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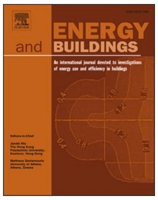

Substitution of heating systems in the Italian buildings panorama and potential for energy, environmental and economic efficiency improvement

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ABSTRACT

In many countries, old inefficient generators are used for heating purposes. A way to improve energy efficiency in those countries can be the choice of the most suitable heating generators to replace the current ones, without the inconveniences caused by other retrofit measures. In this context, we present a methodology to choose the most appropriate generator through dynamic simulations applied to building stock energy models. Economic, energetic, and environmental parameters guide the choice. The methodology is applied in the Italian residential building scenario, where the most widespread heating device is traditional boiler. Three options are considered: condensing boiler, heat pump, and hybrid heat pump (an alternative-working system with a condensing boiler and heat pump). For a detailed analysis, a white-box bottom-up building stock energy model is defined, through a statistical analysis, consisting of four building typologies in three different external climates. An hourly dynamic building-system simulation has been performed to obtain energy performance, emissions, and operational costs. The results have demonstrated that condensing boiler allows limited economic, environmental, and energy savings (8 −14%), compared to traditional boiler. The highest economic savings are obtained with the hybrid heat pump (20%), while the heat pump alone leads to higher costs, but the highest savings in emissions and non-renewable primary energy (25 −50%). The flexibility offered by the hybrid heat pump allows to obtain high savings in different cost scenarios, but also to further reduce CO_2 emissions by implementing an environmental-based control strategy.

1. Introduction and state of the art

1.1. Context

Buildings are key contributors to final energy requirements and greenhouse gas emissions [1]: in the European Union, these shares count for 40% of the final energy and 33% of the emissions. Many efforts have been set up to reduce these values, through focused policies and strict objectives. The European Green Deal [2], for instance, established that all new buildings should be NZEB (Nearly-Zero Energy Buildings) starting from 2021. At the same time, it recognized that existing buildings are often deeply inefficient, so higher savings in energy and emissions reductions would be obtained through the renovation of this stock. In Directive 2021/27/EU [3], the existing building stock has been defined as the "*single biggest potential sector for energy savings […], crucial to achieving the Union objective of reducing greenhouse gas emissions by 80–95% by 2050 compared to 1990*". The importance of renovating the existing building stock has been confirmed by the revised EPBD [4] and the Renovation Wave Plan [5].

Space heating represents 70% of the end-use energy consumption in EU buildings [6], with some differences related to external climate; so, implementing strategies to reduce energy requirements related to this service would be the first option. Various measures are possible to improve heating service efficiency, e.g., the installation of thermal insulation on external walls, high-performance glazing, and substitution of inefficient boilers with other energy-efficient generators [7]. Compared to the other retrofit solutions (e.g., thermal insulation of the envelope), the substitution of the heating generation system is the easiest to implement, as it minimizes the house physical changes, it does not cause discomfort to users during installation, it can be applied also in heritage or protected buildings (where measures involving the envelope are usually unfeasible), and it is usually the cheapest approach [8]. Besides, the most widespread heating generators are old and inefficient (in EU, about 65% of the heating systems need to be replaced [9]), so, there is room for improvement.

In Italy, the most widespread heating system is the traditional natural-gas boiler, accounting for about 70% [10]. The HARP (Heating

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Nomenclature

Acronyms

BF	Block of flats
BSEM	Building stock energy model
CB	Condensing boiler
HDD	Heating degree days
HHP	Hybrid heat pump (electrically driven heat pump and condensing boiler working alternatively)
HP	Heat pump
HV	High-insulated villa
HVAC	Heating, ventilation, and air conditioning
NZEB	Nearly zero energy building
SF	Single flat
UV	Under-insulated villa

Nomenclature

$\widetilde{c}$	Hourly operative cost [€]
$CO2$	CO_2 emissions [g_{CO2}]
COP	Coefficient of performance of the heat pump [-]
COP^*	Threshold COP for heat pump convenience [-]
COP_{id}	Ideal Carnot COP [-]
CR	Capacity ratio [-]
f	Generic conversion coefficient [-] or [g_{CO2}/kWh] or [€/kWh]
f_{CR}	Penalization factor of COP for heat pump working in partial load conditions [-]
H_{tr}	Transmission losses coefficient [W/K]
H_{ve}	Ventilation losses coefficient [W/K]
nPr	Non-renewable primary energy [kWh]
$OpEx$	Annual operative cost [€]
Q_B	Building heating load [kW]
Q_e	Nominal power at terminal units [kW]
Q_{HP}	Thermal power of the heat pump [kW]
RH	Relative humidity [%]
S_{loss}	Area subject to thermal losses [m^2]
$SCO2$	CO2 emission savings [%]
$SnPr$	Non-renewable primary energy savings [%]
$SOpEx$	Operational costs savings [%]
T_{ext}	External temperature [°C]
$T_{w,out}$	Supply temperature at terminal units [°C]

Greek symbols

δ	Boolean indicator, used to identify hourly the generator used for heating [-]
Δ	Variation
η_b	Boiler efficiency [-]
η_{II}	Exergetic efficiency of the inverse cycle [-]

Subscript

bench	Benchmark
CO2	Referred to CO2 emissions
cr	Switch criterion of the hybrid heat pump
des	Design
eco	Referred to operational costs
i	Referred to a specific timestep in a year
j	Referred to a specific nominal capacity of the heat pump, to be optimized
k	Referred to a specific generator configuration
min	Minimum
max	Maximum
ng	Natural gas
nom	Nominal
nPr	Referred to non-renewable primary energy

Appliances Retrofit Planning) European Project [9] carried out an analysis of the heating generators available on the market for space heating, identifying to this purpose (i) condensing boilers; (ii) heat pumps; (iii) hybrid heat pumps; (iv) biomass boilers, and (v) combined heat and power systems. The choice of the most advantageous generator for the substitution of a traditional boiler is not unique, as external climate and the effective heating load (i.e., partial loads conditions) affect the performance and convenience of these systems. Moreover, for the same building and climate, the most suitable generator can be different if the choice is made considering economic, environmental, or energy parameters. Thus, the most appropriate strategy to correctly choose the generator must include the analysis of the building, the climate, and the objectives to be reached. On a regional/national scale, this strategy involves the whole building stock.

Among the various exploitable techniques, Building Stock Energy Models (BSEMs) are tools that can be used to assess current buildings' energy demand and future trends, considering different upgrade scenarios, and then providing results serving as a basis for national and international strategies and policies by investors and public administration. According to [11–12], four groups for BSEMs can be defined, considering:

- the "design", which means the level of buildings aggregation chosen for the research:
  - o top-down, where the building stock is considered aggregately and optionally divided into subgroups;
  - o bottom-up, where some buildings are identified as "representative" of the aggregate system and studied in detail;
- the "degree of transparency", which means the type of data used in the model:
  - o black-box models, where experimental data are used in models without a physical-based interpretation;
  - o white-box models, where the models implement a physical correlation between input data and energy demand.

The design and transparency levels can be mixed up (e.g., there are top-down black-box models and top-down white-box models). Hybrid models combined different approaches of design and degree of transparency, thus not resulting precisely into one of the four categories.

Even if BSEMs are recognized as a tool to provide both "static" and "dynamic" energy assessment (i.e., the energy request at a specific moment or the evolution of those requests over time), their use in scientific literature is not yet widespread. However, those models would be useful to check the potential of energy and emission reduction for a region or country. In the following section, an analysis of the state of the art on this topic is discussed.

1.2. Literature review

An analysis of the scientific literature has been carried out through the reading of journal articles published in the last 15 years, with particular attention on the most recently published ones. In the analysis, the answers to three research questions have been sought:

- what kind of buildings or building stock are used to test the retrofit measure effectiveness?
- are there retrofit measures involving the replacement of inefficient heating systems?
- what are the indicators used to quantify the effectiveness of retrofit measures?

Thus, SCOPUS database has been used for the review, using the keywords “Building”, “Building stock”, “Retrofit measures”, and “Optimization”. From the initial dataset, the reading of either the abstract or the title revealed works not inherent to the scope; other pieces of research were instead added to the analysis by reading the papers that SCOPUS suggested as correlated.

In Table 1, a summary of the literature analysis is presented, pointing out the found answers characterizing the papers. This analysis highlighted that this topic has gained relevance in the last years, with many different measures discussed to reduce energy demands in the residential sector. The main findings from the literature review are the following:

- the majority of papers analyze single case studies, and only a few works consider building stock [8,13,14], typically through white-box BSEMs;
- typical retrofit measures aim to improve the envelope; retrofit measures involving the heating system are scarce, limited to the study of replacement of current generator with a single-option more-efficient one (e.g., condensing boiler, heat pump) [15–17];
- the majority of papers rank the retrofit measures based on the obtainable energy savings; only a few papers rank them also through the assessment of economic and/or emission savings [15,18,19].

Generally, the literature appears fragmented, lacking a comprehensive analysis of building stock where the most efficient substituting heating system is chosen among different options and depending on the construction characteristics. Compared with envelope retrofit, the replacement of the heating generator is indeed a handy efficiency measure, improving efficiency without unsustainable purchase expenses or huge alteration of indoor spaces. However, being aware that each generator type would perform differently in different contexts, the juxtaposition of different solutions in the residential building stock seems essential to assess the most efficient heating system in each case.

1.3. Aim and novelty of the work

From the literature analysis, as shown in Table 1, a research gap has been found, consisting in the investigation of the performance and comparison of a set of individual heating systems with different energy vectors applied in a specific residential building stock, aimed at finding the most appropriate one according to energy, environmental and economic parameters. This analysis should be carried out in a national context, or at least in a region characterized by similar constructions, heating, ventilation, and air-conditioning (HVAC) component sizing rules, and power production mix. In this research, the proposed methodology is applied to the Italian residential scenario, but it is easily applicable also to other countries.

In Italy, the traditional boiler is the current most widespread generator, and it is then set as the benchmark case. The studied

Table 1
Main topics of the analyzed scientific papers.

Year, Ref	Country	Single case study / Building stock	Is the replacement of inefficient heating system studied?	Economic indicators	Environmental indicators	Energy indicators
2007, [6]	Greece	Residential building stock	Yes, replacement with efficient oil-burners	✘	✓	✓
2013, [20]	Sweden	Residential building stock	No	✘	✓	✓
2015, [18]	Bari, Italy	5 case studies	Yes, replacement with condensing boiler and solar thermal	✓	✓	✓
2015, [17]	Spain	Residential building stock	Yes, replacement with condensation boiler or biomass boiler	✓	✓	✓
2016, [21]	Italy	2 case studies, in 4 different cities	No	✓	✘	✓
2016, [10]	Piedmont region, Italy	Residential building stock	Yes, replacement with condensing boiler	✘	✓	✓
2017, [8]	Italy	Residential building stock	Yes, replacement with condensing boiler	✓	✘	✓
2017, [16]	Turin, Italy	3 case studies	Yes, comparison among natural-gas boiler, electric heater, heat pump and hybrid system	✘	✘	✓
2017, [22]	Canada	Residential building stock	Yes, replacement with heat pump	✓	✓	✓
2018, [23]	West Lafayette, USA	Single case study	Yes, replacement with ground-source heat pump and air-handling unit	✘	✘	✓
2019, [24]	Canada	Single case study in three different climates	Yes, replacement with heat pump	✓	✓	✘
2021, [25]	Italy	Residential building stock	Yes, replacement with heat pump	✘	✘	✓
2021, [26]	Seville, Spain	Single case study	Yes, replacement with heat pump (working with electrical water heater)	✘	✓	✓
2021, [27]	Bilbao, Spain	17 case studies	Yes, replacement with condensing boiler	✓	✘	✓
2021, [13]	Austria, Czech Republic, Germany, Denmark, Italy and Romania	Residential building stock	No	✓	✘	✓
2022, [28]	England, UK	Residential building stock	No	✘	✘	✓
2022, [15]	Italy	Single case study in three different climates	Yes, replacement with CO_2 heat pump or condensing boiler	✓	✓	✓
2022, [19]	Canada	Single case study in 2 different climates	Yes, replacement with air-source heat pump	✓	✓	✓
2022, [14]	Bosnia and Herzegovina	Residential building stock	Replacement with centralized heating system; replacement with heat pump only in multifamily houses	✓	✓	✓
2022, [29]	Suków, Poland	Single case study	Yes, replacement with heat pump	✓	✘	✓

generators are: condensing boiler, electrically-driven heat pump, and hybrid heat pump. All these technologies are considered classic solutions for heating in Italy according to the HARP European Project. Biomass boilers are instead neglected due to the unavailability of this resource across the whole Italian territory. Micro-cogeneration systems (providing both heat and power) is not studied either, as it is not a typical option for residential dwellings, including flats and single-family houses. To do so, a bottom-up white-box BSEM is used. Within this BSEM, a set of case studies is identified as representative of the Italian building heritage, according to a census of the buildings and an analysis of the typical zone climates. A dynamic simulation is then performed, aimed at assessing economic, environmental, and energetic indicators for each building, external climate, and generator. Finally, for each set of case studies, the heating systems are ranked on the basis of these indicators. The results found in this research can be of particular interest for decision-makers, assisting them in formulating sustainable and appropriate energy efficiency policies and strategies, and setting priority goals. As the results relate to a statistically representative building stock, they are thus extendible to the region that the buildings represent; this would have not been possible if simulations had been carried out on single case studies.

2. Methodology

In this section, we present the models of the heating systems. Models developed for energy labeling and technical standards are used for all the generators, avoiding specific values of thermo-physical characteristics and performances that differentiate market-available devices.

2.1. Benchmark generator: Traditional boiler

In Italy, the natural-gas traditional boiler is the most widespread generator [15], which is then considered to calculate economic, environmental, and energy benchmark values. A procedure discussed in the Italian technical standard UNI/TS 11300–2 [30] has been used to assess the efficiency of this system when specific data from manufacturers are not known. For this system, the base value of efficiency is 0.93, but factors such as supply water temperature (depending on the terminal units) and capacity ratio reduce this value, up to 0.85–0.90.

2.2. Condensing boiler (CB)

Condensing boilers (CBs) increase the efficiency of traditional boilers in recovering latent heat of vaporization in exhaust gases. As in the previous case, Italian technical standard UNI/TS 11300–2 [30] has been used to assess the base value of efficiency, which is 1.01; correction factors apply, depending on the return water temperature and the temperature difference between the return temperature and exhaust gas temperature, resulting in an efficiency ranging from 0.95 to 1.00.

2.3. Electrically driven heat pump (HP)

The efficiency of electrically driven air-to-water heat pump (HP) is assessed by using the COP indicator, which is the ratio between the thermal energy provided to the building and the electrical energy needed to run the compressor. The performance of heat pump is influenced by physical-based and technological-based effects:

- at full load, the COP is influenced by source and sink temperatures (respectively, the temperature of the supply water temperature $T_{w,out}$, and external temperature T_{ext}) and by the irreversibilities of each heat-pump component; as a result, the COP at full load can be expressed as the product of the ideal Carnot COP (COP_{id}) and the exergetic efficiency of the inverse cycle (η_{II}), as in Eqs. (1a)-(1b);
- at partial loads, the capacity ratio CR causes the reduction of the COP through the factor f_{CR} (Eq. (1c)), as the efficiency of the inverter tends to decrease during modulation.

Ref. [31] is the base reference for the evaluation of COP as in the following equations:

$$COP = COP_{id} \times \eta_{II} \times f_{CR} \tag{1a}$$

$$COP_{id} = \frac{T_{w,out} + 273.15}{T_{w,out} - T_{ext}} \tag{1b}$$

$$f_{CR} = \begin{cases} 1, \; if \; CR \geq 0.5 \\ \left(\dfrac{CR}{0.8 \times CR + (1 - 0.9)}\right), \; if \; CR < 0.5 \end{cases} \tag{1c}$$

The heating capacity of the heat pump is chosen based on the design heating request of the building.

2.4. Hybrid heat pump (HHP)

This generator consists of an electrical air-to-water heat pump and a natural-gas condensing boiler, working alternatively. The methodology for the evaluation of hybrid heat pump (HHP) performances is based on the two different methodologies presented in Section 2.2 and 2.3. Almost all the market-available alternative hybrid heat pumps have a management strategy of the two generators based on the lowest operational cost. In other words, an economic switch criterion is used to choose which of the two generators should provide the heating load. For the *i*-th timestep, the following inequality is then checked:

$$\frac{Q_{B,i}}{COP_i} \times f_{eco,el} < \frac{Q_{B,i}}{\eta_{b,i}} \times f_{eco,ng} \tag{2}$$

Then, the effective *i*-th operative cost is:

$$\widetilde{c_i} = \min\left(\frac{Q_{B,i}}{COP_i} \times f_{eco,el}; \frac{Q_{B,i}}{\eta_{b,i}} \times f_{eco,ng}\right) \tag{3}$$

Differently from the case of the single generator, sized according to the design conditions based on the peak thermal request, the use of the hybrid heat pump allows the choice of the generators' nominal power that can be different from the design value of the building. In particular, as the heat pump performances are more strongly influenced by the capacity ratio, the nominal heat capacity of this generator is chosen through an exhaustive-search optimization procedure resulting in the minimum operating costs, written as in Procedure 1. For each tested heat capacity ($Q^j_{HP,nom}$), the maximum heat that can be provided in the operating conditions (external temperature: T_{ext}; supply water temperature: $T_{w,out}$) is evaluated (Eq. (4d)) [32], that value being necessary to assess the capacity ratio (Eq. (4c)), COP (Eq. (4b)), and operating economic outputs (Eq. (4a)).

Procedure 1. Choice of heat pump nominal capacity in hybrid heat pumps.

$$Find \; \widehat{Q}_{HP,nom} \; in \; the \; range \; Q^j_{HP,nom} \in \left[0, Q^{max}_{HP,nom}\right]$$

$$which \; minimizes \; the \; objective \; function \; Z = OpEx$$

$$OpEx^j = \sum_{i=1}^{8760} \widetilde{c_i} = \sum_{i=1}^{8760} \min\left(\frac{Q_{B,i}}{COP^j_i} \times f_{eco,el}; \frac{Q_{B,i}}{\eta_{b,i}} \times f_{eco,ng}\right) \tag{4a}$$

$$where \;\; COP^j_i = \frac{T_{w,out,i} + 273.15}{T_{w,out,i} - T_{ext,i}} \times \eta_{II} \times \frac{CR^j_i}{\left(C_d \times CR^j_i + (1 - C_d)\right)} \tag{4b}$$

$$CR^j_i = \frac{Q_{B,i}}{Q^j_{HP,max,i}} \tag{4c}$$

$$Q^{j}_{HP,max,i}\left(T_{w,out,i},T_{ext,i}\right)=Q^{j}_{HP,nom}\times\left(\frac{\left(T_{w,out,nom}+273.15\right)}{\left(T_{ext,nom}+273.15\right)}\times\frac{\left(T_{ext,i}+273.15\right)}{\left(T_{w,out,i}+273.15\right)}\right)^{3}\tag{4d}$$

2.5. Indicators

In this piece of research, the effectiveness of the generic k-th generator type is assessed through a comparison with the benchmark case. Three indicators are defined, representing the potential savings in operating costs, non-renewable primary energy, and equivalent emissions, obtainable via the k-th generator compared with the benchmark cases. Those indicators are::

- Operating cost savings, $SOpEx_k$, defined as the operating cost savings when using the k-th generator compared to traditional boiler solution:

$$SOpEx_k=\frac{\sum_i\tilde{c}_{bench}-\sum_i\tilde{c}_k}{\sum_i\tilde{c}_{bench}}=\frac{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{eco,ng}-\sum_i\left(\delta_{k,i}\times\frac{Q_{B,i}}{\eta_{b,k,i}}\times f_{eco,ng}+\left(1-\delta_{k,i}\right)\times\frac{Q_{B,i}}{COP_i}\times f_{eco,el}\right)}{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{eco,ng}}[\%]\tag{5}$$

- Non-renewable primary energy savings, $SnPr_k$, defined as the non-renewable primary energy savings using the k-th generator, compared to traditional boiler solution:

$$SnPr_k=\frac{\sum_i nPr_{bench}-\sum_i nPr_k}{\sum_i nPr_{bench}}=\frac{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{nPr,ng}-\sum_i\left(\delta_{k,i}\times\frac{Q_{B,i}}{\eta_{b,k,i}}\times f_{nPr,ng}+\left(1-\delta_{k,i}\right)\times\frac{Q_{B,i}}{COP_i}\times f_{npr,el}\right)}{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{nPr,ng}}[\%]\tag{6}$$

- CO_2 emission savings, $SCO2_k$, defined as the CO_2 emission savings between the k-th generator and the benchmark generator:

$$SCO2_k=\frac{\sum_i CO2_{bench}-\sum_i CO2_k}{\sum_i CO2_{bench}}=\frac{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{CO2,ng}-\sum_i\left(\delta_{k,i}\times\frac{Q_{B,i}}{\eta_{b,k,i}}\times f_{CO2,ng}+\left(1-\delta_{k,i}\right)\times\frac{Q_{B,i}}{COP_i}\times f_{CO2,el}\right)}{\sum_i\frac{Q_{B,i}}{\eta_{b,bench,i}}\times f_{CO2,ng}}[\%]\tag{7}$$

In Eqs. (5)–(7), $\delta_{k,i}$ is a Boolean being equal to 1 if the natural-gas boiler is used (in the mono-source generator case or in the hybrid configuration, limited to the hours of effective use); it is instead equal to 0 if the heat pump is used.

In the assessment of the three indices, the values of $f_{eco,ng}$, $f_{eco,el}$, $f_{nPr,ng}$, $f_{nPr,el}$, $f_{CO2,ng}$, and $f_{CO2,el}$ depend on the country in analysis and strongly influence the outcomes. Thus, different energy vector costs and primary energy mix will result in different generators being optimal for each national scenario.

3. Energy model and simulation to the Italian residential building stock

The objective of the research is the identification of the most suitable heating generator to be installed in substitution of traditional boilers in a specific country. In this Section, we define a set of reference buildings, representative of the Italian residential scenario. Different external climates, stratigraphy, terminal units, and type of users characterize these buildings. For this analysis, the 2011 National People and Building Census [33], national technical standard [34], and civil engineering texts [35] are adopted as references.

In the following subsections, the characteristics of climate and buildings are separately presented.

3.1. External climate

The external climate is very variable across the country, leading to the definition of six different climate zones, spanning from colder (F-zone) to milder (A-zone). These climatic zones were defined in 1993 [36] depending on the heating degree-days (HDD), where the base temperature is set at 20 °C. Among these zones, we consider only three climatic zones, where 90% of the Italian residential buildings are set. Three towns are chosen as representative of the climatic zones. This choice has been made through statistical analysis, calculating for each town the product of its HDDs and its number of buildings. Those values are averaged for climatic zones; then, within the climate zone, the town with the closest value to the average zone value is chosen as representative.

For these three towns, hourly data for temperature, solar radiation on the horizontal, relative humidity, and wind speed are provided by the Italian Thermo-technical Committee [37]. Details on the external climate for the three chosen towns are found in Table 2.

3.2. Buildings

The 2011 Italian Census [33], provided by the National Institute of Statistics (ISTAT), is used as reference for the characterization of the Italian residential building stock. The Census reports the number of dwellings for each Italian town (about 12 million), divided into three typologies: flats, detached houses, and semi-detached houses. According to the Census, 57% of people live in flats (mainly built since the 20th century, usually within condominiums of medium size), and 30% live in detached houses (usually built more than a century ago; in some cases, they have undergone retrofit). For each category of building and town, the Census provides the floor area, the volume, the glass area, the number of floors, and the area subject to transmission losses. In another section of the Census, some socioeconomic details on people (e.g., the employment rate) are reported, too, for each town.

Using all those data, four types of constructions are identified as statistically representative of the Italian building stock:

- single dwelling in a block of apartments, with an individual heating system (*SF*);
- four-story block of flats (with 12 units), with a centralized heating system (*BF*);
- under-insulated detached house (*UV*);
- high-insulated detached house (*HV*).

For each type of dwelling, average values of size and envelope characteristics have been assessed for the three climatic zones (grouping the data of towns falling within the C, D, and E zones). Slight differences in the average area subject to thermal losses in the three climatic zones have been found.

Additional envelope characteristics have been retrieved from databases and specification sheets [34,35], reporting differences in the buildings' stratigraphy depending on the climatic zone, thus allowing

Table 2

External climate for the three chosen towns: HDDs, lowest temperature ($T_{ext,min}$), average temperature ($\overline{T}_{ext}$) and relative humidity ($\overline{RH}_{ext}$) during the heating season.

Town	Climatic zone [35]	Buildings' share in this climatic zone [%]	Köppen classification [38]	HDDs	$T_{ext,min}$ [°C]	$\overline{T}_{ext}$ [°C]	$\overline{RH}_{ext}$ [%]
Pavia	E	47	Cfb	2623	−7.9	8.1	82
Pisa	D	25	Csa	1694	−4.6	9.3	80
Latina	C	19	Csa	1220	0.0	9.2	75

the evaluation of the transmission losses coefficient.

The nominal power at terminal units (Q_e) has been chosen according to typical rules of thumb applied by thermo-technical installers ($35-40\frac{W}{m^3}$). This choice was driven by considerations on thermo-technical practices: the size of terminal units in buildings is typically chosen only using the volume of the dwelling, resulting in oversized systems. The typology of terminal units (e.g., radiant panels for the high-efficiency villa, radiators for all the other cases) has been chosen considering reviews on heating systems and databases [39,40].

Two different load profiles, discussed in the next Section 3.3, were defined, based on people's presence inside the dwelling: these profiles are also correlated to internal gains, ventilation, and indoor setpoints.

Thus, 12 reference buildings were created (four building types per climate), differing for transmittance and ventilation losses, dynamic users' profiles, terminal units, and geometry. The characteristics of the 12 buildings are reported in Table 3, showing the design temperature for each climate ($T_{ext,des}$), the area subject to thermal losses (S_{loss}), the transmission losses coefficient (H_{tr}), the ventilation losses coefficient (H_{ve}), the nominal power at the terminal units (Q_e) and the associated users' profile.

3.3. Users' profiles

As previously mentioned, the 2011 Italian Census [33] also reports the employment rate for each climatic zone. These figures have been applied to associate the profile type (i.e., *workers* or *non-workers*) with the building type. In particular, the share of flats in BF occupied by *workers* or *non-workers* has been assessed by data referred to occupants in each climatic zone.

The two profiles differ for hours and days of people's presence inside the dwellings: the *workers'* profile relates to individuals with a discontinuous presence inside the dwelling during workdays and a more continuous presence during weekends; the *non-workers'* profile, instead, is characterized by a more regular presence inside the dwelling, without relevant differences between workdays and weekends. The presence of people inside the dwelling influences internal gains (e.g., electrical appliances), heating setpoint profiles, and ventilation profiles (i.e., windows being open or closed).

In particular, the profiles implemented for the internal air setpoint are the following:

- *non-workers* (in under-insulated detached houses, or in part of the apartments in blocks of flats): 20 °C from 7 a.m. to 4 p.m. and from 6 p.m. to 9 p.m. on workdays, 20 °C from 7 a.m. to 9 p.m. in weekends, 18 °C otherwise;
- *workers* (in apartments, high-insulated detached houses, or in part of the apartments in blocks of flats): 20 °C from 7 a.m. to 9 a.m. and from 6 p.m. to 9 p.m. on workdays, 20 °C from 7 a.m. to 4 p.m. and from 6 p.m. to 9 p.m. in weekends, 18 °C otherwise.

3.4. Simulation of the building-heating system and supply water temperature

For the evaluation of the hourly heating requirements of each building, a simulation using TRNSYS 17 [41] and MATLAB [42] is performed. Type 56 ("Multizone Building") in TRNSYS is used for the thermo-physics simulation of the envelope: all the features in terms of opaque and transparent walls, internal and electrical gains, ventilation, and internal air setpoint are inputs. The climate data discussed in Section 3.1 are used as the external climate in TRNSYS Simulation Studio. The results are ideal heat requests to maintain the air temperature setpoint, then used in MATLAB to assess the dynamic and annual performances of each simulated generator. Mathematical models [43,44] for the assessment of thermal exchange and dynamic efficiency at radiators and radiant panels, are used also for the evaluation of supply/return water temperature, influencing the generators' performance, the estimation of which is carried out through the models presented in Section 2.1-2.4. The one-hour timestep is considered as a compromise between results accuracy and computational effort.

Summing up, a total of 36 case studies are simulated: 4 building types in 3 climates with 3 possible generators (i.e., CB, HP, HHP). Separately, 12 case studies are used as benchmark (4 building types in 3 climates, implementing traditional boilers as reference generator).

Thanks to the choice of characteristic building dimensions, stratigraphy, occupancy, and location, the present analysis provides meaningful results, extendible to the whole Italian residential building scenario.

Table 3

Features of the reference 12 buildings.

Climate	$T_{ext,des}$ [°C]	S_{loss} [m^2]	H_{tr} [W/K]	H_{ve} [W/K]	Q_e [kW]	Users
			SF; radiators as terminal units			
Pavia	−5	114	176	55	14.8	Workers
Pisa	0	111	170	53	12.6	Workers
Latina	2	112	172	53	11.2	Workers
			BF; radiators as terminal units			
Pavia	−5	2005	2551	663	178	Workers in 7 units, non-workers in 5 units
Pisa	0	1946	2455	633	151	Workers in 6 units, non-workers in 6 units
Latina	2	1962	2481	641	134	Workers in 6 units, non-workers in 6 units
			UV; radiators as terminal units			
Pavia	−5	285	286	55	14.8	Non-workers
Pisa	0	280	280	53	12.6	Non-workers
Latina	2	281	281	53	11.2	Non-workers
			HV; radiant panels as terminal units			
Pavia	−5	285	167	55	7.4	Workers
Pisa	0	280	172	53	7.2	Workers
Latina	2	281	185	53	7.1	Workers

3.5. *Economic, energy, and environmental coefficients for Italy scenario*

For each case study, the three indicators in Section 2.5 are evaluated and compared with those assessed using traditional boilers as generator. The values of the non-renewable energy factors f_{nr} and emission factors f_{CO2} for both energy vectors are reported in Table 4 [45–47]. The average costs of electrical energy and natural gas are taken from [48,49]. Using these inputs, the threshold values of COP above which the heat pump is the convenient generator in the hybrid system can be calculated knowing the average boiler efficiency, for each timestep. Depending on which indicator is used to check the heat pump convenience, the following equation is used:

$$COP^{*}_{nPr/CO2/eco} = \eta_b \times \frac{f_{*,el}}{f_{*,ng}} \tag{8}$$

where $f_{*,el}$ and $f_{*,ng}$ are the conversion factors in Table 4.

4. Results

4.1. *Ideal heat request of the buildings*

As the first results of the analysis, Fig. 1 shows the annual ideal heat requests per floor area, differing from external climate and building type. Those differences are primarily due to variations in geometry and wall layer (especially insulation) thickness.

In Fig. 2, the hourly ratio between each building ideal energy requirement and the corresponding terminal unit nominal power is shown: values higher than 70% are rarely reached, while most of these fractions are lower than 40% (single flat, high-insulated villa) and 30% (under-insulated villa, block of flats). This outcome anticipates a result of the building-generators analysis: every heating system operates in partial loads for the majority of the time, with consequences on generator performances.

4.2. *Analysis of the results*

Table 5 shows the main results of the simulation of the 12 case studies, in terms of normalized economic, emission and energy outputs, being the unity the reference value of the "traditional generator" case. In other words, the figures in Table 5 are the ratio between the operative cost/emission/ non-renewable primary energy value assessed for a specific generator and the operative cost/emission/non-renewable primary energy value for the traditional boiler, for each building configuration. A unitary value implies that the analyzed heating system has the same output result of the traditional boiler; a lower-than-one value means that the analyzed heating system performs better than the traditional boiler.

The results in Table 5 show that values greater than the unity are sometimes found for the heat pump in the economic context, meaning that the operative costs are higher than those assessed for the traditional boiler. The results highlight that the hybrid heat pump allows the highest economic savings in all climates and all buildings. The condensing boiler is typically the least convenient generator, in almost all the case studies, when focusing on emission or primary energy; in other words, the other two generators always lead to lower CO_2 emissions and non-renewable primary energy needs. Generally speaking, putting first the economical result, the hybrid heat pump is the most suitable generator in all cases, while the heat pump alone is preferable for emission reduction. Only in the case of high-efficiency buildings, the hybrid generator is the advisable generator for all the indicators.

Table 4
Energy, environmental and economic factors for energy vectors [42–46].

	Natural gas	**Electrical energy**
$f_{nPr}[-]$	1.05	1.95
$f_{CO2}\left[\frac{g_{CO2}}{kWh}\right]$	202.4	284.5
$f_{eco}\left[\frac{€}{kWh}\right]$	0.08	0.20

In the following sections, all the four building types are separately analyzed to explain in detail the results.

4.2.1. *Single flat*

Fig. 3 presents the comparison of the three indicators (discussed in Section 2.5) for the *SF* case study, differing for the three climates. Analyzing the economic savings, percentages around 10% are obtained by replacing the traditional boiler with a condensing boiler, independently from the climatic zone. The efficiency of the condensing boiler is always around 1.0, both in the mono-source generator case and in the hybrid heat pump configuration. Thus, the COP^{*}_{eco} calculated as in Eq. (8) is always almost 2.5. The savings obtained from the use of a heat pump or hybrid heat pump are variable and dependent on the climatic zone. As an example, using the electric heat pump in the E-zone would entail a rise in the costs, thus the settling of a hybrid heat pump should be preferred, leading to an approximately 15%-cost saving. This is due to the value of the heat pump seasonal COP (defined as the ratio of the seasonal thermal energy delivered by the HP and the seasonal electrical energy required), which is 2.26 if the heat pump is the only generator, and 2.56 in the hybrid heat pump (see Fig. 4.a): in this case, this generator can operate in conditions of economic convenience, where the effective COP is higher than COP^{*}_{eco}.

Changing the climate, the differences in the savings obtained using a heat pump or a hybrid heat pump narrow: in C-zone the economic savings are almost the same (20%). Fig. 4.a shows that seasonal COP for the heat pump alone and heat pump in the hybrid one are in fact similar and higher than COP^{*}_{eco}.

The analysis of the *SnPr* shows that using the condensing boiler results in a 10%-saving; a similar percentage is obtained also for the emissions savings. Higher savings are obtained using either heat pump or hybrid generator: in particular, using the heat pump gives a greater benefit, working also when the COP is lower than the COP^{*}_{eco}, but higher than COP^{*}_{nPr} (around 1.9). In the hybrid generator case, instead, the management mode of switch between the two generators turns off the heat pump for $COP < COP^{*}_{eco}$, even if the primary energy convenience would still be guaranteed if $COP > COP^{*}_{nPr}$. Similar results are found for *SCO*2: considering the case of E-zone, a saving of around 42% is obtained using the heat pump, and a saving of slightly less than 30% is obtained using the hybrid heat pump. The difference between these two values is the penalizing management mode of the HHP, which turns off the heat pump for $COP < COP^{*}_{eco}$, whereas it would be environmentally convenient for $COP > COP^{*}_{CO2}$ (around 1.4).

For milder climates (D- and C-zones), the energy and emission savings of HP and HHP are more similar: the number of hours of high efficiency increases. Thus, a reduction in the hours when the boiler in HHP is used for economic convenience, without being the most convenient generator also for emission and energy consideration, is observed.

In Table 6, the optimal sizing of the heat pump in the hybrid generator is shown: a heat pump nominal capacity of around 8 kW is found in each climate (nominal capacity is evaluated in the following conditions: supply water temperature: 35 °C; air temperature: 7 °C). These values are lower than the sizes found in the case of heat pump alone (around $10 - 15$ kW), where the generators work often in partial load conditions, lowering COP.

Considering the share of building thermal load provided by the heat pump in the hybrid generator case (see Fig. 4.b), a value of almost 90% is reached in the mildest climatic zone. The condensing boiler is used in the remaining hours when the low heat requirements would cause the heat pump to work with a too low capacity ratio, and then COP. In the coldest climate, the heat pump works instead for 40% of the time, due to both low capacity ratio (in the hours with limited request) and harsh

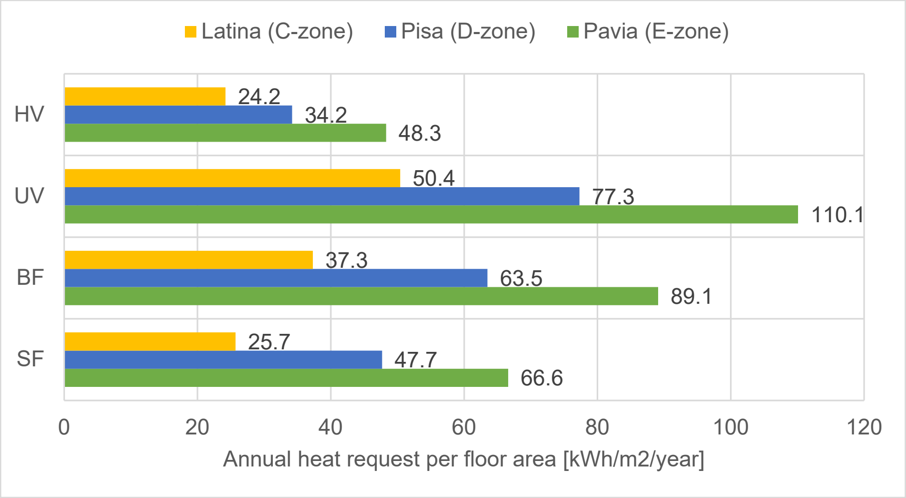


Fig. 1. Annual heat request per floor area, differing for climate and building type.

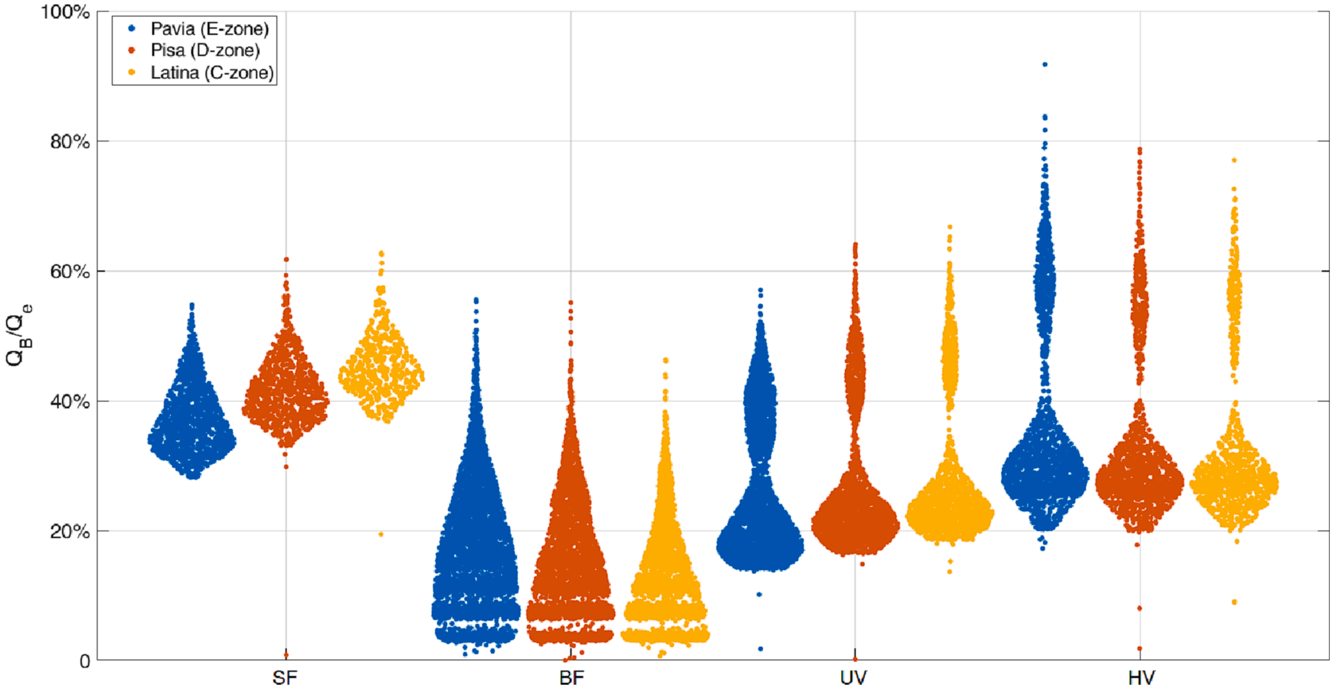


Fig. 2. Hourly ratio between building energy requirement and terminal unit nominal power.

external temperatures.

4.2.2. *Block of flats*

Fig. 5 shows the indicators comparison of the three generators in the three climates for the *BF* case. The condensing boiler leads to lower savings (8%), due to the higher return temperature from the terminal units, which hinders the condensation. The heat pump is never economically convenient, as its seasonal COP, for each of the three climates, is lower than COP^{*}_{eco} (just a little less than 2.50, see Fig. 6).

Conversely, high values of *SnPr* and *SCO2* are found for heat pumps, spanning in the three climates from 18 to 22% (non-renewable energy savings) to 35–40% (emissions savings): the seasonal COP is always over 2.0. As Fig. 6.b shows, the percentage of use of heat pump in the hybrid generator is small (20% in the coldest zone, near 50% in the mildest zone). This outcome is explained considering the nominal heat capacity of the heat pump in this system, resulting from the optimization procedure presented in Section 2.4 and shown in Table 7. For these cases, the heat pump nominal capacity spans from 30 kW (in C- and D-zones) to 45 kW (E-zone), always lower than the design values in case HP is the only generator (between 72 and 96 kW). In these case studies, low heating loads are frequent (see again Fig. 2): using the heat pump in these conditions will cause a drop in COP due to the small capacity ratio. Thus, the optimization procedure for the HP sizing in hybrid generators leads to values that are compromises between the amount of energy provided during the heating season and the seasonal performance, influenced by temperatures and small capacity ratio. Considering the E-zone case as an example, the heat pump cannot provide 35% and 45% of the total building heat requirement because of its undersizing and partial load conditions, respectively.

4.2.3. *Under-insulated villa*

The results obtained for the UV are shown in Fig. 7. All the three

Table 5

Normalized results of the simulation for the 12 case studies, being the unity the reference value for traditional boiler as generator. The "✘" and "✓" marks highlight, respectively, the lowest and highest savings for each category.

		SF			BF		
		CB	HP	HHP	CB	HP	HHP
Operative costs	C	✘ 0.90	0.81	✓ 0.80	0.92	✘ 1.07	✓ 0.87
	D	✘ 0.90	0.89	✓ 0.84	0.92	✘ 1.06	✓ 0.89
	E	0.91	✘ 1.01	✓ 0.87	0.92	✘ 1.13	✓ 0.91
CO_2 emissions	C	✘ 0.90	✓ 0.47	0.51	✘ 0.92	✓ 0.61	0.70
	D	✘ 0.90	✓ 0.51	0.60	✘ 0.92	✓ 0.61	0.79
	E	✘ 0.91	✓ 0.58	0.72	✘ 0.92	✓ 0.65	0.83
Non-renewable primary energy	C	✘ 0.90	✓ 0.60	0.62	✘ 0.92	0.79	✓ 0.77
	D	✘ 0.90	✓ 0.66	0.69	✘ 0.92	✓ 0.79	0.83
	E	✘ 0.91	✓ 0.75	0.78	✘ 0.92	✓ 0.84	0.86

		UV			HV		
		CB	HP	HHP	CB	HP	HHP
Operative costs	C	0.89	✘ 0.90	✓ 0.80	✘ 0.87	0.53	✓ 0.46
	D	0.90	✘ 1.01	✓ 0.85	✘ 0.87	0.59	✓ 0.52
	E	0.91	✘ 1.15	✓ 0.88	✘ 0.88	0.65	✓ 0.58
CO_2 emissions	C	✘ 0.89	✓ 0.51	0.56	✘ 0.87	0.39	✓ 0.35
	D	✘ 0.90	✓ 0.58	0.68	✘ 0.87	0.44	✓ 0.39
	E	✘ 0.91	✓ 0.66	0.79	✘ 0.88	0.48	✓ 0.44
Non-renewable primary energy	C	✘ 0.89	0.67	✓ 0.66	✘ 0.87	0.39	✓ 0.35
	D	✘ 0.90	0.75	✓ 0.75	✘ 0.87	0.44	✓ 0.44
	E	✘ 0.91	0.85	✓ 0.83	✘ 0.88	0.48	✓ 0.45

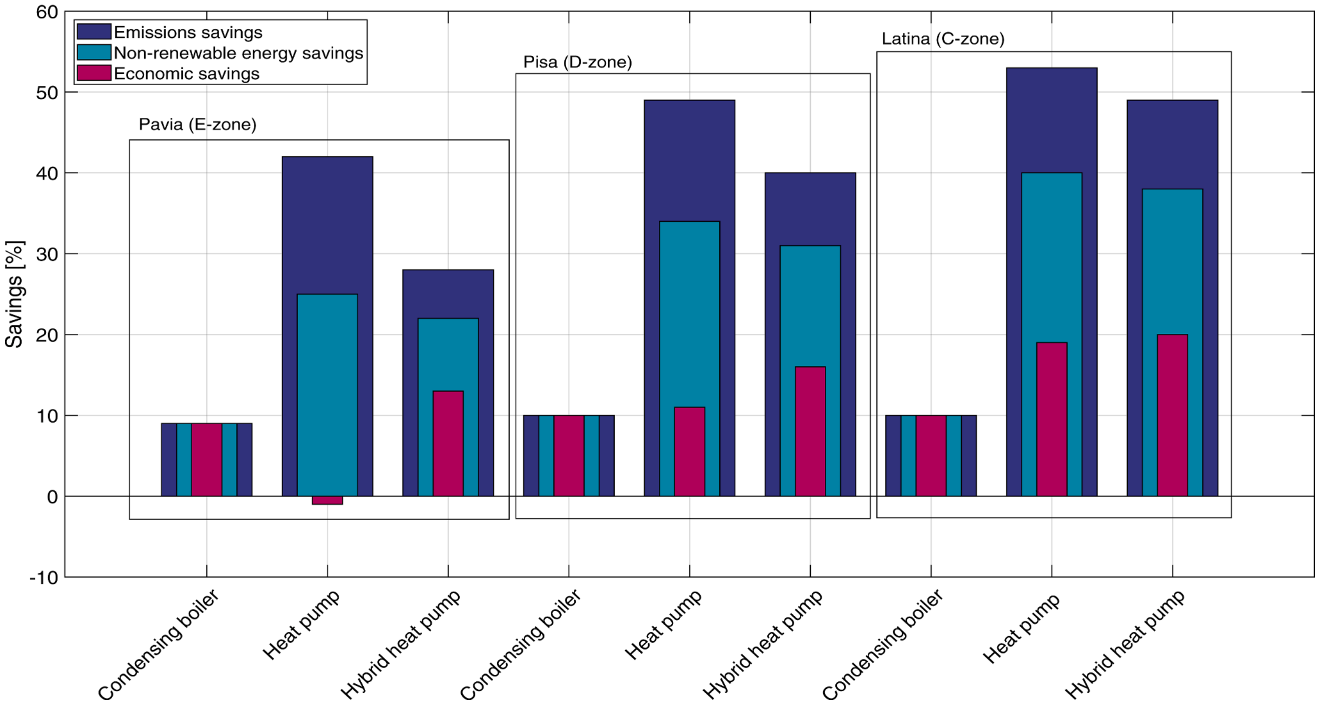
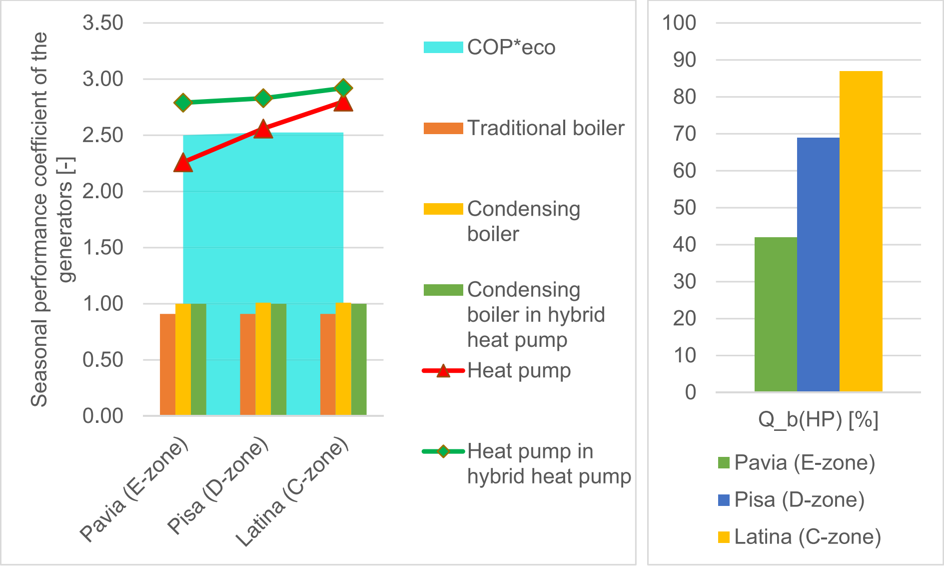


Fig. 3. Values of emissions, energy, and economic savings in the SF case study.

indices, evaluated implementing the condensing boiler in the three climates, are close to 10%. The economic savings associated with heat pump are positive only in the warmer zone (10%), and negative in the other two climates: the use of this generator is then not recommended except when the external climate would ensure high performances. As in the previous case, the hybrid generator provides the highest economic savings, ranging from 12 to 20%. Considering the *SCO2* indicator, the highest values are reached using the heat pump only; for the energy indicator, instead, the two types of generators (i.e., heat pump or hybrid heat pump) perform similarly, with non-renewable primary energy savings up to 30% in Latina.

The comparison of the generators' performances is shown in Fig. 8. From an economic point of view, the heat pump does not perform well in any case, with average seasonal COP lower than COP^{*}_{eco} (in the three cases it is always around 2.50). The hybrid heat pump allows the most convenient operation, with the heat pump working always in high-efficiency conditions and providing only a limited share of the heating load. From an energetic/environmental point of view, instead, the boiler is the worst solution, as both HP and HHP allow for high savings, up to almost 50% in the mildest zone.

Fig. 8.b shows the percentage of building heating requirements provided by the heat pump in the hybrid generator: a strong difference



(a)

(b)

Fig. 4. Generators' seasonal performance (a) and share of building heating load provided by the heat pump (b) for the SF case study.

Table 6
Sizes of the heat pump working as a single generator or as a component of a hybrid system, for the single-flat case study.

	Pavia (E-zone)	Pisa (D-zone)	Latina (C-zone)
HP nominal capacity (HHP) [kW]	8.0	7.5	8.0
HP nominal capacity (HP working alone) [kW]	15.0	12.0	10.0

in this share is visible among the three climates. This is due to the combined effect of frequent partial conditions (see Fig. 2) and high supply temperatures at the emitters, leading to a limited use of the heat pump. Only in the mildest climate (C-zone), higher external temperatures balance that effect, resulting in greater COPs and longer time of use of the heat pump. In all cases, the optimal size of the heat pump is almost halved compared to the nominal size of the HP alone and the nominal power of the emitters, thus reducing recurrent operation in partial mode: see Table 8.

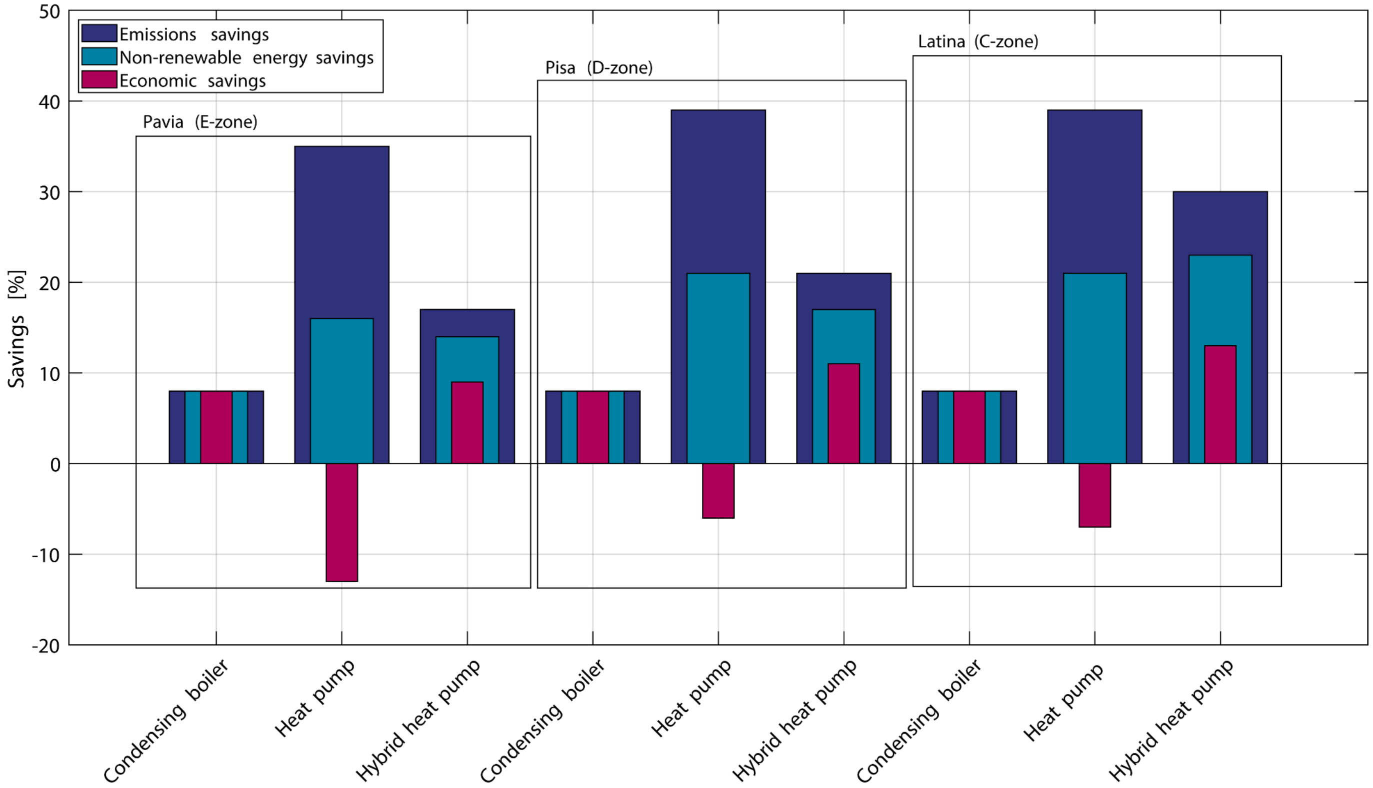
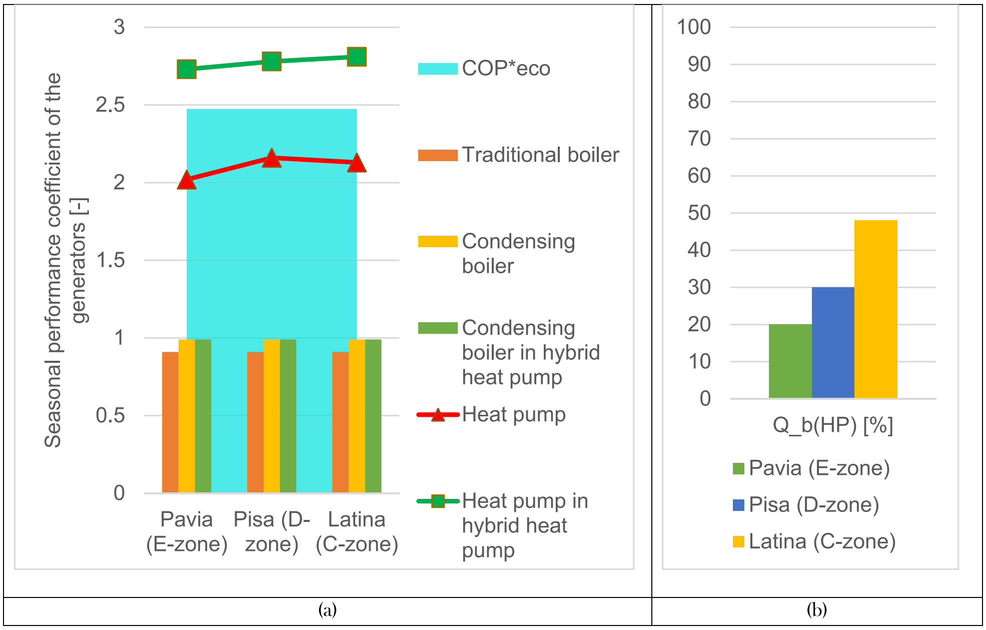


Fig. 5. Values of emissions, energy, and economic savings in the BF case study.



(a) (b)

Fig. 6. Generators' seasonal performance (a) and share of building heating load provided by the heat pump (b) for the block-of-flats case study.

Table 7
Sizes of the heat pump working as a single generator or as a component of a hybrid system, for the BF case study.

	Pavia (E-zone)	Pisa (D-zone)	Latina (C-zone)
HP nominal capacity (HHP) [kW]	45.0	30.0	30.0
HP nominal capacity (HP working alone) [kW]	96.0	72.0	72.0

4.2.4. *High-insulated villa*

The *HV* building type allows the highest savings for all the three indicators compared to the other construction typologies. Fig. 9 shows the calculated values of *SCO*2, *SnPr* and *SOpEx* for this case, varying the external climate. Using the condensing boiler, reduction of costs, emissions, and non-renewable primary energy account for between 10% and 15%. The other two solutions, heat pump and hybrid heat pump, allow for emission and energy savings higher than 50%. Economic savings in the heat pump case are positive for all the climates (ranging from 35 to 45%), hinting that this generator is convenient in the most recent or renovated buildings. In fact, Fig. 10.a shows that the average seasonal COP is always higher than 3.0. Considering the hybrid generator, higher

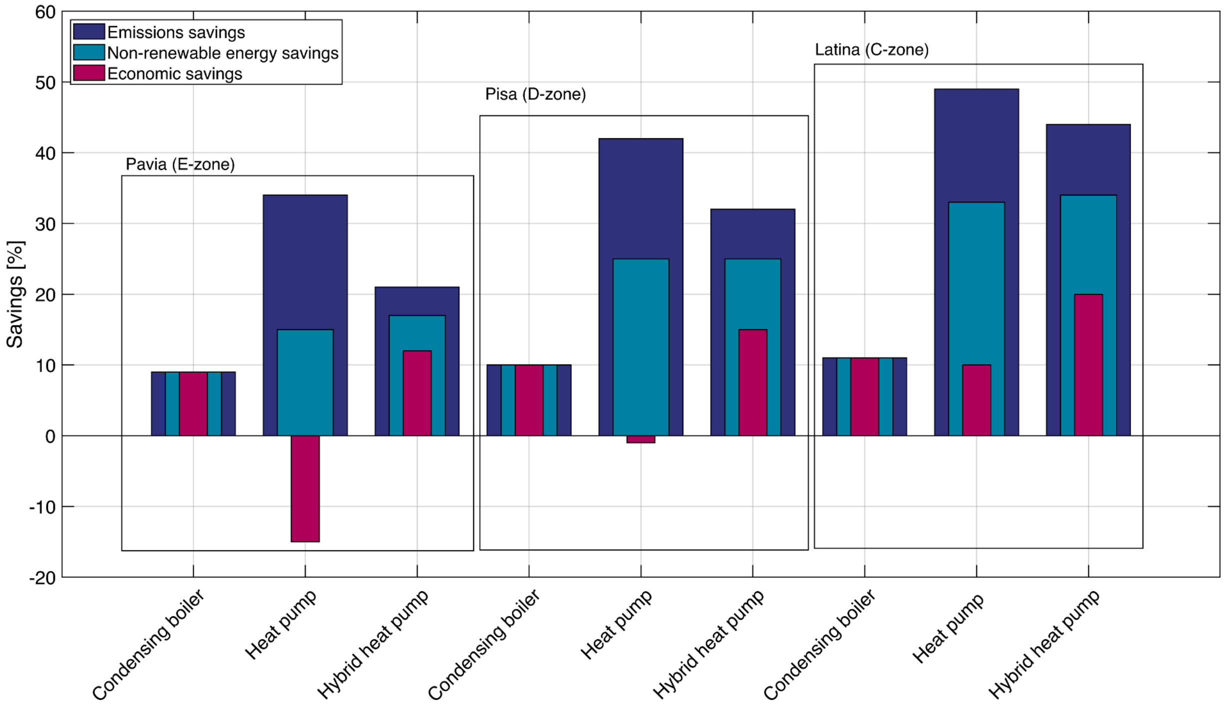


Fig. 7. Values of emissions, energy, and economic savings in the UV case study.

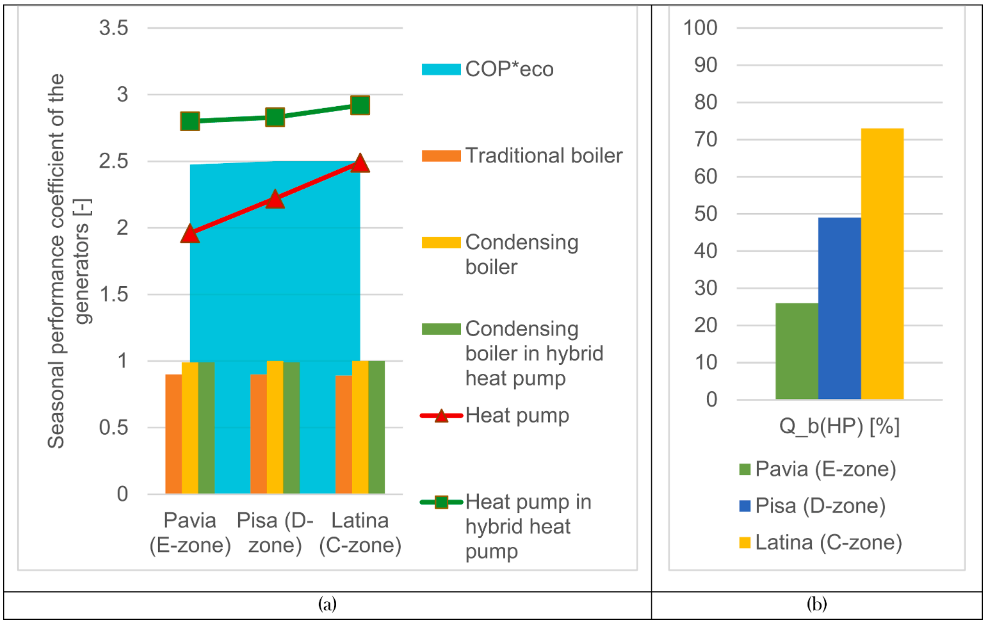


Fig. 8. Generators' seasonal performance (a) and share of building heating load provided by the heat pump (b) for the UV case study.

Table 8
Sizes of the heat pump working as a single generator or as a component of a hybrid system, for the UV case study.

	Pavia (E-zone)	Pisa (D-zone)	Latina (C-zone)
HP nominal capacity (HHP) [kW]	6.0	6.0	6.0
HP nominal capacity (HP working alone) [kW]	15.0	12.0	10.0

economic savings are obtained; however, this is the only case where both heat pump and hybrid heat pump show similar economic savings. The analysis of the generators' performance shows that the heat pump provides more than 90% of the heating load (Fig. 10.b), and very high average seasonal COP, ranging from 4.0 to 5.0 (Fig. 10.a). Compared to the heat pump case, higher performances are reached because the condensing boiler is used for a limited number of hours, the ones where the heating load is too low to be conveniently provided by the heat pump. The optimal sizing of the heat pump in the HHP case (in Table 9) shows in fact that a different and increasing size for the heat pump is chosen for climates going from the mildest to the coldest one, aiming at increasing the operating capacity ratio and working at high performances. This explains the minor deviations in the share of heating load provided by the heat pump in Fig. 10.b. For the same case studies, the size of HP working alone is around doubled (see again Table 9).

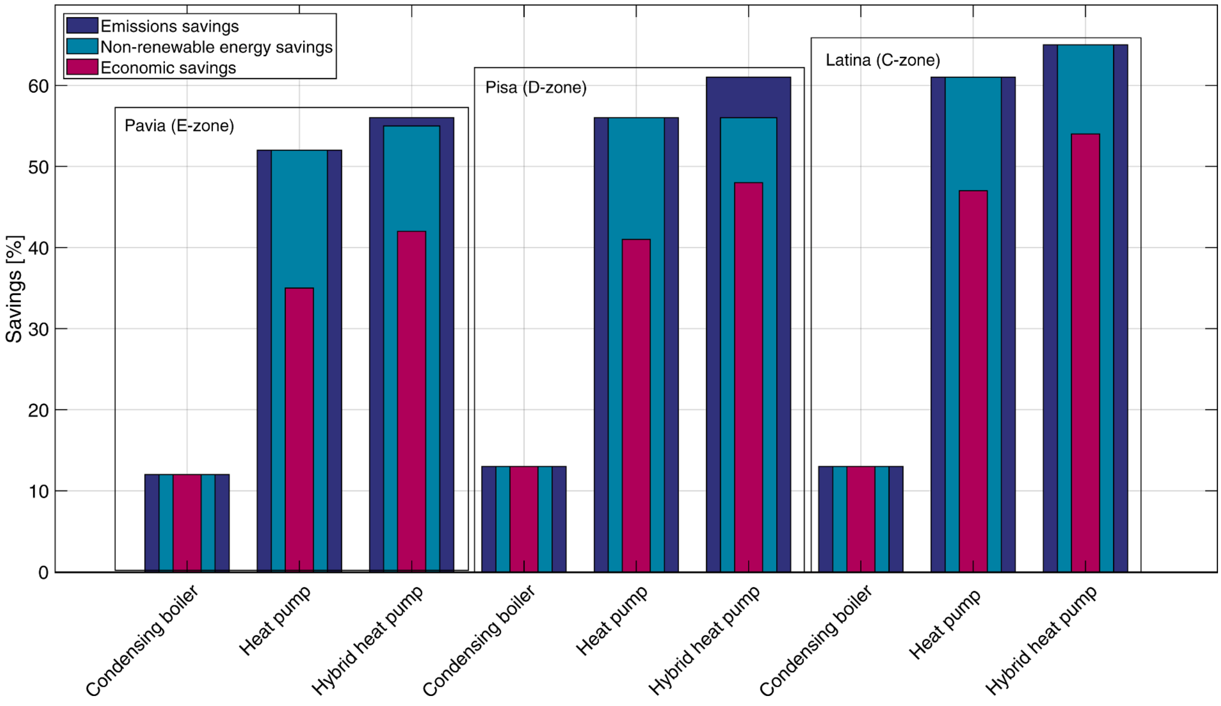
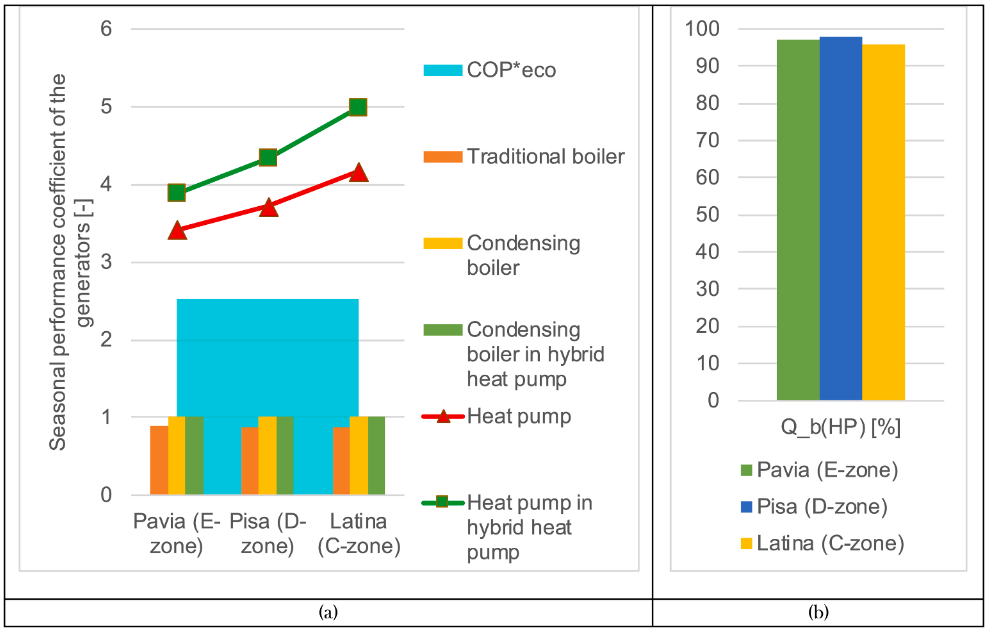


Fig. 9. Values of emissions, energy, and economic savings in the HV case study.



(a) (b)

Fig. 10. Generators' seasonal performance (a) and share of building heating load provided by the heat pump (b) for the HV case study.

Table 9
Sizes of the heat pump working as a single generator or as a component of a hybrid system, for the HV case study.

	Pavia (E-zone)	Pisa (D-zone)	Latina (C-zone)
HP nominal capacity (HHP) [kW]	5.5	5.0	4.5
HP nominal capacity (HP working alone) [kW]	8.0	8.0	8.0

4.3. Additional focus for hybrid heat pumps and discussion

The results of the simulations presented in Section 4.2 highlight that the HHP is the most convenient solution for operative costs reduction, allowing the hourly choice of the most favorable generator depending on external conditions and required load. Generally speaking, the effective convenience of the HP on a gas-fired boiler can be represented as in Fig. 11. The values on the x-axis represent the generic ratio of the conversion coefficients of the electrical and gas vector (i.e., the cost, emission, or energy conversion factor, named $f_{*,el}$ and $f_{*,ng}$ in Eq. (8), the values of which are presented in Table 4); the values on the y-axis represent the threshold performance value (COP^{*}) over which the HP is convenient with reference to that particular economic/environmental/energy goal.

Depending on the conversion coefficients, the effective convenience of the HP varies: as an example, for a ratio equal to 1.86, the HP is convenient over a boiler with an efficiency equal to 0.9 if its COP is higher than 1.67 (see Fig. 11). For a doubled value of the ratio (e.g., due to increased energy vectors costs, or variation in the national power mix), the HP would be convenient only when COP overcomes 3.35, typically a too high value to reach in a cold climate or if the building has not been renovated.

The HHP represents the preferable solution, using the HP only in convenient periods, when the COP threshold is overcome. In the following sections, an additional detailed analysis of HHP is shown, to check the outcome variation in case of a change of switch criterion between the generators or of an increase in energy vector costs.

4.3.1. Effects of a different switch criterion on HHP

The commercial control strategy of hybrid systems is based on the economic convenience of one generator on the other, always choosing the generator ensuring the lowest operational cost. In light of the environmental goals set to contrast climate change, a different control strategy can be implemented in hybrid systems, based on the use of the generator ensuring the lowest emissions. Thus, Eq. (2) changes into:

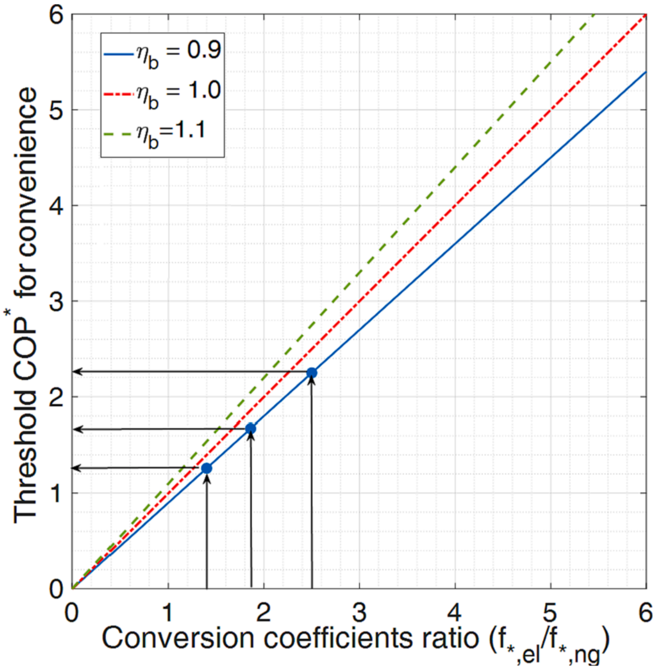


Fig. 11. Threshold COP* for HP economic/environmental/energy convenience, depending on boiler efficiency and the ratio of conversion coefficients. The three points represent the ratio of energy, environmental and economic factors used in this paper.

$$\frac{Q_{B,i}}{COP_i} \times f_{CO2,el} < \frac{Q_{B,i}}{\eta_{b,i}} \times f_{CO2,ng} \tag{9}$$

meaning that the heat pump should have a $COP \geq COP^{*}_{CO2}$ to operate.

In an annual operation, Fig. 12 summarizes the difference in the indicators' values using the generators' switching economic criterion or the environmental criterion, using differential savings:

$$\Delta SOpEx = SOpEx_{cr=CO2} - SOpEx_{cr=eco} \tag{10a}$$

$$\Delta SnPr = SnPr_{cr=CO2} - SnPr_{cr=eco} \tag{10b}$$

$$\Delta SCO2 = SCO2_{cr=CO2} - SCO2_{cr=eco} \tag{10c}$$

A positive value in Fig. 12 means an improvement in the value of the index.

The following considerations can be made:

- a variable rise in the costs should be expected for all the case studies with the only exception of the HV, depending on the building type and climate condition. In particular, in the E-zone, the savings compared to the traditional boiler can range from 7% (single flat) to −4% (block of flats): in the latter case, thus, there is no economic convenience compared to currently used heaters. In the milder climatic zones, the differences in economic savings are less marked;
- considering the non-renewable primary energy, improvements of the savings of around 2–8% are reached. Even if this strategy brings different energy savings for each case compared to the traditional boiler (e.g., 31% for the single flat in E-zone, 24% for the block of flats in D-zone), small differences between the two hybrid-generator control criteria are found. This is due to the value of COP^{*}_{nPr} (1.86), higher than COP^{*}_{CO2} (1.43): the heat pump operates both in energy convenient hours, excluded in economic control criterion, but also in emission convenient hours, when the heat pump working is not advantageous to the non-renewable primary energy reduction;
- further emissions savings spreading from 5% to 20% are obtained. In the C-zone, the savings compared to economic criterion are the lowest, due to the limited number of hours when $COP^{*}_{CO2} \leq COP \leq COP^{*}_{eco}$;
- for the high-insulated villa, the further savings are almost null for all three indicators. The motivation is the high values of COP reached with radiant panels;
- the environmental switch criterion results in broadening the difference between economic and environmental savings found with the economic criterion.

4.3.2. *Effect of different energy vectors costs*

The effective convenience of the hybrid heat pump is checked also through a sensitivity analysis of the specific cost of energy vectors. Maintaining the heat pump sizing, two different economic scenarios have been simulated:

- *scenario #1*, an increase of 25% for the natural-gas cost ($f_{eco,ng} = 0.10\frac{€}{kWh}$) and 50% for the electrical energy cost ($f_{eco,el} = 0.30\frac{€}{kWh}$);
- *scenario #2*, energy vectors cost equal to the average costs in Italy in the first three 2022 quartiles ($f_{eco,ng} = 0.13\frac{€}{kWh}$, $f_{eco,el} = 0.44\frac{€}{kWh}$) [43,44].

The variation of the costs implies an increase of the COP^{*}_{eco}, which is respectively 3.0 and 3.38 in the two economic scenarios. The higher COP^{*}_{eco} causes a reduction of the heating load provided by the heat pump for all the building typologies but the high-insulated villa, where the low supply temperatures guarantee elevated COP. In the other buildings, the heat pump lowers the provided share of heating requirements: see Fig. 13. This generator is used when the operating cost is lower than that of the condensing boiler, thus allowing a profit margin. Thus, the HHP can adapt its operation by changing the energy share to the two generators, representing thus the ideal solution for all those contexts where energy vector costs can vary.

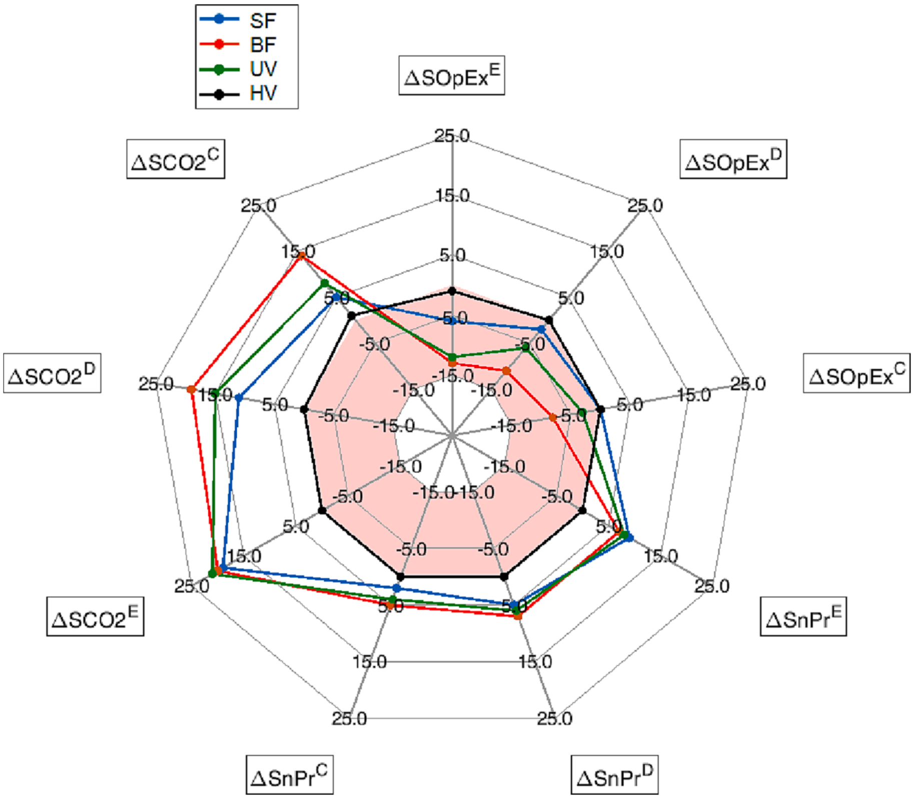


Fig. 12. Economic, energy, and environmental savings differences obtained with a hybrid heat pump controlled with an environmental convenience criterion. The red area highlights the possible negative differences (where the generic index diminishes with the environmental convenience criterion compared to the economic one).

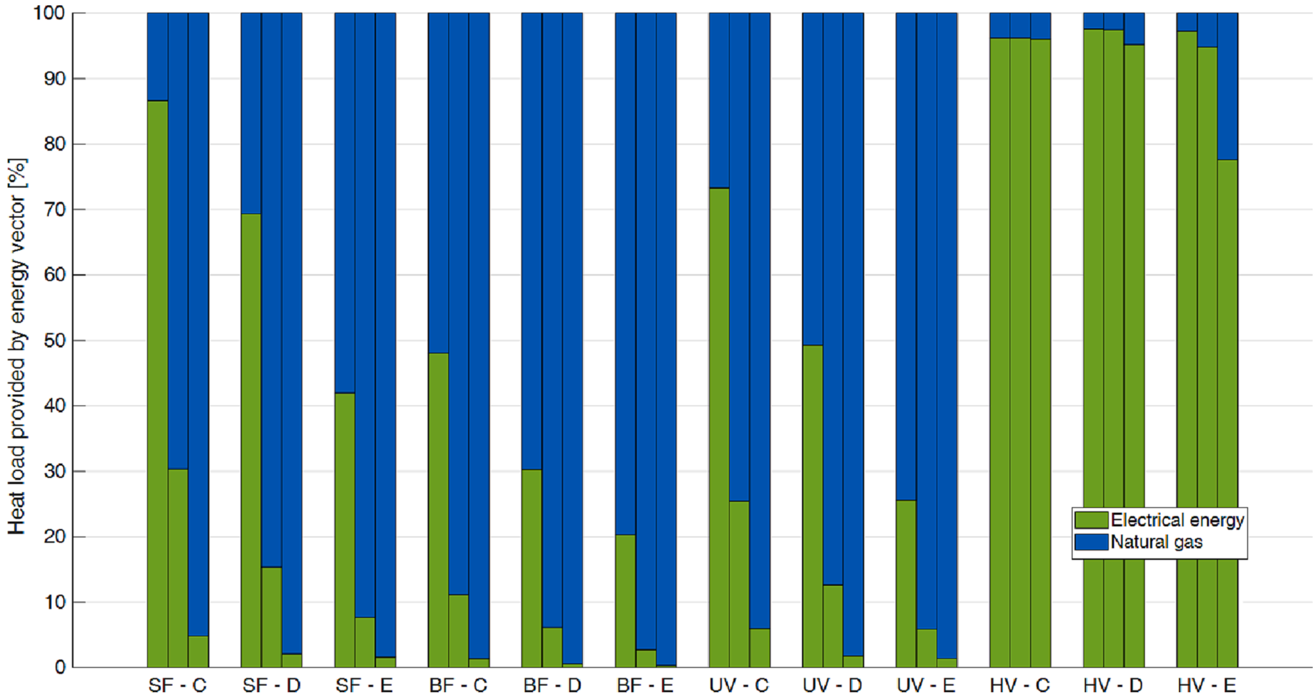


Fig. 13. Heating load provided by condensing boiler or heat pump for the 12 cases. The three economic scenarios (base case, scenario #1 and scenario #2) are presented as bars for each case. In the x-axis, the final letter is associated to the climate zone.

Even if this analysis is referred to scenarios implying cost variation, it is extendable also to variations of the ratio of other conversion factors (environmental factors or non-renewable primary energy factors), as presented at the beginning of Section 4.3, with subsequent change in the generator switch criterion.

4.3.3. Discussion of the results

The results presented in the previous sections have highlighted that insights can be provided about the substitution of the heating generator in current Italian residential building stock:

- from an economical point of view, the HHP is the most convenient choice, allowing savings between 5% (block of flats in coldest climate zone) and 40% (high-insulating villa in mildest climate zone) compared to the condensing boiler;
- the convenience of the HHP is confirmed by a robustness check, using different switch criteria between the two heating generators and different economical scenarios;
- higher savings in emissions and non-renewable primary energy are possible using the heat pump alone, but this generator is also responsible for higher costs in all cases;
- heat pump and hybrid heat pump lead to similar costs only in a limited number of cases, i.e., building with low energy requirements: thus, also the operational costs are themselves low, and the difference in savings is not really relevant;
- the impact of the condensing boiler is limited: the economic, energetic, and emission savings never exceed 15%.

Even if installation costs for these heating systems have not been considered in this research, the following implications can be added:

- the condensing boiler is the less expensive component, but the obtainable savings are limited;
- the heat pump is more expensive and leads to high environmental and energy savings, but low economic savings;
- the hybrid heat pump is the most expensive generator, but its flexibility can guarantee the highest savings on all the indicators, depending on the control mode; its high installation costs could possibly be mitigated with incentive schemes.

Finally, some further considerations relate to the technical challenges to face while substituting heating generators in buildings:

- the difference in the needed space to install the system within the dwelling area: as an example, the boiler in a flat occupies a volume of less than 1 m^3, whereas the hybrid heat pump often needs more volume. Furthermore, also the minimum clearances, in the two cases, are different: for the boiler, minimum clearances are usually less than 1 cm, whereas the external heat exchanger of the heat pump needs a greater empty volume nearby, to foster the heat exchange;
- in the production of domestic hot water, thermal storage is needed, together with the heat pump, if its heat capacity is not sufficient to instantaneously meet the load. Usually, the boiler can instead provide instantaneously also the domestic hot water load, without additional thermal storage;
- due to the lower water supply temperature, the installation of heat pumps or hybrid units may require also enlarged terminal units, in the buildings where their typical installation oversizing is absent;
- in Italy, the power rating of dwelling electric meters is traditionally 3 kW; this limit should be increased if a heat pump or a hybrid heat pump is installed. Due to this change, the electric meter should be also substituted, with an additional purchase cost;
- if the heat pump or hybrid heat pump is properly integrated with a renewable energy system (e.g., a photovoltaic system), operative costs, non-renewable primary energy, and emission costs may further decrease due to the self-consumption of renewable energy.

5. Conclusions

This research has been aimed at identifying the most promising heat generator technology and quantitatively assessing the possible economical, emissions, and non-renewable primary energy advantages at the whole Italian residential level, obtainable by the substitution of existing systems. Condensing boilers, electrical heat pumps, and hybrid heat pumps have been compared to traditional gas boilers, which are currently the most widespread heat generator system in Italian houses. The national residential building stock has been simulated using a bottom-up statistical model, based on the white-box energy simulation of four benchmark buildings (i.e., single flat, block of flats, under-insulated and high-insulated villa). The considered technologies have been dynamically simulated for all the building types, considering three different climate zones.

The results have shown that the hybrid heat pump is almost-ever the most convenient solution to reduce operating costs, also under different energy price scenarios and various control strategies: operative cost savings are 20% on average, exceeding 50% in mildest climates and high-insulated buildings. The heat pump technology allows for the highest savings in non-renewable primary energy and emissions (within the range of 25 – 50%), but its convenience is hindered by operative costs, in particular in colder climates and operative conditions characterized by low capacity ratios. The condensing boiler emerges as the less efficient option in all building types and climatic conditions leading to possible savings of about 10%.

The results and the statistical methodology presented in this research can be used by policymakers and energy planners to develop strategies at the national level aimed at evaluating energy and environmental benefits related to the substitution of inefficient heat generators, also guaranteeing high savings in operative costs for final users.

Future developments of this research will study the identification of the most appropriate heating generator considering both heating and domestic hot water services; the system configuration might also include thermal storage. Another path of development will be the study of generators using other fuels, such as hydrogen-natural gas mixtures and biogas.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniele Testi reports financial support was provided by Anima ASSOTERMICA.

Data availability

Data will be made available on request.

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