Primary energy consumption of heat pumps in high renewable share electricity mixes

Original
Primary energy consumption of heat pumps in high renewable share electricity mixes / Jarre, M.; Noussan, M.; Simonetti, M.. - In: ENERGY CONVERSION AND MANAGEMENT. - ISSN 0196-8904. - 171:(2018), pp. 1339-1351. [10.1016/j.enconman.2018.06.067]

Availability:
This version is available at: 11583/2710855 since: 2018-08-22T15:51:48Z

Publisher:
Elsevier

Published
DOI:10.1016/j.enconman.2018.06.067

Primary energy consumption of heat pumps in high renewable share electricity mixes

M. Jarre[a], M. Noussan[a], M. Simonetti[a,*]

[a]*Politecnico di Torino - DENERG, c.so Duca degli Abruzzi 24, 10129, Turin, Italy*

Abstract

The increase of power plants' conversion efficiencies, together with the high share of renewable energy sources in the electricity production for some countries, pushes for the use of heat pumps for space heating when aiming at reducing the associated primary energy consumption. However, the effective reduction of primary energy consumption should be supported by careful evaluations, as a number of parameters influence the heat pumps performance, including outdoor temperature, supply temperature, heat load and electricity primary energy factor. The variability of such parameters increases the complexity of the analysis, and annual or monthly average calculations might lead to incomplete evaluations and thus to sub-optimal solutions. This paper performs a hourly simulation of the operation of an air-source heat pump for space heating, relying on the available heat demand data of real buildings currently connected to a district heating network. In addition, the paper proposes the calculation of the hourly primary energy factor of the electricity supplied by the power grid, as the variability of the generation sources plays a key role in the global analysis of the energy system's conversion efficiency. The results show that in all the considered cases the heat pumps provide potential primary energy savings compared to natural gas boilers, thanks to the combined effect of their high coefficient of performance and the low electricity primary energy factor in the analyzed context. The primary energy consumption reduction obtained in each case is in the range 10% - 40%, with a median value close to 30%. Moreover, the comparison between average and high-resolution calculations of primary energy factors shows the possible underestimation of the potential primary energy savings when yearly or monthly data are adopted.

Keywords: heat pumps, primary energy, simulation, data analysis

1. Introduction

In the past years, there has been an increasing interest in reducing the heat consumption of the residential building sector, as it accounts for about half of total primary energy consumption in Europe [1]. Even if the near Zero Energy Building (nZEB) perspective represents a promising scenario, an increasing amount of literature shows that the number of new constructed buildings in the next years will likely remain very low compared to existing buildings [2]. For this reason, the need for reducing the carbon footprint and the fossil fuel energy consumption of buildings focuses on finding a proper balance between deep renovation solutions and the necessity to decrease the primary energy consumption of existing buildings. In particular, the constraint of operating on existing buildings poses significant barriers to the possibility of acting at large scale on the average insulation levels of buildings and on the structure of the heat distribution system inside the buildings.

Heat pumps (HP) are one of the most promising technologies that could be used to increase the renewable share of energy used for space heating in buildings [3, 4], in particular in countries with high renewable share

*Corresponding author
Email address: marco.simonetti@polito.it (M. Simonetti)

in the electricity generation mix. Italy is one of the European countries where the share of Renewable Energy Sources (RES) for electricity production is higher, with a share of renewables in the electricity generation production in 2015 of about 37% [5]. In this context, even the assumption of the convenience of combined vs. separate heat and power production starts to be questioned [6], opening the discussion about the role of HP for sustainable heat production. On the other hand, the problem of the widespread adoption of HP into the building sector (in Southern European countries in particular) is the difficult matching between this generation technology and the heat distribution and emission solutions that are most commonly adopted in existing buildings. In particular, HP are traditionally found in buildings with low temperature heating systems; on the other hand, medium-to-high temperature radiators represent by far the most common heating emission technology in many European countries [7].

Nevertheless, many solutions, like the adoption of climatic regulation and the installation of thermostatic valves, can help decrease the water temperature needs of these heating systems [8]. Moreover, the data-analysis carried out multiple works [9, 10] has shown that a significant gap exists between the nominal operation of plants and generation systems and their real-time operation. This gap is caused by different factors but it is important to highlight that only by analyzing real-operation data (and not only design/nominal ones) can the actual behaviour of a system be studied and truly understood [11]. As shown in this paper, for example, a detailed analysis of real weather data shows that the very-low outdoor temperatures that are commonly used as design parameters for heating systems occur rarely even on a hourly basis over a full heating season; if a climatic regulation is adopted in a building, therefore, also the maximum water supply temperature is seldom (if never) reached, and the average one is in fact much lower. This qualitative consideration suggests that HP and hybrid systems - i.e. a HP and a traditional natural gas boiler (NGB) working alternatively - could reach average efficiencies much higher than those calculated at ‘nominal’ conditions [12], due to the large variability of HP performances in off-design conditions [13]. Much research work has been done in the field of HP energy simulation and modeling [14, 15, 16], as well as optimization tools as a support for HP design and sizing in space heating applications [17, 18, 19]. Some studies have also estimated the energy consumption of the HP by including temperature-dependent coefficients of performance [20].

However, the overall system efficiency of a HP must be calculated by taking into consideration the primary energy factor (PEF) of each electricity generation system; such calculation has been proposed in [21] through the use of yearly average values. The PEF, which is characteristic of every generation mix, is strongly variable on a hourly basis in those countries (like Italy) in which the share of non-programmable renewable sources in the electricity sector is high. This variability should also be taken into account when evaluating the real performance of HP in terms of consumed primary energy [6]. Other authors have recently highlighted the importance of considering dynamic boundary conditions of the power grid to evaluate the primary energy consumption of HP (e.g. for Germany see [22]). Conversely, a massive development of HP could in turn have an impact on the electricity demand profiles at national level (e.g. an estimation for UK has been performed in [23]); such effect shall be taken into account for future local energy planning evaluations.

The previous considerations form the basis of the work presented in this paper, in which the use of air-source HP for space heating of the case-study buildings stock is simulated and the results are compared with a baseline scenario. The analysis is based on real data monitored at a hourly time step, which allow to accurately simulate the HP behaviour under different off-design conditions, which have a strong influence on the annual performance. The accuracy of the primary energy calculation is related to the use of both time-dependent outdoor temperature - and therefore HP coefficients of performance - and time-dependent PEF of the electricity production in Italy to account for the boundary conditions in which each HP is operating. Results might therefore be quantitatively different depending on the considered country because of different weather conditions and electricity mixes, but the results obtained in this paper can be qualitatively extended to other cases that have comparable boundary conditions.

2. Methodology

The aim of the study is to compare different generation technologies for satisfying heat demand of the case-study buildings stock in terms of primary energy consumption. The heat demand and the supply/return temperatures profiles of buildings served by a District Heating (DH) network are here taken as input data; DH networks are currently the only context in which detailed data for a large number of buildings are being monitored and stored. In fact, the possibility to study the secondary side of a large number of buildings is precious since it allows to simulate the effect of different generation technologies for producing the same heat demand at the same temperatures as those produced by the DH network.

Four different scenarios are proposed for heat generation through different technologies / combination of technologies:

1. **Electric Resistance (*ER*)**: a simple electric resistance (ER) with constant efficiency is used.

2. **Natural Gas Boiler (*NGB*)**: a non-condensing NGB with constant efficiency is simulated.

3. **Heat Pump + backup Electric Resistance (*HP+ER*)**: an air-source HP is used if the required water supply temperature does not exceed the operational limit defined for the analyzed unit. Otherwise, a backup ER is operated. The Coefficient Of Performance (COP) of the HP is a function of both outdoor temperature T_{out} and water supply temperature T_{sup}; it is therefore calculated on a hourly basis for each building through the available data (see figure 1).

4. **Hybrid Natural Gas Boiler and Heat Pump + backup Electric Resistance (*NGB+HP+ER*)**: either the 'NGB' or the 'HP+ER' scenarios are applied alternatively based on the primary energy consumption of each solution. This last scenario represents therefore the 'minimization' of the primary energy between the two previous ones.

The HP reference COP is defined as a function of outdoor temperature T_{out} and water supply temperature T_{sup}. A double-fluid cascade HP model commercially available (using R410A as low cycle fluid and R134a as high cycle fluid) has been considered in this section as reference model; the characteristic curves of the analyzed HP are represented in figure 1 as a result of an elaboration from data reported in [24].
Figure 1 reports data as declared by the manufacturer of the high temperature HP considered as the case-study for this work. Such technology is normally constituted by a double-fluid (also referred to as cascade cycle) HP in which two different heat transfer fluids are used and in which an additional heat exchanger is adopted for heat transfer between the two. In the analysed case, R410A is used at the lower temperatures (outdoor circuit in winter mode) while R134a is used at higher temperatures (indoor circuit in winter mode) thus allowing the HP to reach supply temperatures as high as 80°C, even if with considerably lower efficiency levels with respect to the nominal ones.

Figure 1 shows that a double negative effect on COP exists: COP decreases as T_{sup} increases and as T_{out} decreases; also, it can be noted that COP average value decreases rapidly in correspondence of the defrost cycles that occur when outdoor temperatures are close to 0°C. The COP trends reported in the chart represent hourly values, i.e. the defrost cycles result in a decrease of the average COP. However, even at maximum $T_{sup} = 80°C$ and minimum $T_{out} = -10°C$ the COP minimum value is still equal to about 1.5. An additional parameter that has an influence on the defrost cycle is the air humidity [16, 25]. However, few information is available on its impact on the actual COP, in particular for the chosen commercial HP model. For this reason, the COP values reported in [24] have been reduced by considering a constant reduction factor that has been applied to each COP function. The effective values of COP are therefore calculated as:

$$COP_{HP} = COP_{HP,nom} * r_{COP} \tag{1}$$

where COP_{HP} is the effective value of COP adopted for the calculations (as a function of outdoor temperature and water supply temperature), $COP_{HP,nom}$ are the nominal values reported by the constructor in [24] and r_{COP} is the COP reduction factor due to the aforementioned influences on the performance of the HP. This reduction factor aims also at taking into account possible differences between the nominal values declared and measured by the HP constructor and the real-life functioning of the device. For the initial scenario analysis, it has been assumed:

$$r_{COP} = 90\% \tag{2}$$

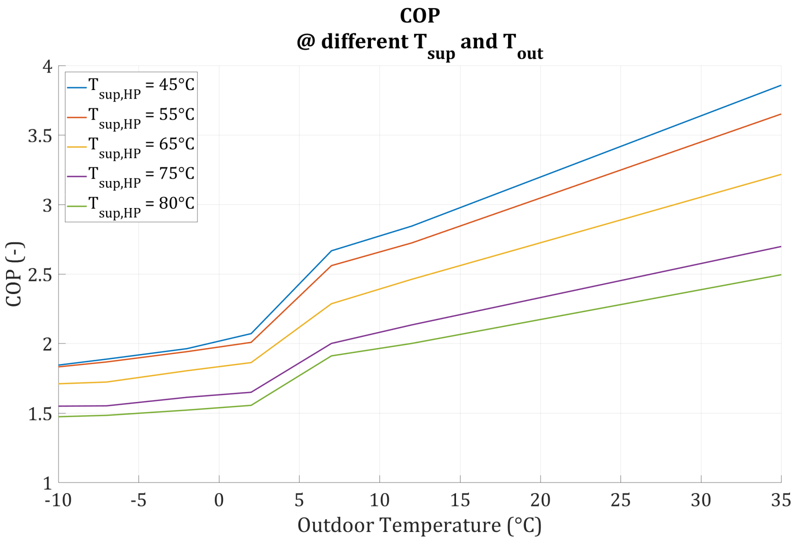

Figure 1: $COP_{HP,nom}$ as a function of outdoor temperature and water supply temperature.

or a reduction of 10% on each calculated value of COP for given pairs of outdoor temperature and supply temperature values. In section 3 a sensitivity analysis of the results with respect to this parameter is reported to study its influence on the obtained primary energy consumption values and the comparison among the different scenarios.

The NGB, on the other hand, is set to have a constant thermal efficiency $\eta_{NGB} = 0.90$, as its variations with supply temperature are lower than for HP. No condensation effect has been considered in this analysis in order to (1) simplify the results comparison; (2) take into account the fact that traditional, non-condensing boilers represent the most common type of NGB currently installed in residential buildings, especially in those equipped with high temperature radiators. A further study could take into consideration condensing heat boilers as additional generation technology, by including in the analysis the return temperature of each system.

2.1. Case studies - buildings stock

The analyzed buildings stock was initially composed of a total of 85 buildings located in the south-center of Turin, Italy. All of the buildings considered are residential. It has to be noted that the term residential is here used as a general term for non-tertiary/non-industrial, but no real specification is made about the activity or occupation type that characterizes the building. In fact, many offices are present within the studied building, but their energy consumption profile or the control unit sets are identical to that of pure-residential buildings.

Within the initial subset, 11 buildings were excluded in which DH provides Domestic Hot Water (DHW) together with heating. 26 more buildings were excluded since the recorded values of supply temperature were not reliable or were completely missing. The final buildings stock is therefore composed of 48 buildings. The only readily available construction information for each building are the address and the gross heated volume, varying between 2,000 m^3 and 20,000 m^3.

The buildings are characterized by variable construction features, geometry, occupation and age of construction. The target of the carried analysis is to build a model to simulate the performance of a HP in different operational conditions; for this reason, only the gross heated volume and the data derived from the substation control unit have been used to build the model.

A number of parameters and variables from the control unit sets and operational data were available for each of the studied substation. A major problem was represented by the fact that several useful parameters were not available for all the substations but only for sub-sets of them. Moreover, the historical period to which the initial dataset referred to was not homogeneous across substations; for this reason, intensive data cleaning and preparation was required to make the dataset homogeneous and suitable for comparative analysis.

In most cases, the original dataset was composed of variable readings from the substation control unit at 6-7 minutes time-steps. Since the time-step itself was not uniform across buildings and within the single building, data preprocessing was carried out in order to average all the available data to uniform hourly time steps; such value has been considered appropriate to balance different needs: (1) the necessity to avoid excessive instantaneous variations that could be due to meter readings sensitivity;(2) the necessity to have coherent time steps with respect to other data (outdoor temperature, electricity PEF); (3) as previously stated, the need to make the whole dataset homogeneous across and within buildings.

2.2. Preliminary weather analysis

Figure 1 shows the dependency of COP on the outdoor temperature; in particular, the common practice of design procedures considers a certain temperature as the lower limit for HP operation convenience; such limit is usually set around 5° C since at this temperature defrost cycles are necessary in order to prevent ice formation at the evaporation side of the HP. The negative effect of defrost cycles on COP is clearly visible in figure 1. For this reason it is interesting to carry a preliminary statistical data analysis of weather data, aimed at evaluating the effective occurrence of lower temperatures in typical northern Italy climates. Figures 2 and 3 report the relative and cumulative relative frequency of outdoor temperatures for the three most populated cities of northern Italy (Milan, Turin and Genoa); the 5° C limit temperature is also reported in red. The weather data are reported as hourly averages and they have been collected from one representative weather station for each city over a total period of 12 years (2005-2016), thus constituting a reliable and statistically significant dataset. For simplicity, the considered period has been set equal to the heating season of Turin and Milan, i.e. 15^{th} October - 15^{th} April (the heating season of Genoa is shorter). Figure

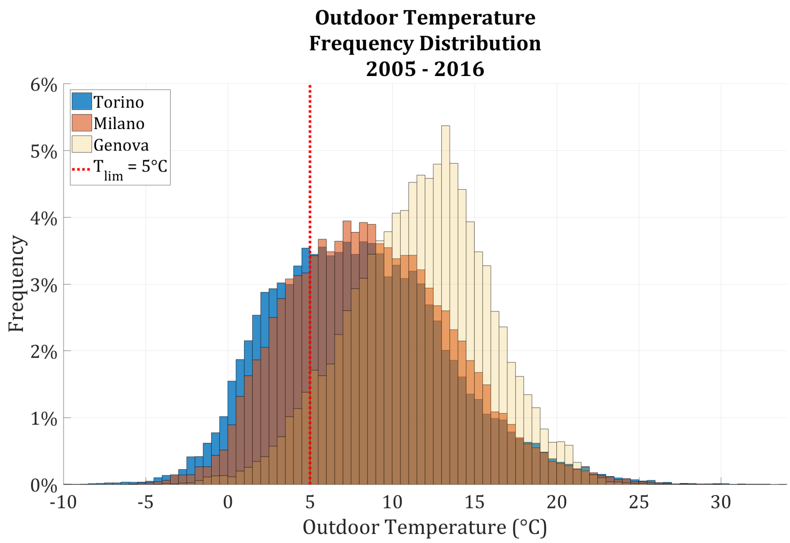

Figure 2: Relative Frequency Distribution of Outdoor temperature (15 Oct - 15 Apr).

3 shows that both in Milan and in Turin the limit temperature of 5° C has been reached in less than 30% of the hours in the last 12 years; in the city of Genoa this limit has been reached in less than 10% of the hours. This preliminary analysis suggests that excessively low temperatures are not predominant within major cities in Northern Italy. Two additional considerations must be made about the carried analysis:

1. The whole 24h day has been considered for the weather data collection, both for ease of interpretation and for keeping results generally valid; on the other hand, it must be noted that most of the residential

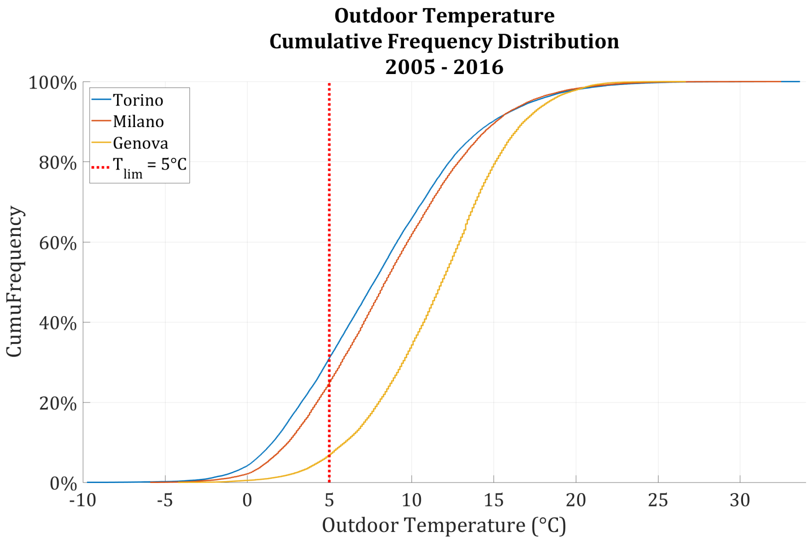

Figure 3: Cumulative Relative Frequency Distribution of Outdoor temperature (15 Oct - 15 Apr).

buildings are never heated in the central hours of the night (approximately 1 a.m. - 5 a.m.), which are also the coldest ones. If a specific analysis would be made considering only temperatures in which the building has been actually heated (e.g. 6 a.m. - 10 p.m.), the temperature levels would have been even higher than the reported ones.

2. The reported temperatures have been collected by weather station data, that are considered to be the most reliable and accurate ones. Some local effects, however, can contribute to a slight change in the actual temperature in different locations, even if the general trend cannot differ substantially between two different measurements in the same location.

2.3. Electricity primary energy factor

The primary energy factors for the electricity consumed by the HP and the ER are equivalent to those of the generation mix of the country in which they operate. The primary energy factor is the ratio between the primary energy consumption (PE_{EE}) needed for the electricity production on the network, and the electricity production itself (EE):

$$PEF = \frac{PE_{EE}}{EE} \tag{3}$$

The calculation of the PEF of the electricity produced by the Italian power grid has been performed on a hourly basis for the period 2011-2016 by considering the actual share of electricity produced by thermoelectric, hydro, PV, wind and geothermal plants (authors' elaboration on data from [26]).

The necessity to consider a hourly PEF is related to the increasing share of non-programmable, unpredictable RES in the electricity mix of Italy, which is similar to the evolution of other countries in Europe and around the world. The sustainability goals push for the implementation of increasingly high shares of renewables within electricity mixes, and solar and wind play a significant role in such transition. As a result, the primary energy consumption for electricity production can show a greater variability both on a seasonal and daily basis in comparison with traditional, fossil-fueled power plants production. Currently, the increasing available information on the power mix supports high time resolution analyses that can provide more reliable results, as highlighted in section 3.3.

The calculation of a hourly PEF requires some hypotheses about the conversion efficiency of the power plants supplying the network. For the thermoelectric plants only aggregated data were available that did not allow to distinguish among the different used fuels; the share of each fuel has thus been approximated as the annual share declared by Terna [27] (i.e. 64.7% gaseous fuels, 32.5% solid fuels and 2.8% petroleum products). The annual average PEF of the thermoelectric power plants that has been used is 2.21 (calculated from actual data of 2015). This indicator was equal to 2.30 in 2014, showing an increase of the average conversion efficiency, due to renewal of some generation units and an increased use of more efficient fuels. The PEF for geothermal power plants has been set to 10, while the other RES (wind, PV and hydro) have been considered with a PEF of 1. For the calculation of the renewable share, 10.4% of the thermoelectric power plants has been considered as renewable (biomass, biogas, organic share of Municipal Solid Waste, etc. according to Terna [27]).

Figure 4 and figure 5 show the variations over the months and hours respectively of the calculated PEF for the year 2015 only, showing that:

1. The PEF has never been higher than 2.5 on a hourly basis over the whole year.
2. The 3^{rd} quartile of the hourly values of PEF are never higher than 2.25, i.e. the PEF has been lower than this value for 75% of the hours in the year (i.e. around 6.570 hours).
3. The impact of PV plants is clearly visible as a significant decrease of PEF during summer months and in the central hours of the day; similarly, it is clearly visible the impact of the use of hydro plants as peak units during the day, with the effect of lowering the PEF and increasing the renewable share.

In figure 6 it is then reported the PEF vs. the RES share of the power plants for the different months, highlighting the clear relation between these two indicators.

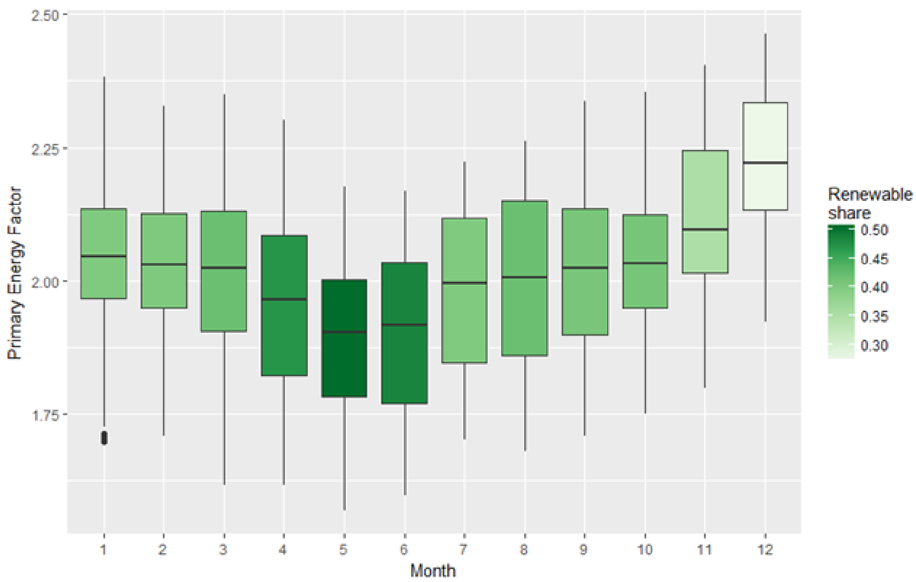

Figure 4: Box-plot of monthly values of PEF in Italy (2015).

2.4. Primary energy consumption for space heating

The different technologies considered in this analysis have been compared by means of their primary energy consumption.

A HP supplying a building with a heat quantity Q_{supply} , which is the gross heat demand of the building and includes all the efficiencies of the system (beside that of the heat production unit), would have a primary energy consumption PE that is calculated as:

$$PE_{HP} = PEF * EE_{HP} = PEF * \frac{Q_{supply}}{COP_{HP}} = \frac{PEF}{COP_{HP}} * Q_{supply} \tag{4}$$

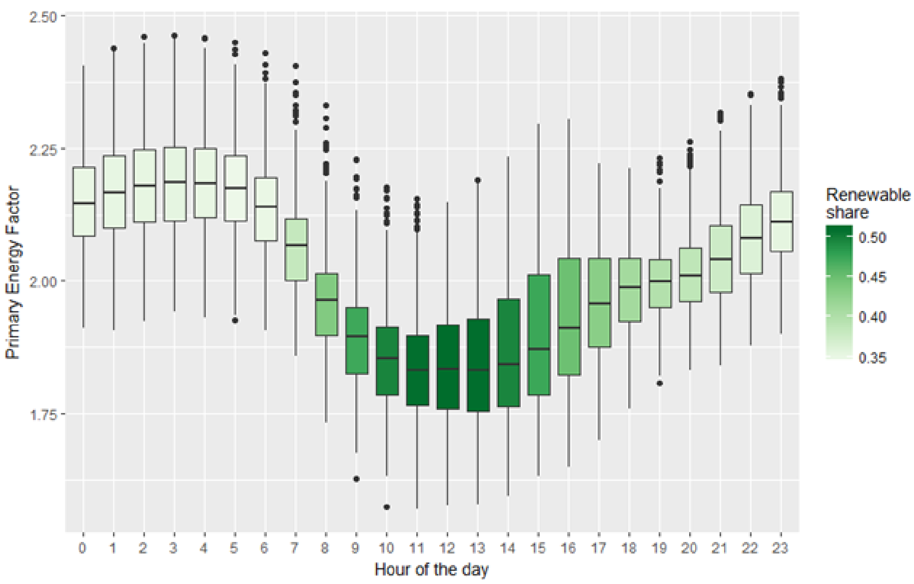

Figure 5: Box-plot of hourly values of PEF in Italy (2015).

where EE_{HP} is the electricity consumption of the HP. The primary energy consumption of an electric resistance would be simply equal to that of a HP with COP=1, while that of the NGB is here supposed to depend uniquely on the boiler's efficiency as:

$$PE_{NGB} = \frac{Q_{supply}}{\eta_{NGB}} \tag{5}$$

The previous equations show that, in principle, an HP would have a primary energy consumption that is lower than that of a NGB if:

$$PE_{HP} < PE_{NGB} \tag{6}$$

$$\frac{PEF}{COP_{HP}} * Q_{supply} < Q_{supply}\eta_{NGB} \tag{7}$$

$$\frac{PEF}{COP_{HP}} < \eta_{NGB} \tag{8}$$

If η_{NGB} is taken as a constant value, it is clear that the ratio between PEF and COP_{HP} must be analyzed to establish which generation solution has the lowest primary energy consumption. Since, as shown, both COP_{HP} and PEF have variable profiles, this evaluation cannot be made by simply looking at nominal values but should be made punctually considering the actual profiles of each variable, as proposed in this work.

Finally, an electricity losses factor of 10.4% has been calculated by summing up electric transmission losses for high, medium and low voltage transmissions [27]. Such losses factor *allows us* to calculate an average electricity network efficiency $\eta_{net} = 89.6\%$; such factor has been applied constantly over the year to calculate the effective primary electricity consumption associated with the electricity consumption of a HP for heat production, as in:

$$PE_{HP,real} = \frac{PE_{HP}}{\eta_{net}} = \frac{PEF}{\eta_{net} * COP_{HP}} * Q_{supply} \tag{9}$$

Equation 9 shows that the effect of the electricity network losses is equivalent to that of a decrease of the COP of the HP. It has to be remarked that the COP of the analyzed HP had been already diminished conservatively by a factor of 10% with respect to the values declared by the constructors.

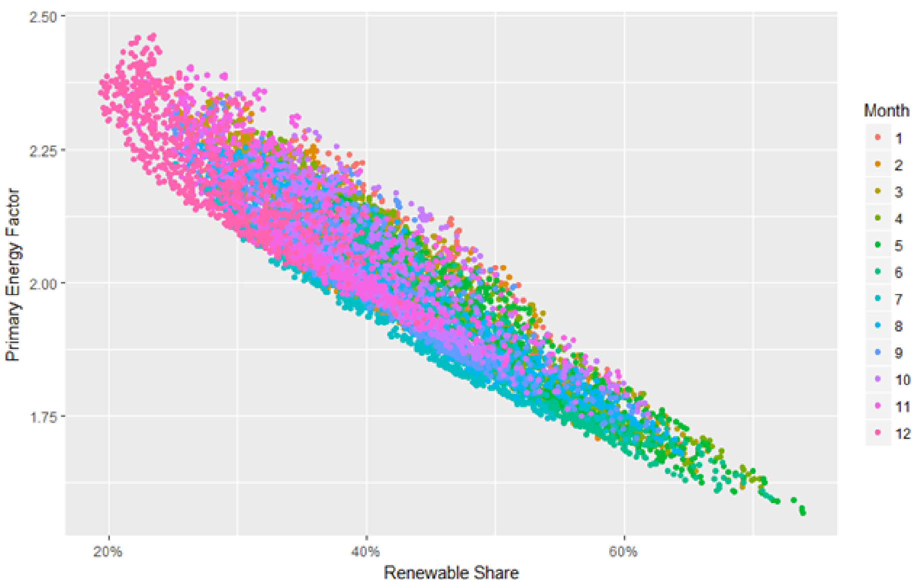

Figure 6: Hourly Correlation between PEF and RES share.

Finally, the results obtained with variable PEF calculation have been compared with those obtained with the average PEF calculation from hourly values, as well as the value of PEF provided by the Italian Regulation (i.e. $PEF = 2.42$ from [28]).

3. Results

No renovation is hypothesized on the heat distribution and emission systems of the studied buildings. For this reason, the measured water supply temperature T_{sup} must be guaranteed at any time in order to ensure that thermal comfort conditions equivalent to the current status are kept. For the same reason and since the transmission and ventilation losses of each building are unchanged, the thermal power hourly profile P_{th} is also a fixed constraint and is not modified with respect to the current ones in each building.

Demand profiles of specific buildings are reported to discuss some relevant aspects, while results relative to the buildings stock are analyzed to discuss the whole picture.

3.1. Energy profiles of specific buildings

In figure 7 an example of the real water supply temperature distribution for one building shows that (1) the mean and median temperature values are much lower than the nominal one; (2) for the given example, a supply temperature lower than 60°C is required for almost 50% of time; (3) for a total of 95% of time such temperature is lower than 70°C, even if the nominal supply temperature value is equal to 80°C. An additional example is reported in figure 8, for which analogous considerations can be made; these two example buildings have been chosen since they are characterized by different design supply temperature values, and are therefore representative of a vast majority of the considered buildings.

In terms of primary energy consumption, the four scenarios have been compared and the results are reported in the following figures. The daily average profile of the COP_{HP} value for the third scenario (HP+ER), that is to be compared with the daily max/mean/min values of the PEF, is also reported. In figures 9 to 12 an example of the primary energy profile for the central days of January and a comparison between daily average values of COP and PEF for one year are reported.

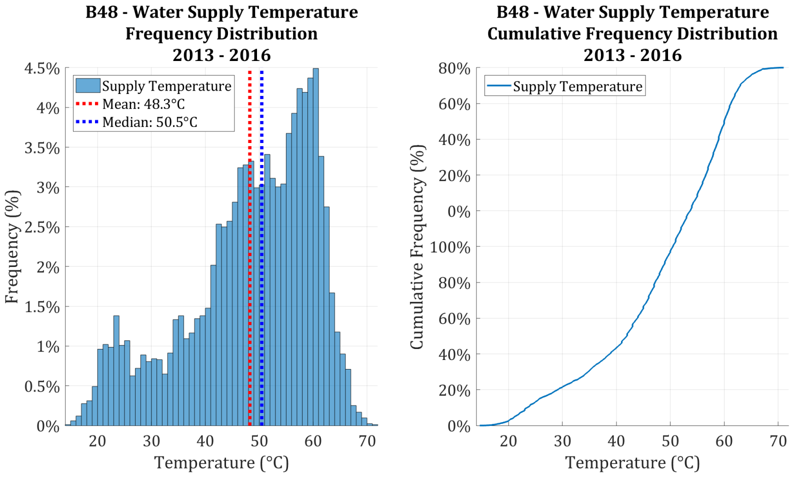

Figure 7: B48 - Water supply temperature relative and cumulative relative distribution.

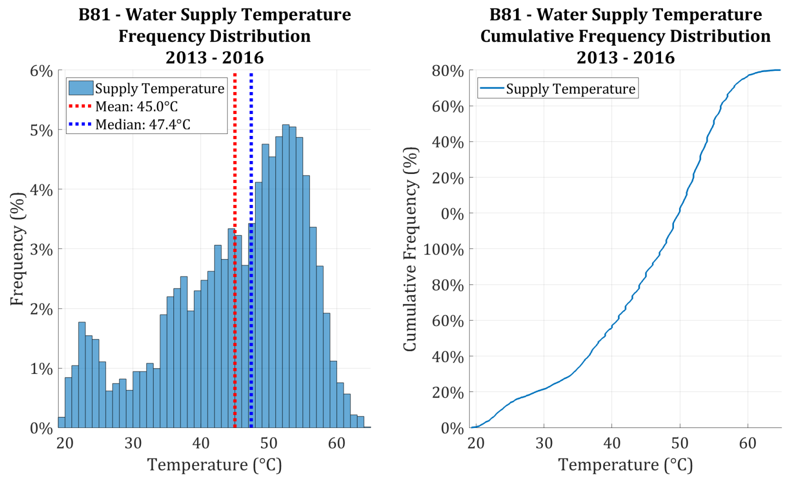

Figure 8: B81 - Water supply temperature relative and cumulative relative distribution.

3.2. Analysis of the entire buildings stock

The results discussed above for single buildings can be extended to the entire buildings stock that has been considered for this analysis. In figures 13 and 14 the results for all the analyzed buildings are summarized in terms of primary energy consumption difference with respect to the NGB scenario taken as the baseline one (i.e. = 100%). As expected, the *ER* scenario is characterized by a primary energy consumption that is always much higher than that of the *NGB* scenario. This result is trivial and is led by the fact that the use of an ER is practically always less favorable than that of a HP since the COP_{HP} value is never lower than 1 even at very high supply temperature values or very low outdoor temperatures (see figure 1).
On the other hand, it is interesting to note that the *HP+ER* and *HP+ER+NGB* scenarios are characterized by lower primary energy consumptions than that of the *NGB* scenario for most of buildings and most of the time. If the reported examples are considered, it can be noted that the COP average daily value of the HP is often higher than the maximum value of the PEF; this is mainly due to the low water supply temperature levels that characterize some buildings.

In figure 15 the results of the calculation with variable PEF and constant PEF values, both with a real average calculated as the mean of the available hourly values and the reference value provided by the National Regulation, are reported. Two distinctive boxplots show the variability within the analyzed buildings stock by reporting the mean value over the whole buildings stock of the primary energy consumption reduction

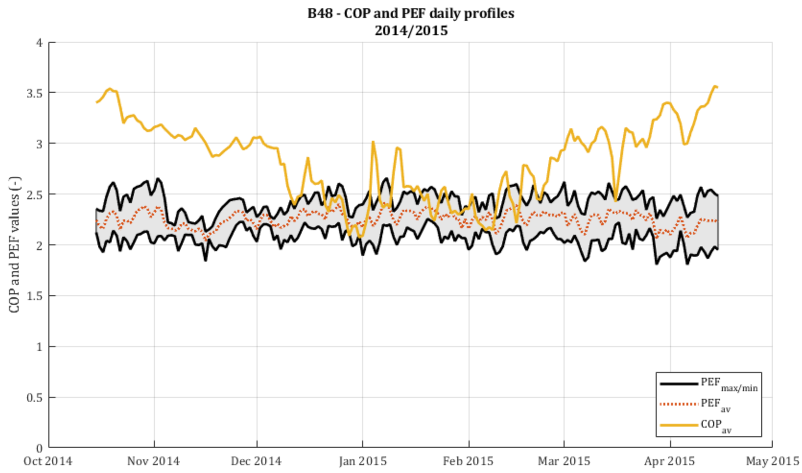

Figure 9: B48 - COP vs. PEF Daily Profile.

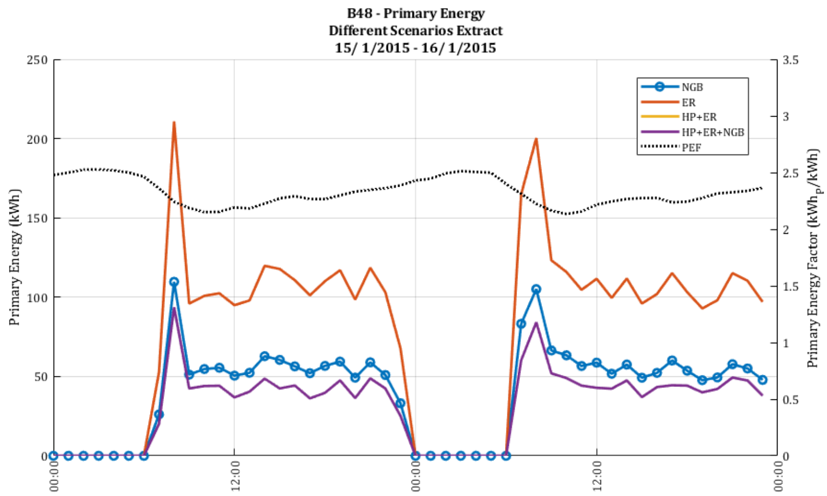

Figure 10: B48 - Primary energy profiles for different scenarios.

with respect to the reference NGB case. The plot clearly shows the results obtained through the different calculation methods, with the hourly one being the most favorable towards the operation of HP with respect to NGB in both 'HP+ER' and 'HP+ER+NGB' scenarios. In particular, the primary energy saving calculated through hourly values has a median value about 8% lower than the one obtained by using the normative reference value.

3.3. Sensitivity analysis

The obtained results have been derived from the application of the proposed model to a total of 48 buildings. The proposed methodology includes some fixed coefficients, in particular for the calculation of the COP_{HP} and the NGB efficiency. As previously stated, a reduction factor of 90% has been applied for the determination of hourly COP with respect to the values declared by the constructor in [24]; a constant value of 90% has been adopted for the hourly average efficiency of the NGB. In order to evaluate the role of these parameters in the procedure, a sensitivity analysis has been performed in which they have been varied and the different scenarios are consequently re-calculated. In particular, the following ranges were adopted

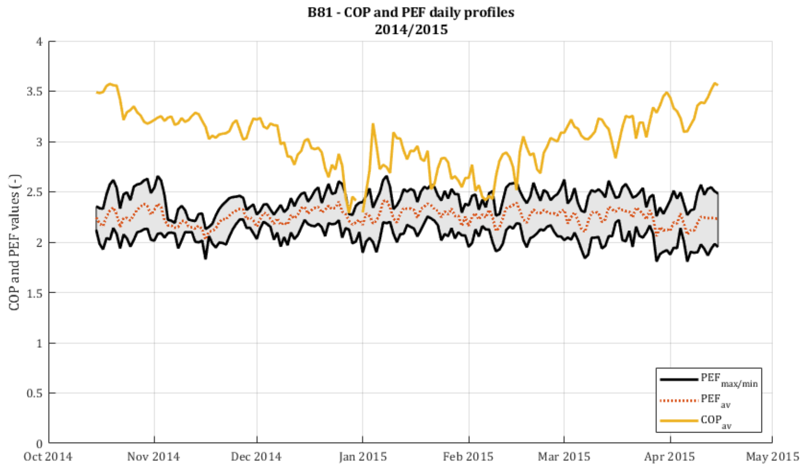

Figure 11: B81 - COP vs. PEF Daily Profile.

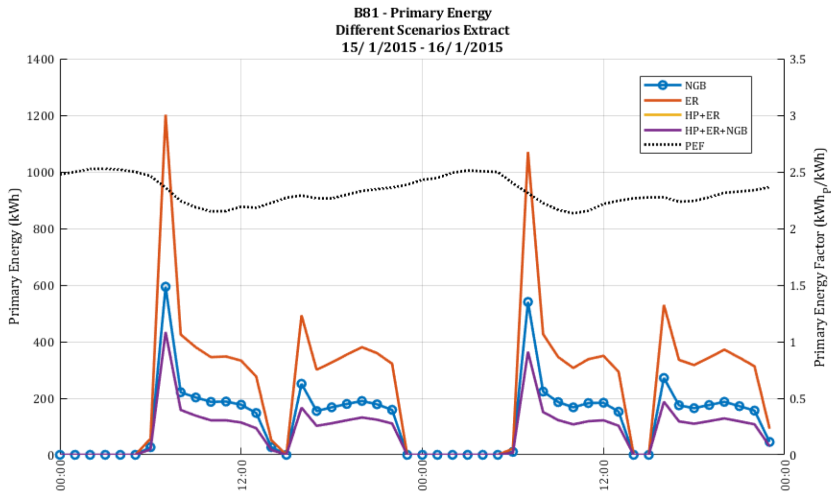

Figure 12: B81 - Primary energy profiles for different scenarios.

for the two parameters:

$$r_{COP} = [70\% - 75\% - 80\% - 85\% - 90\% - 95\% - 100\%]$$
$$\eta_{NGB} = [85\% - 87.5\% - 90\% - 92.5\%] \tag{10}$$

The original scenario was calculated, as previously stated, with values of $r_{COP} = 90\%$ and $\eta_{NGB} = 90\%$; the results were reported for the single buildings in terms of 'primary energy consumption' and 'primary energy consumption reduction' with respect to the *NGB* scenario. In the proposed sensitivity analysis it would be impractical to report the results for each single building and each single configuration and scenario. For this reason and similarly to what done previously for the different PEF calculation methods, the primary energy consumption reduction with respect to the *NGB* scenario is calculated for the whole buildings stock as the mean of the values for the single buildings; this makes it possible to actually compare the different scenarios.

In figure 16 the sensitivity analysis results are reported; each figure is relative to one value of the η_{NGB} parameter, and the different values of the r_{COP} parameter are reported on the x-axis. As previously done, the *NGB* case is taken as a reference scenario, and the *ER* scenario is not shown since not interesting for

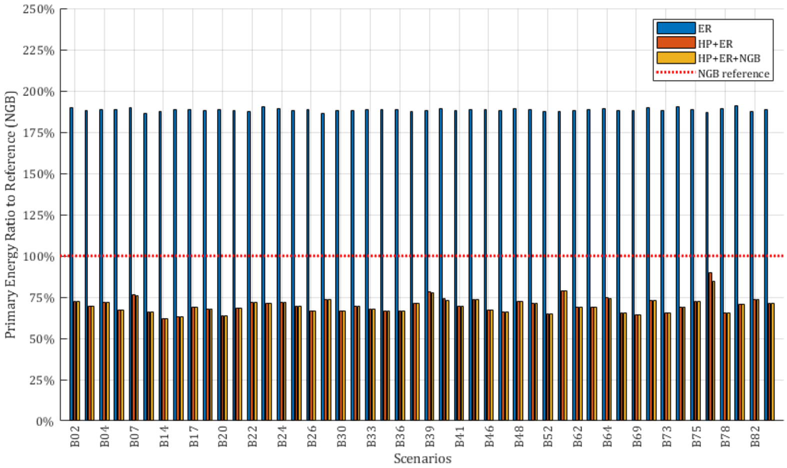

Figure 13: Scenarios comparison: primary energy savings for all the buildings.

the obtained results. The sensitivity analysis shows that the results of our simulations are, in qualitative terms, almost independent from the values of the parameters. In fact, while the absolute values of the estimated primary energy consumptions can vary as a function of the parameters values, the comparison among different scenarios confirms the same order of performance index. The increase of η_{NGB} decreases the convenience of adoption of the HP as expected; on the other hand, only for values of η_{NGB} as high as 92.5% the difference in terms of primary energy consumption between the two scenarios is lower than 10%. Moreover, this happens only for very low values of the COP reduction factor r_{COP}. In fact, only for the 'worst-case' scenario of $r_{COP} = 70\%$ and $\eta_{NGB} = 92.5\%$ the HP+ER scenario has a primary energy consumption that is less than 10% lower than the NGB baseline scenario. Nevertheless, the hybrid scenario of HP+ER+NGB is characterized even in this 'worst-case' by an 11% primary energy saving with respect to the NGB scenario, therefore proving the robustness of the proposed methodology and the convenience of the adoption of HP in terms of primary energy consumption in the analyzed context.

Finally, it is interesting to note that the difference between scenarios 3 and 4 (HP+ER and HP+ER+NGB) increases as the COP reduction factor is increased, thus confirming the suitability of the hybrid solution in all the cases in which the HP is expected to work consistently out of its nominal conditions.

4. Discussion

This paper has been focused on the study of the primary energy consumption of different technologies, but other aspects are worth mentioning.

The results have been obtained by considering the current heat profile of the buildings, which includes a night set-back control resulting in a significant peak during the morning. Other approaches are possible, and could potentially help in lowering the supply temperatures of the systems. An example could be the constant operation of the system 24/7, possibly resulting in increased total energy consumption but at the same time lower peak demand and, depending on the site, lower supply temperatures. This could lead to higher COP_{HP} and potentially to higher efficiencies when considering primary energy consumption. However, such calculation would require a complex simulation based on detailed data about the buildings' characteristics, as the indoor comfort conditions should be guaranteed with every operation logic. These simulations could be tested in future research carried out on a more limited number of case studies.

Even if in many buildings the difference between scenarios 3 and 4 is quite small in the carried analysis, several factors suggest that the installation of a hybrid system could constitute the most flexible and reliable solution: (1) in case of (rare) lower temperatures, the heat production would be guaranteed; (2) the outdoor

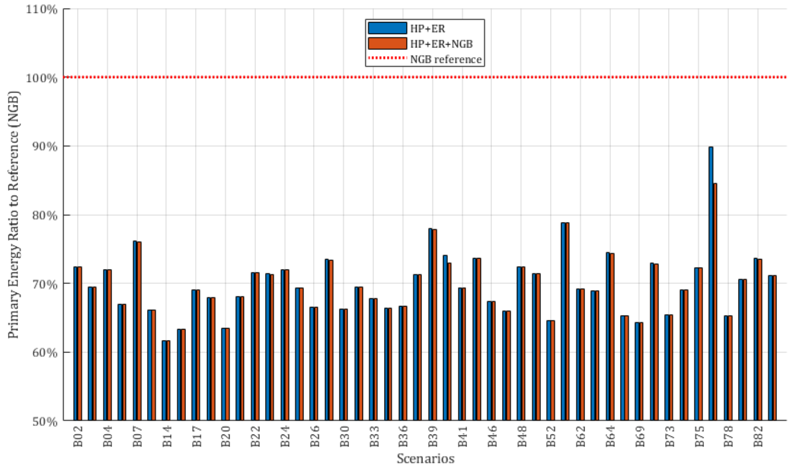

Figure 14: Scenarios comparison: primary energy savings for all the buildings - detail.

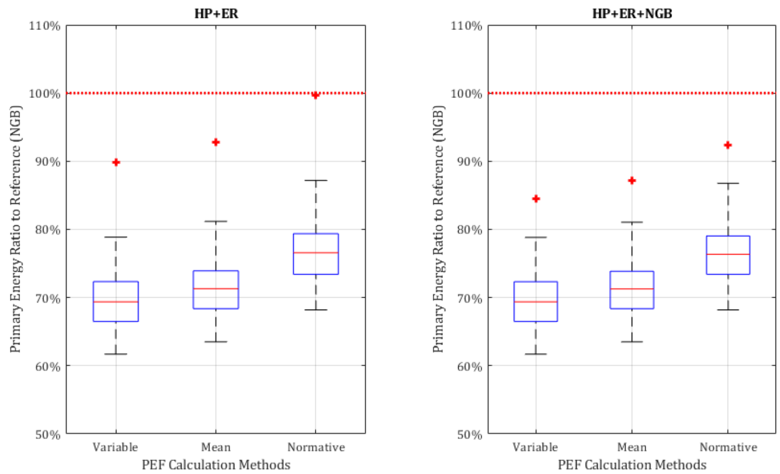

Figure 15: Comparison of the results obtained with variable PEF and constant PEF

temperature of the analyzed period have never been excessively low, thus not constituting a globally general example; (3) no condensation effect has been considered for simplicity for the *NGB* scenario, and a constant efficiency value has been used. Nevertheless, the obtained results show that the use of HP as heat generation technology in substitution or in parallel to traditional NGB can significantly decrease the yearly primary energy consumption of a large buildings stock. This result could be generalized to different buildings stocks provided that a sufficient database is available reporting at least measurements of heat load and average required supply temperature at hourly level.

The sensitivity analysis has provided sufficient insights about the robustness of the proposed methodology to the variation of two important parameters (the efficiency of the NGB and the reduction of the COP_{HP}). In particular, the adoption of the HP has been shown to be convenient in terms of primary energy consumption with respect to the baseline scenario for all the possible values of these parameters.

The comparison with the results obtained through the adoption of a constant average PEF, and even more of the reference PEF value provided by the national regulations, demonstrates the importance of carrying out high time resolution analyses. The weight of the variability is reflected in the results, that show

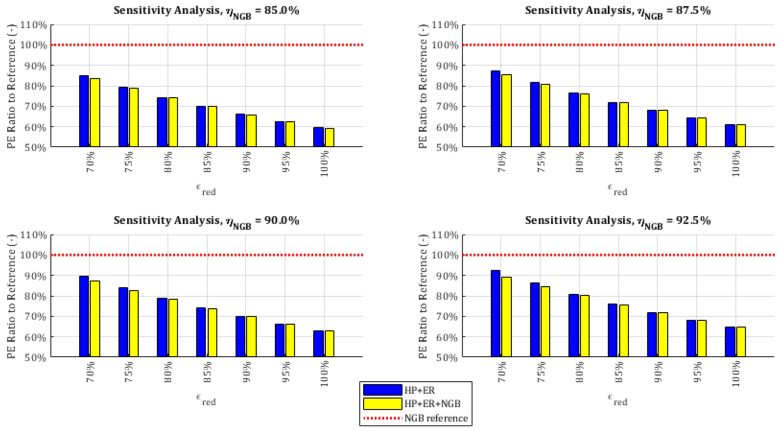

Figure 16: Sensitivity Analysis: primary energy savings for different η_{NGB} and r_{COP} .

significantly lower primary energy consumption when considering real electricity production values with respect to average annual values. The importance of high time resolution in similar analyses has already been the results of other research works [6, 11, 22], and the results that have been obtained in this study are in line with the primary energy savings calculated by [21] in the same geographical context.

Moreover, in large cities (especially in northern Italy) air pollution could become a key factor when choosing among different technologies. While NGB are a diffused source of NO_X emissions (and boilers fired with other fuels could also lead to PM_{10} emissions), HP show no local emissions. However, attention must be paid to the source of electricity generation, which can in some cases represent a significant de-localized source of air pollution.

Moreover, the wide diffusion of HP should be considered also on a policy perspective, as their impact on the current electricity network should be carefully evaluated. Currently, other technologies are already increasing the electricity consumption (e.g. cooling in residential buildings, electric vehicles), and therefore their use should be part of a wider energy policy. A large increase of electricity demand should be coupled to a development plan for RES, to avoid the necessity of using fossil fuels to cover the additional load. A future decrease of the electricity PEF would transform the benefits of high electricity penetrations into major drawbacks.

Finally, economic aspects could play a major role, and must be carefully addressed by any development policy aiming at increasing the performance of space heating in buildings. The increase of electricity penetration, together with the higher market prices volatility and the increased share of non-programmable generation, has led to an increase of the electricity costs for the final users. This aspect can hinder the development of HP, and for this reason Italy has defined a specific electricity tariff dedicated to HP users. However, such a tariff shifted the majority of the costs from energy to power, resulting in a lower incentive for the final user in decreasing the electricity consumption.

5. Conclusions

This paper presents an analysis of the primary energy consumption related to space heating in selected case-studies. The analysis is based on a database containing high resolution heat loads and supply temperature data for a large number of buildings located in Italy. Different heating generation scenarios are compared in terms of consumed primary energy, given the same heat loads and supply temperature profiles.

The presented work considers a high time resolution for the calculations: hourly values are used to increase the reliability of the evaluation of the primary energy consumption, as multiple parameters that show a significant variability on a daily and seasonal basis have an impact on the performance of the HP (including outdoor temperature, heat supply temperature, PEF of the electricity supplied by the power grid).

The results show that HP adoption for space heating in residential buildings can provide a significant reduction in terms of primary energy consumption with respect to the current heat generation based on NGB. The primary energy consumption reduction for the buildings considered in this study is in the range 10% - 40%, with a median value close to 30%. Such reduction is due to a number of coexisting factors, among which the most important ones are the low PEF in the specific considered country, the sufficiently high COP at low outdoor temperature for the considered model of air-source HP and the relevant difference between design and off-design conditions in terms of both experienced outdoor temperatures and measured supply temperatures. A sensitivity analysis has been carried out to evaluate the potential effects of different NGB efficiency and lower HP COPs than the ones declared by the manufacturer. The HP shows lower primary energy consumption than NGB in all the cases considered in the sensitivity analysis.

The results confirm the importance of carrying high time resolution analyses, especially with respect to the electricity that is supplied by the power grid. The comparison with the results obtained by using average annual values for the electricity PEF highlights that annual calculations lead to an underestimation of the primary energy savings that can be achieved by using a HP in comparison with a NGB (up to 8% of difference on an annual basis).

A trivial result of the performed simulations is that the use of electric resistances is never convenient. Much less trivial is the result in terms of comparison between hybrid solutions and HP alone: the carried analysis shows that the difference in terms of primary energy consumption between these two solutions is very low, at a first glance suggesting that HP alone could meet the final users thermal energy needs while guaranteeing at the same time a considerable reduction of primary energy consumption. On the other hand, some practical considerations suggest that the hybrid solution could be the most suitable for guaranteeing a flexible and reliable heat supply to the end-user.

Finally, the carried study will be followed by economic and policy-oriented analyses to evaluate the economic regimes that would make the adoption of HP more attractive and the impact of such adoption at large scale on the electricity generation system of a country.

References

[1] Eurostat, Eurostat database.
URL http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics

[2] F. Meijer, L. Itard, M. Sunikka-Blank, Comparing european residential building stocks: performance, renovation and policy opportunities, Building Research & Information 37 (5-6) (2009) 533–551. doi:10.1080/09613210903189376.

[3] A. D. Carvalho, P. Moura, G. C. Vaz, A. T. de Almeida, Ground source heat pumps as high efficient solutions for building space conditioning and for integration in smart grids, Energy Conversion and Management 103 (Supplement C) (2015) 991 – 1007. doi:https://doi.org/10.1016/j.enconman.2015.07.032.
URL http://www.sciencedirect.com/science/article/pii/S0196890415006834

[4] S. Paiho, S. Pulakka, A. Knuuti, Life-cycle cost analyses of heat pump concepts for finnish new nearly zero energy residential buildings, Energy and Buildings 150 (Supplement C) (2017) 396 – 402. doi:https://doi.org/10.1016/j.enbuild.2017.06.034.
URL http://www.sciencedirect.com/science/article/pii/S0378778816318709

[5] GSE, Rapporto statistico: Energia da fonti rinnovabili - anno 2015, Tech. rep., Divisione Gestione e Coordinamento Generale - Unit Studi e Statistiche (2016).

[6] M. Noussan, M. Jarre, R. Roberto, D. Russolillo, Combined vs separate heat and power production – primary energy comparison in high renewable share contexts, Applied Energy 213 (2018) 1–10. doi:10.1016/j.apenergy.2018.01.026.

[7] I. Ballarini, V. Corrado, F. Madonna, S. Paduos, F. Ravasio, Energy refurbishment of the italian residential building stock: energy and cost analysis through the application of the building typology, Energy Policy 105 (2017) 148–160. doi:10.1016/j.enpol.2017.02.026.

[8] X. Yang, H. Li, S. Svendsen, Decentralized substations for low-temperature district heating with no legionella risk, and low return temperatures, Energy 110 (2016) 65–74. doi:10.1016/j.energy.2015.12.073.

[9] M. Jarre, M. Noussan, A. Poggio, M. Simonetti, Opportunities for heat pumps adoption in existing buildings: real-data analysis and numerical simulation, Energy Procedia 134 (Supplement C) (2017) 499 – 507, sustainability in Energy and Buildings 2017: Proceedings of the Ninth KES International Conference, Chania, Greece, 5-7 July 2017. doi:https://doi.org/10.1016/j.egypro.2017.09.608.
URL http://www.sciencedirect.com/science/article/pii/S1876610217347422

[10] M. Noussan, M. Jarre, A. Poggio, Real operation data analysis on district heating load patterns, Energy 129 (2017) 70–78. doi:10.1016/j.energy.2017.04.079.
URL https://doi.org/10.1016%2Fj.energy.2017.04.079

[11] M. Noussan, Performance based approach for electricity generation in smart grids, Applied Energy 220 (2018) 231 – 241. doi:https://doi.org/10.1016/j.apenergy.2018.03.092.
URL http://www.sciencedirect.com/science/article/pii/S0306261918304318

[12] S. Nižetić, A. Papadopoulos, G. Tina, M. Rosa-Clot, Hybrid energy scenarios for residential applications based on the heat pump split air-conditioning units for operation in the mediterranean climate conditions, Energy and Buildings 140 (2017) 110–120. doi:10.1016/j.enbuild.2017.01.064.

[13] M. H. Moradi, A. Sohani, M. Zabihigivi, H. Wirbser, A comprehensive approach to find the performance map of a heat pump using experiment and soft computing methods, Energy Conversion and Management 153 (Supplement C) (2017) 224 – 242. doi:https://doi.org/10.1016/j.enconman.2017.09.070.
URL http://www.sciencedirect.com/science/article/pii/S0196890417308944

[14] J. Allison, A. Cowie, S. Galloway, J. Hand, N. J. Kelly, B. Stephen, Simulation, implementation and monitoring of heat pump load shifting using a predictive controller, Energy Conversion and Management 150 (Supplement C) (2017) 890 – 903. doi:https://doi.org/10.1016/j.enconman.2017.04.093.
URL http://www.sciencedirect.com/science/article/pii/S0196890417304144

[15] B. Shen, J. New, V. Baxter, Air source integrated heat pump simulation model for energyplus, Energy and Buildings 156 (Supplement C) (2017) 197 – 206. doi:https://doi.org/10.1016/j.enbuild.2017.09.064.
URL http://www.sciencedirect.com/science/article/pii/S0378778817321242

[16] Q. Zhang, L. Zhang, J. Nie, Y. Li, Techno-economic analysis of air source heat pump applied for space heating in northern china, Applied Energy 207 (Supplement C) (2017) 533 – 542, transformative Innovations for a Sustainable Future Part II. doi:https://doi.org/10.1016/j.apenergy.2017.06.083.
URL http://www.sciencedirect.com/science/article/pii/S0306261917308310

[17] R. Chargui, S. Awani, Determining of the optimal design of a closed loop solar dual source heat pump system coupled with a residential building application, Energy Conversion and Management 147 (Supplement C) (2017) 40 – 54. doi:https://doi.org/10.1016/j.enconman.2017.05.025.
URL http://www.sciencedirect.com/science/article/pii/S0196890417304594

[18] M. Dongellini, C. Naldi, G. L. Morini, Sizing effects on the energy performance of reversible air-source heat pumps for office buildings, Applied Thermal Engineering 114 (Supplement C) (2017) 1073 – 1081. doi:https://doi.org/10.1016/j.applthermaleng.2016.12.010.
URL http://www.sciencedirect.com/science/article/pii/S1359431116338741

[19] C. Underwood, M. Royapoor, B. Sturm, Parametric modelling of domestic air-source heat pumps, Energy and Buildings 139 (Supplement C) (2017) 578 – 589. doi:https://doi.org/10.1016/j.enbuild.2017.01.026.
URL http://www.sciencedirect.com/science/article/pii/S0378778817300774

[20] S. N. Petrovi, K. B. Karlsson, Residential heat pumps in the future danish energy system, Energy 114 (2016) 787 – 797. doi:https://doi.org/10.1016/j.energy.2016.08.007.
URL http://www.sciencedirect.com/science/article/pii/S0360544216311100

[21] V. Bianco, F. Scarpa, L. A. Tagliafico, Estimation of primary energy savings by using heat pumps for heating purposes in the residential sector, Applied Thermal Engineering 114 (2017) 938–947. doi:10.1016/j.applthermaleng.2016.12.058.

[22] S. Stinner, T. Schlsser, K. Huchtemann, D. Mller, A. Monti, Primary energy evaluation of heat pumps considering dynamic boundary conditions in the energy system, Energy 138 (2017) 60 – 78. doi:https://doi.org/10.1016/j.energy.2017.07.029.
URL http://www.sciencedirect.com/science/article/pii/S0360544217312045

[23] J. Love, A. Z. Smith, S. Watson, E. Oikonomou, A. Summerfield, C. Gleeson, P. Biddulph, L. F. Chiu, J. Wingfield, C. Martin, A. Stone, R. Lowe, The addition of heat pump electricity load profiles to gb electricity demand: Evidence from a heat pump field trial, Applied Energy 204 (2017) 332 – 342. doi:https://doi.org/10.1016/j.apenergy.2017.07.026.
URL http://www.sciencedirect.com/science/article/pii/S0306261917308954

[24] Daikin, Rotex heat pumps hpsu/hpu - technical sheet, Tech. rep., Daikin Group (2013).

[25] Y. Zhang, Q. Ma, B. Li, X. Fan, Z. Fu, Application of an air source heat pump (ASHP) for heating in harbin, the coldest provincial capital of china, Energy and Buildings 138 (2017) 96–103. doi:10.1016/j.enbuild.2016.12.044.

[26] Terna, Dati statistici sullenergia elettrica in italia - nota di sintesi, Tech. rep., Divisione Strategia e Sviluppo - Direzione Strategia e Market Analysis (2015).

[27] Dati statistici terna, available at https://www.terna.it/it-it/sistemaelettrico/statisticheeprevisioni/datistatistici.aspx.

[28] Ministero dello Sviluppo Economico, Decreto 26 giugno 2015 - applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici. (15a05198) (2015).