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Multi-criteria analysis of the improvement interventions related to the Superbonus 110%: efficiency, renewables

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Abstract. The 2050 long-term strategy of the European Union contains an analysis of the actions that need to be taken for the transition to a zero GHG emission economy and to to build a better future for all by 2050. The outlined scenarios envisage ambitious objectives in terms of the energy efficient building improvements, the use of RES and the reduction of climate-changing emission. Following this European vision, EU Member States have developed national long-term strategies and focusing on the building sector, in Italy the Recovery and Resilience Plan is providing financing and national and European investment is expected to enable the renovation of more than 100,000 buildings, with a total upgraded area of more than 36 million square metres. The expected energy saving is about 191 Ktoe/year with a reduction in greenhouse gas emissions of about 667 Kton CO_2/year. At the end of 2023, the energy requalification of buildings reached about 12 million square metres. By 31 December 2025, the objective is to ensure the energy requalification of buildings for at least 32 million square metres. The proposed research aims to investigate the effects of the renovation activities related to the Superbonus 110% through a multi-criteria analysis, taking into account the beneficial effects consisting of the energy efficiency improvement. The research has been conducted starting from a database of 1,545 dwellings on the territory of Italy, using a data collection questionnaire to estimate the energy consumption of a dwelling, with an in-house developed calculation code based on a simplified dynamic simulation. The database has been set to satisfy different purposes: to characterize the energy uses of residential utilities and identify flexible loads; to estimate the effects of energy upgrading interventions; to analyse the transformation potential of residential buildings with the introduction of an integrated PV-Heat Pump-Thermal Storage system; to evaluate the best energy upgrading proposal based on the climate zone and building location; to evaluate the cost of energy upgrading interventions. The proposed activity aims to complement the studies carried out by projecting the existing situation into more scenarios congruent with the national and European context; the envisioned scenario interprets the need to increase the building stock efficiency and integrate more renewable energy resources into energy systems. In light of the estimates produced and the results achieved, the research aims to emphasize the reuse of building materials issue, looking at circular reuse, offering a different and broader assessment of interventions aimed at the construction sector and, more specifically, the residential sector.

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1. Introduction

The European Green Deal [1], presented by the European Commission, serves as a roadmap for making Europe a climate-neutral continent by 2050. In 2019, the European Parliament reiterated the urgent need to address the worsening climate emergency that has been discussed for decades. The goals set by various states under the Paris Agreement [2] are no longer adequate. Given the limited time available, intensifying efforts beyond previous measures has become inevitable.

The European Green Deal was adopted by the European Parliament on June 24, 2021, making the target of reducing emissions by 55% by 2030 and achieving climate neutrality by 2050 legally binding [3]. To meet the 2030 target, the Commission proposed a legislative package in 2021, known as "Fit for 55," comprising 13 revised interconnected laws and 6 legislative proposals on climate and energy [4].

These reforms aim to reduce, and eventually eliminate, pollutant emissions by promoting sustainable fuel use and enhancing carbon removal regulations across various sectors. Additionally, to support vulnerable households, small businesses, and transport users facing increased energy costs, the Parliament approved the implementation of a Social Climate Fund, ensuring a fair energy transition for all [5].

The European Union's efforts to reduce its greenhouse gas emissions and address the inevitable impacts of climate change span various sectors, including construction and buildings.

A crucial contribution to the success of the strategy can come from the residential sector, currently responsible for more than 25% of the EU's energy consumption, which can be optimized through measures aimed at energy retrofitting along with structural, seismic, plant, and aesthetic renovations. In the Italian context, the residential sector is undergoing intensive energy retrofitting activities, incentivized by the so-called "Superbonus 110%."

The Superbonus 110% is a benefit introduced by the Relaunch Decree [6] that raised the deduction rate to 110% for expenses incurred on specific interventions in energy efficiency, seismic upgrades, or photovoltaic system installations. Tax deductions for property interventions were created to support the residential construction sector and combat tax evasion through the instrument of interest opposition between supplier and client. The 110% deduction measure, new compared to past incentives, has unbound design choices from optimization calculations; additionally, the tight timelines and deduction measures have significantly accelerated design and implementation activities, directing choices toward solutions that allow for rapid execution of work and easy access to tax benefits.

Much of the Italian building stock was constructed before the enactment of energy-saving laws [7-8]. Thus, from an energy perspective, there is significant room for improvement, which must be interpreted coherently with the emerging national and European energy scenario to contribute substantially to achieving community objectives of reducing consumption, and emissions, and increasing the use of renewable energy sources.

Across Europe, buildings that act as both producers and consumers (prosumers) of electricity are increasingly widespread [9-10]; these buildings not only generate energy from distributed energy resources but also use the locally generated energy for heating, cooling, hot water preparation, and appliance operation, potentially supplying excess energy back to the public grid [11]. The spread of such buildings indicates a significant transformation in energy systems, shifting control from utilities to widely distributed and decentralized electricity prosumers [12].

These buildings can be achieved through new constructions or by retrofitting existing building stock [13]. The former inevitably leads to further land consumption, while the latter avoids direct use of new surface areas but may generate waste from replacing building elements, indirectly leading to land use [14]. To develop future strategies, policymakers and planners have the responsibility to best direct available resources towards activities and technologies that maximize positive aspects while minimizing negative ones [15-16]. Given the highly cross-cutting nature of the circular economy theme, a general strategic framework is needed to identify specific intervention areas and sectors with the greatest impact, ensuring coherence and synergy with the planning of other policies.

Mitigation policies for climate change have so far focused on energy efficiency rather than the performance or study of new materials as the main driver of technical performance improvement [17]. Recent international research is beginning to delve specifically into the efficient use of materials [18] and their potential contribution to reducing greenhouse gas emissions [19]. Some studies [20-21] identify specific strategies to improve such efficiency, including: extending the useful life of products; reuse-repair; choosing less carbon-intensive materials in production; reducing materials and selecting lighter materials; better performance in the production process; sharing goods; industrial symbiosis.

Sustainability is not purely an environmental issue [22]. There is increasing awareness in civil society, businesses, administrations, and public opinion that an integrated approach is needed to tackle the numerous and complex challenges of combining development with environmental protection.

Recent developments underscore the urgent need for greater energy self-sufficiency [23]; in this context, substantial resources will still need to be allocated to promoting energy efficiency and renewable energy, with accelerated timelines that could lead to a repetition of what is being observed with the Superbonus 110%.

This research aims to investigate, through a multicriteria analysis, the effects of retrofitting activities connected to the Superbonus 110%, considering the beneficial effects of improved efficiency.

2. Research methodology

This study has been conducted by consulting a database of 1,545 residences across Italy and utilizing a data collection questionnaire that estimates the energy consumption of a residence using an in-house developed calculation code based on a simplified dynamic simulation [24], based on the evaluation of the potential flexible loads for each archetype, and a control strategy for applying load time shifting. This strategy considers both the power demand pattern and the hourly electricity prices. It assumes that end users adopt a pricing mechanism that follows the hourly fluctuations of electricity's economic value, as determined daily in the Italian spot market, rather than using the existing Time of Use (TOU) system. [24].

The database has been employed to:

- Characterize the energy uses of residential utilities and identify flexible loads;
- Estimate the effects of energy retrofitting interventions;
- Analyse the transformation potential of residential buildings with the introduction of an integrated Photovoltaic-Heat Pump-Thermal Storage system;
- Evaluate the best energy retrofit proposal based on the climatic zone and location of the building;
- Assess the cost of energy retrofitting interventions.

The proposed activity aims to complement the studies conducted by projecting the current situation into multiple scenarios consistent with the national and European context. The resulting framework interprets the need to increase the efficiency of the building stock and to further integrate renewable energy resources into current systems. In this context, the research seeks to raise awareness about the issue of reusing building materials, offering a different and broader evaluation of interventions aimed at the residential sector.

As mentioned previously, the Superbonus consists of a 110% tax deduction from the gross tax and is granted for works that increase the energy efficiency of buildings or for seismic retrofitting interventions. Specifically, it is available, under certain conditions, for expenses incurred for interventions on common parts of buildings, on functionally independent housing units with one or more autonomous accesses from the outside, located within multi-family buildings, as well as on individual housing units.

Eligible interventions are categorized as primary or leading and additional or trailing. The category of leading interventions includes:

1. Thermal insulation works on the vertical, horizontal, and inclined opaque surfaces that affect the building envelope, including single-family buildings, with an incidence of more than 25% of the building's gross surface area;
2. Replacement of existing winter heating systems with centralized systems for heating, and/or cooling, and/or hot water supply on the common parts of buildings, or on housing units located within multi-family buildings that are functionally independent;
3. Seismic retrofitting interventions, as provided for by the so-called “Sismabonus” [25].

A housing unit is considered “functionally independent” if it has at least three of the following installations or structures that are exclusively owned: water supply systems, gas supply systems, electrical systems, and winter heating systems.

In addition to the leading interventions, the Superbonus is also available for the following types of trailing interventions, provided they are carried out in conjunction with at least one of the thermal insulation or heating system replacement interventions previously listed:

1. Energy efficiency actions falling within the Ecobonus [26], within the spending limits set by current legislation for each intervention;
2. Works aimed at removing architectural barriers to facilitate internal and external mobility for people with severe disabilities and those over sixty-five years of age;
3. Installation of infrastructure for charging electric vehicles in buildings.

The Superbonus also applies to the following trailing interventions, provided they are carried out in conjunction with at least one of those previously listed:

1. Installation of solar PV systems connected to the building's electricity grid;
2. Concurrent or subsequent installation of storage systems integrated with the subsidized solar photovoltaic systems.

2.1 Proposed scenarios for energy refurbishment

Starting from the housing database, simulations have been conducted to evaluate the effects on energy consumption of a comprehensive retrofitting of residences while maintaining the current energy carriers (for heating and hot water preparation) and with the complete electrification of utilities.

The proposed scenarios have been divided into LIGHT, INTERMEDIATE, and HEAVY interventions, each classified according to the year of construction. Specifically, references are to buildings constructed more than 50 years ago, particularly between 1946 and 1961; more modern buildings constructed between 1991 and 2005; and recent constructions, built between 2006 and 2008.

The effects produced will then be projected and analysed in various regions of Italy, using four cities as reference points: ROME, MILAN, FLORENCE, and NAPLES. The objective will be to determine the most appropriate intervention for each city to minimize energy consumption and consequently reduce emissions.

The following paragraphs illustrate the simulation results, initially focusing on the overall annual data on primary energy, gas and electricity consumption, and subsequently analysing the trends following the retrofitting interventions.

The simulation results are then analysed to establish consumption benchmarks for the identified scenarios.

The intervention strategies and simulated actions in the different scenarios, light, intermediate and heavy, from the current situation are given in the following paragraphs.

2.1.1. Scenario #E1, #E2 and #E3 - EXISTING - Current situation and use of gas generator as primary producer of heating

To best frame, the evolutionary scenarios, Scenario #E1, #E2 and #E3 - EXISTING - were preliminarily considered, in which the priority generator is the gas generator and any air conditioners present are not used to produce heating.

This scenario therefore represents a hypothesis not confirmed by the questionnaires, although plausible concerning the established habits of residential users, useful to constitute a comparison scenario for the other evolutionary scenarios.

The data constituting the results obtained from the questionnaires are given in Section 3, in comparison with the various redevelopment scenarios.

2.1.2. Scenario #L - Light housing intervention with maintenance of energy carriers.

Scenario #L has been simulated to evaluate the potential effects of energy refurbishment while maintaining the current energy carriers.

Specifically, the assumptions underlying the simulations conducted are as follows:

SCENARIO #L1 – Light

Buildings 2006-2008

1. Intervention for replacement of existing winter HVAC systems;
2. Intervention for replacement of winter HVAC systems with condensing boilers ≥ class A;
3. Purchase and installation of solar shading.

SCENARIO #L2 – Light

Buildings 1991-2005

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for the purchase and installation of windows, including window frames;
4. Purchase and installation of solar shading.

SCENARIO #L3 – Light

Buildings 1946-1961

1. Thermal insulation intervention of vertical, horizontal or inclined opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for energy upgrading on the existing building;
4. Intervention for the purchase and installation of windows, including frames;
5. Intervention for the replacement of winter HVAC systems with condensing boilers ≥ class A.

2.1.3. *Scenario #I – Intermediate housing intervention with maintenance of energy carriers*

Scenario #I has been simulated to evaluate the potential effects of energy upgrading while maintaining current energy carriers.

Specifically, the assumptions underlying the simulations conducted are as follows:

SCENARIO #I1 – Intermediate

Buildings 2006-2008

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention of replacement of winter HVAC systems with condensing boilers ≥ class A;
3. Intervention of installation of solar panels/solar collectors;
4. Purchase and installation of solar shading.

SCENARIO #I2 – Intermediate

Buildings 1991-2005

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for the purchase and installation of windows, including window frames;
4. Intervention for replacement of winter HVAC systems with condensing boilers ≥ class A;
5. Purchase and installation of heat pumps for DHW systems;
6. Purchase and installation of solar shading.

SCENARIO #I3 – Intermediate

Buildings 1946-1961

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for the purchase and installation of windows including window frames;
4. Intervention for replacement of winter HVAC systems with condensing boilers ≥ class A;
5. Purchase and installation of solar screens;
6. Intervention of rehabilitation or restoration of the façade of existing buildings.

2.1.4. *Scenario #H – Heavy housing intervention with maintenance of energy carriers*
Scenario #H has been simulated in order to evaluate the potential effects of energy upgrading while maintaining current energy carriers.

Specifically, the assumptions underlying the simulations conducted are as follows:

SCENARIO #H1 – Heavy

Buildings 2006-2008

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention on existing building envelope (except the purchase and installation of windows, including frames);
4. Intervention for purchase and installation of windows, including window frames;
5. Purchase and installation of heat pump for DHW production systems;
6. Purchase and installation of heat pump for winter HVAC systems;
7. Intervention for the installation of grid-connected solar PV systems on buildings;
8. Intervention for the simultaneous or subsequent installation of storage systems integrated into subsidized solar PV systems.

SCENARIO #H2 – Heavy

Buildings 1991-2005

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for purchase and installation of windows, including window frames;
4. Purchase and installation of heat pump for winter HVAC systems;
5. Intervention of rehabilitation or restoration of the façade of existing buildings;
6. Intervention for the installation of grid-connected solar PV systems on buildings;
7. Intervention for the simultaneous or subsequent installation of storage systems integrated into subsidized solar PV systems.

SCENARIO #H3 – Heavy

Buildings 1946-1961

1. Thermal insulation intervention of vertical, horizontal or pitched opaque surfaces affecting the building envelope with an incidence of more than 25%;
2. Intervention for the replacement of existing winter HVAC systems;
3. Intervention for purchase and installation of windows, including window frames;
4. Intervention for replacement of winter HVAC systems with condensing boilers ≥ class A;
5. Purchase and installation of heat pump for winter HVAC systems;
6. Extraordinary maintenance, restoration and conservative restoration or building renovation and ordinary maintenance work carried out on the common parts of a building;
7. Intervention for the installation of grid-connected solar PV systems on buildings;
8. Intervention for the simultaneous or subsequent installation of storage systems integrated into subsidized solar PV systems.

For each of the three hypothesized scenarios, the results obtained from simulations of interventions in the sampled homes in the four different geographical locations are reported in the following paragraph.

3. Results and discussion

The definition of values related to the existing scenario (current situation and use of gas generator as the primary producer of heating), presented in section 2.1.1., and the simulation of intervention strategies and solutions in the sampled houses, in the four geographical contexts (Rome, Milan, Florence and Naples) and the relevant construction epochs (2006-2008; 1991-2005; 1946-1961) led to the definition of the research results that, in this section, are reported in comparison with each other, divided for each construction epoch.

Below are summary tables of the total primary energy consumption of all scenarios, compared with the existing scenarios.

3.1 Comparison of existing and light scenario for buildings constructed between 2006 and 2008

The analysis carried out shows that, in the light scenario #L1, through an intervention of replacing winter HVAC systems with condensing boilers of a class higher than A and the purchase and installation of solar shading, primary energy production is reduced by 10.2% in Rome, 10.7% in Florence, 13.7% in Milan and, finally, reaches a maximum saving of 13.9% of primary energy consumption in Naples, which, therefore, turns out to be the most congenial situation for this type of intervention. However, this scenario is most efficient in areas where the climate is predominantly hot or cold in climate zones C and E, the most "extreme" ones in Italy (Table 1).

Table 1. Difference in total primary energy consumption per unit area in the comparison of existing #1 and light scenario for buildings constructed between 2006 and 2008.

	Scenario #E1R Rome 2006-2008 [kWh/m^2]	Scenario #E1M Milan 2006-2008 [kWh/m^2]	Scenario #E1F Florence 2006-2008 [kWh/m^2]	Scenario #E1N Naples 2006-2008 [kWh/m^2]
All dwellings	118	139	122	122
	Scenario #L1R Rome 2006-2008 [kWh/m^2]	Scenario #L1M Milan 2006-2008 [kWh/m^2]	Scenario #L1F Florence 2006-2008 [kWh/m^2]	Scenario #L1N Naples 2006-2008 [kWh/m^2]
All dwellings	106	120	109	105
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-10.2%	-13.7%	-10.7%	-13.9%

3.2 Comparison of existing and light scenario for buildings constructed between 1991 and 2005

Table 2 shows how, in light scenario #L2, through an intervention of thermal insulation of external vertical opaque surfaces, an intervention of replacement of winter HVAC systems with condensing boilers of a class higher than A, the purchase and installation of windows including frames and solar shading, primary energy production is reduced by 11.3% in Naples, 14.3% in Rome, 15.1% in Florence, and, finally, reaches a maximum saving of 19.8% of primary energy consumption in Milan, which, therefore, turns out to be the best situation for this type of intervention. It can be seen, in this case, that this scenario is most efficient in areas where the climate is predominantly cold, i.e., in the E climate zone, since improving insulation reduces heat loss, resulting in significant savings in energy used for heating. In warmer environments, priority could be given to HVAC, but the benefits may be less obvious in terms of primary energy savings (Table 2).

Table 2. Difference in total primary energy consumption per unit area in the comparison of existing #2 and light scenario for buildings constructed between 1991 and 2005.

	Scenario #E2R Rome 1991-2005 [kWh/m²]	Scenario #E2M Milan 1991-2005 [kWh/m²]	Scenario #E2F Florence 1991-2005 [kWh/m²]	Scenario #E2N Naples 1991-2005 [kWh/m²]
All dwellings	133	167	139	124
	Scenario #L2R Roma 1991-2005 [kWh/m²]	Scenario #L2M Milan 1991-2005 [kWh/m²]	Scenario #L2F Florence 1991-2005 [kWh/m²]	Scenario #L2N Naples 1991-2005 [kWh/m²]
All dwellings	114	134	118	110
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-14.3%	-19.8%	-15.1%	-11.3%

3.3 Comparison of existing and light scenario for buildings constructed between 1946 and 1961

From the results achieved, it can be seen how, in the light scenario #L3, through an energy upgrading intervention on the existing building, a thermal insulation intervention of the external vertical opaque surfaces, an intervention of replacement of the winter HVAC systems with condensing boilers of a class higher than A and the purchase and installation of windows including fixtures, the production of primary energy is reduced by 19.2% in Naples, by 23.4% in Rome, by 23.9% in Florence and, finally, reaches a maximum saving of 27.8% of primary energy consumption in Milan, which, therefore, turns out to be the most convenient situation for this type of intervention. This scenario achieves savings of almost 30% for buildings constructed between 1946 and 1961, particularly in colder areas. This happens because the buildings of that time lacked the technologies that exist today, so implementing energy upgrading on such structures allows for achieving important results (Table 3).

Table 3. Difference in total primary energy consumption per unit area in the comparison of existing #3 and light scenario for buildings constructed between 1946 and 1961.

	Scenario #E3R Rome 1946-1961 [kWh/m²]	Scenario #E3M Milan 1946-1961 [kWh/m²]	Scenario #E3F Florence 1946-1961 [kWh/m²]	Scenario #E3N Naples 1946-1961 [kWh/m²]
All dwellings	167	216	176	151
	Scenario #L3R Rome 1946-1961 [kWh/m²]	Scenario #L3M Milan 1946-1961 [kWh/m²]	Scenario #L3F Florence 1946-1961 [kWh/m²]	Scenario #L3N Naples 1946-1961 [kWh/m²]
All dwellings	128	156	134	122
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-23.4%	-27.8%	-23.9%	-19.2%

3.4 Comparison of existing and intermediate scenario for buildings constructed between 2006 and 2008

This intervention shows that in the intermediate scenario #I1, achieved through thermal insulation of external vertical opaque surfaces, an intervention to replace winter HVAC systems with condensing boilers of class higher than A, the installation of solar panels and the purchase and installation of sunscreens, primary energy production is reduced by 11.9% in Rome, 12.3% in Florence, 15.6% in Naples and, finally, it reaches a maximum saving of 16.5% of primary energy consumption in Milan, which, therefore, turns out to be the ideal context for this type of intervention. The table shows, therefore, that for buildings constructed between 2006 and 2008, savings are most important in climate zones C and E, which are characterized by total degree-days, less than 1400 and more than 2101, knowing that degree-days are the sum for different days of the year of the difference between indoor and average outdoor temperatures: the higher the result of this, the harsher the climate in that area (Table 4).

Table 4. Difference in total primary energy consumption per unit area in the comparison of existing #1 and intermediate scenario for buildings constructed between 2006 and 2008.

	Scenario #E1R Rome 2006-2008 [kWh/m^2]	Scenario #E1M Milan 2006-2008 [kWh/m^2]	Scenario #E1F Florence 2006-2008 [kWh/m^2]	Scenario #E1N Naples 2006-2008 [kWh/m^2]
All dwellings	118	139	122	122
	Scenario #I1R Roma 2006-2008 [kWh/m^2]	Scenario #I1M Milano 2006-2008 [kWh/m^2]	Scenario #I1F Florence 2006-2008 [kWh/m^2]	Scenario #I1N Naples 2006-2008 [kWh/m^2]
All dwellings	104	116	107	103
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-11.9%	-16.5%	-12.3%	-15.6%

3.5 Comparison of existing and intermediate scenario for buildings constructed between 1991 and 2005

From this intervention it's clear that in the intermediate scenario #I2, achieved through a thermal insulation intervention of the external vertical opaque surfaces, an intervention of replacement of winter HVAC systems with condensing boilers of a class higher than A, and one for the production of domestic hot water with a heat pump, the installation of solar panels and the purchase and installation of windows including window frames and solar shading, primary energy production is reduced by 8.9% in Naples, 19.5% in Rome, 20.9% in Florence and, finally, reaches a maximum saving of 27% of primary energy consumption in Milan, which, therefore, appears to be the ideal context for this type of intervention. The table shows that for buildings constructed between 1991 and 2005, savings are most important in climate zone E. There is a significant difference between cities, especially between Naples and Milan, the heating demand is generally higher where winters are harsher, so the improvements made in insulation and heating systems are more effective. In addition, the difference in temperature between seasons in Milan could affect the performance of heat pumps (Table 5).

Table 5. Difference in total primary energy consumption per unit area in the comparison of existing #2 and intermediate scenario for buildings constructed between 1991 and 2005.

	Scenario #E2R Rome 1991-2005 [kWh/m²]	Scenario #E2M Milan 1991-2005 [kWh/m²]	Scenario #E2F Florence 1991-2005 [kWh/m²]	Scenario #E2N Naples 1991-2005 [kWh/m²]
All dwellings	133	167	139	124
	Scenario #I2R Rome 1991-2005 [kWh/m²]	Scenario #I2M Milan 1991-2005 [kWh/m²]	Scenario #I2F Florence 1991-2005 [kWh/m²]	Scenario #I2N Naples 1991-2005 [kWh/m²]
All dwellings	107	122	110	113
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-19.5%	-27%	-20.9%	-8.9%

3.6 Comparison of existing and intermediate scenario for buildings constructed between 1946 and 1961

From the analysis carried out, it results that, in the intermediate scenario #I3, through an energy upgrading of the existing building with annexed façade restoration, an intervention to replace the winter HVAC systems with condensing boilers of a class higher than A and the purchase and installation of windows including frames and solar shading, the production of primary energy is reduced by 27.1% in Naples, 32.3% in Rome, 33.5% in Florence and, finally, it reaches a maximum saving of 39.3% of primary energy consumption in Milan, which, therefore, turns out to be the most congenial situation for this type of intervention. Using this scenario for buildings constructed between 1946 and 1961, net energy improvements are achieved that can reach almost 40% of savings in the coldest climate zones, in this case in Milan. However, the results highlight that this intervention would also be interesting if implemented in the other locations analyzed (Table 6).

Table 6. Difference in total primary energy consumption per unit area in the comparison of existing #3 and intermediate scenario for buildings constructed between 1946 and 1961.

	Scenario #E3R Rome 1946-1961 [kWh/m²]	Scenario #E3M Milan 1946-1961 [kWh/m²]	Scenario #E3F Florence 1946-1961 [kWh/m²]	Scenario #E3N Naples 1946-1961 [kWh/m²]
All dwellings	167	216	176	151
	Scenario #I3R Rome 1946-1961 [kWh/m²]	Scenario #I3M Milan 1946-1961 [kWh/m²]	Scenario #I3F Florence 1946-1961 [kWh/m²]	Scenario #I3N Naples 1946-1961 [kWh/m²]
All dwellings	113	131	117	110
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-32.3%	-39.3%	-33.5%	-27.1%

3.7 Comparison of existing and heavy scenario for buildings constructed between 2006 and 2008

Looking at the table shows how, in heavy scenario #H1, through an intervention of thermal insulation of external vertical opaque surfaces, an intervention of replacement of winter HVAC systems with heat pumps, an intervention of installation of photovoltaic systems equipped with storage and the purchase and installation of windows including frames, the production of primary energy is reduced by 27.1% in Rome, by 28.7% in Florence, by 30.3% in Naples and, finally, reaches a maximum saving of 35.2% of primary energy consumption in Milan, which, therefore, turns out to be the most convenient situation for this type of intervention. This scenario achieves savings of 35% for buildings constructed between 2006 and 2008, particularly in colder areas. The scenario includes a large number of actions to be carried out on the buildings, inevitably improving their energy performance, and Milan is the region that produces a larger amount of consumption in terms of heating among the various cities analyzed, being the northernmost. As a result, by replacing a classic gas boiler with a heat pump, gas consumption will cancel out, while electricity consumption will increase, but it would be covered by the introduction of the photovoltaic system, generating significant savings (Table 7).

Table 7. Difference in total primary energy consumption per unit area in the comparison of existing #1 and heavy scenario for buildings constructed between 2006 and 2008.

	Scenario #E1R Rome 2006-2008 [kWh/m²]	Scenario #E1M Milan 2006-2008 [kWh/m²]	Scenario #E1F Florence 2006-2008 [kWh/m²]	Scenario #E1N Naples 2006-2008 [kWh/m²]
All dwellings	118	139	122	122
	Scenario #H1R Rome 2006-2008 [kWh/m²]	Scenario #H1M Milan 2006-2008 [kWh/m²]	Scenario #H1F Florence 2006-2008 [kWh/m²]	Scenario #H1N Naples 2006-2008 [kWh/m²]
All dwellings	86	90	87	85
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-27.1%	-35.2%	-28.7%	-30.3%

3.8 Comparison of existing and heavy scenario for buildings constructed between 1991 and 2005

The analysis carried out shows that, in the heavy scenario #H2, through an intervention of thermal insulation of external vertical opaque surfaces, an intervention of replacement of winter HVAC systems with heat pumps, an intervention of recovery of the existing façade an intervention to install photovoltaic systems equipped with storage and the purchase and installation of windows including frames, primary energy production is reduced by 31.5% in Naples, 35.3% in Rome, 37.4% in Florence and, finally, reaches a maximum saving of 46.1% of primary energy consumption in Milan, which, therefore, turns out to be the most congenial situation for this type of intervention. However, this scenario is most efficient in areas where the climate is predominantly cold; the further north one moves, the greater the energy savings, which, due to the nature of the intervention, allow almost 50% of the total primary energy consumption of homes to be offset (Table 8).

Table 8. Difference in total primary energy consumption per unit area in the comparison of existing #2 and heavy scenario for buildings constructed between 1991 and 2005.

	Scenario #E2R Rome 1991-2005 [kWh/m²]	Scenario #E2M Milan 1991-2005 [kWh/m²]	Scenario #E2F Florence 1991-2005 [kWh/m²]	Scenario #E2N Naples 1991-2005 [kWh/m²]
All dwellings	133	167	139	124
	Scenario #H2R Rome 1991-2005 [kWh/m²]	Scenario #H2M Milan 1991-2005 [kWh/m²]	Scenario #H2F Florence 1991-2005 [kWh/m²]	Scenario #H2N Naples 1991-2005 [kWh/m²]
All dwellings	86	90	87	85
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-35.3%	-46.1%	-37.4%	-31.5%

3.9 Comparison of existing and heavy scenario for buildings constructed between 1946 and 1961

From this intervention, it is evident that in the heavy scenario #H3, achieved through thermal insulation of the external vertical opaque surfaces, replacement of the winter heating systems with class A+ condensing boilers, installation of heat pump systems for hot water production, installation of photovoltaic systems with storage, extraordinary maintenance of the building, and the purchase and installation of windows including frames, the primary energy production is reduced by 43.7% in Naples, 48.5% in Rome, 50.6% in Florence, and finally reaches a maximum savings of 58.3% in Milan, which thus proves to be the ideal context for this type of intervention. The table shows that for buildings constructed between 1946 and 1961, the savings are more significant in climate zone E. This time, there is a notable difference between the various cities, especially between Naples and Milan, as the heating demand is generally higher where winters are freezing. Therefore, improvements in insulation and heating systems are more effective. This intervention allows for substantial primary energy savings, nearly 60% in the northernmost regions, making it the most efficient among all the analyzed scenarios. (Table 9).

Table 9. Difference in total primary energy consumption per unit area in the comparison of existing #3 and heavy scenario for buildings constructed between 1946 and 1961.

	Scenario #E3R Rome 1946-1961 [kWh/m²]	Scenario #E3M Milan 1946-1961 [kWh/m²]	Scenario #E3F Florence 1946-1961 [kWh/m²]	Scenario #E3N Naples 1946-1961 [kWh/m²]
All dwellings	167	216	176	151
	Scenario #H3R Rome 1946-1961 [kWh/m²]	Scenario #H3M Milan 1946-1961 [kWh/m²]	Scenario #H3F Florence 1946-1961 [kWh/m²]	Scenario #H3N Naples 1946-1961 [kWh/m²]
All dwellings	86	90	87	85
	Difference [%]	Difference [%]	Difference [%]	Difference [%]
All dwellings	-48.5%	-58.3%	-50.6%	-43.7%

4. Conclusions

The presented research serves as a foundational study for considering strategies and intervention solutions aimed at improving the living environment. Enhancing the efficiency of Italy's existing building stock is emerging as a new development path—a green revolution to involve the residential sector, historically one of the major contributors to harmful emissions and energy consumption. Indeed, energy efficiency has become a priority on European and national agendas due to its multiple environmental, economic, and social impacts. The need to reduce emissions, improve energy efficiency, and promote a circular economy are fundamental elements of a strategy that aims to drastically reduce consumption and enhance the livability of cities shortly.

Energy efficiency, in particular, is a crucial step for achieving decarbonization goals, and the retrofitting of Italy's building stock represents a significant lever, bringing tens of billions of euros in investments and fostering the development of an industrial and artisanal supply chain. Two outcomes attributed to the Superbonus interventions that have contributed to significant improvements in the processes of ecological transition are better energy performance and reduced CO_2 consumption.

In its latest annual report, ENEA quantified the energy savings achieved through Superbonus-funded interventions at 9.4 TWh per year, out of a total energy consumption of 316.8 TWh in 2022 (approximately 3% of the year's total consumption). As a result, while energy-intensive buildings remain the majority, their numbers are beginning to decline due to both new construction and retrofitting interventions driven by state incentives.

The analysis led to the primary energy consumption per unit area of buildings constructed in different periods and various Italian cities provided a detailed overview of potential consumption reductions through energy efficiency interventions. The results demonstrate that targeted interventions can lead to significant energy savings, with substantial variations depending on the location and construction period of the buildings.

In comparing existing and light scenarios, interventions such as replacing HVAC systems and installing solar shading produced significant savings, particularly in areas with extreme climates like Naples and Milan. Such interventions are more effective in regions with hot or cold climates where heating or cooling demands are more pronounced. Although the positive effect provided by solar shading devices is, of course, more pronounced in areas with hot summer climates (a global annual energy saving linked to the use of shading devices of around 17% has been estimated for Naples), a global annual energy saving linked to the use of appropriate shading devices of around 8% has nevertheless been estimated for Milan (the coldest climate, among those taken into consideration).

For buildings constructed between 1991 and 2005, intermediate interventions led to substantial energy savings, especially in northern cities like Milan. The combination of the interventions of thermal insulation and installation of heat pumps proved effective in reducing energy consumption, particularly in colder climates where, despite the fact that the COP of heat pumps decreases as the climate gets colder, compensation occurs with an increase in the thermal insulation layer which, in the winter regime, guarantees an improvement in the reduction of energy consumption. At the same time, in the summer regime, although an increase in the layer of thermal insulation may in many cases require the contribution of a cooling system, it is considered that in particularly cold climates, this contribution may continue to be limited. However, this aspect of summer air-conditioning is still being calculated, simulated and further investigated.

In buildings constructed between 1946 and 1961, heavy interventions resulted in the most significant savings, with reductions of up to 58.3% in energy consumption in Milan. These findings highlight the importance of comprehensive energy retrofitting interventions, including thermal insulation, system replacement, and the installation of renewable energy production systems. It is important to note that the effectiveness of interventions also depends on local climatic conditions and the specific characteristics of the buildings. However, the collected data indicate that the energy efficiency of buildings can be significantly improved through a combination of targeted interventions and advanced technologies.

In conclusion, the analysis provides a solid foundation for policy implementation and targeted interventions aimed at improving the energy efficiency of buildings in Italy. The energy efficiency measures adoption will not only help reduce consumption and greenhouse gas emissions but also lead to significant long-term economic savings and greater environmental sustainability.

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