# Air/water heat pumps: energy and environmental assessment in Mediterranean residential building sector

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**Abstract.** The improvement of buildings energy efficiency represents one of the key objectives of current European policy actions, in order to guide the transition towards a low-carbon society. Indeed, nowadays, it is known that the building sector is responsible for 40% of total energy consumption and that heating is recognised as the main cause of this impact. In this context, heat pumps are recognized as promising solutions both for new constructions and for the renovation of existing buildings. For supporting the transition of the building sector, in Italy, within the "Recovery Decree" (D.L. 34/2020), which has introduced diverse social policies and financial support schemes to face the economic crisis following the COVID-19 pandemic, it is worth mentioning the current Superbonus incentive mechanism, accessible also for the installation of heat pumps. In this context, the paper aims to investigate the effectiveness of the use of air-to-water heat pumps as an alternative to traditional condensing gas boilers in residential buildings, either new or existing. Focusing on single-family houses, different models, differing in building size, envelope characteristics and heating systems were simulated, considering three different climatic zones of Italy. In detail, the energy simulations concerned two main application fields, the former considering the installation of heat pumps in new constructions, characterized by envelopes with high performances, while the latter analysing the use of heat pumps in existing buildings, without intervening on their envelopes with poor performances. The work aims to demonstrate the potential energy and environmental benefits associated with the use of heat pump solutions for space heating and domestic hot water production in both cases. The results allow stressing on the goodness of heat pump technologies in terms of energy savings (expressed in total non-renewable primary energy index) and $CO_2$ emissions reduction, as well as their capability in improving the energy efficiency classes of the analysed buildings, only with system upgrading intervention.

**Keywords.** Heat pump, condensing boiler, residential, single-family house
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## 1. Introduction

Improving the energy performance of buildings is fundamental to achieve the desired energy transition. In fact, the increment of buildings energy efficiency represents one of the key objectives of current European policy actions, as outlined by the European Green Deal [1], which aims to achieve climate neutrality and lead Europe towards the transition to a post-carbon society by 2050. Nowadays, the building sector is responsible for 40% of total energy consumption, and building heating is recognized as the main cause of this impact [2]. To decarbonize the building sector, heat pumps are considered the most promising heating solution to be applied in both new constructions and renovated existing buildings [3;4]. In order to support the transition of the building sector, diverse financial mechanisms were introduced, to encourage energy investments in buildings. Recently, focusing on the Italian context, the Decree Law n.34 (D.L. 34/2020) [5], also known as Recovery Decree, was introduced on the 19th May 2020, aiming to provide financial support to face the economic crisis following the Covid-19 pandemic. It is worth mentioning that the Italian Decree introduced an incentive mechanism, the so-call Superbonus, which increased the tax rebate for building interventions from existing 50-65% to 110% [5]. This mechanism involves a considerable amount of actions and technologies, among which the installation of heat pump technologies, aiming to encourage their installation

in new construction or as replacement of existing fossil-fuelled heating systems.
In line with the above, the paper aims to investigate the effectiveness of air-to-water heat pumps as an alternative to the traditional condensing boilers in residential buildings. In detail, the study concerned two main application fields, depending on the type of building intervention: new construction and existing buildings renovation. The former analysis focuses on illustrating the energy and environmental benefits associated to the use of heat pump solutions for space heating and domestic hot water (DHW) services in new residential buildings, excluding the economic evaluation which could be an interesting topic to further explore. Conversely, the second application aims to determine whether an intervention of system upgrading, excluding any actions on building envelope, can guarantee the improvement of two energy efficiency classes for the building under investigation (i.e., a condition required by the D.L. 34/2020 to access the Superbonus 110%) [5]. For both applications, quasi steady-state simulations of a single-family house with different sizes and located in diverse Italian climatic zones were developed, to estimate the energy and environmental benefits that the installation of air-to-water heat pumps can guarantee.
The paper is structured as follows: section 2 describes the methodology used for the analysis, as well as the main parameters considered for the creation of simulation models. Section 3 summarises the main results of the study, divided between new buildings (paragraph 3.1) and existing buildings renovation (paragraph 3.2). Finally, section 4 presents the main conclusive remarks and future perspectives of the work.

## 2. Research Methods

To estimate the impacts in energy and environmental terms associated to the use of heat pumps in both new and existing buildings, the paper defined specific building models, then simulated through the thermo-technical software EdilClima EC700 v10 compliant with UNI/TS 11300 [6] and validated by the Italian Thermo-technical Committee (CTI, Comitato Termotecnico Italiano).
This paragraph summarises the main assumptions done for the models' construction and simulation, in terms of geometrical characteristics, climate zones, building envelope (paragraph 2.1), reference building systems (paragraph 2.3). After the definition of the reference conditions for the building models, paragraph 2.3 introduces diverse HVAC solutions, focusing on heat pumps, to be installed in both new and existing buildings.
The work focuses on single-family houses (SFHs), belonging to the Italian category E1(1) - dwellings used for residential purposes on a continuous basis, such as civil and rural dwellings. Specifically, two SFH models were defined, presenting different building sizes: a model S (small), characterized by an internal area of 150 $m^2$, and a model L (large), with an internal area of 220 $m^2$. Both models S and L present one floor above ground and have a net floor height of 2.7 m. In addition, the south façade of both SFHs has a larger glazed area than the north one, to maximise solar gains and reduce heat loss.

### *2.1 Building envelope performances*

The defined SFHs are considered representative of both new and existing buildings. However, to account for the diverse building envelope performances between these two categories, four levels of envelope performance were considered, in turn characterized by specific thermal transmittance of opaque and transparent envelopes (as reported in Table 2).
Going into detail, all envelopes used in the simulations are in line with the traditional characteristics of Italian single-family house. Generally, bricks and external thermal insulation are used in external walls, and concrete and masonry for floor and ceiling; all windows are equipped with PVC frames with triple low-emissivity glass. Despite a similar structure of the envelope elements, the levels of energy performance are characterized by increased insulation thicknesses, moving from low to very high performance. In order to differentiate the modelled SFHs between new and existing, it was assumed to use envelopes with very high (envelope A) and high (envelope B) performances only for new constructions, while using envelopes with low (envelope C) and very low (envelope D) performances only for existing buildings.
Table 2 summarises the main cited assumptions, reporting the thermal transmittance values of walls, floors, and windows of each model. The 8 models (model S and L, with four level of envelope performance A, B, C and D) were simulated considering three different climatic zones of Italy. In northern Italy, Turin climate was used to represent the climate zone E; in the centre of Italy, the locality of Rome was used for representing the climatic zone D; finally, for the warmer climate of Southern Italy, Palermo was used to represent the climate zone B. Table 1 reported the monthly average temperature for all the three climatic zones of Italy. A total of 24 simulations was carried out; the results obtained in terms of thermal energy requirements for heating ($Q_{h,nd}$) and design thermal load ($P_u$) are shown in Table 2, calculated according to UNI/TS 11300-1 [6] and UNI EN ISO 12831 [7].

**Tab. 1 –** Monthly average outdoor temperatures for Turin, Rome and Palermo respectively (unit °C).

| | Turin [°C] | Rome [°C] | Palermo [°C] |
|---|---|---|---|
| January | 1.20 | 8.10 | 11.9 |
| February | 3.10 | 9.10 | 11.5 |
| March | 8.30 | 11.5 | 13.6 |
| April | 11.9 | 15.9 | 16.8 |
| May | 18.0 | 19.2 | 20.3 |
| June | 22.1 | 22.6 | 24.1 |
| July | 23.6 | 26.4 | 27.1 |
| August | 22.6 | 26.6 | 27.2 |
| September | 19.1 | 21.7 | 24.1 |

| | | | |
|---|---|---|---|
| October | 12.3 | 17.8 | 20.8 |
| November | 6.80 | 12.7 | 16.8 |
| December | 2.60 | 8.70 | 13.1 |

### *2.2 Reference system*

Once defined the main geometrical and envelope the same reference system, composed of an autonomous heating system, used for the production of domestic hot water combined with the space heating provision. A class A condensing boiler generator, with a 22 kW nominal power and a modulating regulation was considered. For each simulated model, two types of emission terminals were analysed; (1) fan coil with hot water temperature of 45°C and (2) radiant floor with hot water temperature of 35°C. The presence of radiators in the bathrooms characterises all models. Finally, new and existing buildings were diversified only in terms of ventilation system type. Specifically, new buildings (characterized by levels A and B) are equipped with a mechanical ventilation system with heat recovery. On the contrary, existing buildings (characterized by levels C and D) present only natural ventilation through windows opening. It is important to specify that, in this paper, attention is devoted only to heating purposes, without considering the space cooling demands of the SFHs under analysis.

### *2.3 Proposed heat pump solutions*

To estimate the performances of heat pump characteristics of the analysed SFHs, a reference system was identified, with the scope of comparing its energy and environmental performances in the different developed building models with those of heat pumps to be potentially installed in these buildings. All 8 models (i.e., 4 new buildings and 4 existing buildings) are assumed to be equipped with solutions when installed in the modelled buildings, diverse system solutions were proposed, considering the replacement of the reference heat generator and the thermoregulation system. Focusing on electric solutions, the following three air-to-water heat pumps were considered:

(1) one-section air-to-water heat pump space heater, ideal for new buildings with medium-low energy requirements and for renovations;

(2) two-section air-to-water heat pump space heater, ideal for new buildings with medium-low energy requirements, for renovation or for the replacement of existing generators;

(3) two-section air-to-water heat pump combination heater with domestic hot water storage, ideal for new buildings with medium-low energy requirements or for renovations.

Considering that the solutions (2) and (3) are characterized by the same thermal power and Coefficient of Performance (COP), these solutions were simulated only once. In all simulations, heat pumps are evaluated only in heating mode (cooling analyses are out of the scope of this paper). The data of heat pumps performances were gathered from technical documentation of real commercial units.

**Tab. 2 –** Characterisation of the building envelope energy performance of the simulated models. $Q_{h,nd}$: thermal energy requirements for heating; $P_u$: design thermal load.

| | | TURIN | ROME | PALERMO |
|---|---|---|---|---|
| **VERY HIGH PERFORMANCE** (Envelope level A) | Model **SA** | $P_u$: 7.15 kW<br>$Q_{h,nd}$: 31.26 kWh/m$^2$ | $P_u$: 5.07 kW<br>$Q_{h,nd}$: 6.55 kWh/m$^2$ | $P_u$: 3.80 kW<br>$Q_{h,nd}$: 2.44 kWh/m$^2$ |
| $U_{wall}$= 0.15 W/m$^2$K<br>$U_{floor}$ = 0.12 W/m$^2$K<br>$U_{window}$ = 1.2 W/m$^2$K | Model **LA** | $P_u$: 9.38 kW<br>$Q_{h,nd}$: 33.39 kWh/m$^2$ | $P_u$: 6.65 kW<br>$Q_{h,nd}$: 8.81 kWh/m$^2$ | $P_u$: 4.98 kW<br>$Q_{h,nd}$: 4.03 kWh/m$^2$ |
| **HIGH PERFORMANCE** (Envelope level B) | Model **SB** | $P_u$: 8.42 kW<br>$Q_{h,nd}$: 47.75 kWh/m$^2$ | $P_u$: 5.98 kW<br>$Q_{h,nd}$: 14.34 kWh/m$^2$ | $P_u$: 4.48 kW<br>$Q_{h,nd}$: 6.81 kWh/m$^2$ |
| $U_{wall}$= 0.28 W/m$^2$K<br>$U_{floor}$ = 0.21 W/m$^2$K<br>$U_{window}$ = 1.4 W/m$^2$K | Model **LB** | $P_u$: 10.92 kW<br>$Q_{h,nd}$: 47.95 kWh/m$^2$ | $P_u$: 7.74 kW<br>$Q_{h,nd}$: 16.41 kWh/m$^2$ | $P_u$: 5.81 kW<br>$Q_{h,nd}$: 8.22 kWh/m$^2$ |
| **LOW PERFORMANCE** (Envelope level C) | Model **SC** | $P_u$: 16.61 kW<br>$Q_{h,nd}$: 163.8 kWh/m$^2$ | $P_u$: 11.82 kW<br>$Q_{h,nd}$: 82.35 kWh/m$^2$ | $P_u$: 8.87 kW<br>$Q_{h,nd}$: 46.59 kWh/m$^2$ |
| $U_{wall}$= 0.86 W/m$^2$K<br>$U_{floor}$ = 0.5 W/m$^2$K<br>$U_{window}$ = 2.2 W/m$^2$K | Model **LC** | $P_u$: 22.43 kW<br>$Q_{h,nd}$: 160.9 kWh/m$^2$ | $P_u$: 16.02 kW<br>$Q_{h,nd}$: 83.66 kWh/m$^2$ | $P_u$: 11.96 kW<br>$Q_{h,nd}$: 47.65 kWh/m$^2$ |
| **VERY LOW PERFORMANCE** (Envelope level D) | Model **SD** | $P_u$: 19.01 kW<br>$Q_{h,nd}$: 183.2 kWh/m$^2$ | $P_u$: 13.54 kW<br>$Q_{h,nd}$: 87.84 kWh/m$^2$ | $P_u$: 10.16 kW<br>$Q_{h,nd}$: 50.42 kWh/m$^2$ |
| $U_{wall}$= 0.86 W/m$^2$K<br>$U_{floor}$ = 0.5 W/m$^2$K<br>$U_{window}$ = 4.5 W/m$^2$K | Model **LD** | $P_u$: 25.3 kW<br>$Q_{h,nd}$: 176.9 kWh/m$^2$ | $P_u$: 18.06 kW<br>$Q_{h,nd}$: 87.46 kWh/m$^2$ | $P_u$: 13.51 kW<br>$Q_{h,nd}$: 50.52 kWh/m$^2$ |

# 3. Results

The analysis aims to illustrate the energy and environmental benefits associated to the use of heat pump solutions for space heating and domestic hot water purposes for both new and existing buildings. Based on the simulation of the SFHs considering both the reference system and the proposed heat pump solutions, total non-renewable primary energy ($EP_{g,nren}$ for heating, domestic hot water and ventilation) and $CO_2$ emissions are computed for all models. Specifically, the use of heat pumps in new constructions is explored in paragraph 3.1, while their deployment for the renovation existing buildings heating systems is reported in paragraph 3.2 (considering not to intervene on the building envelope). In all cases, attention is devoted to understanding the possibility for the modelled SFHs to improve of two energy efficiency classes compared to the reference condition, in order to access the Italian tax benefit known as "Superbonus 110%" [4]. The developed graphs provide the results for the three different climatic zones - Turin, Rome and Palermo - and for the diverse emission systems (i.e., radiant floors and fan coils, respectively in blue and red colours). All graphs present on the x-axis the three building system solutions compared (including the reference system) for the three climates; the y-axes report the total non-renewable primary energy on the left and the $CO_2$ emissions on the right.

### *3.1 New buildings*

Four models of new constructions were developed (models SA, SB, LA and LB), all characterised by the presence of controlled mechanical ventilation and of very high- and high-performance envelopes.

It is clear from the graphs shown in the following figures (from Figure 1 to Figure 4) that the use of one-section and two-section air-to-water heat pump space heater, and two-section air-to-water heat pump combination heater with domestic hot water storage is advantageous both in terms of energy savings and reduced environmental impact, showing a significant reduction in non-renewable primary energy consumptions and $CO_2$ emissions compared to the use of a condensing boiler (i.e., reference system). All buildings are characterised by an energy efficiency class A+ also with the condensing gas boiler, due to the high building envelope performance considered for new construction buildings. In general, different heat pump solutions provide similar total non-renewable primary energy values in the same country, while the variability of the values in relation to each climate is evident. In addition, from the figures presented below, it can be seen that the performances of the aforementioned heat pumps (whether one-section and two-section air-to-water heat pump space heater, and two-section air-to-water heat pump combination heater with domestic hot water storage) are in line with the minimum performance required by law. A detail discussion of the results for each climate zone is here presented.

In Turin, the one-section heat pump, associated with the use of radiant floor, leads to a consistent amount of energy savings, ranging from 27% (Figure 1) to 38% (Figure 4). Also considering the application with fan coils, the energy savings range between 25% and 32% for SA and LB models, respectively. Analysing the results for the two-section heat pump, the situation is very similar; the presence of a radiant floor leads to energy savings ranging from 22% (Figure 1) to 30% (Figure 2), while with fan coils there is no substantial difference (from 21% to 27% respectively for the SA and SB models). For the location of Turin, the analysis was carried out only for the small size model because the useful thermal power required by the large size model cannot be satisfied by the considered heat pumps.

In Rome, the percentages of energy savings and reduction of $CO_2$ emissions are slightly lower than the results shown for Turin. The one-section heat pump, associated with the use of radiant floor, leads to energy savings ranging from 22% (Figure 1) to 32% (Figure 4). Considering the two-section heat pump the amount of energy savings ranging from 19% (Figure 1) to 30% (Figure 4). Again, no substantial difference is visible for the combination of heat pumps with fan coils.

Finally, focusing on Palermo climate, the one-section heat pump, combined with the use of radiant floor, results in energy savings ranging from 20% (Figure 1) to 29% (Figure 4); in the scenario with the replacement with two-section heat pump the values come from 19% to 27%, respectively.

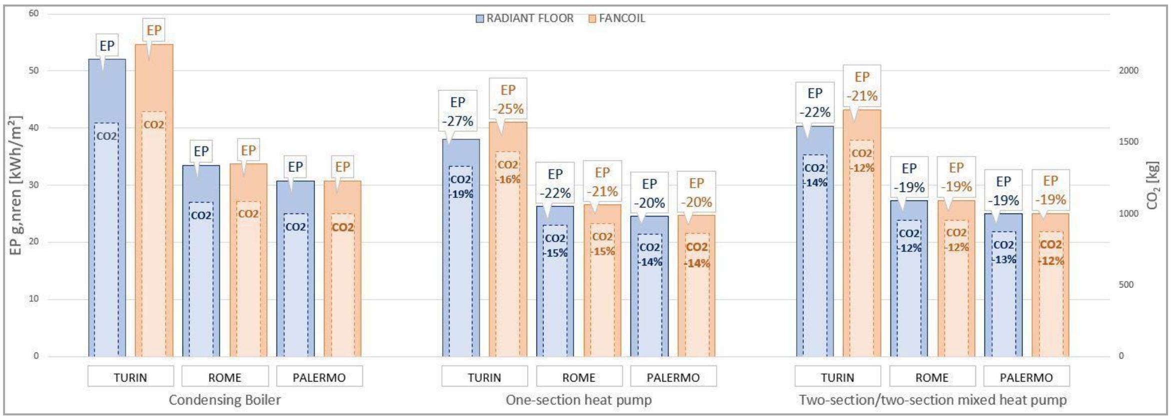


**Fig. 1 –** Energy- and environmental-related outcomes for model SA.

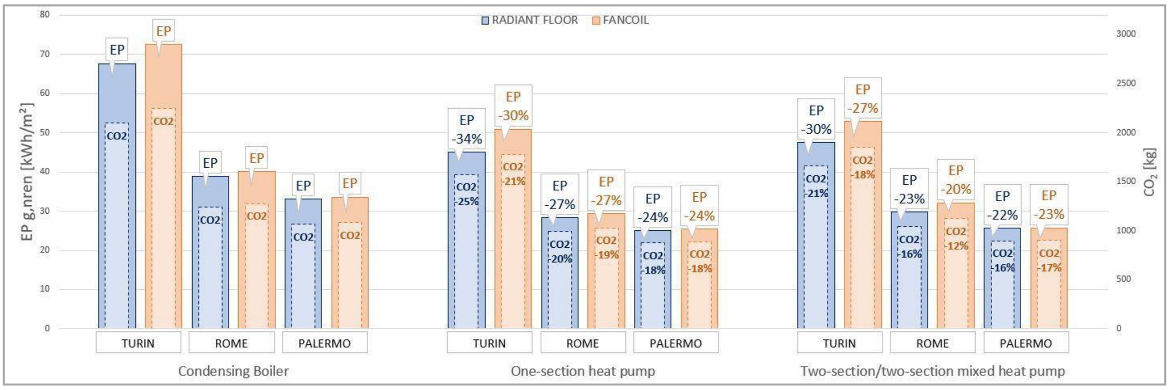


**Fig. 2 –** Energy- and environmental-related outcomes for model SB.

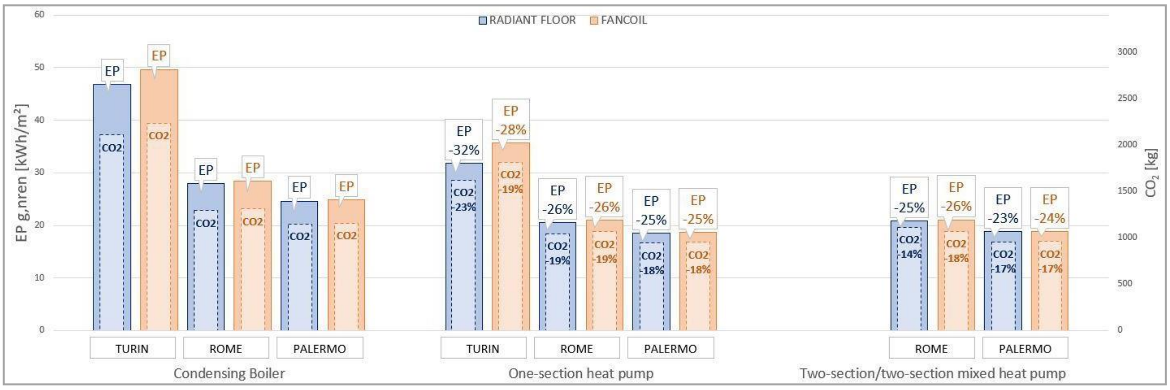


**Fig. 3 -** Energy- and environmental-related outcomes for model LA.

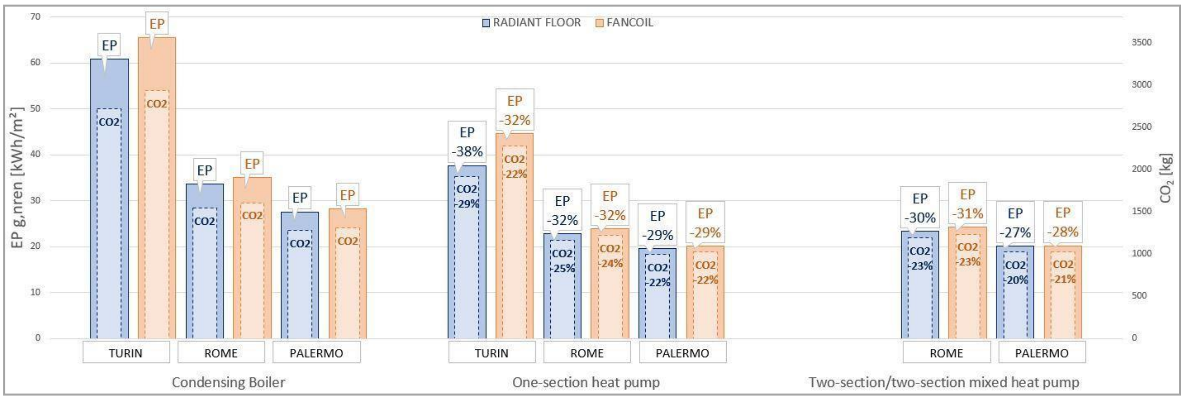


**Fig. 4 -** Energy- and environmental-related outcomes for model LB.

### *3.2 Existing buildings renovation*

Four models of existing buildings were developed (models SC, SD, LC and LD), all characterised by the presence of natural ventilation and of low- and very low-performance envelopes. As previously mentioned, this section aims to determine whether an intervention of sole system upgrading - the replacement of a condensing boiler with an air-to-water heat pump solution - excluding actions on building envelope, can guarantee the improvement of two energy efficiency classes [5].

As it possible to see from the graphs (from Figure 5 to Figure 8), the results clearly show how the replacement of the condensing boiler with an air-to-water heat pump, both one-section and two-section solutions, makes it possible to achieve an improvement of at least two energy efficiency classes, also without intervening on the envelope. Indeed, this double energy class shift is always verified, both in the presence of radiant floors and fan coils (represented in blue and red, respectively). As far as the environmental analysis is concerned, the graphs show a significant decrease in $CO_2$ emissions achieved thanks to the use of heat pump technologies. It is important to specify that the analysis is not available for Turin, because the useful thermal power required by both small and large models cannot be satisfied by the considered heat pumps. Furthermore, the large-size SFHs (models LC and LD, shown in Figure 7 and 8, respectively) were only simulated for Palermo, since the heat pump sizes did not meet the criteria required also for Rome.

In Rome, the one-section heat pump, associated with the use of both radiant floor and fan coils, leads to a consistent amount of energy savings, ranging from 50% to 60% in model SC, as well as in model SD. It can be seen from the graphs that the energy saving achieved leads to 3 to 4 energy class jumps - from class D to A1/A2 in Figure 5 and from class E to B/A1 in Figure 6.

In Palermo, the percentages of energy savings and reduction of $CO_2$ emissions are quite the same. The one-section heat pump, associated with the use of radiant floor, leads to energy savings ranging from 61% (Figure 5) to 63% (Figure 8). Considering the two-section heat pump the amount of energy savings is equal to 54% in all models. No substantial difference is visible for the combination of heat pumps with fan coils.

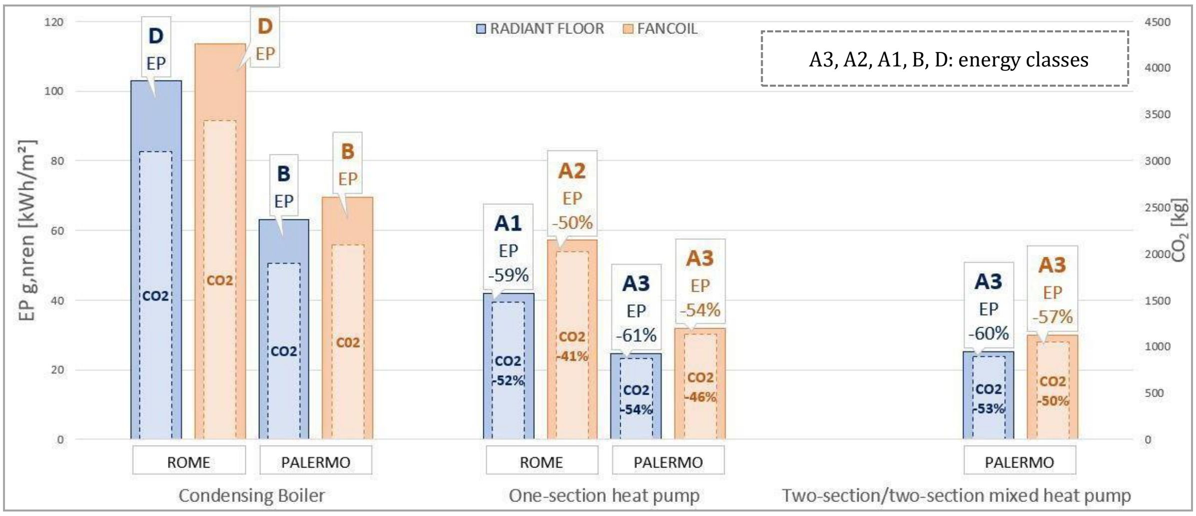


**Fig. 5 -** Energy- and environmental-related outcomes for model SC.

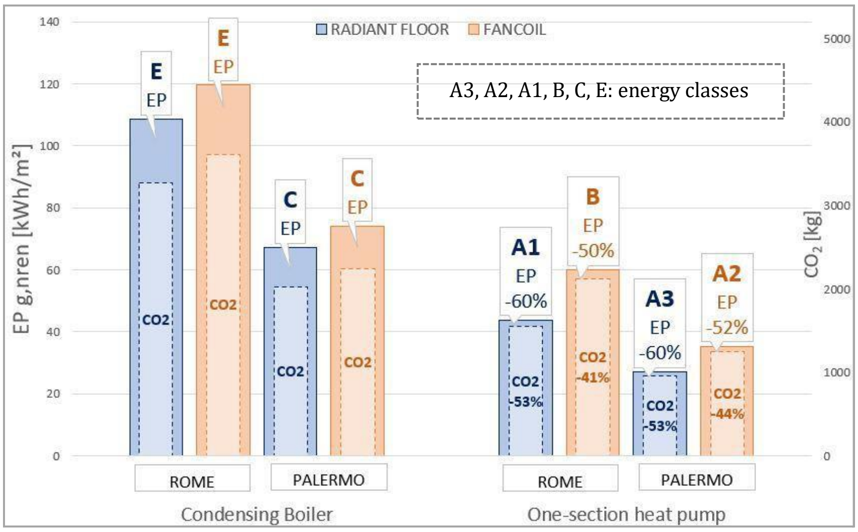


**Fig. 6 -** Energy- and environmental-related outcomes for model SD.

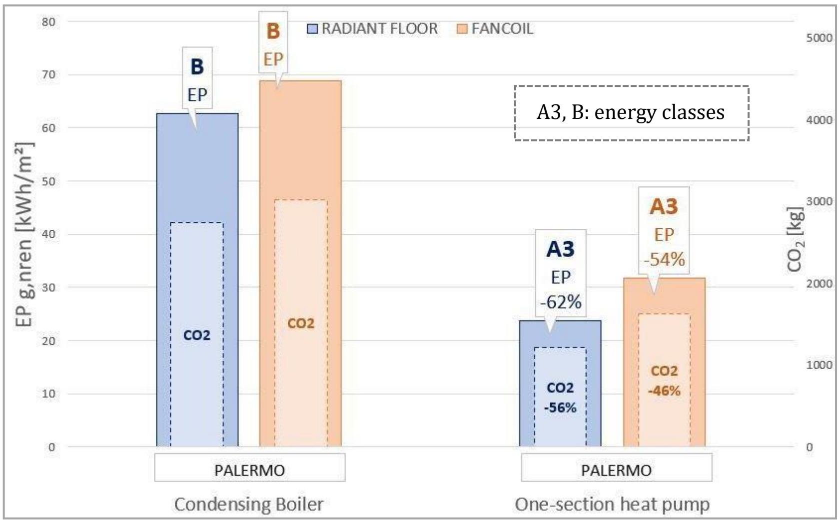


**Fig. 7 -** Energy- and environmental-related outcomes for model LC.

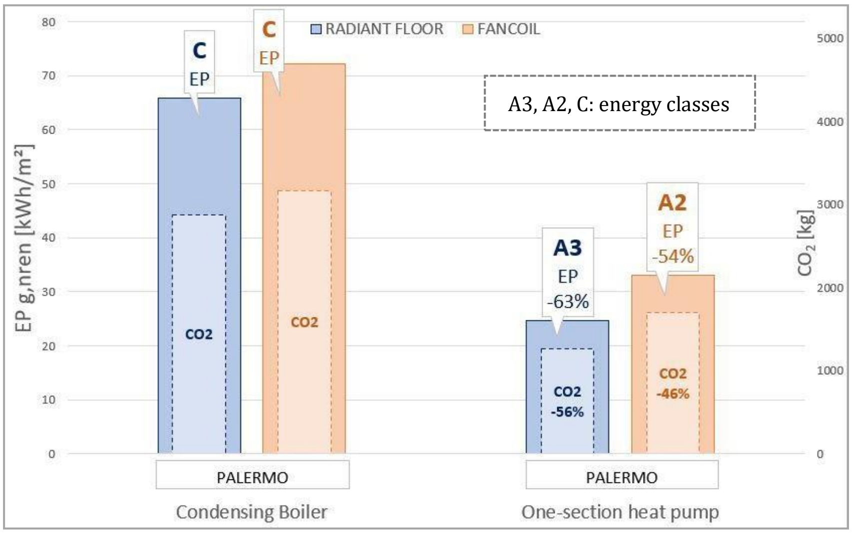


**Fig. 8 -** Energy- and environmental-related outcomes for model LD.

## 4. Conclusions

Energy efficiency of buildings represents the key factor of the current European policy actions in order to achieve the energy transition and the energy efficiency of the building sector. Nowadays, the building sector is responsible for 40% of total energy consumption, in which building heating is recognized as the main sources [2]. In this context, a solution is the widespread adoption of heat pump technologies. In fact, in the Italian residential context, the Decree Law 34/2020 [5] increased the tax incentives to 110%, encouraging the replacement of heating systems with heat pump technologies, among various actions. In this context, the paper aims to investigate the effectiveness of air-to-water heat pumps as an alternative to the traditional condensing boilers in residential buildings. In detail, the study concerned two main application fields, depending on the type of building intervention; new construction and existing buildings renovation. In the first analysis the main goal is to illustrate the energy and environmental benefits of using heat pump solutions for the heating and domestic hot water production. The second application aims to determine whether an intervention of system upgrading can guarantee the improvement of two energy efficiency classes.
The results of the analysis shown that the use of one-section and two-section air-to-water heat pump space heater, and two-section air-to-water heat pump combination heater with domestic hot water storage is advantageous both in terms of energy savings and reduced environmental impact, showing a significant reduction in $CO_2$ emissions compared to the use of a condensing boiler. Furthermore, it has been demonstrated that an intervention of sole system upgrading - the replacement of a condensing boiler with an air-to-water heat pump solution - excluding actions on building envelope, can guarantee the improvement of more than two energy efficiency classes.
The present analysis was carried out on single-family buildings and, in all the simulations, the heat pumps are evaluated only in heating mode. In this view, it might be interesting, as a future development, to consider apartment buildings and to develop the

analysis for the summer season, also considering the cooling mode. In addition, beyond the energy and environmental saving aspect, the impact on the economic value of the building after the energy requalification could be an interesting topic to further explore.

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### *Data statement*

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.