Simulation of the energy performance of building archetypes according to Italian regulations, with the identification of up-grading

Simulation of the energy performance of building archetypes according to Italian regulations, with the identification of up-grading solutions based on cost-benefit analysis in relation to climate change

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Abstract. Starting from the legislation on energy consumption and economic incentives, the energy performance of archetypes related to social housing detached multifamily buildings representative of the national building stock from the postwar period to the 1990s have been simulated. In order to perform energy and economic simulations, three reference periods were taken into account: 2006-35 (short term), 2036-65 (midterm), and 2066-95 (long term). The study focused on central Italy, specifically the climatic zone D of Tuscany, which is the most representative in the region and has interesting characteristics for climate change hypothetical, as it is typical of the temperate Mediterranean climate. Five efficiency strategies have been analysed: Opaque envelope insulation and window replacement; Hybrid system installation; Hybrid system installation powered by photovoltaic; Opaque envelope insulation, window replacement and hybrid system installation; Opaque envelope insulation, window replacement and hybrid system installation powered by photovoltaic. The results of the study have made it possible to identify the most effective building and plant energy retrofitting solutions, both in terms of the effects of climate change and of economic incentives, in order to meet the new energy classification requirements and greenhouse gas emissions neutralization.

1 Introduction

One of the main current goals of our society is surely the reduction of the greenhouse gases (GHG) emissions effects on climate caused by the built environment. On the other hand, the energy performance of buildings are strongly related to the climate they are exposed to. In view of these considerations retrofitting strategies should be assessed taking into account buildings adaptation and resilience towards the climate change [1].

The adaptation to climate change mainly depends on the environmental and energetic quality of the cities where lives and works a great part of the world's population. Many actors can have a direct or indirect impact on climate changes with their activities and actions, such as governments, enterprises, and populations [2]. In particular, the scientific evidence of anthropogenic in climate change in Europe and adaptation responses has been strongly highlighted [3].
As the building sector has become an important target for carbon emissions reduction the Mediterranean climate it has been acknowledged as one of the main hot-spots in climate change studies [4], and the real effectiveness of passive adaptation measures is strategic and should be articulated in a medium and long term analysis [5]. Moreover, cost optimal and cost effective renovation scenarios improving the energy performance must be identified and critically assessed comparing a reference renovation scenario with a series of alternative renovation ones [6,7] taking into account the co-benefits achieved in the renovation related to the increased achieved indoor comfort, but also to the society as a whole, improving health benefits, job creation, energy security, and of course to their positive effect on climate change [5].
Actually, the reduction of energy consumption in residential buildings is regulated by standards and laws that have been established from the 1990s to the 2020s and will need to be updated again to meet the expectations of the future EPBD, currently under discussion by European Authorities [8]. The building sector has benefited from several economic incentives, without which energy efficiency interventions would have been quite modest. However, these incentives have proven to be too costly and long-term unsustainable for the economic budget of the Italian State. For these reasons, it is necessary to evaluate what could be the energy savings obtainable from the most adopted refurbishment strategies and what economic commitment they will require in terms of economic sustainability.
To this end, the energy performance simulations were analysed for public housing archetypes defined on the basis of data from the Building Register and the ATER of the Province of Pistoia, representing the national building stock from the post-war years to the 1990s [9-11], particularly penalized from an energy performance perspective (energy class G). Three time periods were considered for energy simulations and the subsequent economic analysis to evaluate the effects of climate change.
The study focused on the central Italy region, particularly climate zone D of Tuscany, with specific reference to the climate data of the city of Florence. These data present interesting characteristics for the foreseeable climate changes, being typical of the regional climates of central and southern Italy and belonging to the broader category of Mediterranean temperate climate. Efficiency improvement strategies were analysed and divided into five categories based on the analysis of the most commonly used and economically promoted interventions (building bonuses). The study results identified the most effective building-plant energy retrofitting solutions, both considering the effects of climate change and taking into account the contribution that can arise from economic incentives to meet new energy classification requirements and GHG emissions reduction.

2 Materials and Methods

2.1 Definition of Reference Climatic Conditions

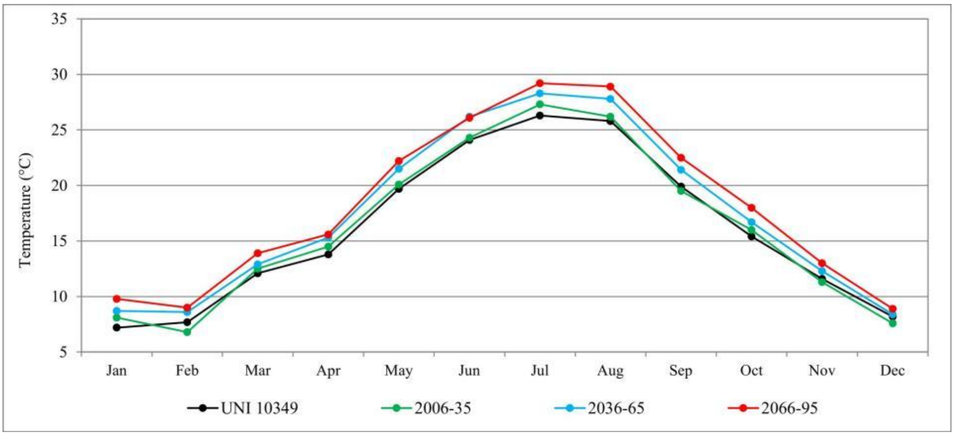
The European Climate Adaptation Platform website indicates that the average number of hot days combined with tropical nights categorizes the city of Florence as the most critical in terms of the annual number of discomforting thermal nights, with a value of 61.4 nights during the period 2002-2012 [12]. For the purpose of energy assessment, the baseline

climate data source used for the city of Florence is the Test Reference Year (TRY) reported in the UNI 10349:2016 standard [13], which is the official reference standard for monthly average climatic values for energy analysis. This standard is created from 2000-2009 hourly temperature data from the "Firenze Città" station [14], which is located in the historical city centre and thus influenced by the urban heat island effect. To preliminarily assess UHI effect these data were compared with those recorded at the Meteorological Station of the Italian Air Force at the Florence Peretola Airport (WMO code 161700), located at the extreme North-eastern periphery of the city [15]. Analysing seasonal average temperatures, the "Firenze Città" station is found to be warmer than "Firenze Peretola" in all seasons. Thus, we assumed that UHI effect is already included on the baseline weather data set used in this study. This is in line with the methodological approach of the present study aimed at assessing more effective energy retrofitting strategies compared to future climatic scenarios, in accordance with previous studies [16].
For future climatic scenarios (Figure 1), three reference periods have been considered: 2006-2035 (current and short term), 2036-2065 (medium term), and 2066-2095 (long term), together with two of the four Representative Concentration Pathways (RCP) scenarios developed in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) [17]:
- RCP 4.5, moderate climate-altering emissions (in terms of CO_2 equivalent) with a peak around 2040 and subsequent decrease and stabilization;
- RCP 8.5, high climate-altering emissions (in terms of CO_2 equivalent) increasing throughout the 22nd century.
The development of future weather data sets from the above-mentioned TRY has been carried out by means of the "morphing" method developed by Belcher et al. [18]. Baseline climate was processed shifting monthly mean dry bulb temperatures values on the base of temperature differences from 2006-2035, 2036-2065 and 2066-2095 projections of regional climate model (RCM) COSMO CLM. To this end average temperature differences from RCP 4.5 and RCP 8.5 RCM projections were used. COSMO CLM RCM was developed by the Euro-Mediterranean Centre on Climate Change (CMCC) with a high resolution grid (0.0715°) in order to downscale IPCC AR5 climate projections to the complex geo-climatic characteristics of the Mediterranean basin and the Italian peninsula. This approach is applicable to researchers, legislators, and planners, similar to what was developed by Jentsch M.F. et al. [19] in Great Britain.

2.2 Definition of Archetypes

Building archetypes for energy performance simulations were identified in previous studies [4,20,21] based on methodologies developed within the framework of the TABULA Project [22] and EPISCOPE [23]. In this paper only two typologies of identified archetype were analysed (types 1.1 and 2.3) since they represent the "limit" conditions among which the other case studies fall, potentially more critical given the expected temperature increase. The building and HVAC system characteristics of these two archetypes are listed in Table I.
For the case studies, in the survey of HVAC systems features it was not possible to detect the presence of summer air conditioning systems in detail. Therefore, in line with CRESME analyses [24] and data collection on the real case study, it was assumed to assign standard equipment for summer air conditioning to the archetype buildings. This standard equipment consists of "multi-split" systems consisting of reversible air-to-air heat pumps, given that the net energy needs for summer air conditioning in the analysed residential buildings need mechanical cooling systems to be met.
For the analysis of overall costs, the systems for summer air conditioning are considered to be installed for the first time at the beginning of the calculation period. Therefore, an

energy efficiency ratio (EER) of 3.4 was assigned to them, which is the minimum value established by national regulations for tax deductions for energy efficiency interventions [25].



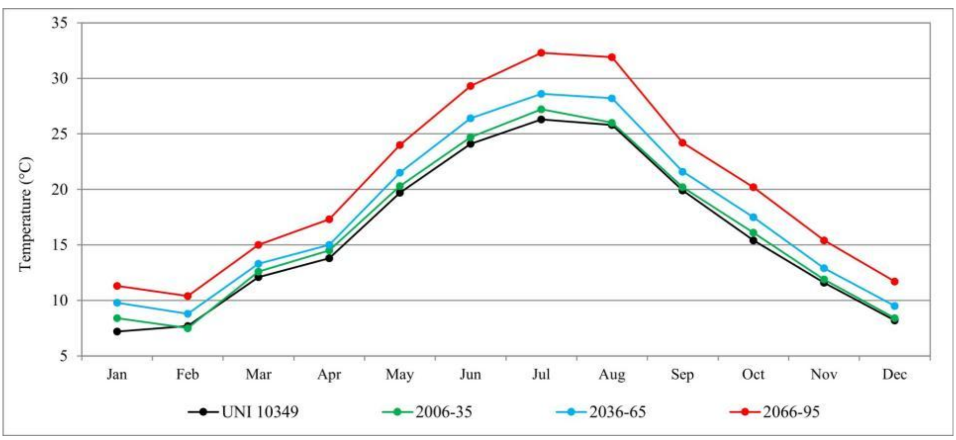
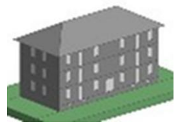


Fig. 1. Monthly average values of the air temperature of the city of Florence based on current and future climate files with RCP scenario 4.5 (up) and RCP 8.5 (down).

For technological elements characterized by a service life shorter than the calculation period or that need significant maintenance costs, it was necessary to determine replacement costs (C_{Rpl}) to be applied at the beginning and end of the service life, as well as annual maintenance costs (C_{ma}), as detailed below:

- The existing type B or C boiler is replaced with a similar one at the beginning of the calculation period and at the end of the service life, considering the following economic parameters: C_{Rpl}: 1500 €/apartment [28], C_{ma}: 30 €/(apartment*year) (2% of C_{Rpl}), service life: 20 years [29];
- The "multi-split" air conditioner is considered to be installed or replaced at the beginning of the calculation period, considering the following economic parameters: C_{inv}=C_{Rpl}: 6500 €/apartment [28]; C_{ma}: 130 €/(apartment*year) (2.0% of C_{inv}); service life: 20 years [29].

Table 2. Analysed archetypes description

	Archetype 1.1 (1946-1960)	Archetype 2.3 (1961-1977)
Typological features		
Geometric data	Number of apartments=6 A_n=496.2 m2; V_n=1488.6 m^3 S=1181.1 m2; V=1987.0 m^3 S/V=0.60 m-1; A_g=79.1 m^2 A_g/A_n=0.16	Number of apartments=16 A_n=1633.2 m2; V_n=4899.6 m^3 S=3130.1 m2; V=6201.9 m^3 S/V=0.50 m-1; A_g=286.4 m^2 A_g/A_n =0.18
Building technologies		
External walls	Solid brick and stone masonry - no insulation (40-50 cm) U=1.50-1.55 W/(m^2K) (MCO01) [26] - Light colour, α=0.3	Not insulated cavity wall with hollow bricks and semi-solid bricks (30 cm) U=1.10-1.25 W/(m^2K) (MCV01) [26] - Light colour, α=0,3
Stairwell wall	Solid brick masonry - no insulation (25–30 cm) U=1.60-1.80 W/(m^2K) (MLP01) [26]	Not insulated hollow bricks wall (12 cm) U=1.60 -1.80 W/(m^2K)
Slab between floors	Reinforced brick-concrete slab - no insulation (25 ÷ 30 cm) (SOL04) [26] Floor on not air-conditioned compartment U=1.30-1.40 W/(m^2K) Floor on outdoor space U=1.65–1.75 W/(m^2K) Ceiling on not air-conditioned compartment U= 1.65-1.75 W/(m^2K)	
Roof	Pitched roof with reinforced brick-concrete slab - no insulation U=1.40-1.60 W/(m^2K) (CIN04) [26] - Medium colour, α=0,6	
Floor on ground	Reinforced concrete floor U=2.20 W/(m^2K)	
Windows and shading systems	Double glazing-wooden frame (3-6-3) U_g=3.3 W/(m^2K), solar factor ($g_{gl,n}$) = 0.75, U_f= 2.1 W/(m^2K); PVC or wooden roller shutters, not insulated roller box U= 6,0 W/(m^2K) [36]	
Heating system		
Description	Autonomous traditional boiler with natural gas	
Heat generator technical features	Total heating power: 24 kW (P_n)-8kW (Pint), type B or C, with external or internal installation (combined production of domestic hot water). η_{gn} =0.84-0.92 (average value=0.88). Full load power of the auxiliaries generation system: 40W-200W depending on the type of boiler (average value =120W) [27, 37]	
Distribution	Separate distribution for each apartment (poor insulation or not insulated pipes). η_d=0,93 (ground floor on unheated compartments and ground)-0,99 (intermediate floor) [27, 37]	
Regulation	Zone thermostat (apartment) on-off. η_r = 0,93 [37]	
Emission	Radiators (70°C-60°C) placed on a not insulated external wall. η_e = 0,92. [37]	
Cooling system (recently installed)		
Description	Autonomous air-to-air heat pumps (multi-split) for cooling only	
Cooling system technical features	Total cooling power=6 kW. EER=3.4. Auxiliaries power of the generation system: 50W (1 room)-200W (1 apartment) [35]	
Distribution	The distribution losses are included in the production efficiency of the heat pump [35]	
Regulation	Control for single environment with modulating regulation (1 °C). η_r = 0,98 [35]	
Emission	Split-system with internal unit. η_e=0.97. Auxiliary power (internal unit fan): 200W [35]	
Ventilation	Natural ventilation by windows opening. n=0,3 vol/h [26]	

2.3 Definition of Energy Retrofit Strategies

The energy efficiency measures to be applied to the archetypes buildings were selected based on the analysis of documentation from the Italian National Agency for Energy Efficiency (ENEA) [30] concerning the distribution of energy retrofit interventions across the country, promoted and facilitated by the Italian government from 2014 to 2021. The most common retrofit strategies include the replacement of windows and the installation of condensing boilers, with a recent increase in the adoption of condensing boilers and, especially, heat pumps (hp). Data related to interventions promoted by the "Decreto Rilancio" [31] through SuperEcobonus until December 31, 2021, showed a significant use of deductions for opaque envelope thermal insulation and the installation of hybrid and heat pump systems supported by photovoltaic.

Tables 2 provides the performance characteristics, initial investment cost (C_{inv}), replacement cost (C_{Rpl}), maintenance cost (C_{ma}), and service life (sl) of the selected and analysed interventions. The costs considered are all-inclusive, covering technical expenses, labour, related works, and VAT, and were hypothesized based on surveys conducted by ENEA within the scope of Ecobonus interventions until 2021 (accompanying descriptive report of the draft Ministerial Decree on "Definition of maximum specific all-inclusive costs eligible for tax deductions for buildings").

Data regarding maintenance costs and the service life of individual energy efficiency measures refer to the technical standard UNI EN 15459-1:2018 [29]. Regarding external thermal insulation composite systems (ETICS), a lifespan of 30 years has been established, derived from considerations based on guidelines for the European Technical Assessment of ETICS [32], which specify a minimum period of 25 years for maintaining the system's performance. This aligns with studies reporting cases where insulation systems installed for even 40 years, with proper maintenance, still retain their performance [33]. Following the guidelines of the regulations on incentives for energy retrofitting of buildings [25], the limit values for thermal transmittance to unheated adjacent spaces were considered equal to those of surfaces dissipating heat outwards.

The above-mentioned energy efficiency measures have been applied by combining them according to criteria of opportunity aimed at developing mutual interactions that increase the positive effects of individual ones. In particular, the following scenarios have been analysed:

1 - (IE + SI) Insulation of the opaque envelope and replacement of windows;

2 - (IC) Installation of a hybrid system;

3 - (IC + FV) Installation of a hybrid system powered by photovoltaic;

4 - (IE + SI + IC) Insulation of the opaque envelope, replacement of windows, and installation of a hybrid system;

5 - (IE + SI + IC + FV) Insulation of the opaque envelope, replacement of windows, and installation of a hybrid system powered by photovoltaic.

For photovoltaic energy production, it is assumed that systems with 0.2 kWp per square meter of available roof area are used. Table III reports the peak powers of photovoltaic systems that can be installed on each analysed building type. The scheme applied for managing electricity from photovoltaic is that of a renewable energy self-consumption group, collectively operated by the condo’s tenants of the analysed building types and extendable to the renewable energy community.

Table 2. Analysed Energy Retrofit Strategies related to the building envelope (IE and SI) and to the building plant (IC and FV)

Acronym	Description	Costs	sl
IE	Insulation of the opaque envelope from the outside; $U \leq 0.26$ W/(m^{2}K)	$C_{inv} = C_{Rpl}$: 207 €/m^2 C_{ma} = 0 €/m2 year	30 years
	Roof slab towards not air-conditioned space; $U \leq 0.22$ W/(m^{2}K)	$C_{inv} = C_{Rpl}$: 112€/m^2 C_{ma} = 0 €/m2 year	
	Floor on outdoor or not air-conditioned space; $U \leq 0.28$ W/(m^{2}K)	$C_{inv} = C_{Rpl}$: 128€/m^2 C_{ma} = 0 €/m^2 year	
SI	Replacement of existing windows with new ones, including box insulation and roller shutter screen; $U \leq 1.67$W/(m^{2}K)	$C_{inv} = C_{Rpl}$: 892€/m^2 C_{ma} = 5 €/m^2 year (0.5% of C_{inv})	30 years
IC	Replacement of the winter and summer air conditioning system with system equipped with hybrid generator (air-water heat pump 6 kW + condensing boiler 24 kW) including replacement of current radiators with residential fan coils. COP hp ≥ 4.1; EER hp ≥ 3.8 Boiler efficiency, at 100% of the nominal useful heating power (P_n), ≥ 93 + 2 log (P_n)	Hybrid System (for each apartment) $Ci_{nv} = C_{Rpl}$: 6 x 2352 €/kW = 14112 € C_{ma} = 635 €/year (4.5% of C_{inv}) Fan coils (for each apartment) $C_{inv} = C_{Rpl}$: 6000 € C_{ma} = 240 €/year (4% of C_{inv})	20 years
FV	Installation of a grid connected photovoltaic system for each apartment	Photovoltaic system 2400 €/kWp	20 years

Table 3. Peak electrical power from photovoltaic that can be installed on the analysed archetypes.

Building	Available surface for each roof pitch (m^2)	Electrical peak power that can be installed (kWp)	Electrical peak power that can be installed for each apartment (kWp)
1.1	70 x 2 = 140	28	4.7
2.3	165 x 2 = 330	66	4.1

The tool used for energy analysis is the Edilclima EC 700 software version 12, by means of which the performance parameters of different technological configurations have been evaluated under semi-stationary conditions on a monthly calculation basis, in accordance with the provisions of the national reference technical standard UNI/TS 11300 series (validated by CTI certificate No. 73) [35-37]. This evaluation includes both a standard case (continuous use of the building systems) used for determining the standardized indicators listed in the paragraph 3, and an evaluation tailored to the users that takes into consideration an intermittent operation of the systems according to the calculation methodology of the [38] standard, used for consumption determination. The economic analysis of the interventions was carried out according to the methodology specified in the UNI EN 15459-1:2018 standard, taking into account some indications of EU Delegated Regulation No. 244/2012 and the accompanying guidelines. The indicators used for economic analysis are as follows:

- Global Cost, GC (€), which is the sum of the present value of initial investment costs, operating costs (maintenance and energy), replacement costs incurred during the calculation period, minus the residual value of initial investments at the end of the calculation period;
- Investment Payback Period, PB (years), which is the time after which the monetary savings achieved through the efficiency intervention offset the investment costs incurred during the useful life of the installed components.

3 Results and Discussion

3.1 Energy performance evaluation of the applied strategies

In this paragraph the results obtained for the analysed building types 1.1 and 2.3 of the Table I are reported. For each analysed energy efficiency strategy, the study results are reported using the following standardized regulatory-level energy demand indicators [34]:
- Energy class according to DM 26/6/2015 [39];
- Primary energy needs for heating, cooling, and domestic hot water, dividing renewable primary energy from non-renewable;
- Emissions of greenhouse gases (CO_2).

Since the calculation of these parameters is strictly regulated by laws and technical standards, their evaluation was conducted without considering possible future climatic variations or specific operating conditions of the HVAC system, such as shutdown or attenuation, as the reported parameters are calculated in accordance with standardized methodologies prescribed by the regulation itself.

Table 4 presents the results of the comparative analysis of the analysed strategies in terms of achievable energy class, non-renewable primary energy needs ($EP_{gl,nren}$), total primary energy needs ($EP_{gl,tot}$), and CO_2 emissions.

From the analysis of the data, it can be observed that all the hypothesized strategies lead to a clear improvement in the energy class and a corresponding reduction in non-renewable energy needs and CO_2 emissions. Building type 2.3 exhibits a lower total primary energy demand than building type 1.1 due to a significantly lower primary energy demand for heating, despite a slightly higher demand for primary energy for cooling. These differences are justified by the following building features:
- A smaller form factor (S/V) of building 2.3, resulting in a smaller dispersant surface compared to the habitable volume;
- Lower thermal transmittance of the building components of 2.3 compared to those of 1.1 due to the presence of air cavity in the external walls (cassette-type closures);
- A larger window surface area in building 2.3 compared to building 1.1, resulting in a greater amount of solar gains.

In Figure 2 and 3, the electricity and gas consumption associated with each intervention strategy are depicted for various future time periods, based on the intermediate climate change scenario between RCP 4.5 and RCP 8.5. It is necessary to consider that the standardized calculation required by law foresees that the portion of self-consumed photovoltaic electricity for the evaluated energy services in this research be determined on a monthly basis.

Table 4. Results of the analysis of efficiency strategies (energy class, non-renewable and total primary energy needs, and CO_2 emissions)

Building 1.1				
Efficiency strategy	Energy class	$EP_{gl,nren}$ (kWh/m^{2}year)	$EP_{gl,tot}$ (kWh/m^{2}year)	CO_2 emissions (kg/m^2)
No intervention	F	237.12	241.04	47.75
IE + SI	A1	74.25	78.29	15.37
IC	D	127.62	240.23	28.52

IC + FV	B	85.98	209.91	18.75
IE + SI + IC	A2	56.33	72.64	12.42
IE + SI + IC + FV	A4	24.07	49.14	4.85
Building 2.3				
No intervention	E	164.36	168.54	33.50
IE + SI	A1	61.30	65.53	12.89
IC	C	97.12	171.95	21.78
IC + FV	A1	62.41	146.66	13.59
IE + SI + IC	A2	49.06	60.05	10.85
IE + SI + IC + FV	A4	21.18	39.74	4.27

This calculation mechanism leads to an overestimate of self-consumed electricity since it does not account for the fact that, for example, part of the electric consumption for winter heating occurs during hours of the day when there is either no or very limited simultaneous photovoltaic electricity production. For this purpose, the calculation of net energy usage of electricity takes into account reduction coefficients that allow for a more accurate estimation of the proportion of electricity effectively self-consumed. With traditional systems, whether the building opaque envelope is insulated or not, electricity consumption is mainly due to summer air conditioning and increases with the increase of temperature rise compared to the reference climate. Conversely, for gas, consumption is primarily linked to winter heating. Thermal insulation of the building envelope results in a reduction of winter air conditioning consumption by approximately 3-5 times. On the other hand, summer consumption remains essentially in line with pre-intervention levels, except in the medium and long term when thermal insulation of the opaque envelope has a positive effect on reducing heat gains due to the high difference between the indoor and outdoor air temperature.

Replacing a traditional boiler system with a hybrid system allows for shifting consumption to electricity, enabling the utilization of the photovoltaic system. Moreover, the hybrid system, with the gradual increase in external winter temperatures, increases its efficiency, allowing the limitation of the use of the auxiliary generator (condensing boiler) to only domestic hot water production.

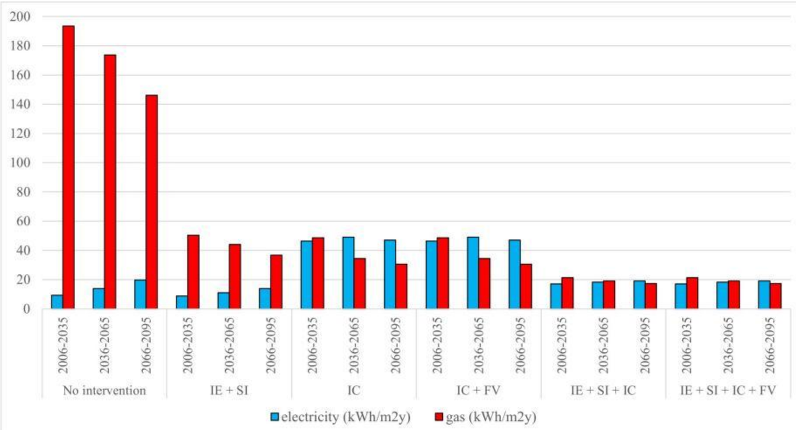


Fig. 2. Building 1.1 – Yearly electricity and gas consumption for each time period.

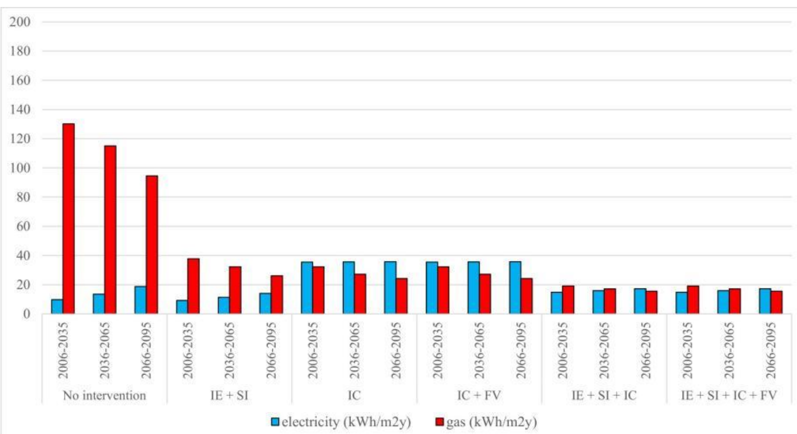


Fig. 3. Building 2.3 – Yearly electricity and gas consumption for each time period.

3.2. Economic evaluation of the applied strategies

Based on simulated consumption data, an economic assessment of the analysed efficiency strategies has been conducted. Table V provides the values of the global cost (GC) and payback period (PB) for each efficiency strategy, considering a maximum lifespan of 30 years (maximum life cycle of thermal insulation of opaque surfaces and windows). Due to difficult prediction of future trends of economic parameters, real discount rate (1%) and fuel prices (equal to inflation, 3%) were considered constant during cost-analysis calculation period. The economic evaluation was performed both without and with a hypothetical tax incentive in the form of income tax deduction spread over 10 annual instalments, covering 50% of the overall investment expense incurred. It is important to underline that the deduction was considered only for the initial investment expenses and, therefore, does not cover replacement expenses at the end of the life cycle of individual components.

Table 5. Economic evaluation of the applied efficiency strategies*

Building 1.1				
	without tax incentive		with tax incentive	
Efficiency strategy	GC (€/m^2) - service life of 30 years	PB (years)	GC (€/m^2) - service life of 30 years	PB (years)
No intervention	625	-	625	-
IE + SI	847	> 30	594	27
IC	774	> 30	659	15
IC + FV	895	> 30	716	18
IE + SI + IC	1082	> 30	714	> 30
IE + SI + IC + FV	1208	> 30	776	> 30
Building 2.3				
	without tax incentive		with tax incentive	
No intervention	463	-	463	-
IE + SI	726	> 30	504	> 30
IC	582	> 30	489	14
IC + FV	664	> 30	524	16
IE + SI + IC	902	> 30	587	> 30
IE + SI + IC + FV	987	> 30	626	> 30
* Real discount rate (1%) - Fuel prices (Equal to 3% as the inflation rate)				

The analysed energy retrofit interventions exhibit a total cost over 30 years (sum of annual cash flows discounted to present value) always higher than the scenario where no intervention is applied. Generally, interventions with the lowest overall cost in the absence of incentives are those with a lower initial outlay, specifically those involving only the replacement of systems. In the presence of incentives (tax deductions), even the envelope insulation intervention, which yields excellent energy savings, has a more contained overall cost, as tax deductions help to mitigate the impact of the costly initial investment.

The limited economic convenience of energy retrofit interventions is primarily due to the high investment costs required, which, in turn, result from the significant increase in costs incurred in construction and systems work in recent years. Only in cases where the initial cost is reduced (interventions involving only system replacement, possibly combined with the installation of photovoltaic panels) and is partially offset in the short term through the mechanism of tax deductions (hypothetically set here at a generic 50%), do we achieve payback periods of around 15 years, which are shorter than the service life of the components used. The effects of climate variations on the economic performance evaluation was taken into account since the yearly energy consumption values reported in Figures 2 and 3, that are the base for the 30 year (2025 -2055) economic analysis (Table 5), are calculated using future weather data sets.

4 Conclusions

In this work, some energies retrofit strategies and the related economic aspects were analysed and applied to two archetypes of residential buildings which are the extremes of a matrix representative of a large building stock to be energetically redeveloped. Regarding the determination of the energy consumption, these have also been assessed in relation to climate change scenarios and the effects of HVAC systems under attenuation and interruption regimes. The examined interventions in terms of economic sustainability highlight the following aspects:

- Thermal insulation interventions on the building opaque envelope are the most effective from an energy perspective as they reduce the energy demand at the source but entail investment costs that are currently not congruent with achievable savings. In this case, the presence of incentive mechanisms is necessary to recover part of the investment cost in subsequent years, hypothetically estimated at 50%;
- Interventions involving the replacement of traditional heat generators with high-efficiency ones (heat pumps) require lower investment costs but do not guarantee a net reduction in energy costs, also due to the high cost of electricity. In this case, it is desirable to integrate the installation of communal PV systems (through the mechanism of a self-consumption group collectively operated) that significantly reduce the energy bill through the economic flows resulting from the incentivization of shared energy (consumed by the heat pump during the same hours it is produced) and the paid sale of electricity fed into the grid. This second approach, if accompanied by fiscal incentive mechanisms, has reasonable payback periods.

Symbology

A_n	Net heated area, m^2
V_n	Net heated volume, m^3
S	Total dissipating area, m^2
V	Gross heated volume, m^3
A_g	Glazed area, m^2
U	Thermal transmittance, $W/(m^2\ K)$
U_g	Window glass thermal transmittance, $W/(m^2\ K)$
U_f	Window frame thermal transmittance, $W/(m^2\ K)$
$g_{gl,n}$	Solar factor, dimless
P_n	Nominal useful heating power, kW
P_{int}	Intermediate load heating power, kW
EER	Energy efficiency ratio, dimless
n	Air flow spare time, dimless
C_{Rpl}	Replacement costs, €/m^2
C_{ma}	Annual costs of maintenance, €/(m^2 year)
C_{inv}	Investment costs, €/m^2
COP	Coefficient of performance of the heat pump, dimless
$EP_{gl,nren}$	Non-renewable primary energy needs, kWh/(m^2 year)
$EP_{gl,tot}$	Total primary energy needs, kWh/(m^2 year)
GC	Global Cost, €/m^2
PB	Investment Payback Period, years
Greek symbols	
α	Absorption coefficient, dimless
η_{gn}	Generation efficiency, dimless
η_d	Distribution efficiency, dimless
η_r	Regulation efficiency, dimless
η_e	Emission efficiency, dimless

References

1. P. De Wilde, Coley D. The implications of a changing climate for buildings. Build. Environ., Implications of a Changing Climate for Buildings **55**, 1–7 (2012). https://doi:10.1016/j.buildenv.2012.03.014
2. A. Revi, D.E. Satterthwaite, f. Aragón-Durand, j. Corfee-Morlot, R.B.R Kiunsi, m. Pelling, D.C. Roberts, W. Solecki. Urban areas, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535–612, 2014)
3. R.S. Kovats, R. Valentini, L.M. Bouwer, E. Georgopoulou, D. Jacob, E. Martin, M. Rounsevell, J.F. Soussana. In: V.R. Barros, C.BField, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, White L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267–1326, 2014)
4. L. Pierangioli, G. Cellai, R. Ferrise, G. Trombi, M. Bindi. Effectiveness of passive measures against climate change: Case studies in Central Italy. Build. Simul. **10**, 459–479, (2017). https://doi.org/10.1007/s12273-016-0346-8
5. M. Almeida, M. Ferreira. IEA EBC Annex56 Vision for Cost Effective Energy and Carbon Emissions Optimization in Building Renovation. Energy Procedia, 6th International Building Physics Conference, IBPC 2015 **78**, 2409–2414 (2015). https://doi:10.1016/j.egypro.2015.11.206
6. M. Almeida, A. Bencresciuto, M. Ferreira, A. Rodrigues. Cost-effective Energy and Carbon Emission Optimization in Building Renovation – A Case-Study in a Low Income Neighbourhood. Energy Procedia, 6th International Building Physics Conference, IBPC 2015 **78**, 2403–2408 (2015). https://doi:10.1016/j.egypro.2015.11.203
7. S. Ferrari, F. Zagarella. Costs Assessment for Building Renovation Cost-optimal Analysis. Energy Procedia, 6th International Building Physics Conference, IBPC 2015 **78**, 2378–2384 (2015). https://doi:10.1016/j.egypro.2015.11.193
8. European Parliament. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (2018)
9. A. Acocella. L'edilizia residenziale pubblica in Italia dal 1945 ad oggi, Problemi e tendenze dell'architettura contemporanea. (Published by CEDAM, Padova 1980)
10. P.G. Bardelli, R. Capomolla, R. Vittorini. L'architettura INA casa (1949-1963): aspetti e problemi di conservazione e recupero, Architettura e costruzione 2. (Published by Gangemi, Roma 2003)
11. F. Nuti. Tre quartieri INA-casa in Toscana. (Published by Polistampa, Firenze 2004)
12. European Climate Adaptatation Platform. . Urban vulnerability Map book - Climatic threats - Heat waves - Exposure [WWW Document] (2016). URL http://climate-adapt.eea.europa.eu/tools/urban-adaptation/climatic-threats/heat-waves/exposure
13. UNI. 2016a. UNI 10349-1 Standard. Riscaldamento e raffrescamento degli edifici - Dati climatici - Parte 1: Medie mensili per la valutazione della prestazione termo-energetica dell'edificio e metodi per ripartire l'irradianza solare nella frazione diretta e

diffusa e per calcolare l'irradianza solare su di una superficie inclinata. (Milano: Italian Organization for Standardization, 2016)
14. Servizio Agrometereologico Regione Toscana. Consultazione archivi storici (1990-2010) [WWW Document] (2015). URL http://agrometeo.arsia.toscana.it
15. ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale. SCIA - Sistema nazionale per la raccolta, l'elaborazione e la diffusione di dati Climatici di Interesse Ambientale [WWW Document] (2015). URL http://www.scia.isprambiente.it/home_new.asp
16. T. Berger, C. Amann, H. Formayer, A. Korjenic, B. Pospichal, C. Neururer, R. Smutny. Impacts of urban location and climate change upon energy demand of office buildings in Vienna, Austria. Build. Environ. 81, 258–269 (2014). https://doi.org/10.1016/j.buildenv.2014.07.007
17. U. Cubasch, D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, J.G. Winther. Introduction, In: T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013)
18. S.E. Belcher, J.N. Hacker, D.S. Powell. Constructing design weather data for future climates. Building Services Engineering Research and Technology 26, 49–61 (2005). https://doi.org/10.1191/0143624405bt112oa
19. M.F. Jentsch, P.A.B. James, L. Bourikas, A.S Bahaj. Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. Renew. Energy 55, 514–524 (2013). doi:10.1016/j.renene.2012.12.049
20. L Pierangioli. Effetti dei cambiamenti climatici sulle prestazioni energetiche degli edifici residenziali in clima Mediterraneo. Il caso del patrimonio residenziale pubblico INA-Casa e Gescal della Toscana. (Università degli Studi di Firenze, 2016)
21. L. Pierangioli, C. Carletti, G. Cellai, F. Sciurpi. Energy refurbishment of social housing stock in Italy: Analysis of some scenarios from the impact of climate change to occupant behaviour. Building Simulation Applications, February, pp. 257-264 (2017)
22. Institut Wohnen und Umwelt GmbH. IEE Project TABULA (2009 - 2012) [WWW Document] (2016). URL http://episcope.eu/iee-project/tabula/
23. Institut Wohnen und Umwelt GmbH. IEE Project "EPISCOPE" [WWW Document] (2016). URL http://episcope.eu/iee-project/episcope/
24. F. Toso, A. Mura. Analisi della dotazione impiantistica di climatizzazione (estiva ed invernale) del patrimonio edilizio ad uso residenziale e terziario e valutazione dell'impatto economico in relazione a misure di politiche energetiche e ambientali finalizzate a incidere sensibilmente sull'efficienza negli usi finali e alla promozione di fonti di energia rinnovabile - Report RdS/PAR2014/ 06. (ENEA, Roma, 2014)
25. DM 6/8/2020 "Requisiti tecnici per l'accesso alle detrazioni fiscali per la riqualificazione energetica degli edifici - cd. Ecobonus" (GU Serie Generale n.246 05-10-2020)
26. UNI. 2014c. UNI/TR 11552 Standard. Abaco delle strutture costituenti l'involucro opaco degli edifici. Parametri termofisici. Milano: Italian Organization for Standardization
27. Corrado V., Ballarini I., Corgnati S.P. 2014. Building Typology Brochure – Italy
28. DEI. 2022. Prezzi informativi dell'edilizia – Impianti tecnologici 2° semestre 2022. (DEI Tipografia del Genio Civile, Roma, 2022)

29. UNI. 2018. UNI EN 15459-1 Standard. Prestazione energetica degli edifici - Sistemi di riscaldamento e sistemi di raffrescamento idronici negli edifici - Parte 1: Procedura di valutazione economica per i sistemi energetici negli edifici, Modulo M1-14.(Milano: Italian Organization for Standardization, 2018)
30. ENEA - Agenzia nazionale efficienza energetica. Rapporto annuale detrazioni fiscali - Le detrazioni fiscali per l'efficienza energetica e l'utilizzo delle fonti rinnovabili di energia negli edifici esistenti. https://www.efficienzaenergetica.enea.it/pubblicazioni/rapporto-annuale-detrazioni-fiscali.html (2022)
31. Decreto Rilancio del 19 maggio 2020, n. 34, coordinato con la legge di conversione 17 luglio 2020, n. 77, «Misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonché di politiche sociali connesse all'emergenza epidemiologica da COVID-19» (GU n.189 del 29.07.2020 - Suppl. Ordinario n. 26)
32. EOTA - European Organisation for Technical Assessment. 040083-00-0404 - External thermal insulation composite systems (ETICS) with renderings. EOTA (2019)
33. K. Lengsfeld, M. Kru., Hartwig Künzel, Helmut Künzel. Beurteilung des Langzeitverhaltens ausgeführter Wärmedämmverbundsysteme. IBP-Mitt. 539 (2015)
34. D. Lgs. 192/2005 "Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia". (GU n. 222 del 23 settembre 2005 - suppl. ord. n. 158)
35. UNI. 2010. UNI/TS 11300-3 Standard. Prestazioni energetiche degli edifici. Parte 3: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione estiva. (Milano: Italian Organization for Standardization, 2010)
36. UNI. 2014a. UNI/TS 11300 Standard. Prestazioni energetiche degli edifici. Parte 1: Determinazione del fabbisogno di energia termica per la climatizzazione invernale ed estiva. (Milano: Italian Organization for Standardization, 2014)
37. UNI. 2014b. UNI/TS 11300-2 Standard. Prestazioni energetiche degli edifici. Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazione in edifici non residenziali. (Milano: Italian Organization for Standardization, 2014)
38. UNI EN ISO 52016-1:2018. Prestazione energetica degli edifici - Fabbisogni energetici per riscaldamento e raffrescamento, temperature interne e carichi termici sensibili e latenti - Parte 1: Procedure di calcolo. (Milano: Italian Organization for Standardization, 2018)
39. DM 26/6/2015 "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici"