integrated planning of energy demand and supply, as electrification alone is not a solution to decarbonize the energy system, if it is not matched with a parallel deployment

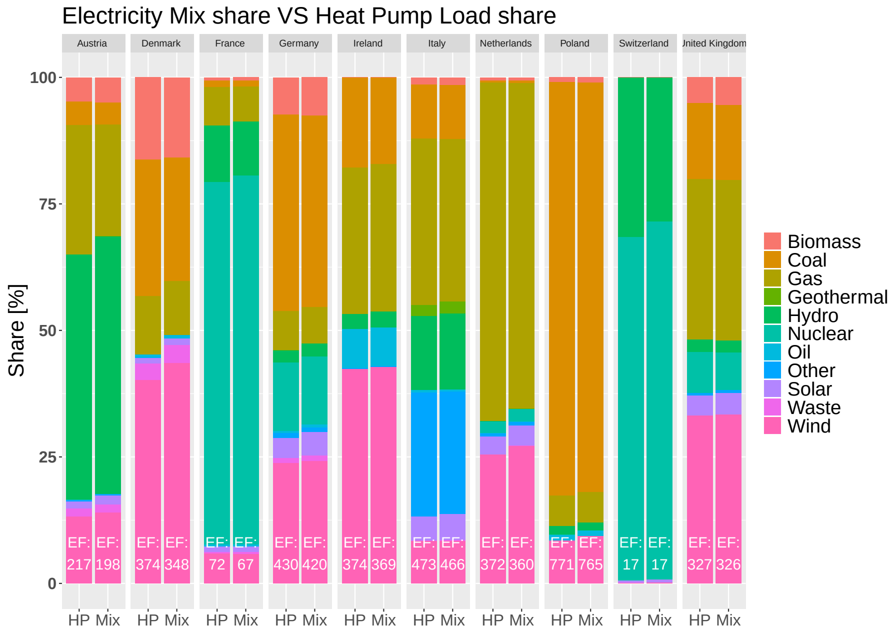


Figure 8: C3 Load profile - Effects on different countries

of power generation from low-carbon sources. Detailed information on the expected consumption profiles for the heating sectors will be key to an effective deployment of flexibility solutions, given the challenges related to the variability of solar and wind resources. HPs themselves could guarantee a certain degree of flexibility when properly coupled to heat storage units and equipped with control systems that can be remotely operated based on optimization algorithms.

For this reason, the role of policies will be crucial in supporting an effective and efficient energy transition. A coordination at different levels and across different sectors is required to ensure the adherence between the expected results from simulations and the actual behavior of energy systems in their real operation. In this context, flexibility will become more and more important, to increase the power grid resilience against the variability caused both on the supply side and on the demand side.

The installation of new HPs should be fostered together with heat storage and advanced monitoring and control systems, to allow a higher degree of flexibility in their operation. At the same time, the optimization of the HPs operation will require updated forecast information on the performance of the electricity system, together with a live feed on the unexpected variations. In some countries virtual aggregators already use advanced optimization algorithms and variable tariffs to try to optimize the operation of several distributed power producers and consumers.

Finally, it is worth remembering that all these aspects need to be based on an economic value awarded to the carbon emission savings that may be obtained. Any system optimization is generally obtained through additional investments and operation costs, that need to be justified in comparison with the benefits. While the environmental benefit may be clear, the lack of an effective pricing of carbon emissions on a wide basis may prove to be a strong burden to the development of decarbonization solutions.

## 5. Conclusions

Heat pumps systems represent a key technology to decarbonize the thermal energy sector, if properly coupled with low-carbon electricity generation. Nevertheless, their power demand profile can substantially change their effectiveness in reducing the $CO_2$ emissions. In this work, an analysis has been conducted by considering a weighted average of the hourly production mix of different countries, on the basis of the hourly demand profile of multiple real HP users in winter season. Depending on the production portfolio it has been highlighted a variability of the emission factor in comparison with the average unweighted emission factor, which is usually the reference indicator for these analyses.

However, it has to be noted that the additional accuracy that can be obtained remains generally limited, thus confirming that for general analyses the additional complexity and the required data may not always be justified. In fact, the average differences for the considered European countries remain lower than 5%, while for specific HP users the differences of the accurate calculation against the average calculation can range from a maximum increase of +9.6% (Austria) and a maximum decrease of -3.0% (France).

The results of this study therefore carry a double message. On one hand, the real electricity mix of the heat pump systems can be reasonably approximated by annual average values, although with very high penetrations of variable RES this result may no longer be applied. On the other hand, for specific demand profiles the actual emissions savings may be overestimated by an annual average analysis.

The results of this analysis may be further improved by considering a larger number of operational profiles of HPs in different countries and for different final users. Furthermore, the analysis could be further extended to summer time operation, since many reversible HPs are also supplying cooling, and RES like solar and hydro are abundant. These analyses are currently limited by the scarcity of reliable historical data of HPs operation with acceptable time resolution. Moreover, the availability of longer historical trends for generation mixes may increase the reliability of the results that have been presented.

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