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The impact of low electricity Primary Energy Factors on the heating sector: heat pumps simulations in existing monitored buildings

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Abstract

The increase of power plants' conversion efficiencies, together with the high share of RES in the electricity production for some countries, push for the use of heat pumps for space heating when aiming at reducing the primary energy consumption. However, a number of parameters influence the heat pumps performances in terms of primary energy consumption, 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 values are unable to provide reliable results. This paper performs a simulation of an air-source heat pump for space heating, relying on the available operation data of real monitored buildings currently connected to a district heating network. The analysis is based on an hourly time step, and allows to compare different technologies given the heat and supply temperature demand of the buildings. The results show that in most cases the heat pumps can provide lower primary energy consumption compared to natural gas boilers, thanks to the combined effect of their high COP and the low electricity primary energy factor in the context of the case studies.

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

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1. Introduction

In the last years there has been growing interest towards the necessity to reduce the heat consumption in the residential building sector, since this sector accounts in Europe for about half of the total primary energy consumption [1]. Even if the '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 forces to find 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, even more, 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 in the electricity generation mix. Italy is one of the European countries in which the share of electricity generation by RES is highest, with an yearly share of renewables in the electricity generation production in 2015 of about 37% [5]. In this context, even the assumption of the convenience of

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combined vs. separate heat and power production starts to be questioned [6], opening the discussion about the role of heat pumps for sustainable heat production. On the other hand, the problem of the widespread adoption of heat pumps 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, heat pumps 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 in 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) the actual behaviour of a system can 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 an 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 heat pumps and hybrid systems (i.e. a heat pump and a traditional natural gas boiler 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]. Finally, the overall efficiency of an heat pump must be calculated by taking into consideration the primary energy factor of each electricity generation system [20]; such factor, which is characteristic of every generation mix, is strongly variable on an hourly basis in those countries (like Italy) in which the renewable share in the electricity sector is high. This variability should also be taken into account when evaluating the real performance of a heat pump in terms of consumed primary energy. The previous considerations are at the basis of the work presented in this paper, in which the use of air-source heat pumps for satisfying the heat loads 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 with an hourly time step, which allows to simulate with accuracy the heat pump behaviour under several different off-design conditions, which have a strong influence on the annual performance.

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 these buildings are kept identical to the real ones that have currently being monitored; 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 DHS.

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

1. **Electric Resistance (*ER*)**: a simple electric resistance is used, with a constant efficiency.
2. **Natural Gas Boiler (*NGB*)**: a non-condensing natural gas boiler with constant efficiency is simulated.
3. **Heat Pump + backup Electric Resistance (*HP+ER*)**: an air-source heat pump 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 an 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 $R-410A$ commercially available HP model 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 [21]. It can be seen 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, it can be seen also that 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],[22]. 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 [21] have been reduced by considering a constant reduction factor that has been applied to each COP function. The effective values of COP values 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 [21] 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:

$$r_{COP} = 80\% \tag{2}$$

or a reduction of 20% on each calculated value of COP for given couples of outdoor temperature and supply temperature. In section 3 a sensibility analysis of the results with respect to this parameter is reported to analyze its influence on the obtained Primary Energy consumption values and the comparison among the different scenarios.

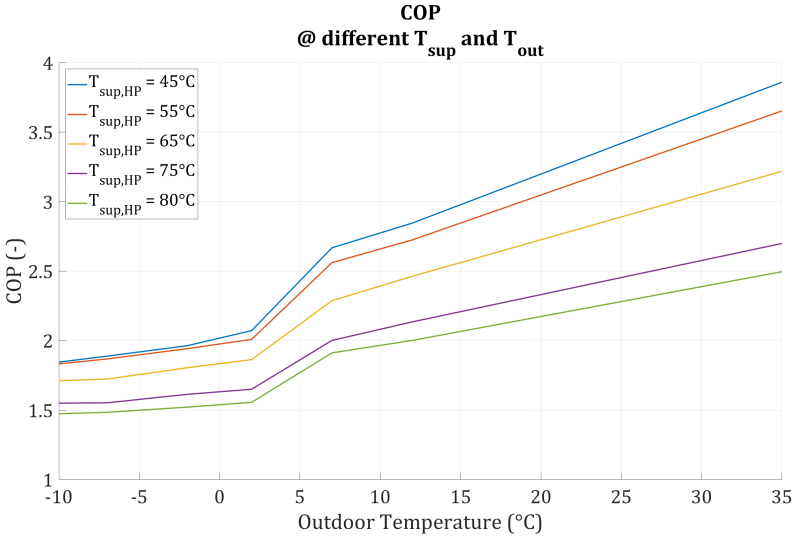

Figure 1: $COP_{HP,nom}$ as a function of outdoor temperature and water supply temperature.

The natural gas boiler, on the other hand, is set to have a constant thermal efficiency $\eta_{NGB} = 0.95$, as its variation with supply temperature are lower than for HPs. No condensation effect has been considered in this analysis in order to (1) simplify the comparison of final results; (2) take into account the fact that traditional, non-condensing boilers represent the most common type of natural gas boilers currently installed in residential buildings. 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. All the considered buildings are residential ones. 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 an heat pump 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 was referred 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 reading 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 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 variable 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 to 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 reports the relative and cumulative relative frequency of outdoor temperatures for the three most populated cities of northern Italy (Milano, Torino and Genova); 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 Torino and Milano, i.e. 15th October - 15th April (the heating season of Genova is shorter).

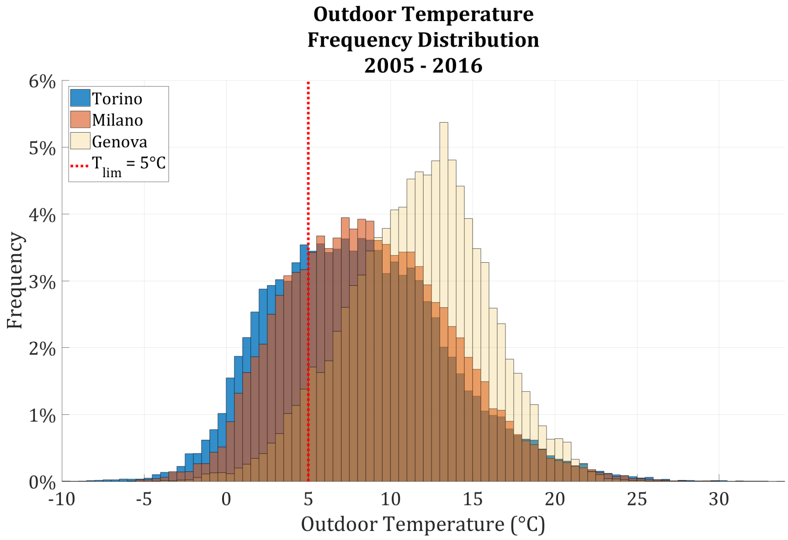

Figure 2: Relative Frequency Distribution of Outdoor temperature (15 Oct - 15 Apr).

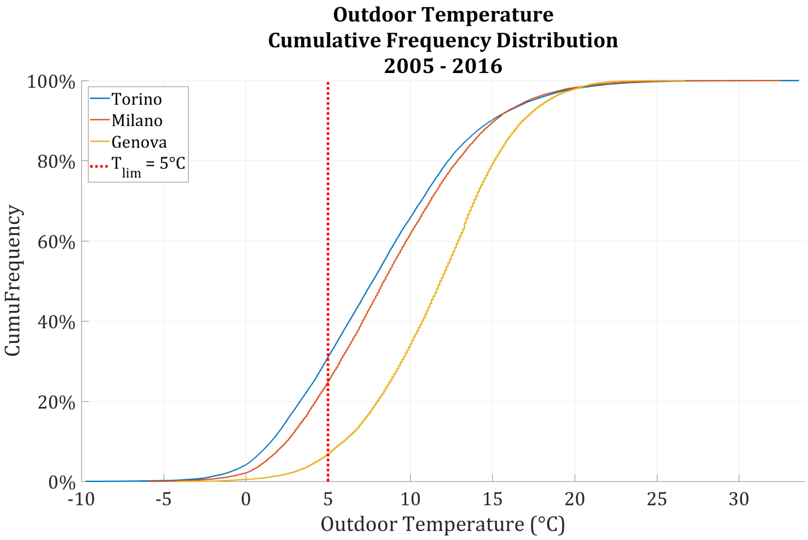

Figure 3: Cumulative Relative Frequency Distribution of Outdoor temperature (15 Oct - 15 Apr).

It can be seen that in both Milano and Torino 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 Genova this limit has been reached for less than 10%. This preliminary analysis suggests that excessively low temperatures are not predominant within major cities in Northern Italy. Three 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 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 heating period for the city of Genova is 15 days shorter than that of Milano and Torino [23]; if the actual heating period would have been applied to Genova, its temperature levels would have been higher than the reported ones, and likely they would have shown close to zero hours in which outdoor temperatures were lower than 5°.

3. 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 slightly change 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 (PEF) 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 primary energy factor (PEF) of the electricity produced by the Italian Power Grid has been performed on an 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 [24]).

The calculation of an 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 [25] (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 MSW, etc. according to Terna [25]).

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 an 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 hrs).

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.

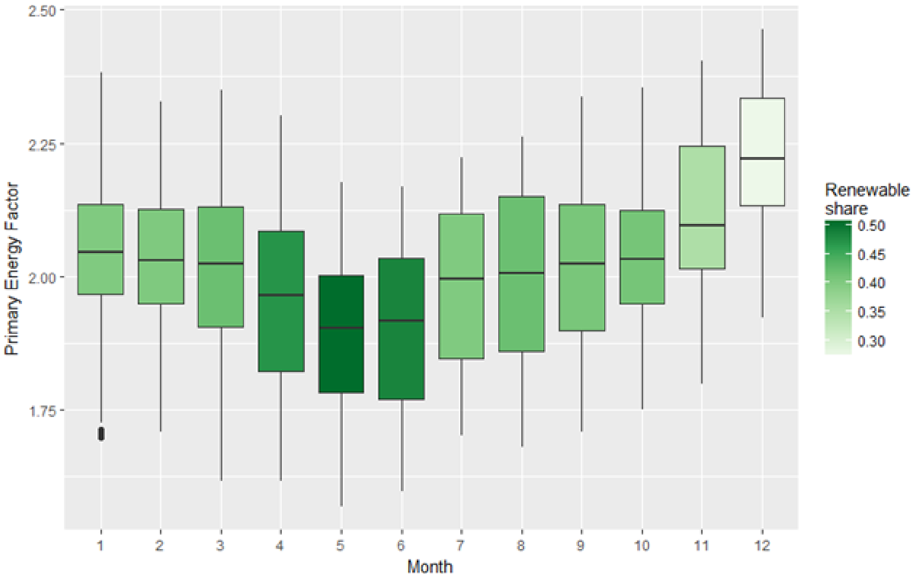

Figure 4: Box-plot of monthly values of PEF in Italy (2015).

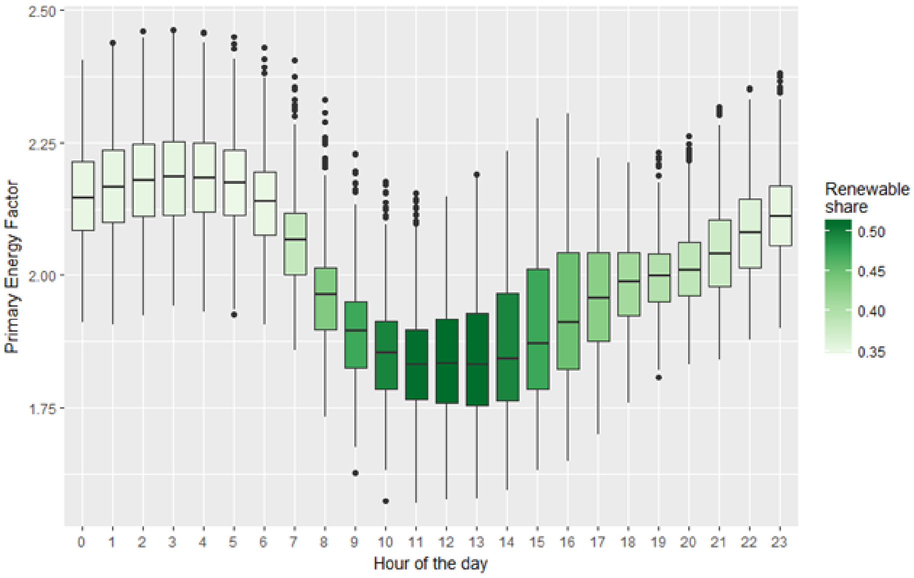

Figure 5: Box-plot of hourly values of PEF in Italy (2015).

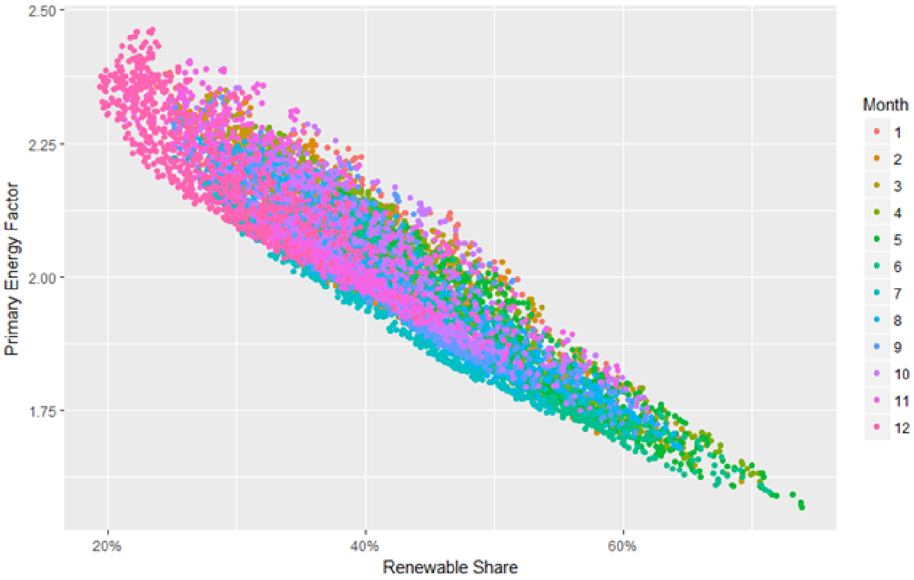

Figure 6: Hourly Correlation between PEF and RES share.

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 heat pump supplying a building with a heat quantity Q_{supply} , which is a gross heat demand of the building and includes all the efficiencies of the system but the generators one, would have a primary energy consumption PE that is calculated as:

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

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

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

The previous equations shows that, in principle, an Heat Pump would have a primary energy consumption that is lower than that of a natural gas boiler 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 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 [25]. Such losses factor allow to calculate an average electricity network efficiency $\eta_{net} = 0.896$; such factor has been applied constantly over the year to calculate the effective primary electricity consumption associated with the electricity consumption of a heat pump for heat production, as in:

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

From equation 9 it can be seen that the effect of the electricity network losses is equivalent to that of a decrease of the COP of the heat pump. It has to be remarked that the COP of the analyzed heat pump had been already diminished conservatively by a factor of 20%.

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.

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 ones; (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.

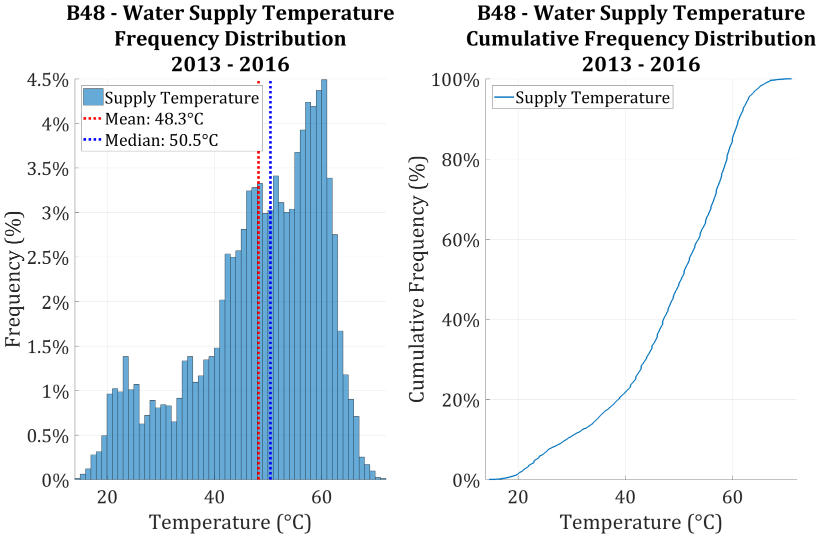

Figure 7: B48 - Water supply temperature relative and cumulative relative distribution.

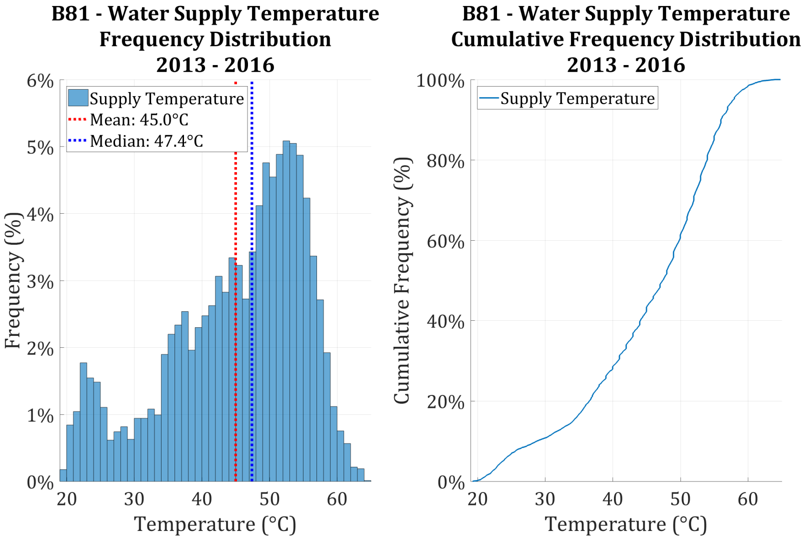

Figure 8: B81 - Water supply temperature relative and cumulative relative distribution.

In terms of primary energy consumption, the four scenarios have been compared and the results are reported in the next Figures. It is also reported 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. In Figures 9 to 12 an example of the primary energy profile for the middle days of January and a comparison between daily average values of COP and PEFs for one year are reported.

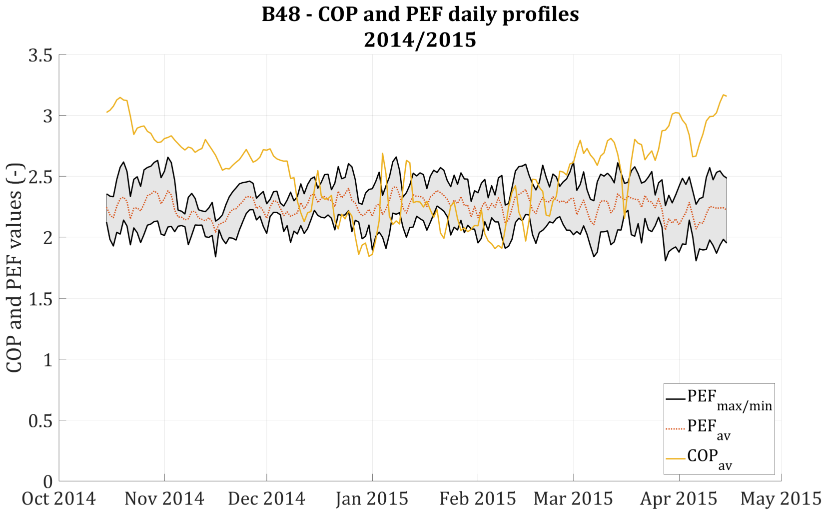

Figure 9: B48 - COP vs. PEF Daily Profile.

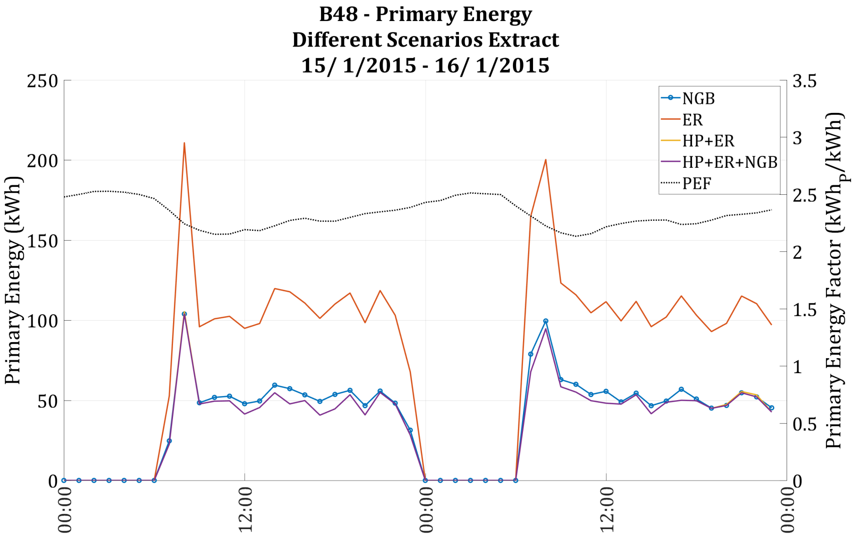

Figure 10: B48 - Primary Energy profiles for different scenarios.

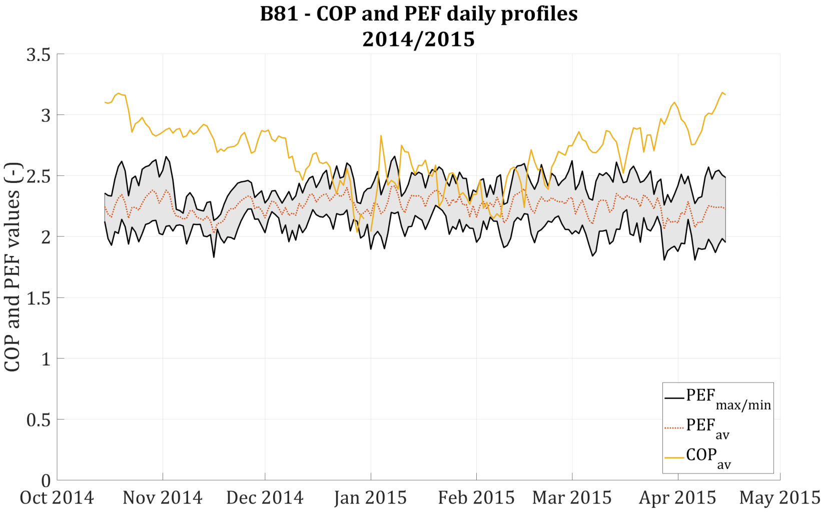

Figure 11: B81 - COP vs. PEF Daily Profile.

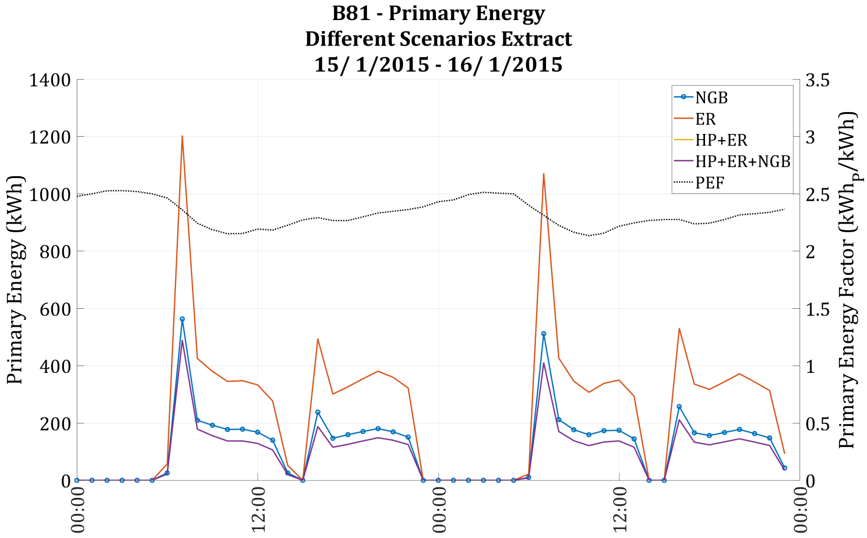

Figure 12: B81 - Primary Energy profiles for different scenarios.

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%).

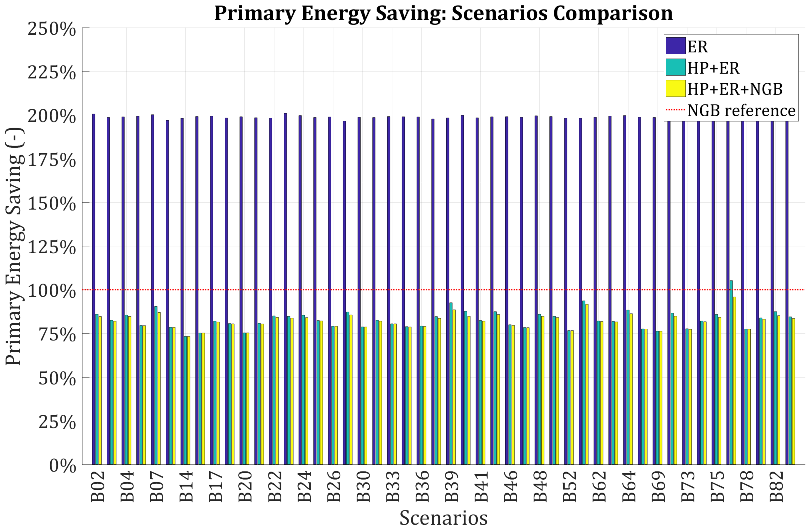

Figure 13: Scenarios comparison: Primary Energy savings for all the buildings.

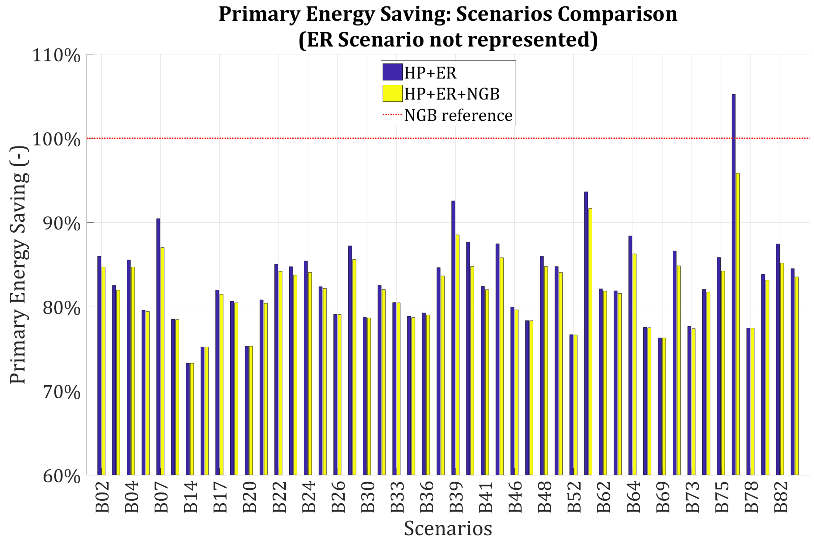

Figure 14: Scenarios comparison: Primary Energy savings for all the buildings - detail.

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 HP average daily value is often higher than the maximum values of the PEF; this is mainly due to the low water supply temperature levels that characterize some buildings.

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 80% has been applied for the determination of hourly COP with respect to the values declared by the constructor in [21]; a constant value of 95% hourly average efficiency has been adopted instead for the NGB. In order to evaluate the role of these parameter in the procedure, a sensitivity analysis has been performed in which these two parameters are being varied and the different scenarios are consequently re-calculated. In particular, the following ranges were adopted for the two parameters:

$$\begin{aligned} r_{COP} &= [70\% - 75\% - 80\% - 85\% - 90\% - 95\% - 100\%] \\ \eta_{NGB} &= [90\% - 92.5\% - 95\% - 97.5\%] \end{aligned} \tag{10}$$

The original scenario was calculated, as previously stated, with values of $r_{COP} = 80\%$ and $\eta_{NGB} = 95\%$; the results were reported for the single buildings in terms of PE consumption and PE 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, the PE consumption reduction with respect to the *NGB* scenario are calculated for the whole buildings stock as the mean of the single buildings; this makes it possible to actually compare the different scenarios and comparison.

In Figure 15 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 done previously, the *NGB* case is taken as reference scenario *ER* scenario is not shown since not interesting for the obtained results.

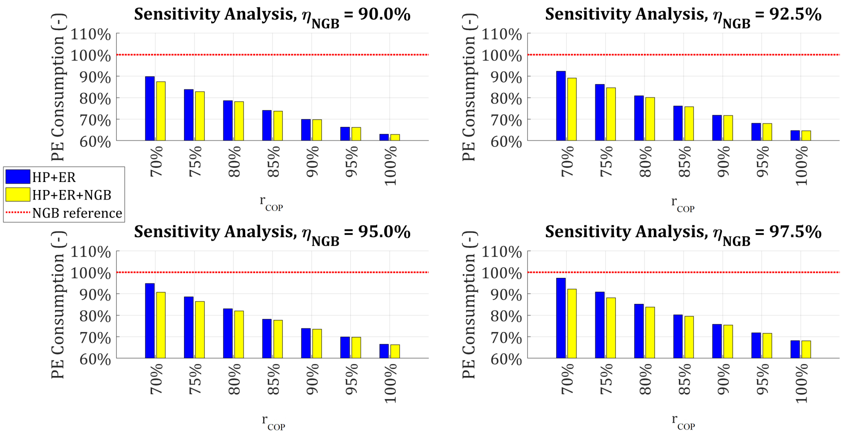

Figure 15: Sensitivity Analysis: Primary Energy savings for different η_{NGB} and r_{COP} .

The sensitivity analysis shows that the results of our simulations are, in relative terms, almost independent from the parameters. In fact, while the absolute values of the estimated PE consumptions significantly 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 97.5% the Primary Energy consumption between the scenarios is comparable. In particular, this happens only for very high values of the COP reduction factor r_{COP}. In fact, only for the 'worst-case' scenario of $r_{COP} = 70\%$ and $\eta_{NGB} = 97.5\%$ the HP+ER scenario has a primary energy consumption that is almost equal to the NGB baseline scenario. nevertheless, the hybrid scenario of HP+ER+NGB is characterized even in this 'worst-case' by a 9% 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 to be mentioned.

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 HP's COPs and potentially to a better efficiency when considering primary energy consumption. However, such calculation would require a complex simulation based on detailed data on the buildings characteristics, as the indoor comfort conditions should be guaranteed with any operation logic. These simulations could be performed in a future work on a 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 an hybrid system could represent the most flexible and reliable solution: (1) in case of (rare) lower temperatures, the capability of producing heat would be assured; (2) the outdoor 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 Heat Pumps as heat generation technology in substitution or in parallel to traditional natural gas boilers 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 DB is available reporting at least measurements of heat load and average required supply temperature at hourly level.

The proposed sensibility analysis has provided sufficient insights about the robustness of the proposed methodology to the variation of two important parameters (the efficiency of the natural gas boiler and the reduction of the heat pump COP). 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. In large cities, especially in northern Italy, the air pollution could become a key factor when choosing among different technologies. While natural gas boilers are a diffused source of NO_X emissions (and boilers fired with other fuels could also lead to PM10 emissions), HPs show no local emissions. However, attention must been paid on the source of electricity generation, which can in some cases represent a significant de-localized source of environmental impacts.

The wide diffusion of heat pumps should be considered also through a policy perspective, as their impact on the current electricity network should be carefully evaluated. Other technologies are nowadays 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 missing power production. 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 HPs, 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 interest for the final user in decrease its total electricity consumption.

5. Conclusions

This paper presents an analysis of the primary energy consumption related to space heating in some case studies, by comparing different technologies. The analysis has been 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 have been compared in terms of consumed primary energy, given the same heat load and supply temperature profile needs. The results show that heat pumps 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 natural gas boilers. This 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 temperatures for the analyzed model of HP and the relevant difference between design and off-design conditions in terms of both experienced outdoor temperatures and measured supply temperatures. A trivial result shows also that the use of electric resistances is never convenient. Much less trivial is the result in terms of comparison between hybrid solutions and heat pumps alone: the carried analysis shows that the difference in terms of primary energy consumption between these two combinations is very low, at a first glance suggesting that heat pumps alone could satisfy 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 and prudent considerations suggest that the hybrid solution could be the most suitable for guaranteeing a flexible and reliable solution to the end-user. Finally, the carried study will be followed by economic and policy-oriented analysis aiming at analyzing the economic regimes that would make the adoption of heat pumps more attractive and the impact of such adoptions at large scale over the electricity generation system of a country.

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