Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 134 (2017) 499–507

Procedia Engineering

www.elsevier.com/locate/procedia

9th International Conference on Sustainability in Energy and Buildings, SEB-17, 5-7 July 2017, Chania, Crete, Greece

Opportunities for heat pumps adoption in existing buildings: real-data analysis and numerical simulation

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

[a]*Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, 10129, Italy*

Abstract

The space heating of buildings represents one of the most important causes of energy consumption in Europe. The necessity to increase the share of renewable energy within the sector is hindered by the difficulty to renew and refurbish the existing building stock. In this context, heat pumps can have an important role in helping increase the renewable share of thermal energy production for the civil sector, in particular in those countries in which the electricity generation mix has large contributions from renewable energy sources. The paper presents a real-data analysis and a numerical simulation to evaluate the opportunity to substitute traditional heat generation systems (natural gas boilers) with air-source heat pumps or hybrid solutions. Three buildings located in Turin (Italy) are taken as case-study, and the hourly profiles of outdoor temperature, water supply temperature and absorbed thermal power are used to simulate four heat generation scenarios, that are compared in terms of primary energy consumption. Results show that (1) the substitution of the traditional natural gas boiler with a heat pump (with backup electric resistance) is always favorable (18% to 32% of primary energy reduction); (2) the influence of water supply temperature of each building on the overall primary energy saving is very high; (3) the adoption of a hybrid system (heat pump and natural gas boiler working alternatively) provides advantages in terms of reduced primary energy consumption only if the required supply water temperature is high. Further studies will investigate the economic aspects and will introduce comparisons with condensation natural gas boilers.

Peer-review under responsibility of KES International.

Keywords: Heat pumps; retrofit; data analysis; existing buildings.

1. Introduction

In Italy, buildings account for about 37% of the total primary energy consumption. About 70% of it is used for space heating and cooling [1]. While the renewable share in the elecitricity generation has constantly grown in the last decade, the generation of thermal energy for space heating purpose is still both inefficient and strongly dependant on fossil fuels [2].

Even if nZEBs do represent a promising scenario to achieve energy efficiency targets, most studies show that the number of new constructed buildings in the next years will likely remain very low, and that the future building stock will be basically constituted by buildings that already exist today [3]. For this reason, much effort is being put into

* Corresponding author. Tel.: +39-011-090-4529;
E-mail address: matteo.jarre@polito.it

1876-6102
Peer-review under responsibility of KES International.
10.1016/j.egypro.2017.09.608

finding suitable solutions for balancing deep renovation needs and the necessity to deal with existing buildings in which many constraints coexist.

Heat pumps are one of the key technologies that could be used to increase the renewable share of energy used for space heating in buildings, in particular in countries with high renewable share in the electricity generation mix. The problem of the widespread adoption of heat pumps into the building sector in most of European countries (and in southern Europe in particular) lies in 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 solution in many European countries [4]. Asaee et al. [5] did study the influence of retrofitting air-source heat pumps into existing buildings, but they also introduced some major modifications (notably storage systems and hydronic terminals) that could not be easily implemented within existing buildings without significant economic investment. Similarly, Touchie et al. [6] did simulate the impact of HP retrofitting in Toronto, in which winter climate is very rigid; they design therefore a system in which the HP is mounted over an enclosed balcony, therefore the evaporation temperature would be much higher with respect to the outdoor temperature thanks to solar gains. Though this being an interesting and elegant approach, it is once again not strictly compliant with the necessity to avoid heavy buildings refurbishment and to the general applicability of the approach

The adoption of simple control logics like climatic regulation and thermostatic valves can help decrease the average water temperature of these heating systems [7]. Moreover, detailed analyses of real weather data show that the very-low 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. These two influences (outdoor temperature and related supply temperature) must be both taken into account as they both affect consistently the efficiency of heat pump units. Madonna et al. [8] presented a detailed simulation tool to calculate the efficiency of a air-source heat pump considering outdoor temperature, defrost cycles and partial load influences on the performance of the unit; however, they considered only one supply temperature for all buildings for being able to compare the different solutions. The proposed 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 [9]. Finally, the overall efficiency of an heat pump must be calculated by taking into consideration the primary energy factor of each electricity generation system [10]; such factor, which is characteristic of every generation mix, is strongly variable on an yearly 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 .

This article thus present a detailed analysis of real-data collected from existing buildings to analyze the opportunity for HPs adoption in complete or partial substitution of traditional heating generation systems. A detailed analysis of weather data for the three largest cities in Northern Italy is presented to show that the concern of excessively low temperatures for proper operation of HPs is probably excessive. These data are then used together with real heating data collected from three different buildings located in Turin, Italy, to build a numerical model to compare four different scenarios in which different generation technologies / combination of technologies are adopted. These scenarios are then compared in terms of final primary energy consumption and total CO_2 emissions.

2. Methodology

The aim of the article is to compare different thermal energy generation technologies to provide space heating to three existing buildings located in Turin, Italy. These buildings are heated through traditional natural gas boilers and water radiators are used as heat emission systems. 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*)**: equivalent to the existing system, 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 nominal 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.
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.

2.1. Weather Statistical Analysis

Air-source heat pumps efficiencies are strongly dependent on outdoor temperature. In particular, most design procedures consider 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 [11]. 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. Figure 1 reports the relative and cumulative relative frequency of outside temperatures for the three most populated cities of northern Italy; the 5°C limit temperature is also highlighted. The weather data are reported as hourly means and they were collected for a total period of 12 years (2005-2016), thus constituting a reliable and statistically significant dataset. Only Turin's heating season period is considered, i.e. 15^{th} October - 15^{th} April.

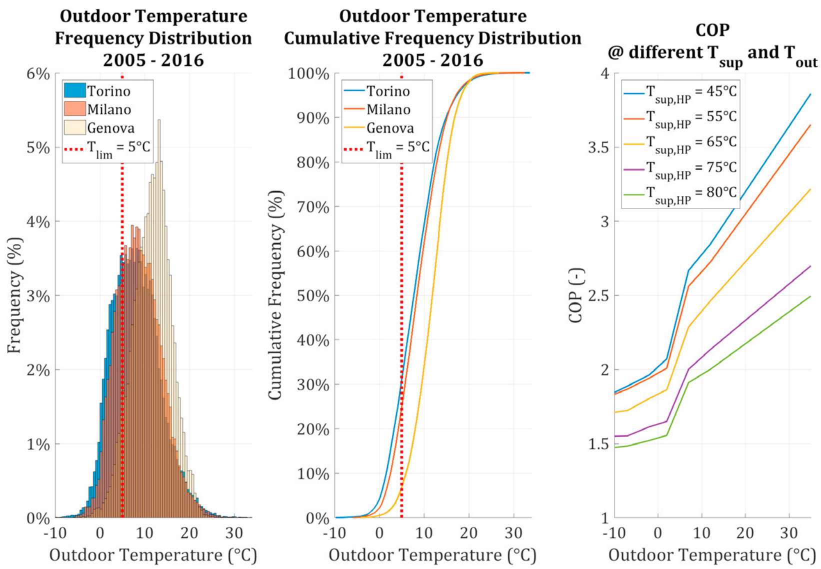

Fig. 1. Relative and Cumulative Relative Frequency Distribution of Outdoor temperature.

As it can be seen, 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.

2.2. Heat generation technologies performances definition

The HP COP is defined as a function of T_{out} and T_{sup}; the characteristic curves of the analyzed HP are also represented in Figure 1. The double negative effect on COP of increasing water supply temperature and decreasing outdoor temperature are clearly visible; also, it is evident the sudden COP drop that corresponds to the defrost cycles that occurr when outdoor temperatures are close to 0°C. Many studies exist about the possibility to to lower the energy consumption during defrost cycles [12] or to avoid them at al [13]; however these approaches However, it can be seen also that even at maximum $T_{sup} = 80°C$ and minimum $T_{out} = -10°C$ the COP value is not lower than 1.5. The natural gas boiler, on the other hand, is set to have a constant thermal efficiency $\eta_{NGB} = 0.95$. No condensation effect has been considered in this analysis since traditional, non-condensing boilers represent the most common type of natural gas boilers currently adopted.

2.3. Primary Energy Factors

The primary energy factors for the HP and the ER are, of course, dependant on the considered country: Italian generation mix has been used in this article. The Primary Energy Factor (PEF) for the Italian generation mix has been calculated at hourly level for the period 2011-2016 (authors' elaboration on [14]). In addition, the Primary Energy Factor for Fossil Energy only (PEF_{fossil}) has been calculated; this is the primary energy factor calculated as if only fossil energy was 'consumed' for producing the same amount of electricity. As it can be seen in Figure 2, the two factors differ for almost 40% in average since the renewable share in the Italian generation mix is very high [2].

In Figure 2 it is also evident that (1) the PEF has never been higher than 2.5 on an hourly basis in the last 5 years; (2) PEF mean and median value are both approximately equal to 2, meaning that for half of the hours in the last 5 years the PEF value has been lower than that; (3) if PEF_{fossil} is considered, values above 1.5 have been seldom reached. If a comparison is made between these PEF values and COP values as presented in Figure 1, it is evident that the operation of heat pump can be favorable even at low outdoor / high supply temperature conditions.

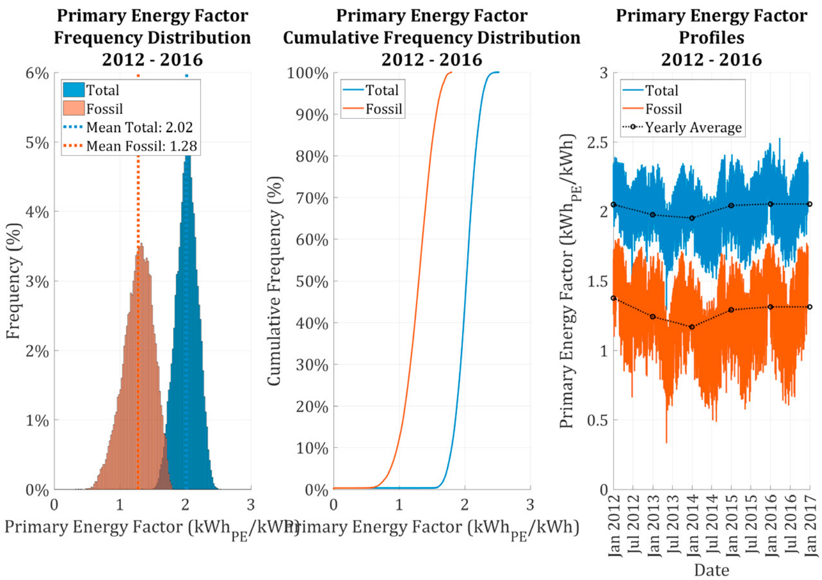

Fig. 2. Relative and cumulative relative frequencies of Primary Energy Factor (w/o fossil).

3. The Case-Study

The case-study is constituted by three residential buildings located in Turin, Northern Italy. For these buildings, detailed hourly data are available for:

- **Outdoor Temperature** $T_{out}(°C)$: is the temperature used by the control unit to set-up the climatic control .
- **Water Supply Temperature** $T_{sup}(°C)$: is the temperature of water exiting the generator and entering the radiators. The three buildings have been chosen to have three different values of the nominal maximum T_{sup} as described in the Table 1; as shown, the real maximum T_{sup} value that has been detected is always lower than the nominal one.

- **Thermal Power** $P_{th}(kW)$: is the average thermal power produced on an hourly basis by the natural gas boiler.

Table 1. Nominal supply water temperatures.

Building ID	Heated Volume (m^3)	Nominal Thermal Power P_{th} (kW)	Nominal Maximum T_{sup} (°C)	Real Maximum T_{sup} (°C)
B1	2737	106	70	66
B2	4200	145	80	75
B3	4753	243	90	84

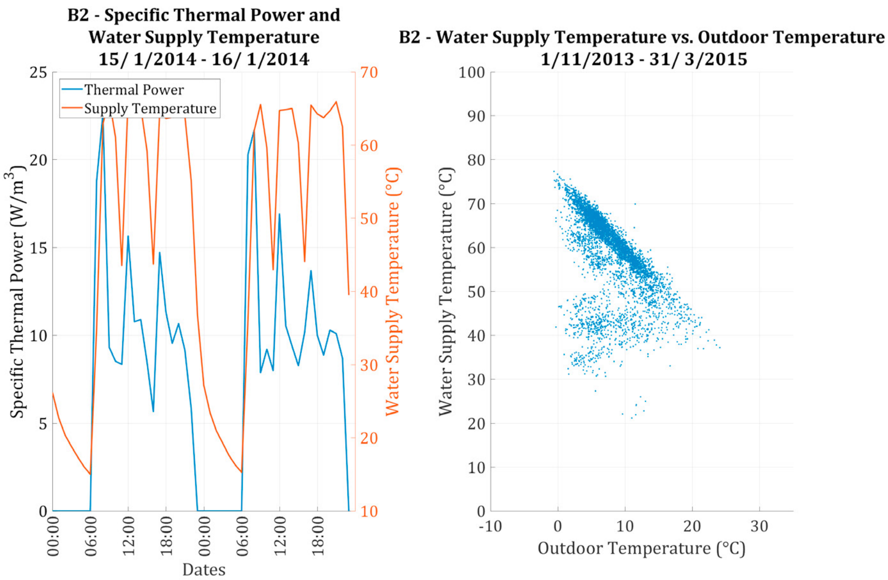

Fig. 3. P_{th} and T_{sup} example profiles (left) - Climatic control of T_{sup} (right).

No renovation is hypotesized on the heat distribution and emission systems; 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. Figure 3 reports an example of the hourly profile of P_{th} and T_{sup} on the left, where the morning power peak can be observed. On the right the result of the climatic control of the water supply temperature is also shown. In Figure 4 the real water supply temperature distribution shows that (1) the mean real value is 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.

4. Results

The four scenarios have been compared in terms of total primary energy consumed within the analyzed period. In addition, it is also shown the daily average of the COP for Scenario 3 to be compared with the daily mean, maximum and minimum values of PEF. In Figures 5, 6, 7 an extract of the primary energy profile and a comparison between daily average values of COP and PEFs are reported.

An obvious result is that the *ER* Scenario is characterized by a primary energy consumption that is always much higher with respect to the *NGB* scenario. Much less obviously, the *HP+ER* and *HP+ER+NGB* scenarios are characterized by lower primary energy consumptions at almost anytime. For building B1 it can be noted that the COP HP average daily value is never lower than the maximum values of the PEF; this is mainly due to the low water

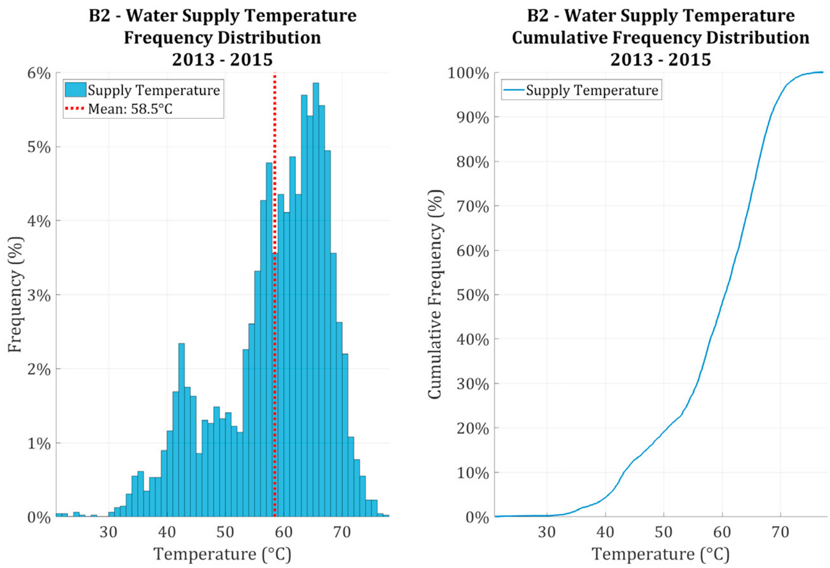

Fig. 4. Water supply temperature relative and cumulative relative distribution.

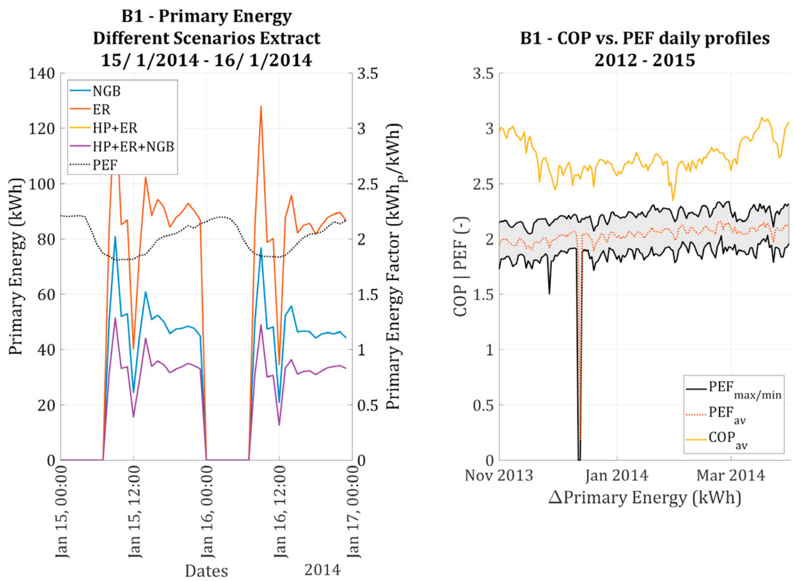

Fig. 5. B1 - Primary Energy profiles and comparison with COP.

supply temperature levels that characterize this building. For buildings B2 and B3 the HP COP has values that are comparable with those of the PEF during colder periods (December to February) but once again when the outdoor temperature increases (and the water supply temperature consequently decreases) the COP increase compensates the decrease of PEF. For these reasons, in the first building there is substantially no difference between the *HP+ER* and the *HP+ER+NGB* scenarios, since if the primary energy factor is used as decision parameter, the natural gas boiler is never switched on. In the other two buildings there is a small difference between these two scenarios, meaning that the *NGB* operation has a lower PEF than the *HP+ER* at least for some hours.

The same considerations can be made considering Figure 8: (1) the *ER* scenario is never convenient in terms of primary energy consumption; (2) the use of an HP can substantially decrease the primary energy consumption of the

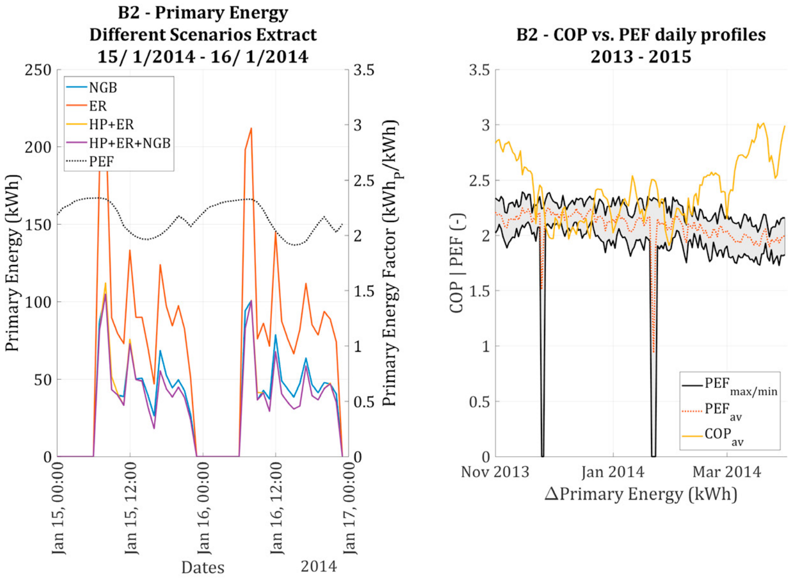

Fig. 6. B2 - Primary Energy profiles and comparison with COP.

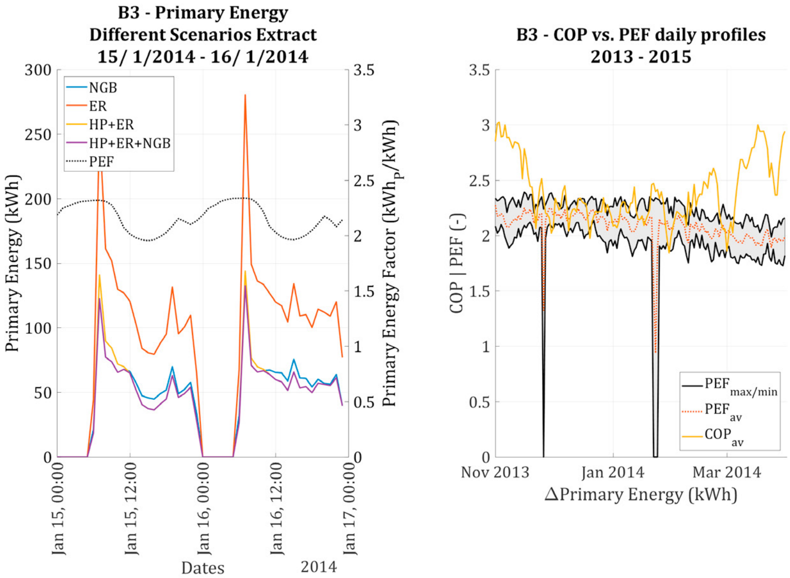

Fig. 7. B3 - Primary Energy profiles and comparison with COP.

three considered buildings; (3) the required supply temperature has an important role in determining the convenience between the simple *HP+ER* solution and the hybrid *HP+ER+NGB*.

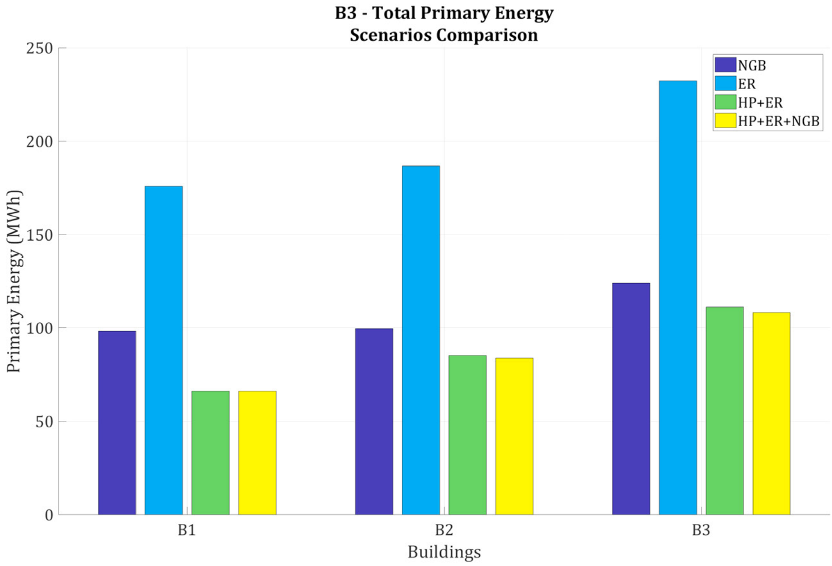

Fig. 8. Scenarios comparison: Total Primary Energy consumption in the analyzed buildings.

5. Discussion

The proposed model has allowed to compare different heat generation scenarios based on real collected data from three different buildings. The availability of real data regarding both heat consumption and working temperatures is fundamental since it highlights the relevant difference between design conditions and operationg conditions; the fact that these data were available for several years has also allowed to extend the analysis over different thermal seasons, thus increasing the validity of the obtained results since these were obtained under different conditions (in particular weather conditions). Moreover, this availability allowed to consider the influence over the COP of the considered heat pump of both outdoor temperature and real collected supply temperatures, a feature that was not found in current literature and that revealed to have a strong influence over the final comparisons of heat generation scenarios. Similarly, the use of an hourly profile of the PEF leads to very different considerations with respect to the use of an average seasonal value, and should therefore be recommended in further studies whose target is to compare different heating generation solutions in terms of primary energy consumptions.

The obtained results have shown that the adoption of air-source heat pumps as retrofit mechanism within existing building can significantly decrease their primary energy consumption; this important result is driven by the high share of renewable energy within the elecitricity mix of Italy, as considered in this paper. This result makes the case for a greater *electrification* of the heat generation across all countries but in particular in those with a particularly renewable electricity sector. It also indicates that as renewable sources become more and more adopted across Europe, a greater share of space heating could be provided by RES as well thanks to the adoption of heat pumps.

Finally, the obtained results have shown that hybrid solutions are suitable and convenient only in buildings characterized by high design supply temperatures. Moreover, even in such buildings the overall difference in primary energy consumption with the *HP+ER* option has been simulated to be very small, thus suggesting that the adoption of these systems should be carefully addressed. On the other hand, it must be highlighted that several factors suggest that the installation of an hybrid system could represent the most flexible 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 (see Figure 3), thus not constituting a general example; (3) no condensation effect has been considered for simplicity for the *NGB* scenario, and a constant efficiency value has been used.

6. Conclusions

A detailed data-analysis and numerical simulation have been presented to show the opportunity to use heat pumps as main heat generation systems in existing buildings in order to reduce the associated primary energy consumption. A preliminary weather data analysis has shown that in the three most populated cities in Northern Italy the temperatures are not often sufficiently low to deteriorate the performances of heat pumps systems.

Three buildings located in Turin have then been analyzed in detail, and four different heat generation scenarios have been evaluated in terms of consumed primary energy. The obtained results show that the use of an heat pump can consistently lower the primary energy that is required for space heating in the studied buildings. This results is due to some coexisting factors: (1) the analyzed heat pump has a COP that is very often higher or anyway comparable with the primary energy factor at hourly level; (2) Italy has a high renewable share in its electricity mix, thus causing the PEF to have lowered consistently in the recent years, being nowaday fluctuating around a value of 2.0 ; (3) the studied buildings had experienced, for the analyzed period, much lower water supply temperatures with respect to nominal ones, thus contributing to increase the simulated COP value.

Further studies will investigate in detail HP performances (and in particular the produced thermal power at different conditions), the comparison with a condensation natural gas boiler and also economics evaluation will be made to confirm if the primary energy convenience does match with an economical one.

References

[1] ENEA, Rapporto Annuale sull'Efficienza Energetica (Jun. 2016).

[2] G. dei Servizi Energetici (GSE), Rapporto statistico: Energia da fonti rinnovabili - anno 2014, Tech. rep., Divisione Gestione e Coordinamento Generale - Unit Studi e Statistiche (2015).

[3] 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.

[4] 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.

[5] S. R. Asaee, V. I. Ugursal, I. Beausoleil-Morrison, Techno-economic feasibility evaluation of air to water heat pump retrofit in the canadian housing stock, Applied Thermal Engineering 111 (2017) 936–949. doi:10.1016/j.applthermaleng.2016.09.117.

[6] M. F. Touchie, K. D. Pressnail, Evaluating a proposed retrofit measure for a multi-unit residential building which uses an air-source heat pump operating in an enclosed balcony space, Energy and Buildings 85 (2014) 107–114. doi:10.1016/j.enbuild.2014.08.048.

[7] 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.

[8] F. Madonna, F. Bazzocchi, Annual performances of reversible air-to-water heat pumps in small residential buildings, Energy and Buildings 65 (2013) 299–309. doi:10.1016/j.enbuild.2013.06.016.

[9] 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.

[10] 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.

[11] C. Underwood, M. Royapoor, B. Sturm, Parametric modelling of domestic air-source heat pumps, Energy and Buildings 139 (2017) 578–589. doi:10.1016/j.enbuild.2017.01.026.

[12] M. Qu, T. Li, S. Deng, Y. Fan, Z. Li, Improving defrosting performance of cascade air source heat pump using thermal energy storage based reverse cycle defrosting method, Applied Thermal Engineering 121 (2017) 728–736. doi:10.1016/j.applthermaleng.2017.04.146.

[13] W. Su, X. Zhang, Performance analysis of a novel frost-free air-source heat pump with integrated membrane-based liquid desiccant dehumidification and humidification, Energy and Buildings 145 (2017) 293–303. doi:10.1016/j.enbuild.2017.04.024.

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