

Energy efficiency of the Italian office buildings: Highlights from mandatory energy audits

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ABSTRACT

This study analyzes the energy performance of hundreds of Italian office buildings using data from mandatory energy audits submitted by large banking and insurance companies. The database comprises 260 buildings and 512 retrofitting measures, reporting the most common strategies for reducing energy consumption and carbon emissions. Installing new heat generators presents the highest energy and emissions savings—up to 30%—but also high upfront costs and long payback times. Retrofitting the lighting system with LED is the most frequent intervention due to its low initial costs and fast returns, typically under five years. The cost-benefit analyses show that the energy-saving potential of retrofitting interventions increases with building energy intensity and size. Retrofitting the most inefficient buildings maximizes returns, but it requires multiple interventions and the support of public incentives, such as the Conto Termico and White Certificates, to improve financial viability and reduce unit costs. Our analysis provides policymakers and stakeholders with actionable guidance on designing effective retrofit strategies and incentive programs, thereby accelerating progress toward national and European climate goals.

1. Introduction

The service sector accounted for approximately 60% of global value added in 2023, while manufacturing accounted for less than 20% [1]. This share is equivalent to the combined output of several key service sub-sectors, including retail, finance, and information and communications. Given the economic significance of the services sector, it is likely to play a crucial role in the energy transition and drive improvements in energy efficiency. Buildings account for over 40% of the total energy consumption and one-third of the greenhouse gas emissions of the European Union [2]. The *Renovation Wave* initiative shapes the efforts of the Member States to retrofit their building stock [3]. The latest Directive 2024/1275/EU on the energy performance of buildings strengthens the enabling framework for renovations and introduces the Building Renovation Passport schemes throughout the EU to help building owners to plan retrofitting programs [4]. Furthermore, the Directive stipulates that each Member State must develop its long-term building renovation strategy, including plans and policies for renovating the national building stock, in line with the EU's climate goals for 2030 and 2050. The key initiatives for improving the energy efficiency of the Italian building stock are in the National Energy and Climate Plan and the Italian Strategy for Energy Retrofitting of National Building Stock [5,6]. This

study focuses on the European and Italian regulatory context, as it directly frames the dataset used and reflects the policy environment that developed the analyzed energy audits and retrofit interventions.

These documents report the renovation rate needed to fill the gap between the current and target energy performance of the building stock, indicating an urgent need for more ambitious retrofitting policies. The estimated *virtual deep renovation rate*, based on the data from tax deductions for energy efficiency, represents the renovation rate that would result if all interventions were associated with comprehensive building and system upgrades. The virtual deep renovation rate for 2014–2018 is 0.85%, yielding an energy savings of 0.332 Mtoe/year, and a recent study estimates the current renovation rates in Italy for residential and non-residential buildings to 0.3% and 0.6%, respectively [2]. The target renovation rate was estimated by cost-optimal data, distinguishing between residential and tertiary sectors and obtaining higher values in the second case, equal to 2.8% per year in the period 2020–2030 and 2.6% in the period 2030–2050; this overall renovation rate implies interventions on about two-thirds of the national housing stock [6]. Although the current renovation rate in Italy is higher than the EU average [7], it needs to increase by more than three times to reach the targeted one. The European Commission has expressed concerns about the feasibility of such an ambitious goal [8].

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Insufficient investments may be the cause of such a slow building renovation rate. Italy has been the third State in terms of investments for non-residential buildings retrofitting between 2012–2016, investing an average of €5.5 billion per year, of which €0.5 billion was for “deep” renovation (more than 60 % savings) [9]. Investments in real estate were approximately €2.05 billion for 2023 and increased to €3 billion in 2024; specifically for office buildings, the investments grew to €800 million in 2024 [10,11]. However, recent studies [12–14] estimate that the annual investment to meet European climate targets ranges from €23.6 to €31.4 billion (normalized for the 2020–2030 period), and, accordingly to BPIE calculations [15], the total renovation investment opportunity in the EU is estimated at €243 billion per year to bring the building stock in line with climate-neutrality by 2050, of which €64 billion/yr are necessary for non-residential buildings renovation. These figures show that the current investment trend is significantly below the magnitude required to meet the EU’s climate goals for 2030 and 2050.

The lack of investments results from multiple barriers hindering the building energy retrofitting. Rodriguez et al. [16] recognize financial, informational, and administrative obstacles to energy-efficient design practices in the construction sector. In particular, the administrative barriers include regulatory complexity, fragmented schemes, and slow approval processes for incentives, which lead to project delays, as observed in Italy during the implementation of the Superbonus 110 % tax credit [17]. The financial barriers, such as elevated initial costs of deep energy renovations, discourage private investors, particularly when long payback periods make returns uncertain [18,19]. Finally, the informational gaps result in poorly informed decision-making, a lack of investment transparency, and a shortage of skilled workforce [20]. Another example of an informational barrier is when building owners, despite financial incentives, hesitate to invest in retrofitting due to worries about future energy prices and skepticism about financial returns [21].

Cost-benefit analysis (CBA) helps overcome barriers to retrofitting by enhancing the transparency and predictability of energy-saving investments, reducing investor hesitation, and combating greenwashing. Calculating long-term financial savings from energy bills and increased property value makes the investor reevaluate the high initial costs and long payback times [22]. Additionally, the CBA, which integrates multiple benefits of energy efficiency, such as improved indoor air quality, enhanced occupant comfort, and safety, could strengthen investors’ interest in large-scale retrofitting [23–25].

An incentive program supported by a CBA enhances the adoption rates of retrofitting interventions since it helps policymakers refine subsidy structures and optimize resource allocation for high-impact energy measures, rather than those with short payback periods and poor energy-saving potential [26–28]. However, cost-benefit analysis presents the risks of incorrect estimation of costs and benefits, and is susceptible to systematic bias. The study by Flyvbjerg and Bester [29] analyzes over 2000 public investment projects, finding recurrent cost underestimation and benefit overestimation that result in exaggerated benefit-cost ratios that can mislead decision-makers. In the context of building retrofits, such biases can lead to misallocation of incentives, over-investment in technically unsuitable projects, and a loss of credibility for retrofit programs. Recognizing the limitations of CBA and the risks it poses is therefore essential to ensuring effective and equitable policy design.

Non-residential buildings are, on average, 40 % more energy-intensive per square meter than residential buildings [30], and the EU accounts for about 47 % of the global market for building energy retrofitting, which will further grow [31,32]. In Italy, retrofitting non-residential buildings has been the primary activity of the national construction sector [33] 2023, with an estimated energy saving potential of 3.3 Mtoe to 2030, surpassing that of industry or transport [13].

However, despite the opportunities for profitable investments, the non-residential building sector received less attention than the residential sector. The most recent cost-benefit analyses (CBA) focus on retrofitting the residential buildings sector [34–36], mainly on histor-

ical buildings [37–39]. Recent works on non-residential buildings focus on single and specific case studies. For instance, Di Turi et al. [40] discusses the feasibility of net-zero energy building offices in Italian climate zones through an integrated energy-economic analysis. The CBA by Astiaso Garcia et al. [41] examines energy-efficiency measures in four selected public buildings. We aim to fill this research gap by assessing the energy performance of hundreds of office buildings distributed across the national territory, seeking general trends and issues with the implemented retrofitting strategies, and answering the following research questions:

- Q.1 What are the most common energy retrofitting interventions implemented in Italian office buildings, and how do their technical and economic characteristics vary by the building features and climate zones?
- Q.2 How does the pre-retrofit energy performance of Italian non-residential buildings influence the energy and financial outcomes of the retrofit action?
- Q.3 Which strategies and tools (e.g., incentives) are most effective for maximizing energy savings and addressing the barriers to energy retrofitting of non-residential buildings?

This work examines the energy performance and retrofitting interventions of 260 office buildings distributed over the national territory. We collected data from the energy audits submitted by large enterprises from the banking and insurance sectors (Chapter 2). We created a database with various features, including building age, size, heated space, and energy performance (Chapter 3.1). Also, the database includes energy savings, financial returns, and payback times of the energy-saving measures reported in the energy audits (Chapter 3.2). The data analysis examines the primary variables that impact the energy performance of the building stock and retrofitting strategies, addressing the challenges that investors encounter. Finally, we investigate the conditions that optimize energy savings and financial returns by the CBA of the collected interventions, estimating the support of public incentives to overcome economic barriers (Chapter 3.3 and 3.4). The ultimate goal is to guide policymakers and investors in shaping or adhering to national strategies and incentive programs for retrofitting office buildings.

2. Materials and methods

2.1. Legislative framework for data collection

The Energy Efficiency Directive 2012/27/EU (EED) establishes a legislative framework for achieving the European energy efficiency targets. of the EED introduced the obligation for large enterprises with over 250 employees and a budget of more than €43 million or a turnover of more than €50 million to submit an energy audit of their production sites every four years, starting from December 2015. The Legislative Decree 102 of 2014 transposed the EED in Italy, with , which entrusts ENEA (the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development) with the task of collecting energy audits and verifying their quality and legislative compliance. From 2015 to the present, ENEA has conducted over 40,000 energy audits. Most are from manufacturing companies, but tertiary sectors have also sent many energy audits to ENEA. In particular, large banking or insurance companies submitted energy audits of their office buildings to fulfill the obligations of the EED 2012/27, by December 2023, the starting year of the third cycle of mandatory energy audits. We built our database by analyzing these documents.

Since the Italian Legislative Decree 102/2014 Art. 8 disciplines the audit obligation exclusively for private companies, the offices of public administrations, government, and educational institutions are excluded from our analysis. Additionally, our sample excludes smaller service companies, whose energy use generally falls below the threshold defined by the regulation.

Table 1
Descriptive statistics of buildings and intervention features.

Variable	Buildings				
	Min	Median	Mean	Max	Standard Deviation
Heated Area [m^2]	190	5.5×10^3	11.7×10^3	113.9×10^3	15.5×10^3
Electricity use [MWh/yr]	17.4	593.7	1.8×10^3	24.1×10^3	3.4×10^3
Natural gas use [kSm^3/yr]	0.03	45.4	144.1	5967	591.7
Total energy use [toe/yr]	4.5	147.8	440	6250	808
	Interventions				
	Min	Median	Mean	Max	Standard Deviation
Investment [$k€$]	0.3	30	94.7	3734.5	282
Energy saving [toe/yr]	0.1	4.9	12.9	296.5	28.4
Payback time [yrs]	0.6	4.3	5.7	26.1	4.4

2.2. Database architecture

We collected energy audits from 260 office buildings, which reported 512 retrofitting interventions. These constitute the records of our database, which we structured into raw and derived data features. Raw features are unprocessed inputs, directly extracted from the energy audits [42]:

- **Building features** are the year of construction, building location, heated floor area, and the amount of yearly purchased, self-produced, consumed, and sold back energy, distinguished by source.
- **Intervention features** include a description of the intervention, its cost, energy saving, and cash flows. Such data are based on estimates or market benchmarks of the auditor.

The descriptive statistics of the raw data features are in Table 1.

Derived features were calculated from the raw data to compare records and implement cost-benefit analyses; these are the heating and cooling daily degrees, which identify the climate zone of the building site; the Building Energy Performance Index (EPI), given by total energy use over the floor area; the annual CO_2 emissions, estimated by referenced emission factors, and net energy use, derived from subtracting on-site production from total delivered energy. We also derived the payback times as the ratio of intervention cost to yearly savings. Stratification variables, such as EPI quartiles, were also derived to support segmented analysis of retrofitting effectiveness (as shown in the Section 3.4).

We have not incorporated data on occupancy patterns or usage intensity because these variables are not required by the energy audits as mandated by Legislative Decree 102/2014 and technical standard UNI EN ISO 16247:2022 [42]. Occupancy-related input, such as the daily operational electricity usage curve, encompasses all building systems, including lighting in halls and corridors, server loads, and HVAC, at a typically broader resolution than at the room level; further, the usage curve dilutes spot yearly consumption (e.g., the electricity use of a conference room during an event). Therefore, the extraction of occupancy-related energy uses from the usage curve applies to a limited number of samples and requires multiple assumptions, which can result in potentially misleading outcomes.

2.3. Classification of the retrofitting interventions

The auditors outline retrofitting actions for improving energy efficiency, using their terminology and selection of commercial products. Thus, we classified interventions into four hierarchical classes to reduce the variability and semantic complexity of 512 retrofit interventions, allowing a consistent grouping and comparison of interventions across buildings. The classes are groups of labels, indicating the intervention's saved energy source, the retrofitted building component, the retrofitting approach, and the (eventually) new component:

- **Class 1 - Saved Energy Source** indicates the energy source whose consumption is reduced by the intervention. In our sample, the energy sources are just electricity and natural gas, and therefore, Class 1 comprises three labels: `electricity`, `gas`, and `multi`. The label `multi` denotes interventions that reduce gas and electricity consumption.
- **Class 2 - Existing Building Component** indicates the building component targeted for the intervention, and its labels are the `gasBoiler`, `heatPump`, `chiller`, `lighting`, `heatDistribution`, `structure`, and `otherElectricityService`. The latter refers to all building energy services that consume electricity, distinct from lighting (e.g., servers, video surveillance, and general IT systems).
- **Class 3 - Type of Intervention** describes the nature of the retrofit action by the following labels:
 - `renovation`: the existing component is replaced with a more efficient version of the same technology (e.g., gas boiler replaced by a condensing gas boiler).
 - `replacing`: the component is replaced by a new technology offering the same energy service (e.g., a gas boiler replaced by a heat pump).
 - `installing`: a new system is added to an existing one; for example, the installation of a Building Energy Management System (BEMS) to manage an existing heat distribution system.
- **Class 4 - New Installed Component** specifies the new component installed by retrofitting. The labels are: `heatPump`, `LED`, `powerQuality`, `BEMS`, `windows`, `walls`, and `highPerformanceEngineOrFan`.

The combination of four labels, each corresponding to a class, yields a concatenated label that describes a retrofitting intervention. Some examples of the interventions classification are in Table 2.

2.4. Data quality check

As a first step in data validation, we checked the completeness of our data by verifying that all essential fields—raw inputs—were fully populated. Records with incomplete key variables were excluded from the analysis, and duplicate records were identified and verified based on unique data labels for buildings and interventions. The outliers were identified by combining interquartile range thresholds and visualizing the data; implausible values were excluded from the analysis, while extreme but valid observations were retained and analyzed separately where relevant. In particular, we verified that all numerical data are within plausible ranges; for example, the energy savings did not

Table 2
Examples of combined intervention labels with descriptions.

Combined Label and Description
1) <code>gas_gasBoiler_renovation_gasBoiler</code> : renovating an existing gas boiler with a more efficient one (e.g., condensing boiler).
2) <code>gas_gasBoiler_replacing_heatPump</code> : replacing a gas boiler with an electric heat pump.
3) <code>multi_heatDistribution_installing_BEMS</code> : installing a building energy management system to optimize control of an existing heat distribution network, reducing gas and electricity use.
4) <code>multi_structure_renovation_windows</code> : renovating existing windows with high-performance windows that reduce heat losses, external gains, and improve thermal comfort.
5) <code>multi_structure_renovation_walls</code> : enhancing the wall thermal insulation to reduce heating and cooling demands.
6) <code>electricity_lighting_replacing_LED</code> : replacing the existing fluorescent or incandescent lamps with LED.
7) <code>electricity_chiller_renovation_chiller</code> : renovating the existing compression chiller with a more efficient one.
8) <code>electricity_otherElectricityService_installing_powerQuality</code> : installing equipment for power quality, such as voltage regulators, harmonic filters, or dynamic voltage restorers in the electrical distribution systems to reduce losses, stabilize voltage, and increase equipment lifespan [43].

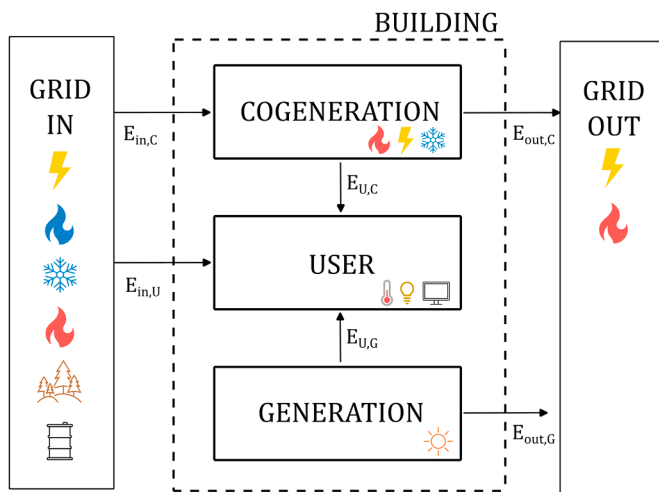


Fig. 1. The energy balance of an office building in energy audit.

exceed baseline consumption, the EPI values remained within acceptable bounds, and payback times did not exceed the intervention's technical lifetime. Based on standardized conversion factors, we ensured Unit consistency by converting all energy data into comparable formats (*toe, kWh, Sm³*).

Finally, we validated the consistency of the raw energy data by applying an annual energy balance model (Fig. 1) to each building, for the k -energy source (e.g., electricity and natural gas):

$$\sum_k (U_k + E_{out,C,k} + E_{out,G,k} - E_{in,U,k} - E_{in,C,k} - G_k) = 0, \quad (1)$$

where U is the net energy use of the building, $E_{in,U}$ is the energy input from the grid to the building and used by many energy services (e.g., space heating, lighting, and IT), the $E_{in,C}$ is the grid input feeding the cogeneration system, the term G is the energy generated by the on-site renewable systems (e.g., photovoltaic panels or wind turbines), and terms $E_{out,C}$ and $E_{out,G}$ represent the (eventually) energy in excess given back to the grid. All these terms were raw inputs from the energy audits, and we verified them by balancing whether they indicated a physically plausible energy use; this step ensured that derived data features were calculated from consistent raw inputs.

From the net energy use U of the building, we calculated the CO_2 emissions of each building related to the annual use of the k -energy source as:

$$E_{CO_2} = \sum_k^n (U_k \gamma_k), \quad (2)$$

where source-specific emissions factors γ_k are provided by the Italian Institute for Environmental Protection and Research (ISPRA) [44]. The energy savings, multiplied by emission factors, give the potential CO_2 emissions that each intervention avoids. We assume no emissions for the generation term G since all energy generation units are renewable systems.

3. Results and discussion

3.1. The current state of the Italian office buildings

Italy presents six climate zones defined by heating degree days (HDD) intervals [45,46], and most of the sampled buildings are located in zones E and D, primarily in the central and northern regions of Italy (Fig. 2). The headquarters of most real estate companies are located in these zones, which feature a temperate climate that becomes colder as they approach the Apennine and Alpine mountains. The warmest climate we mapped is in zone C, which includes the coastal southern area,

with punctual coverage, as sampled buildings aggregate in the most densely populated and urbanized regions of Campania, Puglia, and Sicilia. A few buildings are located in Zone F, which has the coldest climate. Despite the non-homogeneous data distribution, our sample represents the national office building stock and its energy use, as zones D and E are the most populated and exhibit the highest thermal demand [47]. Additionally, heat pumps offer the highest economic advantages in zones D and E compared to other climates [48], and the heat demand of the sample is indeed met by electricity.

We compare the energy performance of the sample to values from the Italian Informative System on Energy Performance Certificates (SIAPE in Italian), established by the Ministerial Decree 26/06/2015 and implemented by ENEA in 2016 [49]. The office buildings of our sample outperform SIAPE benchmarks, particularly in zones D and E, confirming that large insurance and banking companies have effectively invested in office retrofitting in recent years, prioritizing the sustainability of their assets [11].

Most of the sampled buildings were built between 1955 and 2000, consistent with the overview from SIAPE of the Italian building age [49]. Buildings of that period present poor attention to energy-saving measures and an urgent need for retrofitting since the first Italian regulation introducing regulations for energy efficiency in the building design took place in late 1991 [50]. The second most populous class comprises buildings older than 70 years, which are part of the national heritage. This class includes the historical headquarters of banks and insurance in the old towns. The enhancement of their energy efficiency while protecting their historical value is challenging for many reasons [51,52]: (i) their energy performance presents a great uncertainty due to the heterogeneity of the construction materials and scarce knowledge of their lifespan transformations; (ii) their retrofitting needs on-site analysis, documentary research, and site-specific technical solutions (i.e., low standardization) which affect their financial sustainability; (iii) the administrative procedure for the approvals of the interventions increases costs and works duration. Therefore, a suitable retrofitting strategy should accept that historical buildings cannot reach the contemporary standards on energy performance and focus on multiple benefits of energy efficiency, such as the safety and aesthetic preservation of historical neighborhoods, saving of fuel and emissions, and enhancing the comfort of occupants, especially in future hotter climates [53]. A private and public partnership should support the retrofitting of historical buildings. Incentives and simplified administrative procedures could enhance the profitability of retrofitting interventions, allowing industries and skilled workforces to experiment with non-invasive solutions for energy efficiency.

The conservation of historical buildings with improvements of their energy efficiency aligns with the core ideas of positive energy buildings and districts, as defined by [54]. PEBs and PEDs play a crucial role in making historic districts more efficient by integrating renewable energy technologies in a way that minimizes their impact on individual buildings. For example, the case study by Gouveia et al. [55] estimates the retrofitting measures to reduce the energy needs of the historical district of Alfama (Lisbon) and produce renewable electricity decentralized, at district scale.

3.2. Energy, emissions, and economics of the retrofitting interventions

The energy savings, emission reduction, and financial analyses of the sampled retrofitting interventions are presented in Figs. 3–5.

Most interventions reduce electricity use, with the most frequent solution being the replacement of fluorescent lamps with LED lamps (example 6 in Table 2). This action reduces the building's pre-retrofit energy use and CO_2 emissions by 1–10%, with the highest frequency in the 5–10% range. As observed in financial analysis, the payback time of LED installation varies with the initial investment, accumulating between 1 and 5 years for investments of €40k and increasing between 5 and over 10 years for more expensive investments. The main benefit of

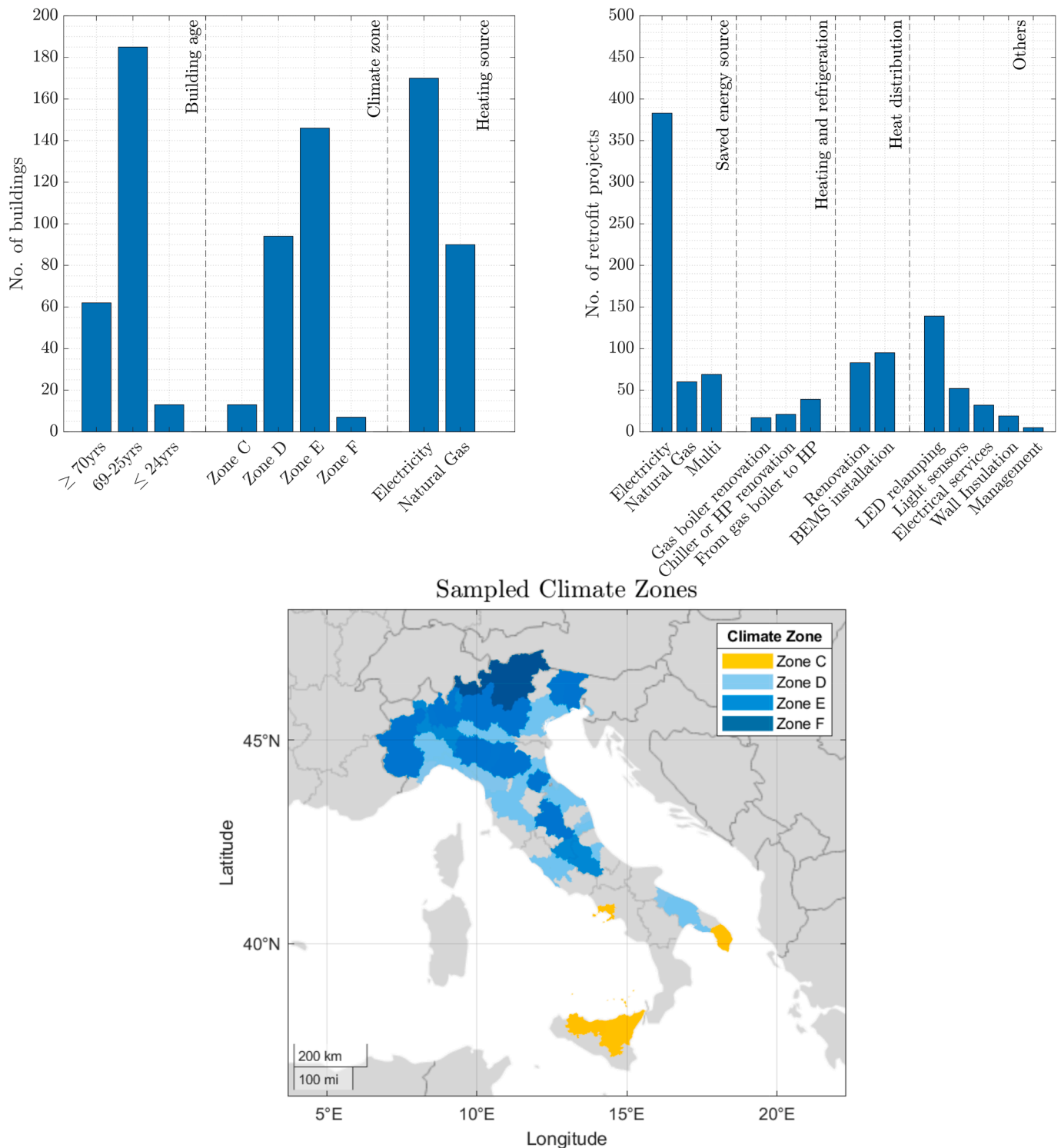


Fig. 2. The buildings (left), retrofitting interventions (right), and the geographic distribution of the sample by climate zones (bottom). The left graph groups buildings by age, climate zone, and energy source used for heat generation. The right graph illustrates the energy sources that the retrofitting intervention saves, including the actions implemented on heating generators and chillers, the BEMS installation, and general renovation (e.g., the installation of new fans or pumps) of the heat distribution system, as well as interventions on the lighting system, building structure, and power quality.

LED installation is the reduction in electricity use. However, the CBA can also include minor effects, such as a reduction in cooling loads and an increase in heat demand and related CO₂ emissions, as LED lamps reduce internal heat gains compared to fluorescent lamps [56].

Other measures that reduce electricity use include power quality solutions and the renovation of IT systems (last example in Table 2), which

result in modest energy and emissions savings over the total use (1–5%) and present a payback time of 3 to 5 years.

The primary buildings' energy consumption in the EU is for space heating [57], and we consistently observe that retrofitting of heat generators presents the highest benefits, resulting in 10–30% of energy and emissions savings. These interventions include revamping the heat

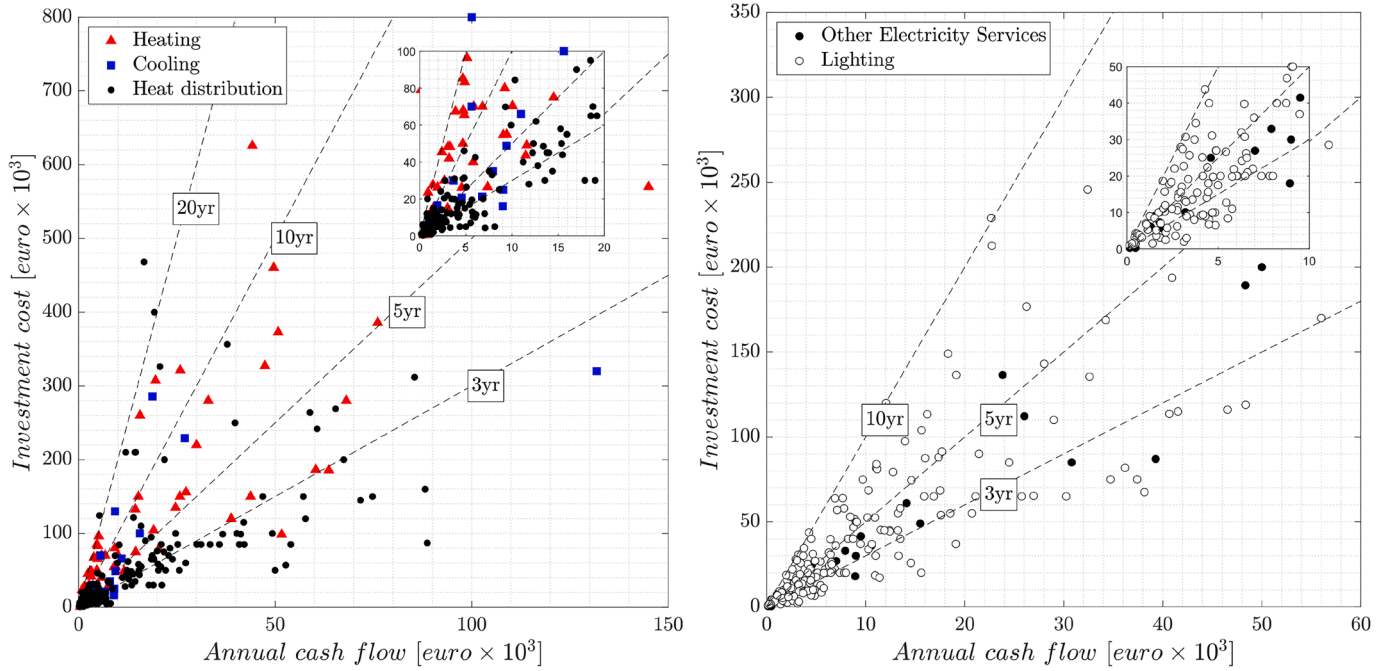


Fig. 3. The left plot compares the investment costs against annual cash flows of replacing or renovating (see labeling in Table 2) heating generators, chillers, and heat distribution systems. The right plot shows the financial figures for LED installations and interventions that reduce the electricity use of services other than lighting (e.g., IT systems, elevators, and security appliances). Dashed lines indicate reference values of the payback times.

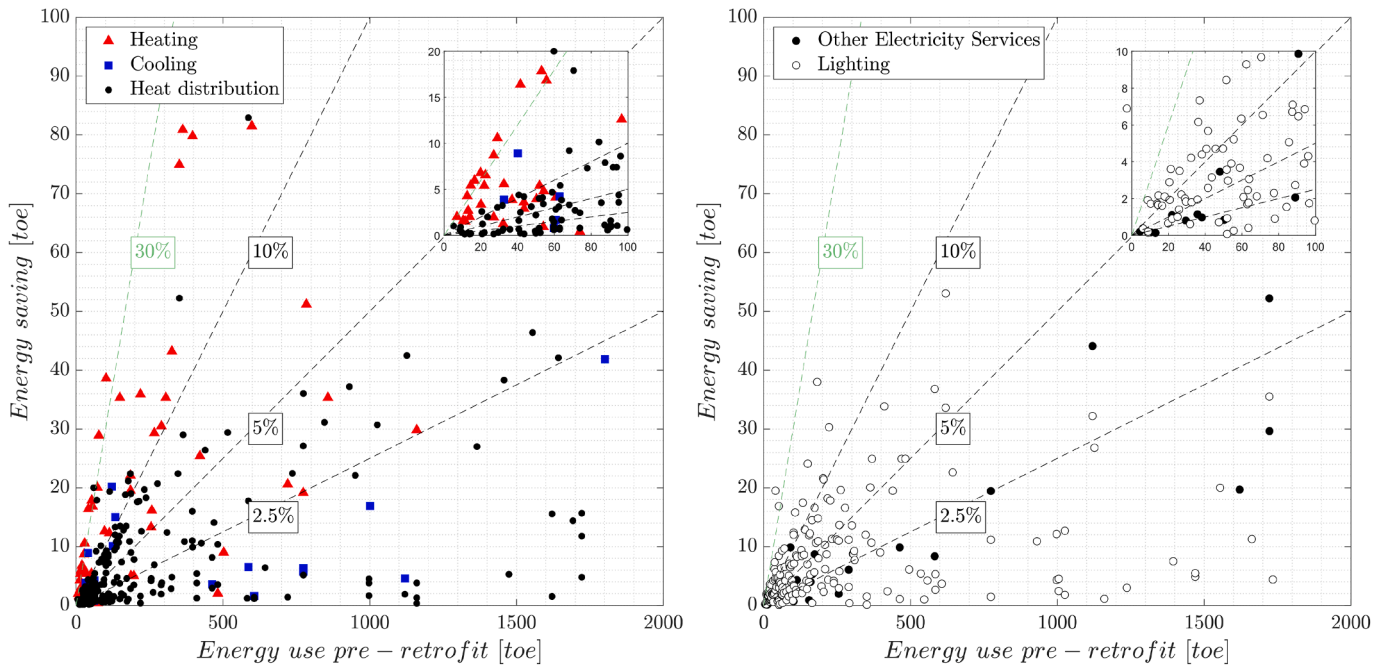


Fig. 4. The left plot compares the total yearly energy use of the building before retrofitting against the energy savings that replacing or renovating (see labeling in Table 2) heating generators, chillers, and heat distribution systems procures. The right plot shows the energy savings analysis of LED installations and other electricity services. Dashed lines indicate the share of energy savings relative to the building's overall pre-retrofit energy use. The interventions that reduce energy use by at least 30% (dashed green line) fulfill the EU Green Taxonomy Regulation [60]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

generators or replacing the gas boiler with a heat pump (the first two actions of Table 2), and they are the least numerous in our database, likely due to their high initial costs and extended payback times (≥ 10 years). However, when the initial investment (i.e., installed thermal load) increases, the interventions reduce their payback time in the range between 5–10 years; this effect seems reasonable since the costs of a heat

generator decrease by increasing its size [58]; in the following paragraph, we will further explore this effect.

Retrofitting the building's heat distribution involves upgrading the fan electrical engines or circulation pumps, as well as the installation of automated building energy monitoring and control systems (example 3 in Table 2). Energy savings of these actions range mainly between 2.5%

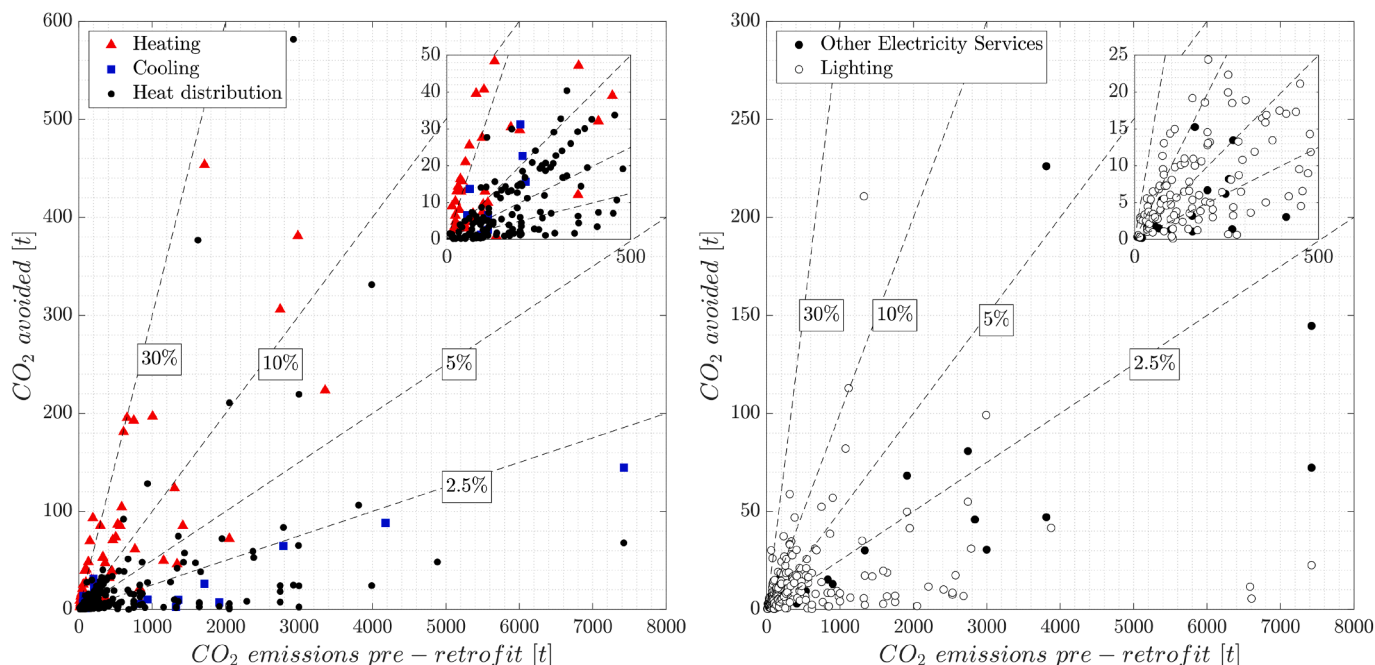


Fig. 5. The left plot compares the total CO_2 building emissions related to its yearly energy use against the emission avoided by replacing or renovating (see labeling in Table 2) heating generators, chillers, and heat distribution systems. The right plot shows the CO_2 emission analysis of LED installations and other electricity services. Dashed lines represent the proportion of CO_2 emissions avoided relative to the annual CO_2 emissions of the building. Emission factors are by [44].

and 10%, and the related CO_2 emissions between 5% and 10%; their payback times are between 5 and 10 years for investments over €50k, and reduce to 1 to 3 years for lower investments. The energy savings of the cooling system renovation (example 7 in Table 2) are low, as most interventions reduce the pre-retrofit energy use and CO_2 emissions by less than 2.5%, and their payback time is around ten years. However, we need more data for significant remarks.

We observed that revamping or replacing heat generators results in the highest energy and emissions savings, as well as enhancements in thermal comfort and indoor air quality.

The installation of BEMS and more efficient fans and pumps in the heat distribution system moderately reduces energy use and CO_2 emissions with short- and medium-term financial returns; also, these interventions enhance the awareness of the building owner on the energy consumption and reduce exposure to noise of occupants.

All interventions present co-benefits beyond energy and financial savings; for example, they enhance asset attractiveness and market valuation [59], facilitate compliance with sustainability requirements, and support long-term regulatory resilience. All these benefits contribute to the reputational branding value. Only a few renovations of heat generators and LED installations reduce energy use before retrofitting by 30%, fulfilling the technical regulation of the EU Green Taxonomy [60] by a single intervention (Fig. 4). Indeed, the 30% reduction in pre-retrofit energy use is a challenging goal that requires multiple energy-saving measures; for example, in the study by Yun et al. [61], the energy savings resulting from various interventions vary between 17% and 23%. The EU Green Taxonomy compliance enhances the multiple benefits mentioned before, as it unlocks access to green finance instruments (e.g., ESG-aligned funds and preferential loans), and improves asset attractiveness and market valuation [62].

3.3. Cost-benefits analysis of building retrofitting and incentives support

We present the cost-benefit analysis of the sampled interventions and simulate the effects of existing incentive mechanisms. First, we assess the cost-benefits of new heat generators - replacing existing gas boilers with heat pumps as action 2 in Table 2 - since these interventions

present the highest energy and emission savings but are expensive and present long payback times. Following, we aggregate the retrofitting of heat distribution and lighting systems (merging actions 3 and 6 in Table 2 to other interventions, such as the retrofitting of the HVAC fan and circulator), focusing the analysis on the broadest population in our database. The Italian incentives we considered are:

1. **White Certificates:** companies earn these tradable obligations for each tonne of oil equivalent they save by energy efficiency interventions [63,64]. Then, companies can sell their white certificates at the market price (which we assume equals about €250, the 2024 average price). All interventions in our cost-benefit analysis are suitable for requesting White Certificates if they guarantee a minimum energy saving of $10t_{oe}$. This type of incentive rewards exclusively, for each technology, the additional energy savings compared to the market average.
2. **Conto Termico (v2.0)**[65]: an incentive program that supports thermal energy-saving measures in public and private buildings, covering from 40% to 65% of their initial costs [66]. Installing new HPs is the only action in our database suitable for this financial support, and the maximum available coverage is 45% of the investment, since all sampled buildings are from large enterprises. The financial support varies with the yearly heat demand and installed thermal power of the building's heating system.

The benefits of a new HP and related incentives support increase with the installed thermal load (Fig. 6). We could explain this as a combined effect of augmenting the HP size: (i) the efficiency, and therefore the annual energy savings, enhance [67]; (ii) the cost per kW of installed thermal load decreases [68]. The financial support of white certificates increases with energy savings and, therefore, as the installed thermal load increases. The heat pumps with the lowest thermal load ($\leq 35kW$) have no support by white certificates since they present insufficient energy savings ($\leq 10t_{oe}$). At the same thermal power, Conto Termico supports heat pump installation more than white certificates. The latter rewards additional energy savings compared to the market average of the implemented technical solution. On the other hand, the yearly financial rate of the Conto Termico is calculated per

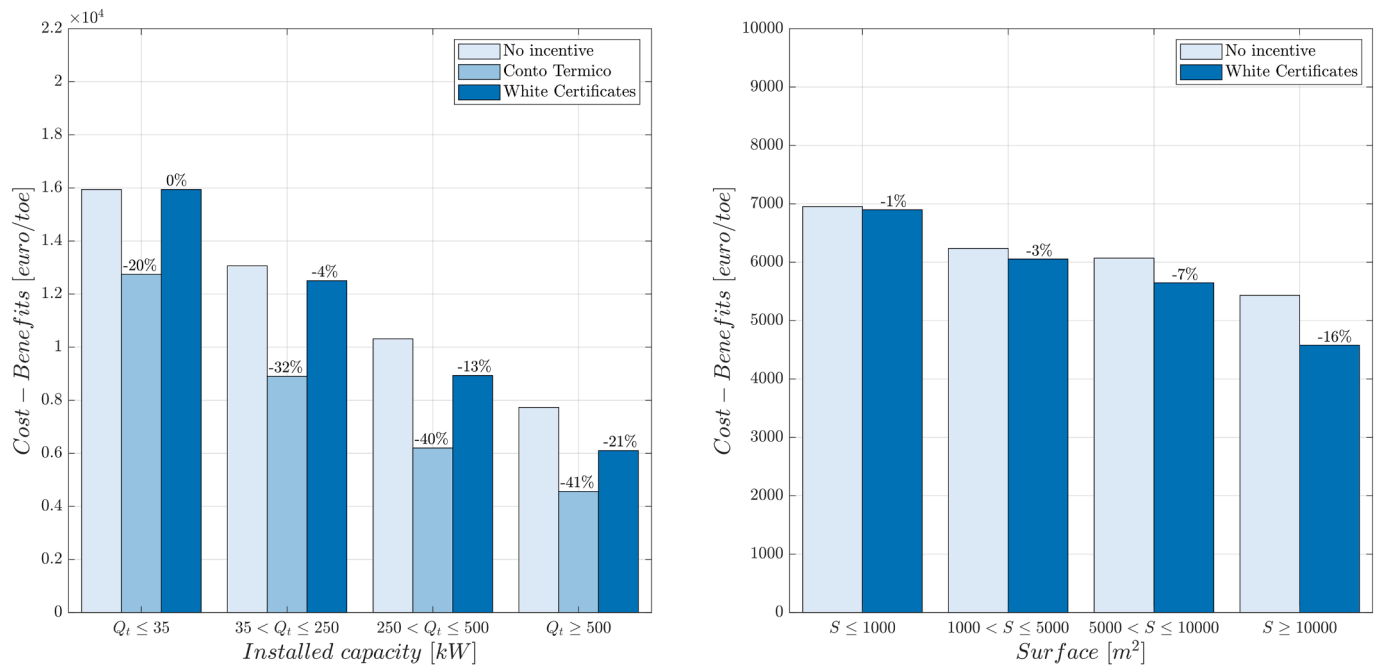


Fig. 6. Cost-benefits of a new heat pump by the installed thermal load (left), and cost-benefits of a renovated heat distribution and lighting systems by square meter of the served surface (right).

kilowatt-hour (kWh) of thermal energy consumed. Furthermore, the support of the Conto Termico increases with the heat pump size because (i) the annual rate is extended from two to five years when the installed thermal load is more than $35kW$, (ii) the cost per kW of thermal load decreases when the HP size augments, and (iii) the HPs with the largest capacities, installed in energy-intensive building complexes, quickly reach the maximum incentive support.

The retrofitting of heat distribution encompasses interventions applied to all components of an HVAC system, including controllers, pipes or ducts, and terminals (our terminology refers to the retrofitting domains by Krajčůk et al. [69]), excluding heat generation. The analysis encompasses low-cost actions, such as adjusting the thermostat or installing zonal control systems, as well as more expensive investments, including pipe and duct insulation, pump and circulator replacements, and automation of building energy management and monitoring (BEMS [70]). The lighting systems retrofit replaces fluorescent lamps with LEDs. Results show that these interventions become more convenient when the building surface area increases (Fig.6), as their initial cost per square meter decreases, and their resulting energy savings increase when implemented in buildings with intensive energy use. Indeed, the largest and most energy-intensive buildings of our analysis are office complexes, also distributed over multiple floors in high-rise buildings; this category presents an elevated energy demand that scales with size, and it is also exposed to several penalties, such as lower temperature, winds, and solar gains [71–73]. Renovating both the lighting system and heat distribution is the only way to access white certificates, overcoming the $10toe$ minimum threshold of energy saving, and, nevertheless, the financial aid is relevant only when retrofitting the largest buildings. Thus, an alternative strategy for accessing public incentives involves combining the retrofitting of heat distribution and lighting systems with the replacement of heat pumps.

The discussion in this paragraph highlights the fundamental role of incentives, which is crucial in significantly reducing the payback times of investments, especially those with very long payback periods that are not attractive to companies. Decision makers should consider incentive schemes that address the specific needs of different building types and energy use profiles. For instance, larger buildings with higher energy

use could benefit more from long-term, large-scale interventions. At the same time, smaller offices can see quicker returns from smaller measures, such as LED lighting retrofits.

3.4. Technical-economic analysis

This section presents the cost-benefit and energy analysis of retrofitting heat generators, heat distribution systems, and lighting systems. We split the database into three sub-samples of buildings, each implementing an intervention. We then calculate the energy benefits and economic impact for sub-sample quartiles based on energy use per square meter (EPI) before retrofit.

Buildings with the worst energy performance present an EPI higher than Q_3 (Table 3). They start with few or missing energy efficiency measures, and their EPI is 1.5 times that of the following quartile and up to 2 times the energy use of the whole sub-sample; focusing on heat generators, this scale factor augments to 1.7 and 2.9 times, respectively.

Table 3

The savings of the retrofitting measures by the building energy use per square meter before the intervention. The analysis begins with the fourth percentile of buildings (the worst 25% in terms of EPI) and expands to the whole sub-sample. All figures are average values computed over quartiles.

Retrofitted Component	Buildings selection by EPI	EPI [$toe/1000m^2$]	ΔEPI after retrofitting	$\frac{En.Saving}{Surface}$ [$toe/1000m^2$]
Heat generator	$\geq Q_3$	84, 20	-4, 7%	3, 92
	$\geq Q_2$	48, 33	-5, 0%	2, 42
	$\geq Q_1$	35, 40	-6, 0%	2, 12
	all sample	29, 14	-6, 9%	2, 00
	Heat distribution	$\geq Q_3$	65, 35	-1, 8%
$\geq Q_2$		42, 96	-2, 9%	1, 25
$\geq Q_1$		38, 58	-3, 1%	1, 19
all sample		32, 04	-3, 1%	0, 99
Lighting system		$\geq Q_1$	75, 52	-1, 3%
	$\geq Q_2$	51, 89	-1, 5%	0, 79
	$\geq Q_3$	45, 42	-1, 8%	0, 84
	all sample	35, 07	-2, 3%	0, 81

Table 4

The cost-benefits, retrofit cost per square meter, and payback years of retrofitting measures by the building energy use before the intervention. We included the support of the Conto Termico and White Certificates for each measure. All figures are average values computed over quartiles.

Retrofitted Component	Buildings selection by EPI	$\frac{\text{Costs}}{\text{Benefits}}$ [€/toe]	Retrofit cost [€/m ²]	with CT [€/m ²]	with WC [€/m ²]	Retrofit pbck [yrs]	with CT [yrs]	with WC [yrs]
Heat generator	$\geq Q_3$	19.713,50	77,21	60,31	63,34	9,3	6,2	8,1
	$\geq Q_2$	16.557,66	40,10	29,69	33,53	10,1	6,9	9,1
	$\geq Q_1$	13.137,35	27,89	19,81	22,98	9,6	6,5	8,7
	<i>all sample</i>	13.859,28	27,78	20,36	23,31	9,6	6,6	8,6
Heat distribution	$\geq Q_3$	6.825,00	7,95	–	6,66	5,1	–	4,8
	$\geq Q_2$	7.434,42	9,31	–	7,76	4,7	–	4,3
	$\geq Q_1$	6.961,44	8,27	–	6,91	4,8	–	4,5
	<i>all sample</i>	6.871,54	6,79	–	5,71	4,7	–	4,5
Lighting system	$\geq Q_3$	5.263,03	5,01	–	4,09	4,4	–	4,1
	$\geq Q_2$	5.066,77	3,99	–	3,28	4,5	–	4,2
	$\geq Q_1$	5.570,14	4,67	–	3,89	4,5	–	4,2
	<i>all sample</i>	6.033,82	4,87	–	4,08	4,6	–	4,3

Almost all these buildings were built between 1955 and 2000, the second class by age we considered in our analysis (Fig. 2), revealing that historical buildings can show competitive energy and comfort performance, probably due to their natural ventilation systems and materials with high thermal inertia [74].

Although the worst 25% buildings present the highest energy-saving potential, the proposed interventions reduce their EPI less than those in more efficient buildings. Indeed, inefficient buildings have a higher energy-saving potential because retrofitting starts from a low-performance baseline; however, the impact of a single intervention on their energy use may be relatively small due to the widespread inefficiencies. Such buildings require multiple interventions or global retrofitting [75,76]. In contrast, buildings with previously implemented energy-saving measures present lower energy-saving potential since many of the most effective efficiency measures have already been implemented, diminishing the returns of further interventions.

The retrofitting of the worst 25% buildings presents the highest costs. However, the financial support of both incentives is more effective than in other quartiles: the average cost reduction is 22% by Conto Termico and 18% by White Certificates (Table 4). The cost-benefits of retrofitting decrease for more efficient buildings; in particular, we observe lowest costs in the medium performance range (above Q_2 and Q_1) showing that retrofitting highly inefficient buildings faces prohibitive costs without incentives or it becomes less convenient when multiple efficiency measures have already been implemented [76,77].

This section showed that the main national incentive schemes, White Certificates and Conto Termico, are based on the principle that the greater the energy savings achieved, the greater the financial support awarded. Incentive programs abroad, such as Germany's KfW [78] and the U.S. Section 179D [79], follow the same logic: they implicitly reward deep renovation, but lack specific targeting based on building type or pre-renovation EPI. Although deep retrofits are implicitly favored, incentives may be applied inefficiently to buildings whose technical condition or structural obsolescence make renovation economically unjustifiable. To improve policy precision in the Italian context, we propose the formalization of a new building category: pre-regulation, non-historic buildings—constructed before the introduction of national energy efficiency laws (L. 373/1976 or L. 10/1991) – but not subject to preservation constraints. These buildings often have high energy demand and low architectural barriers to intervention, making them ideal candidates for well-calibrated, multi-measure retrofits. As a future research direction, we plan to map this segment in detail, analyzing its structural condition, geographic distribution, and retrofit feasibility, to define technical thresholds for incentive differentiation. The goal is to exclude degraded buildings from incentives (where demolition may be

preferable) while enhancing support for retrofit-ready assets with high energy-saving potential.

4. Conclusions

The energy audit of an office building describes its energy services, construction features, location, and final energy use; it also proposes energy-saving measures to enhance the building's energy performance. ENEA collected mandatory energy audits of large banks and insurance companies in Italy, constituting a database that accurately represents the national office building stock.

Our analysis revealed that most buildings are located in cold-temperate climate zones D and E, primarily concentrated in the Lombardy region, and were built between 1950 and 2000, before the implementation of national regulations on building energy performance. The majority of buildings utilize electrical boilers, while gas boilers are still widely used. The data revealed a building stock that requires renovation to comply with the latest EU regulations on building energy use and emissions reduction by 2050. We extended the analysis to energy-saving measures from energy audits, aiming to support decision-makers and investors in retrofitting office buildings through the most profitable investment opportunities. Retrofitting the heat distribution constitutes the dominant strategy for reducing the building energy needs (the 47% of sampled interventions), and it substantially takes place by replacing the heat generator with modern heat pump systems and renovating the heat distribution; these interventions could reduce up to 30% of energy needs and 10% of emissions. However, new heat generators are expensive and have extended payback times. Therefore, investors usually favor the renovation of lighting systems with LEDs, 37% of the sampled interventions, since these investments are cheaper than others and procure faster returns, reducing the building energy need by 2.5–5% with a payback time of about 4 years. Saving measures for data centers and their cooling systems are residual, indicating that companies are migrating to cloud computing.

We analyzed the cost-benefits of retrofitting heat generators, heat distribution, and renovating the lighting system. We compared the case when the private investor covers the initial investment to the scenarios with public economic support; the incentives we studied are Conto Termico (CT) and white certificates (WC). The cost-benefit ratio decreases as the size of the installed energy system increases, since larger systems result in greater energy savings (i.e., benefits) and lower unit cost of the installed system (expressed in €/kW or €/m²). The support of CT and WC depends on the yearly energy use and savings, making these incentives more advantageous for the largest energy systems. Compared to the WC, the CT significantly reduces the cost-benefits of a new heat generator, as this incentive framework is explicitly designed for measures

that save thermal energy. The WC could support multiple measures for a global building retrofit, and it is less effective when exploited for a stand-alone intervention.

We completed our analysis by investigating how the building's energy use per square meter before the intervention (EPI) is a proxy indicator of whether retrofitting is convenient in terms of financial costs and energy savings. Buildings with poor energy performance are expensive to retrofit, particularly without incentives, and a single action reduces the initial EPI lower than in more efficient buildings. However, inefficient buildings have the highest energy-saving potential and fastest returns, so investors could maximize profits by combining multiple actions in a single investment to reduce the initial unit costs. In more efficient buildings, new energy-saving measures are merging or replacing those already implemented, and they inevitably yield slower energy savings and financial returns than when implemented in less efficient buildings. Therefore, retrofitting these buildings should prioritize the interventions based on the state of the building before retrofitting (e.g., degree of degradation, structural transformation, and existing energy systems), the interdependencies among interventions with their cumulative impact, and generally ensure the best energy savings and financial returns.

The analysis developed in this paper could be helpful to both policymakers and company investors in monitoring potential savings and identifying the benefits associated with energy retrofitting for offices having different EPIs and operating in various climatic zones. The EED 2023/1791 requires companies to develop an energy audit and draft annual implementation plans of energy efficiency measures; thus, the quantitative information provided in this work could help prioritize energy efficiency interventions at the company level.

The limit of our analysis is in the resolution of the database. The energy audits track the energy use of the office building and suggest measures for saving energy in that specific case; they lack many details about the building features, such as insulation level, glazing, external shading, and building orientation that could have been useful for studying the cost-benefits of interventions aggregated by building typology. Some audits include qualitative descriptions, but we have not incorporated them in our analysis since they are not consistent in format and technical depth.

Additionally, we missed the small office buildings widely distributed across the national territory, particularly in the climatic zones we scarcely covered. Also, our analysis does not cover public offices, as these fall outside the application parameters of Legislative Decree 102/2014, Art. 8 regarding the obligation of an energy audit. Even within the banking and insurance sector, we included only the most energy-intensive buildings. Therefore, caution is needed when generalizing the results to smaller or public-sector offices: multi-tenant offices or consulting firms often lack control over building-wide systems, which limits retrofitting options to single, low-cost measures; government and educational offices operate with fixed operating hours and seasonal closures, lowering their baseline energy use and the relative impact of interventions; finally, the smallest companies could not qualify for incentives, and the cost-effectiveness observed in our analysis cannot be downscaled to them.

Future studies will enhance the accuracy of the analysis since the New EED 2023/1791 Art. 11, published in September 2023, has modified the previous Directive, linking the energy audit obligation to the company's energy consumption, rather than its size. This update will further expand our dataset for future analysis and research. For example, we will examine the temporal planning of interventions, establishing a timeline for implementing these solutions following the EU's emissions pathway to 2050. Also, ENEA is developing a freely available energy management tool to conduct sensitivity analysis on key financial parameters for the cost-benefit analysis of the interventions, such as investment costs, energy prices, and discount rates. Furthermore, our analysis considered only the economic and energy benefits associated with the energy efficiency interventions reported in the mandatory en-

ergy audits presented by the companies. We have not yet evaluated the multiple benefits of energy efficiency, including reduced environmental impact, social benefits, enhanced indoor environmental quality (IEQ), and improved company green branding. Although these effects were not quantifiable by our dataset, we consider their analysis critical for future research since their positive impact on occupant productivity and company visibility can result in financial gains that exceed direct energy savings.

CRediT authorship contribution statement

Andrea Aquino: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization; **Marco Bassetti:** Formal analysis; **Fabrizio Martini:** Writing – review & editing, Supervision; **Chiara Martini:** Writing – original draft, Validation, Supervision, Conceptualization; **Marcello Salvio:** Validation, Supervision, Project administration.

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Data availability

The authors do not have permission to share data.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fabrizio Martini reports financial support was provided by Government of Italy Ministry of Environment and Energy Security. Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] International Energy Agency, Energy technology perspectives 2024, 2024. (Accessed: 10 July 2025), <https://iea.blob.core.windows.net/assets/34511d5d-8dc8-42a2-8faf-b83606cfcfed/EnergyTechnologyPerspectives2024.pdf>.
- [2] C.A. Balaras, E.G. Dascalaki, M. Patsioti, K.G. Droutsas, S. Kontoyiannidis, T. Cholewa, Carbon and greenhouse gas emissions from electricity consumption in European union buildings, *Buildings* 14 (1) (2023) 71.
- [3] European Commission, Renovation Wave, 2025, (https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en). (Accessed 16 April 2025).
- [4] European Union, Directive 2024/1275 on the energy performance of buildings (EPBD), 2024. (Accessed 11 April 2025), <https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng>.
- [5] Ministero dell'ambiente e della sicurezza energetica, National Energy and Climate Plan, 2024. (Accessed 01 April 2025.) https://commission.europa.eu/publications/italy-final-updated-necp-2021-2030-submitted-2024_en#details.
- [6] M.d. I. e.d. Economico, Ministero dello Sviluppo and del Territorio e, Ministero dell'Ambiente e della Tutela and Trasporti, Strategy for Energy Retrofitting of National Building Stock, 2020. (Accessed on 01 April 2025). https://energy.ec.europa.eu/document/download/49a04289-fd3e-4b4f-a398-644101813e6a_en?filename=2020_itr_italy_en.pdf.
- [7] A. Esser, A. Dunne, T. Meeusen, S. Quaschnig, W. Denis, A. Hermelink, S. Schimschar, M. Offermann, A. John, M. Reiser, et al., Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU final report, *Public. Off. Eur. Union: Luxembourg* (2019) 87.
- [8] European Commission, Assessment of Italy's National Energy and Climate Plan (NECP), 2023. (Accessed 01 April 2025). https://commission.europa.eu/system/files/2023-12/SWD_Assessment_draft_updated_NECP_Italy_2023.pdf.
- [9] P. Zangheri, L. Castellazzi, D. D'Agostino, M. Economidou, G. Ruggieri, S. Tsemekidi-Tzeiranaki, C. Maduta, P. Bertoldi, et al., Progress of the member states in implementing the energy performance of building directive, *Public. Off. Eur. Union: Luxembourg* (2021) 7.

- [10] PwC Italy, Real Estate Market Overview 2023, 2023. (Accessed 02 April 2025). <https://www.pwc.com/it/it/publications/docs/pwc-real-estate-market-overview-2023.pdf>.
- [11] PwC Italy, Real Estate Market Overview 2024, 2024. (Accessed 04 April 2025). <https://www.pwc.com/it/it/publications/docs/pwc-real-estate-market-overview-2024.pdf>.
- [12] ECCO Climate, How Much Investment is Needed for the Decarbonisation of the Italian Economy? 2023. (Accessed 04 April 2025). <https://eccoclimate.org/wp-content/uploads/2023/09/How-much-investment-is-needed-for-the-decarb-onisation-of-the-italian-economy.pdf>.
- [13] Confindustria, Presentazione Rapporto FT for 55, 2024, (Accessed 02 April 2025). (<https://confindustria.it/home/appuntamenti/eventi-confindustria/dettaglio-evento/presentazione-rapporto-ft-for-55>).
- [14] The European House - Ambrosetti, Ambrosetti Report 2024, 2024. (Accessed 02 April 2025). https://www.enelfoundation.org/content/dam/enel-foundation/topics/2022/09/net-zero-e-economy/R22_Executive%20summary_ITA_190822_04.pdf.
- [15] Buildings Performance Institute Europe (BPIE), Building Renovation: A Kick-Start for the EU Recovery, 2020. (Accessed: 07 July 2025). https://www.bpie.eu/wp-content/uploads/2020/05/Recovery-investments-in-deep-renovation_BPIE_2020.pdf.
- [16] N. Rodriguez, A. Katooziani, I. Jeelani, Barriers to energy-efficient design and construction practices: a comprehensive analysis, *J. Build. Eng.* 82 (2024) 108349.
- [17] G. De Gasperis, S.D. Facchini, I. Letteri, Leveraging multi-agent systems and decentralised autonomous organisations for tax credit tracking: a case study of the superbonus 110% in Italy, *Appl. Sci.* 14 (22) (2024) 10622.
- [18] D. Ürge-Vorsatz, R. Khosla, R. Bernhardt, Y.C. Chan, D. Vérez, S. Hu, L.F. Cabeza, Advances toward a net-zero global building sector, *Annu. Rev. Environ. Resour.* 45 (1) (2020) 227–269.
- [19] M. Economidou, V. Todeschi, P. Bertoldi, et al., Accelerating energy renovation investments in buildings, *EUR-Scit. Techn. Res. Rep. ISPR: Joint Res. Centre* (2019). <https://publications.jrc.ec.europa.eu/repository/handle/JRC117816?mode=full>.
- [20] H.-L. Kangas, D. Lazarevic, P. Kivimaa, Technical skills, disinterest and non-functional regulation: barriers to building energy efficiency in finland viewed by energy service companies, *Energy Pol.* 114 (2018) 63–76.
- [21] M. Bensouda, M. Benali, Behavioral barriers to energy efficiency and policy interventions: a survey of the literature, *Intern. J. Energy Eco. Policy* 12 (6) (2022) 305–310.
- [22] M. Jakob, Marginal costs and co-benefits of energy efficiency investments: the case of the swiss residential sector, *Energy Policy* 34 (2) (2006) 172–187.
- [23] S. Zambotti, S. Pezzutto, A. Bisello, Multiple-benefits from buildings' refurbishment: evidence from smart city projects in Europe, in: *International Symposium on New Metropolitan Perspectives*, Springer, 2018, pp. 157–164.
- [24] W. Kuckshinrichs, T. Kronenberg, P. Hansen, The social return on investment in the energy efficiency of buildings in germany, *Energy Policy* 38 (8) (2010) 4317–4329.
- [25] ENEA, Benefici multipli dell'efficienza energetica per le imprese, 2024. (Accessed 15 April 2025). <https://www.pubblicazioni.enea.it/le-pubblicazioni-enea/edizioni-enea/anno-2024/benefici-multipli-dellefficienza-energetica-per-le-imprese.HTML>.
- [26] S.A. Sharbaf, P. Schneider-Marin, Cost-benefit analysis of sustainable upgrades in existing buildings: a critical review, *Energy Build.* 328 (2025) 115142.
- [27] G. Napoli, L. Gabrielli, S. Barbaro, The efficiency of the incentives for the public buildings energy retrofit. the case of the italian regions of the "objective convergence", *Valori e valutazioni* (18) (2017).
- [28] G. Aruta, F. Ascione, N. Bianco, T. Iovane, M. Mastellone, Assessment of the incentive rate to favor the energy retrofit of public buildings: a comprehensive approach for an italian university facility, *Energies* 16 (11) (2023) 4483.
- [29] B. Flyvbjerg, D.W. Bester, The cost-benefit fallacy: why cost-benefit analysis is broken and how to fix it, *J. Benefit-Cost Anal.* 12 (3) (2021) 395–419.
- [30] E. Commission, Energy efficiency in buildings: a european perspective, *EU Publications* (2020). (Accessed 03 April 2025). https://energy.ec.europa.eu/system/files/2016-11/energyuse_0.pdf.
- [31] S. Research, Energy Retrofit Systems Market Size, Share & Trends Analysis Report By Product, By Application, By Region, And Segment Forecasts, 2024 - 2030, 2022. (Accessed 04 April 2025). <https://www.grandviewresearch.com/industry-analysis/energy-retrofits-systems-market>.
- [32] I. Research, Energy Retrofit Systems Market Size, Top Trends to 2032, 2022. (Accessed 02 April 2025). https://www.inkwoodresearch.com/reports/europe-energy-retrofit-systems-market/?srsltid=AfmBOoq4d6q7_H1EbYzeUmN5t7q02bCuX-AXf1vmtQPvYDtDl-VLBO7PPE.
- [33] FIEC, Italy - FIEC Statistical Report 2024, 2024, (<https://fiec-statistical-report.eu/italy>). (Accessed 02 April 2025).
- [34] D. Palladino, S. Di Turi, Energy and economic savings assessment of energy refurbishment actions in italian residential buildings: comparison between asset and tailored calculation, *Sustainability* 15 (4) (2023) 3647.
- [35] L. Forni, F. Fortuna, E. Giarda, F. Giovanardi, D. Panarello, The 'green buildings' directive: a quantification of its costs and benefits in two Italian regions, *J. Hous. Econ.* 68 (2025) 102057.
- [36] U.F. Oberegger, R. Perneti, R. Lollini, Bottom-up building stock retrofit based on levelized cost of saved energy, *Energy Build.* 210 (2020) 109757.
- [37] L. Evangelisti, C. Guattari, P. Gori, Energy retrofit strategies for residential building envelopes: an Italian case study of an early-50s building, *Sustainability* 7 (8) (2015) 10445–10460.
- [38] G. Ciulla, A. Galatioto, R. Ricciu, Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings, *Energy Build.* 128 (2016) 649–659.
- [39] G. Rospi, N. Cardinale, E. Negro, Energy performance and economic feasibility study of historical building in the city of Matera, Southern Italy, *Energies* 10 (12) (2017) 2009.
- [40] S. Di Turi, L. Ronchetti, R. Sannino, Towards the objective of net ZEB: detailed energy analysis and cost assessment for new office buildings in Italy, *Energy Build.* 279 (2023) 112707.
- [41] D. Astiaso Garcia, F. Cumo, M. Tiberi, V. Sforzini, G. Piras, Cost-benefit analysis for energy management in public buildings: four Italian case studies, *Energies* 9 (7) (2016) 522.
- [42] B.S. EN, 16247-2: 2014, "Energy audits—Part 2: buildings", *British Standards Institute*, London (2014).
- [43] A. Moreno-Munoz, J.M. Flores-Arias, A. Gil-de Castro, J. De La Rosa, Power quality for energy efficient buildings, in: 2009 International Conference on Clean Electrical Power, IEEE, 2009, pp. 191–195.
- [44] E. Marrasso, C. Roselli, M. Sasso, Electric efficiency indicators and carbon dioxide emission factors for power generation by fossil and renewable energy sources on hourly basis, *Energy Convers. Manage.* 196 (2019) 1369–1384.
- [45] L. Fantini, C. Schenone, Degree-days, population distribution and heating energy consumption: the Italian case, *Int. J. Ambient Energy* 22 (4) (2001) 199–210.
- [46] Italian Presidential Decree no. 412/93 (In Italian), Regulation containing rules for the design, installation, use and maintenance of the heating systems in buildings for containing energy consumption, in implementation of Art. 4, paragraph 4 of Law No. 10 of 9th January 1991, 1993.
- [47] Italian National Institute of Statistics (ISTAT), Resident population by single age, gender and citizenship - data by Italian provinces, 2019. (Accessed 08 April 2025). <https://esploradati.censimentopopolazione.istat.it/databrowser>.
- [48] M. Pieve, R. Trinchieri, The heat-pump market in Italy: an in-depth economic study about the reasons for a still unexpressed potential, *Clean Energy* 3 (2) (2019) 126–143.
- [49] F. Pagliaro, F. Hugony, F. Zanghirella, R. Basili, M. Misceo, L. Colasuonno, V. Del Fatto, Assessing building energy performance and energy policy impact through the combined analysis of EPC data—The Italian case study of SIAPE, *Energy Policy* 159 (2021) 112609.
- [50] International Energy Agency (IEA), National Energy Plan, 2019. (Accessed 09 March 2025). <https://prod.iea.org/policies/2165-national-energy-plan>.
- [51] C. Panakaduwa, P. Coates, M. Munir, Identifying sustainable retrofit challenges of historical buildings: a systematic review, *Energy Build.* (2024) 114226.
- [52] V. Pracchi, Historic buildings and energy efficiency, *The Hist. Environ.: Policy Pract.* 5 (2) (2014) 210–225.
- [53] A.L. Webb, Energy retrofits in historic and traditional buildings: a review of problems and methods, *Renewable Sustainable Energy Rev.* 77 (2017) 748–759.
- [54] O. Lindholm, H.U. Rehman, F. Reda, Positioning positive energy districts in European cities, *Buildings* 11 (1) (2021) 19.
- [55] J.P. Gouveia, J. Seixas, P. Palma, H. Duarte, H. Luz, G.B. Cavadini, Positive energy district: a model for historic districts to address energy poverty, *Front. Sustain. Cities* 3 (2021) 648473.
- [56] C. Ciacci, F. Bazzocchi, Retrofitting of the italian precast industrial building stock. LCA analysis as decision-making tool, *J. Clean. Prod.* (2024) 143933.
- [57] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on building energy information: trends, end-uses, fuels and drivers, *Energy Reports* 8 (2022) 626–637.
- [58] L.D. Tommasi, H. Ridouane, G. Giannakis, K. Katsigrakis, G.N. Lilis, D. Rovas, Model-based comparative evaluation of building and district control-oriented energy retrofit scenarios, *Buildings* 8 (7) (2018) 91.
- [59] M. Gholamzadehmir, A.M. Pandolfi, C. Del Pero, F. Leonforte, L. Sdino, Increasing the market value of buildings through energy retrofitting: a comparison of actual retrofit costs and perceived values, *Buildings* 15 (3) (2025) 376.
- [60] European Commission, Delegated Regulation (EU) 2021/2139 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council. (Accessed 04 April 2025). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02021R2139-20250101>.
- [61] W.-S. Yun, W. Ryu, D. Lee, H. Seo, Energy-saving potential estimation of retrofitting aged buildings considering external wall insulation degradation, *J. Build. Eng.* 94 (2024) 110022.
- [62] B. Wiphagen, S. Farcas Lohan, Changes in Energy Efficiency Implementation due to the EU Taxonomy: An Analysis of Shifts in Property Owning Companies' Strategies, 2023.
- [63] P. Bertoldi, S. Rezessy, Tradable white certificate schemes: fundamental concepts, *Energy Effic.* 1 (4) (2008) 237–255.
- [64] D. Di Santo, E. Biele, D. Forni, White certificates as a tool to promote energy efficiency in industry, *Proceedings of the ECEEE Summer Studies, Industrial Efficiency* (2018).
- [65] C. Toro, E. Biele, C. Herce, C. Martini, M. Salvio, A. Threpsiadi, J. Wilkinson-Dix, Overview of energy efficiency policies and programmes for SMEs in Italy, *Proceedings of the Energy Evaluation Europe*, Paris (2022).
- [66] European Construction Sector Observatory (ECSO), Policy fact sheets of the European construction sector observatory - Italy - Conto Termico, 2018. (Accessed 03 April 2025). https://single-market-economy.ec.europa.eu/sectors/construction/observatory/policy-fact-sheets/thematic-objective-3_en.
- [67] T. Marsik, V. Stevens, R. Garber-Slaght, C. Dennehy, R.T. Strunk, A. Mitchell, Empirical study of the effect of thermal loading on the heating efficiency of variable-speed air source heat pumps, *Sustainability* 15 (3) (2023) 1880.
- [68] J. Levy, S.R. Petersen, Economic efficiency in the sizing of residential heat pumps, *Final Report National Bureau of Standards* (1981).

- [69] M. Krajččík, M. Arıcı, Z. Ma, Trends in research of heating, ventilation and air conditioning and hot water systems in building retrofits: integration of review studies, *J. Build. Eng.* 76 (2023) 107426.
- [70] K. Sayed, H.A. Gabbar, Building energy management systems (BEMS), *Energy Conserv. Residential, Commercial, and Indus. Facil.* (2017) 15–81.
- [71] M.A. Malakoutian, Y. Malakoutian, P. Mostafapoor, M. Amjadi, Correlation between energy consumption and building size, *Eng. Trans.* 2 (2021) 1–6.
- [72] C. Marincu, D. Dan, L. Moga, Investigating the influence of building shape and insulation thickness on energy efficiency of buildings, *Energy for Sustainable Devel.* 79 (2024) 101384.
- [73] D. Godoy-Shimizu, P. Steadman, I. Hamilton, M. Donn, S. Evans, G. Moreno, H. Shayesteh, Energy use and height in office buildings, *Build. Res. Inform.* 46 (8) (2018) 845–863.
- [74] A.R. Rempel, J. Danis, A.W. Rempel, M. Fowler, S. Mishra, Improving the passive survivability of residential buildings during extreme heat events in the pacific North-west, *Appl. Energy* 321 (2022) 119323.
- [75] K. Kuusk, T. Kalamees, Retrofit cost-effectiveness: estonian apartment buildings, *Build. Res. Inform.* 44 (8) (2016) 920–934.
- [76] J. Hirvonen, J. Jokisalo, J. Heljo, R. Kosonen, Towards the EU emissions targets of 2050: optimal energy renovation measures of finnish apartment buildings, *Int. J. Sustainable Energy* 38 (7) (2019) 649–672.
- [77] P. Fairley, D. Parker, Cost-Effectiveness of Home Energy Retrofits in Pre-Code Vintage Homes in the United States, Technical Report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.
- [78] J.-S. Broc, E. Trauchessec, C. Milin, Revisiting the KfW and green deal programmes: it's not all about finance!, in: *ECEEE Summer Study*, paper 2-150-15, ECEEE (European Council for an Energy Efficient Economy), 2015, 321–331.
- [79] U. S. Department of Energy, 179D Energy Efficient Commercial Buildings Tax Deduction, 2024. Accessed: 2025-07-04, https://www.energy.gov/eere/buildings/179d-energy-efficient-commercial-buildings-tax-deduction?nrg_redirect=471714.