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Abstract

The EU Member States are being involved to develop long-term strategies and to promote investments aimed at improving the energy efficiency of the building stock, at increasing the use of Renewable Energy Sources (RES) and at growing the number of Nearly Zero-Energy Buildings (NZEBs). The aim of this article is to investigate energy and economic implications related to the exploitation of RES in the transformation of an Italian social housing building-type into a NZEB. The research is based on a detailed energy audit procedure that includes cost-optimal assessment and compliance check with the legal requirements. A parametric analysis was performed to find out the technical building system configurations that verify the minimum share of RES established by the Italian regulations, and at the same time to assess global cost and payback period. The intersection between legal compliancy and cost-effectiveness narrows the field of applicable RES technologies that are limited to electric heat pump for heating and cooling coupled with PV system, and low size solar collectors coupled with low temperature generator for domestic hot water. Improvements in the energy policy are necessary to guarantee the best trade-off between RES exploitation, energy efficiency and costs, as to preserve market equilibrium.

Keywords: building energy refurbishment; nearly zero-energy building; energy performance requirements; renewable energy share; cost-optimality; renewable energy policy.

Nomenclature

Quantities		
A	area	m^2
C	cost	€
c	specific cost, per unit of power or area	$€\cdot kW^{-1}$, $€\cdot m^{-2}$
COP	coefficient of performance	-
EER	energy efficiency ratio	-
EP	energy performance (indicator)	$kWh\cdot m^{-2}$
f	factor, coefficient	-
GC	global cost	$€\cdot m^{-2}$
H'	mean overall heat transfer coefficient	$W\cdot m^{-2}K^{-1}$
HDD	heating degree days	°C·d
P	power	kW
PB	payback period	a
RER	renewable energy ratio	%
U	thermal transmittance	$W\cdot m^{-2}K^{-1}$
V	volume	m^3
VAT	value-added tax	-
Greek symbols		
η	efficiency	-
τ	transmission coefficient	-

Subscripts			
C	space cooling	P	primary (energy)
coll	collector	PV	photovoltaic (system)
env	envelope	rec	recovery (heat)
f, fl	floor	ren	renewable (energy)
g	gross	sol	solar
gl	global	sum	summer
gn	generator	T	thermal transmission
H	space heating	tot	total
lo	lower	up	upper
nd	need (energy)	W	domestic hot water
nren	non-renewable (energy)	w	window

Acronyms	
CTEPA	Calibrated Tailored Energy Performance Assessment
DHW	Domestic Hot Water
EEM	Energy Efficiency Measure
EEO	Energy Efficiency Option
EP	Energy Performance
EU	European Union
HVAC	Heating Ventilation Air Conditioning
LT	Low Temperature
MV	Mechanical Ventilation
NV	Natural Ventilation
NZEB	Nearly Zero-Energy Building
OEPA	Operational Energy Performance Assessment
RES	Renewable Energy Sources
SEPA	Standard Energy Performance Assessment
TEPA	Tailored Energy Performance Assessment

1. Introduction

1.1 Towards an effective renovation of the existing building stock

The existing building stock accounted for 42% of final energy consumption and 17% CO_2 emissions from fuel combustion in 2017 in Europe. Specifically, the residential sector is responsible of 65% final energy consumption and 71% CO_2 emissions of the European overall building sector. The share of Renewable Energy Sources (RES) on the gross final energy consumption for heating and cooling grew up from 11% in 2005 to 19.5% in 2017. In Europe, the electricity production from RES increased from 15% in 2005 to 31% in 2017 [1].

Since 2007, the European Union (EU) has been adopting a strong policy to reduce the energy consumption and to improve the overall energy savings. The Energy and Climate Policy Framework for 2030 [2] establishes ambitious EU commitments to reduce greenhouse gas emissions by at least 40% as compared with 1990, to increase the share of renewable energy on the final consumption, to increment energy efficiency, and to improve energy security, competitiveness and sustainability. The goals for renewables and energy efficiency were then revised upwards in 2018. In 2015, Paris Agreement on climate change [3] following the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) has enhanced the decarbonisation of the building stock, by renovating the existing buildings characterised by low energy performance, giving priority to energy efficiency and considering the deployment of renewables.

The recently issued Directive 2018/844 [4], which amends Directive 2010/31/EU [5], requires that each Member State establishes a long-term strategy and promotes investments aimed at improving the energy efficiency of the existing residential and non-residential, either public and private, building stocks, as to reach decarbonised and high energy-efficiency building stocks within 2050. Likewise, a cost-effective transformation of the existing buildings into Nearly Zero-Energy Buildings (NZEBs) should be facilitated.

As pointed out by Zeiler and Boxem [6], the design and construction of low-energy buildings require totally different approach from conventional buildings, as both advantages and disadvantages can arise in NZEBs. Within this framework, many researches investigate the role of renewable energy sources as fundamental aspect in reaching high performance level of NZEBs, as effectively demonstrated in the certification process carried out by Dall'O' et al. [7]. At a community level, multiple decision criteria are needed to select the most viable RES technologies, as pointed out by Karunathilake et al. [8]. In addition, RES allow multiple uses as demonstrated by Barone et al. [9], who included both buildings and transport in the energy balance at a district level. Anyway, the implementation rate of RES in buildings is still slow mainly due to economic issues. Policies have been established in European countries to support the exploitation of renewable energy sources through incentives. For instance, United Kingdom introduced the Renewable Heat Incentive (RHI) [10], while in Italy, the so called "Thermal Account" supports small-scale renewable energy sources of heat, including solar thermal, heat pumps and biomass as well as envelope insulation measures [11]. In many countries, the current promotion mechanism for electricity produced by RES trusts on feed-in tariffs, as well described by Tükenmez and Demireli [12] for Turkey. In addition, the Energy Performance Contracting represents an effective initiative to support the installation of technologies using RES, as also demonstrated in the work of Frangou et al. [13].

As it emerges in recent scientific literature, the investigation of economic aspects related to RES is today a key point of interest. In the analysis of Petersen and Svendsen [14], a simplified and transparent economic optimisation method was presented with the aim to be used at initial design process of low-energy buildings. In the work of Jo et al. [15], a parametric analysis was carried out to identify cost-optimal solutions to deploy photovoltaic systems taking into account different finance scenarios. Marszal et al. [16] developed a life cycle cost analysis considering different renewable energy supply options to design a cost-optimal Net ZEB in Denmark; the cost-optimal combination between energy efficiency and renewable energy generation was found out. The research of Mateus et al. [17] focused on the environmental and life cycle costs of different energy renovation scenarios, specifically addressed to the use of solar systems in a transformation of a detached single-family house into a NZEB in Portugal; the authors pointed out the need of raising awareness in building owners through the life cycle benefits that solar systems have at environmental and economic levels. A study performed by Sadineni et al. [18] in the USA was aimed to find out the cost-benefits of various energy efficiency measures as to develop an economically feasible energy efficiency refund program to be offered to consumers and home-owners by the electric utility.

As the interest in cost-optimal analysis for the renovation of existing buildings into NZEBs is still increasing and several methodologies are proposed in literature, the accuracy of the most common procedures for the assessment of the energy performances of buildings is investigated and new tools or methods are developed, as in the works of Dalla Mora et al. [19] and Ascione et al. [20]. Despite the use of effective assessment methodologies, a still open issue concerns the verification of NZEB minimum energy performance requirements established by national energy policies, specifically with reference to the minimum RES share required and the cost-effectiveness of the renovation process.

In most of European countries, the energy performance targets for nearly zero-energy buildings generally refer to limit values of primary energy, building envelope thermal transmittance, heating and cooling energy needs, CO_2 emissions. Most countries require a minimum renewable energy share of the primary energy use that usually varies among countries and in some cases is higher than 50%. About one third of the countries have only indirect obligations on RES; the maximum value of primary energy use has to be verified and it is required, to be covered by "very significant extent of renewable energy" [21]. Municipalities in the European Member States have started to design and construct pilot projects of public NZEBs when obligation for new public buildings was approaching (Directive 2010/31/EU [5]). In 2016, the uptake of NZEBs in Europe (EU28 level) was about 20% of total number of buildings newly constructed and renovated. Anyway, nearly zero-energy standards are preferably applied to newly constructed buildings: on EU28 level, 27% times more new buildings are constructed in nearly zero-energy buildings standard than renovated buildings [22]. One of the main barriers to the early application of the NZEB level in Europe is the considerably higher investment cost, as pointed out in the study of Erhorn-Kluttig et al. [23].

Data collected on the first realised NZEBs in Europe – above all educational buildings – show that the majority of pilot cases present very low *U*-values (0.16 $W \cdot m^{-2}K^{-1}$ on average for walls), heat pumps, mechanical ventilation with heat recovery and PV systems. These projects reached ambitious energy performance targets, but were not cost-effective. The documented additional costs compared to conventional new educational buildings are on average very high (603 $€ \cdot m^{-2}$ floor area) [24].

On this matter, in case of major renovation of an existing building, recent studies found out that the energy efficiency measures able to guarantee total compliance with the requirements fixed by national regulations are not cost-optimal configurations. This is the case of Italy, in which a study conducted by Ferrari and Romeo [25] demonstrated that the retrofit measures of a school building chosen to meet the NZEB requirements led to very high payback periods (up to 26 years). In addition, the authors pointed out that the adoption of solar shading devices, required by the Italian energy regulations, was revealed inconsistent and cost-ineffective. Likewise, a research of Corrado et al. [26], aimed at identifying cost-optimal configurations of energy efficiency measures, demonstrated that these configurations do not guarantee total compliance with the NZEB requirements set by the national legislation, above all those that concern the RES share.

1.2 The requirements of nearly zero-energy buildings in Italy

The Italian building stock amounts to 14.5 million buildings, of which 84% are residential. About 26% of residential buildings were built before the Second World War, about 60% was built between 1945 and 1990, while only the remaining 14% was built after 1991 [27]. To be noted that more than 60% of Italian residential buildings were built before the issue of the first law on energy saving in 1976. The potential of energy savings is high, not only for uninsulated buildings but also for those buildings that, despite being constructed after 1976 and presenting a discrete level of thermal insulation, have high heat losses due to thermal bridges and related mould problems in indoor spaces. Examples of these buildings are the social housing buildings that were designed in periods of housing emergency, when the use of cheap materials and very rapid construction processes were often needed.

The Italian National Energy Strategy of 2017 [28] recently established a programme to meet the European Energy and Climate Policy Framework goals by 2030, aiming for industrial leadership to exploit the great international growth of efficient technologies. Currently, the main Italian regulations in terms of building energy efficiency are

Legislative Decree (Lgs. D.) 192/2005 [29] and subsequent amendments, which transposes Directive 2010/31/EU [5], and Lgs. D. 28/2011 [30], which transposes Directive 2009/28/EC [31] on the use of renewable energy sources. The main objective of Lgs. D. 192/2005 is to promote the improvement of the energy performance (EP) of buildings taking into account climatic external conditions, as well as indoor climate requirements and cost effectiveness. Among the implementing regulations, the Interministerial Decree (Interm. D.) 26 June 2015 [32] specifies the application of EP minimum requirements of buildings and the use of renewable energy sources, the latter also governed by Lgs. D. 28/2011.

For major renovations of existing buildings (i.e. refurbishment that affects more than 50% of the building envelope surface and includes the renovation of the HVAC system) and their transformation into NZEBs, the Interm. D. 26 June 2015 [32] requires compliance of:

- the limit values of the mean overall heat transfer coefficient by thermal transmission (H'_{T}, in $W \cdot m^{-2}K^{-1}$) and of the summer solar effective collecting area of the building per unit of useful floor area ($A_{sol,sum}/A_{fl}$),
- the annual energy needs for space heating and space cooling divided by the building conditioned net floor area ($EP_{H,nd}$ and $EP_{C,nd}$, respectively), and the overall annual total primary energy divided by the conditioned net floor area ($EP_{gl,tot}$), both determined with the use of the reference building [33],
- the mean overall seasonal efficiencies of the heating system, of the cooling system and of the domestic hot water system (η_{H}, η_{C} and η_{W}, respectively), determined with the use of the reference building [33],
- the use of renewable energy sources to cover a share of the building energy consumption.

As far as the renewable energy use is concerned [30], the obligations for NZEBs are listed as follows:

- a minimum share of RES (i.e. Renewable Energy Ratio, *RER*) for heating, cooling and domestic hot water production (RER_{H+C+W}) equal to 50%,
- a minimum share of RES (i.e. Renewable Energy Ratio, *RER*) for domestic hot water production (RER_{W}) equal to 50%, and
- a minimum electrical power of a system fed by RES equal to 1/50 of the building footprint.

Legislative Decree 28/2011 [30] specifies that the above listed obligations cannot be fulfilled through plants fed by RES that exclusively produce electricity which, in turn, supplies devices or systems for the production of domestic hot water, heating and cooling through Joule effect. In addition, for public buildings, the above listed requirements must be increased by 10%.

The number of realised NZEBs in Italy is still low. In June 2018, the percentage of NZEBs did not exceed 0.03% of the existing building stock on a regional basis. Most of the pilot cases are new constructions (90%) and are residential buildings (85%). Some of the latter are retrofitted social houses. The existing buildings retrofitted as NZEBs are usually public buildings (above all schools). All these buildings reached and even overcame the EP targets for NZEBs fixed by the Italian legislation, but the realisation costs were very high for a renovation (about 1400-1600 €·m^{-2}) and all projects got access to substantial incentives [34].

As also highlighted in Section 1.1, recent studies underlined situations in which it is difficult to comply with all the minimum energy performance requirements set by current legislation, because some requirements either cause cost-ineffective building renovation [25, 26] or reflect opposing needs [35]. Thus, further research is needed to improve regulations, above all as regards the share of renewable energy sources on the overall energy consumption of the NZEB with a view to economic implications.

1.3 Aim of the research

The present research is aimed at investigating the technical building system technologies and related performance parameters that allow to verify the minimum energy performance requirements set by Italian regulations and to guarantee a cost-effective building transformation into NZEB at the same time. This study explores the conditions in which the fulfilment of the EP requirements and of the RES share determine a significant variation of the global cost and the payback period of different energy efficiency measures applied in the building renovation.

The analysis is based on a methodology developed in a previous work [36], in which a detailed energy audit procedure was set up. The procedure includes building model calibration, explores several configurations of energy refurbishment interventions, detects the cost-optimal package of energy efficiency measures (EEMs) and allows to check the compliance with the minimum energy performance requirements. In case of non-fulfilment of the requirements, in the last step, the methodology provides for the identification of other EEMs that allows to verify the regulations and calculates the economic parameters.

In the present work, the methodology has been extended, by adding a parametric analysis to the last step. Starting from a unique configuration of EEMs that complies with the NZEB requirements of the building envelope components, the parametric analysis explores different technical building system configurations, including RES technologies, with a wide range of system sizes and efficiency parameters.

The methodology was applied to a social house located in Torino (Northern Italy) that can be considered representative of the Italian social housing category built in the period 1980-1990. The choice to select this building category for a NZEB renovation is due to the high energy saving potential that it offers, as also pointed out in Section 1.2.

The present article addresses socio-economic and policy issues related to the renewable energy exploitation in the building sector. To overcome the research gap identified in the literature review (Section 1.1), this work is going to answer to the following research questions:

- what technical building systems and technologies using RES can allow the NZEB requirements to be verified and, at the same time, can lead to the lowest global cost in the building economic lifecycle?
- what is the sensitivity of the economic parameters, such as the global cost and the payback period, to the increase of the Renewable Energy Ratio (*RER*) in a building renovated and transformed into a NZEB?
- what recommendations can be addressed to the improvement of the energy policy towards both the promotion of the use of RES and the cost-effectiveness of building renovations?

The article has been structured as follows: Section 2 provides the methodology, with the description of the energy audit procedure and the parametric analysis, Section 3 presents the case study, the selected energy efficiency measures for the building renovation and the calculation and modelling assumptions, Section 4 deals with the results, and Section 5 provides the discussion of the main findings.

2. Methods

A case-study approach was used to facilitate the achievement of the research goals. The methodology applied is based on a first phase, consisting of a detailed energy audit (Section 2.1) of the case study, and a second phase in which an extensive parametric analysis to the technical building systems (Section 2.2) is performed. The energy audit of the case study was performed in a previous work [36]; the results of the energy audit are the basis for the parametric analysis which was carried out in the present work to address the research questions.

2.1 Building energy audit procedure

A detailed energy audit was performed in accordance with EN 16247 parts 1-3 [37-39] technical standards, following the procedure shown in the flowchart in Figure 1, as described by Corrado et al. [26].

The procedure is composed of two main steps, the pre- and the post-retrofit phase respectively. Depending on the purpose of the specific evaluation, for each phase energy ratings are performed (white boxes in Figure 1), considering different types of user and climate profiles (actual or standard). In the pre-retrofit phase, the building is analysed in its current state and two different energy performance assessments are performed: the Operational Energy Performance Assessment (OEPA) and the Tailored Energy Performance Assessment (TEPA), as defined in EN ISO 52000-1 [40]. The former refers to the detailed analysis of the actual building energy consumptions, while the latter consists in the estimated building energy performance calculation, adopting the actual climatic data and users' behaviour. In [36], the

TEPA was carried out by means of a detailed dynamic simulation, using EnergyPlus [41], as implemented in the DesignBuilder software [42]. The aim of the pre-retrofit phase is to have a reliable building model. For this reason, the results of the two energy performance assessments (OEPA and TEPA) are then compared to perform the building energy model calibration according to ASHRAE Guideline 14 [43]. Starting from the calibrated model, a further energy assessment step is performed, defined as Calibrated Tailored Energy Performance Assessment (CTEPA) and characterised by actual user data and standard climatic data. The use of standard climatic data makes the subsequent analysis independent from specific climatic conditions.

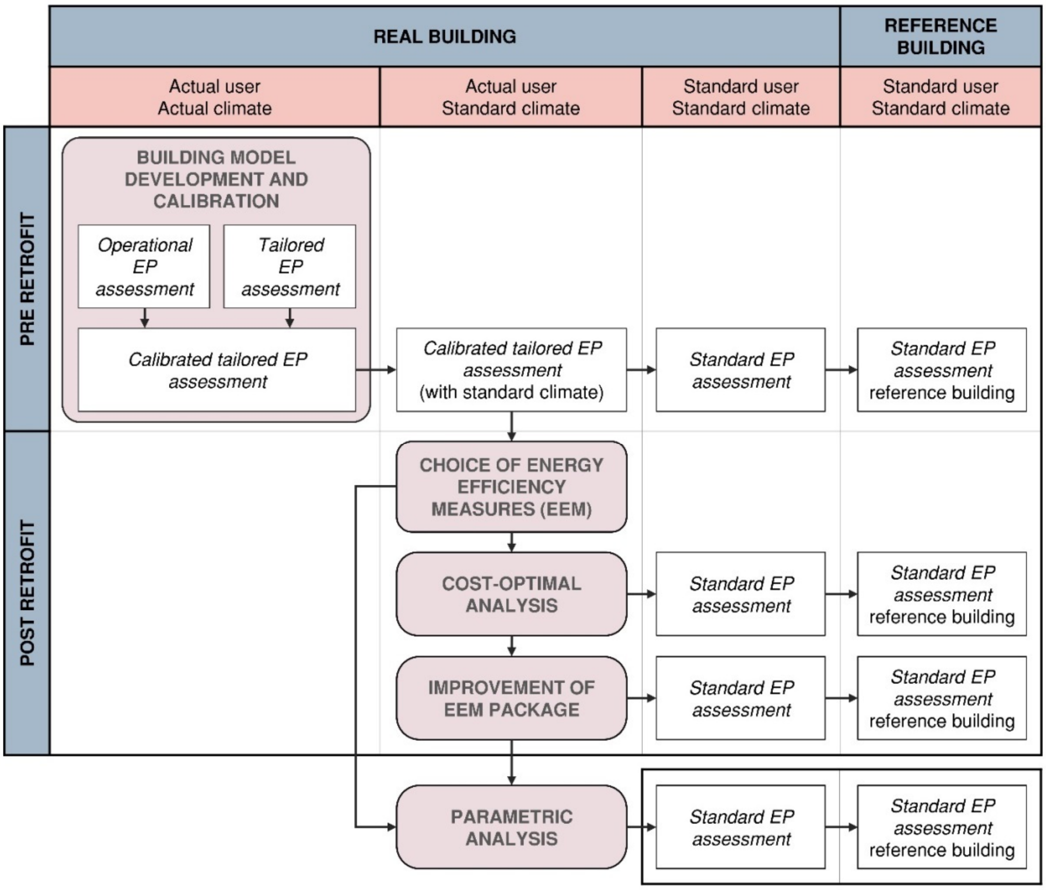


Figure 1: Detailed energy audit procedure.

Once defined the CTEPA, the post-retrofit phase includes the choice of the energy efficiency measures (EEMs), and the relative energy efficiency options or levels (EEOs), to be tested on the building and the evaluation of their energy performance and economic impacts. The EEMs considered are those selected by the Italian Ministry of Economic Development, in applying the comparative methodology to identify cost-optimal levels of energy performance requirements for buildings [44]. The cost-optimal analysis is based on the global cost calculation, as specified by the EN 15459 technical standard [45], and consists in the identification of the package of energy efficiency measures that guarantee the lowest global cost in the building lifetime. The identification of the *cost-optimal* package was carried out in [36] by means of a sequential search-optimisation technique, based on the optimisation algorithm NSGA-II (Elitist Non-Dominated Sorting Genetic Algorithm), as described in Corrado et al. [46]. Lastly, the energy performance class and the compliance with the minimum energy performance requirements is assessed through a Standard Energy Performance Assessment (SEPA) for all the considered configurations: the CTEPA (pre-retrofit), the *cost-optimal* package and the further EEM package improvements. The SEPA is performed by applying the reference building approach, in compliance with Interm. D. 26 June 2015 [32], considering standard user and climate.

2.2 Parametric analysis on the use of energy from renewable sources

Compared to the procedure presented in Section 2.1, an additional phase has been introduced in the present work (lower part of the flowchart in Figure 1). It consists in a parametric analysis of different technical building system configurations, focusing on the use of renewable energy sources, and the assessment of their economic implications.

Before performing the parametric analysis, the compliance with the minimum NZEB energy requirements referred to the building envelope (requested by Interm. D. 26 June 2015 [32]) was verified for the *cost-optimal* configuration. To fulfil the NZEB requirements, an EEM package improvement (from now referred as *reference case*), consisting of a minimum level of thermal insulation and solar shadings, was introduced. The *reference case* is thus characterised by the NZEB building envelope and the technical building systems of the building before the refurbishment. Afterwards, the parametric analysis of the energy efficiency measures identified in Section 2.1 and related to the technical building systems is carried out, starting from the *reference case* configuration. One for each EEM, all the combinations of energy efficiency options (EEOs) are tested, and the building energy performance and the economic implications are assessed. As for as the former, the overall non-renewable primary energy ($EP_{\mathrm{gl,nren}}$), and the Renewable Energy Ratio for domestic hot water production (RER_{W}) and for space heating, cooling and domestic hot water production ($RER_{\mathrm{H+C+W}}$) are calculated. The economic implications are instead evaluated through the actualised global cost (GC) and payback period (PB). The compliance with the minimum energy performance requirements for the NZEB is assessed for each combination analysed.

The calculation methods applied within the parametric analysis are those indicated by the National application of Directive 2010/31/EU [32], i.e. the *quasi-steady state* method for the building energy performance assessment (UNI/TS 11300 parts 1-5 technical standards [47-51]) and the EN 15459 technical standard [45] for the economic evaluations.

3. Material

3.1 Case study

The selected case study (Figure 2) is a social housing building, located in the suburbs of Torino (Northern Italy), in the climatic zone E (2100 °C·d < HDD ≤ 3000 °C·d, assuming 20 °C as indoor air temperature [52]), and was built between the end of the eighties and the beginning of the nineties. This building is representative of many buildings that present hygrothermal critical issues (such as discontinuity of the insulating layer, mould problems in correspondence of thermal bridges, etc.), although they were built after the first laws on energy saving. The building hosts 30 apartments and is composed of five above ground conditioned storeys and one unconditioned attic floor. The geometrical characteristics of the building are reported in Table 1.

Figure 2: Visualisation of the building.

Table 1: Main geometrical data of the building.

Characteristic	Symbol	M.U.	Value
Gross heated volume	V_g	m^3	7641
Net floor surface	A_f	m^2	2103
Envelope surface	A_{env}	m^2	3608
Building compactness ratio	A_{env}/V_g	m^{-1}	0.47

The building is characterised by a load-bearing structure made up of reinforced concrete pillars, coupled with external cavity wall (with a thermal transmittance of 0.45 $W{\cdot}m^{-2}K^{-1}$). The lower floor of the building is a slab on grade, while part of the floor between the first and second floor above ground is exposed to the external environment.

Each apartment is served by an individual system for the combined heating and domestic hot water production with methane gas fuelled boilers, characterised by a useful thermal power of 23 kW and a declared useful efficiency of 0.914. The emission system is characterised by radiators (installed on the internal walls), while the control of the heating system is managed by a room thermostat.

For the energy audit presented in Section 2.1, the actual user behaviour regarding internal heat gains, natural ventilation and shading devices operation were derived from extensive in situ surveys. The model calibration, developed in [36], was based on the actual building energy consumption for one heating season (from October 15th, 2017 to April 15th, 2018) obtained from bills collected during the in site inspections.

3.2 Energy Efficiency Measures (EEMs) and related costs

The energy efficiency measures concern both the building envelope and the technical building systems. The investigated EEMs represent the typical energy efficiency measures for the refurbishment of the Italian apartment building typology built between 1977 and 1990 [44]. For the definition of the EEMs, the point of view of the occupants of the social housing was considered, in order to reduce running costs (maintenance and energy). Due to the presence of hygrothermal critical issues, measures concerning the improvement of the building envelope were considered, although the current envelope components are characterised by an acceptable level of thermal insulation. The improvements involving the insulation of the opaque envelope were subject to thermo-hygrometric verification, to exclude interstitial and superficial condensation, and no condensation phenomena were observed [36].

The energy efficiency measures for the technical building systems, with their energy efficiency options and costs, are reported in Table 2. They mainly concern the replacement with or the installation of high efficiency generators for cooling, heating and domestic hot water, the installation of a mechanical ventilation system with heat recovery and control systems with high efficiency. Added to these are the measures on solar energy systems, which consist in the installation of solar collectors for domestic hot water production, and photovoltaic systems.

While only one configuration was tested for the cooling system (EEM7/EEO1: multisplit individual system), various configurations were instead tested for the heating and domestic hot water production, such as the replacement of the existing heat generator with high efficiency generators (EEM10/EEO2: low temperature boiler, EEM10/EEO3: condensing boiler). The replacement of the existing technical building system configuration with a centralised heating generator (EEM8/EEO1: low temperature boiler, EEM8/EEO2: condensing boiler, EEM8/EEO3-4: air-to-water electric heat pumps) and individual boilers for DHW production (EEM9/EEO1: low temperature boiler, EEM9/EEO2: condensing boiler) was also tested. Together with the replacement of the generators, the replacement of the heat emitters is foreseen, as well as heat recovery units for ventilation (EEM13). A constant configuration for the control system (room climatic control system) was adopted in all the simulations. Thermal solar systems for the DHW production (EEM11) were included with different sizes. The photovoltaic system (EEM12) was considered as well; the efficiency options of EEM12 were defined considering the minimum installed peak power required by the Legislative Decree 28/2011 [30] (EEO2), its 20% variation – lower (EEO1) and higher (EEO3) – and its increase of 40% (EEO4) and 60% (EEO5). The current technical building system was included among the considered configurations; a total of 2200 combinations were tested in the parametric analysis.

The performance parameters of the EEMs were set in [44] to involve a representative sample of the technologies present on the market. Furthermore, although in Northern Italy there is an energy demand for space cooling, a cooling system is seldom present in existing buildings, except for the individual multisplit systems. Thus, since the existing building is not supplied by any cooling system, two different conditions were assumed: the first one is characterised by the absence of any cooling system (the same energy services as in the current building were considered), while a cooling system with individual multisplit was considered in the second condition. The parametric analysis was performed separately for the two conditions, considering 1100 different technical building system configurations each.

The costs of the considered EEMs were derived from market analysis and pricelist and were considered inclusive of VAT, transport, labour and installation costs [53-55]. Technology (per unit or depending on the installed power or area) and labour costs were considered and expressed either in €·kW^{-1} or €·m^{-2} (c) or € (C) for technical building systems. The costs of energy carries (electricity and natural gas) were instead supplied by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [56]. No financial incentives for the implementation of the energy efficiency measures were considered as to take into account unfavourable conditions.

Table 2: EEMs and EEOs of the technical building systems considered in the parametric analysis.

EEM id.	EEM	Parameter	EEO 1	EEO 2	EEO 3	EEO 4	EEO 5
7	Multisplit cooling generator	EER [-]	3.00				
		C [€]	2445				
		Emitters	Fan coils				
		c [€·kW^{-1}]	90				
8	Centralised heating generator	η_{gn} or COP [-]	0.95	1.00	3.70	4.10	
		c [€·kW^{-1}]	35	39	243	270	
		Emitters	Radiators	Fan coils	Fan coils	Fan coils	
		c [€·kW^{-1}]	118	63	63	63	
9	Individual generator for DHW production	η_{gn} [-]	0.93	1.00			
		c [€·kW^{-1}]	35	105			
10	Individual generator for heating and DHW production	η_{gn} [-]	0.91 *	0.93	1.00		
		c [€·kW^{-1}]	-	94	94		
		Emitters	Radiators *	Radiators	Fan coils		
		c [€·kW^{-1}]	-	118	63		
11	Thermal solar system (for DHW)	$A_{coll,sol}$ [m^2]	20	30	50	70	90
		c [€·m^{-2}]	804	804	804	804	804
12	Photovoltaic system	P_{PV} [kW]	7.6	9.5	11.4	13.3	15.2
		c [€·kW^{-1}]	1250	1250	1250	1250	1250
13	Ventilation heat recovery	η_{rec} [-]	- *	0.6	0.7	0.9	
		C [€]	- *	3390	8628	15507	

* Current building configuration

3.3 Modelling options

Within the SEPAs and the parametric analysis, the energy performance assessment was carried out according to the UNI/TS 11300 series [47-51] and Interm. D. 26 June 2015 [32] specifications. In particular, a conventional user behaviour was assumed in the simulations. A mean monthly value of 4.20 W·m^{-2} was considered for internal heat gains; likewise, mean monthly ventilation airflow rates equal to 0.30 h^{-1} and 0.41 h^{-1} were applied in case of natural and mechanical ventilation respectively [47]. A continuous operation of the heating and cooling system (if applicable), with constant set-points equal to 20°C and 26°C for heating and cooling respectively, was assumed. Standard monthly weather data were used and derived from the Italian Thermotechnical Committee [57]. The overall primary energy performance (for energy from non- and renewable sources) was calculated separately for each energy service with a monthly time-step. The energy from renewable sources produced and used within the system boundaries was taken into account up to the full coverage of the monthly energy need of the same energy carrier, in accordance with the rules described in [32]. The primary energy conversion factors are reported in Table 3.

For the assessment of the actualised global cost and payback period, the EN 15459 technical standard [45] specifications were applied, in particular:

- the financial perspective was adopted,
- initial investment costs, energy, maintenance, replacement costs and residual value were considered,
- a calculation period of 30 years was assumed, in accordance with the Commission Delegated Regulation (EU) No 244/2012 [58],
- lifespan of the technical building system components varying from 15 to 35 years depending on the technology,
- a real interest rate of 4% while no VAT was considered (the costs were considered inclusive of the VAT),
- a variable increase rate for the energy costs was adopted over the calculation period [44],
- annual maintenance costs varying from 0% to 4% of the investment cost, depending on the technology,
- maintenance and replacement costs of the existing windows and heating and domestic hot water generators were considered.

Table 3: Non-renewable ($f_{P,nren}$) and renewable ($f_{P,ren}$) primary energy conversion factors [32].

Energy carrier	$f_{P,nren}$	$f_{P,ren}$
Natural gas	1.05	0
Electricity from grid	1.95	0.47
Thermal energy from solar collectors	0	1.00
Electricity from PV	0	1.00
Thermal energy from outdoor (heat pumps)	0	1.00

4. Results

The results of the present work are organised as in the data flow-chart shown in Figure 3. In Section 4.1 a comparison between the current building, the *cost-optimal* solution and the *reference case* in terms of energy and economic performance is presented. The results of the subsequent parametric analyses are provided in Section 4.2.1 and Section 4.2.2, considering the absence and the presence of the cooling system respectively. In both parametric analyses, all packages of EEMs are analysed in terms of compliance with *RER* requirements for the NZEB, and economic feasibility. Further economic analyses are then carried out on the packages of EEMs in compliance with the *RER* requirements.

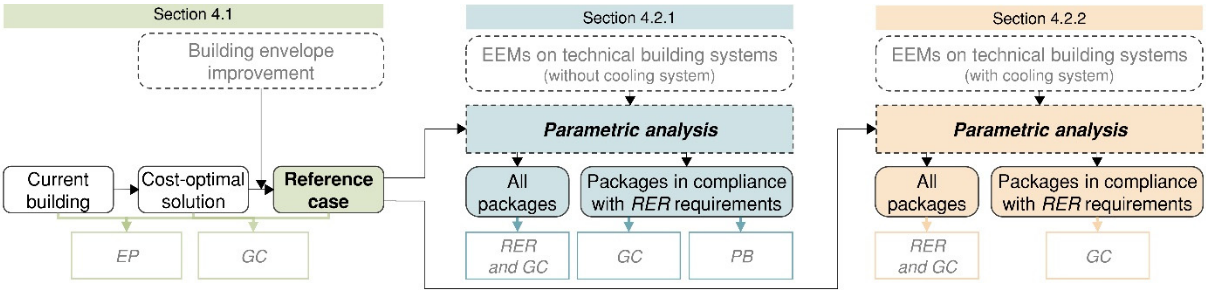


Figure 3: Flow-chart of the procedure and results.

4.1 Definition of the *reference case* in terms of building envelope performance

The present work starts from the findings of the energy audit and *cost-optimal* analysis presented in [36] and identified as described in Section 2.1. As shown in Table 4, the *cost-optimal* configuration is characterised by the thermal insulation of the upper and lower floors. The external walls and windows, instead, remains unchanged with respect to the current building configuration, as well as the technical building systems, if you exclude the installation of solar collectors for the domestic hot water production. The compliance with the NZEB requirements related to the building envelope was evaluated for the *cost-optimal* configuration, as reported in Table 5. Since the *cost-optimal* configuration does not include any thermal insulation improvement, neither for the external walls nor for the transparent envelope, both the H'_{T} and $EP_{\mathrm{H,nd}}$ values exceed the limits enforced in Italy from 2021 (NZEB target). While the *cost-optimal* building does not satisfy the heating performance requirements, it complies with the cooling ones ($A_{\mathrm{sol,sum}}/A_{\mathrm{f}}$ and $EP_{\mathrm{C,nd}}$).

In order to achieve the minimum compliance with the NZEB target (Table 5), a *reference case* was configured. It is characterised by thermal transmittances of 0.21 W·m^{-2}K^{-1} for the external walls, of 1.40 W·m^{-2}K^{-1} for windows, plus the installation of movable solar shading devices (τ_{sol} = 0.2), as shown in Table 4.

Table 4: *Cost-optimal* and *reference case* EEMs for the building envelope.

EEM id.	EEM	Parameter	*Cost-optimal*	*Reference case*
1	Opaque envelope thermal insulation	U_{wall} [W m^{-2}K^{-1}]	0.45 *	0.21
2	Upper slab insulation	$U_{\mathrm{up,slab}}$ [W m^{-2}K^{-1}]	0.26	0.26
3	Lower slab insulation	$U_{\mathrm{lo,slab}}$ [W m^{-2}K^{-1}]	0.26	0.26
4	Windows replacement	U_{w} [W m^{-2}K^{-1}]	3.17 *	1.40
5	Solar shadings installation	-	Lacking *	Movable

* same as current building

Table 5: *Cost-optimal* and *reference case*: verification of the compliance with the NZEB requirements for the building envelope.

Parameter	NZEB target	*Cost-optimal*	*Reference case*
H'_{T} [W m^{-2}K^{-1}]	0.55	0.87	0.33
$A_{sol,sum}/A_{f}$ [-]	0.04	0.04	0.01
$EP_{H,nd}$ [kWh m^{-2}]	30.2	82.8	30.2
$EP_{C,nd}$ [kWh m^{-2}]	14.8	12.6	10.9
$EP_{W,nd}$ [kWh m^{-2}]	18.0	18.0	18.0

Figure 4 shows the energy performance and economic evaluation for the current building, the *cost-optimal* and the *reference case* configurations, calculated by means of the UNI/TS 11300 technical specifications series [47-51]. The additional thermal insulation of the building envelope in the *reference case* leads to a consistent reduction of the $EP_{gl,nren}$ from 137 to 75 kWh·m^{-2} with respect to the *cost-optimal*. Anyway, the energy improvement of the building envelope leads the *reference case* to be not cost-effective (356 €·m^{-2}) with respect to the current building (316 €·m^{-2}).

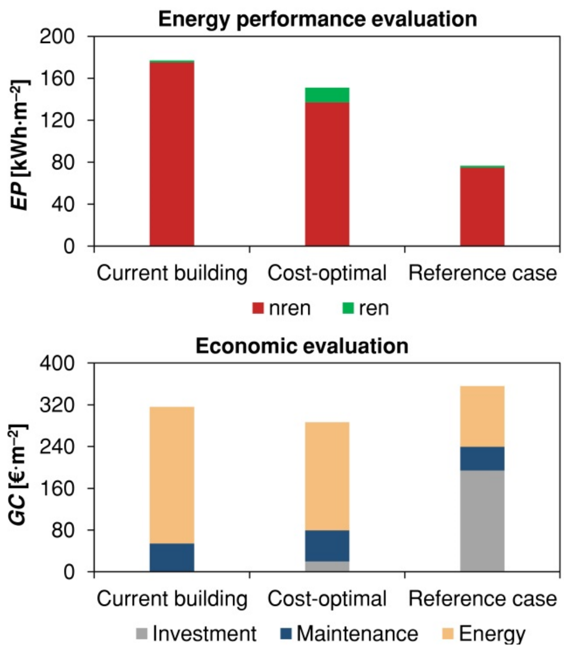


Figure 4: Energy performance and economic evaluation of current building, *cost-optimal*, and *reference case*.

4.2 Parametric analysis on the use of renewable energy sources

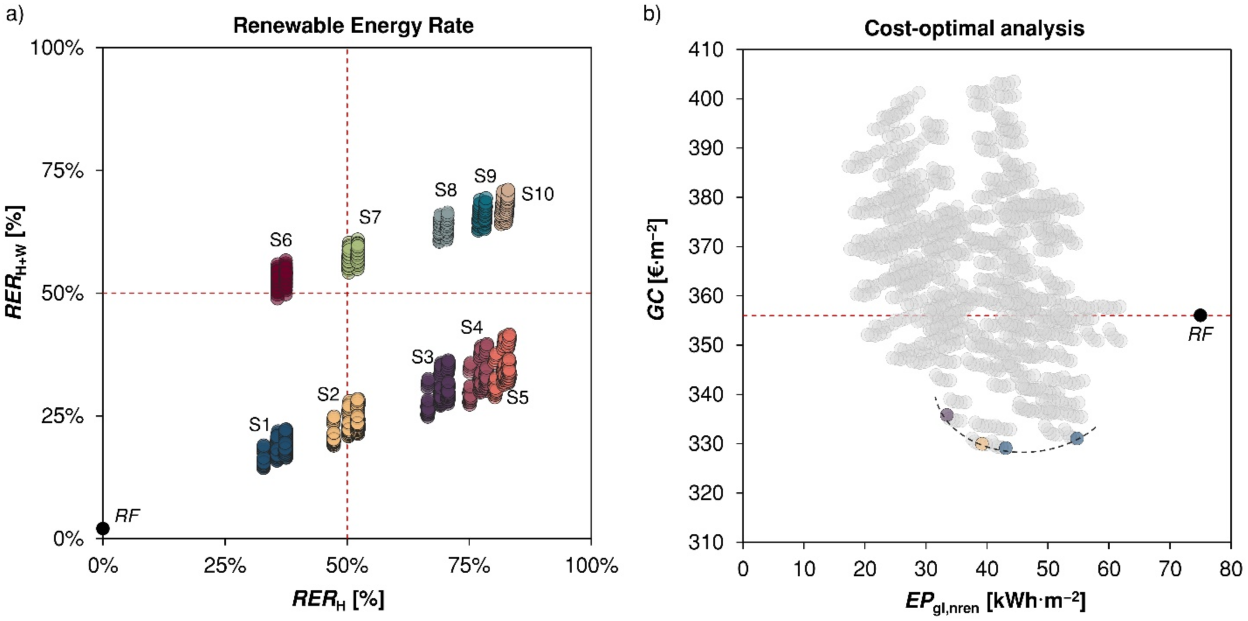
4.2.1 Technical building system configurations without any cooling system

In this first stage, the parametric analysis of the technical building system configurations was performed without including the cooling systems (EEM7). Results are shown in Figure 5, in which the *reference case* was used as reference point to evaluate the cost-effectiveness of the different technical building system configurations and the reduction of the $EP_{gl,nren}$ value.

In Figure 5a, each point describes one of the tested configurations, while the red lines represent the RER_{W} and

RER_{H+W} targets for the NZEB (both equal to 50%, see also Section 1.2). Among all the tested configurations, only 320 out of 1100 (29.1%) comply with both RER_W and RER_{H+W} requirements. Different groups (*Series*) can be identified in Figure 5a; they refer to specific technologies and/or system sizes. Among the groups that comply with the *RER* requirements, there are specific solar collector sizes and types of heat generator. This is the case of an installed solar collector size of 30 m^2 or more, that allow to verify the RER_W limit value. Furthermore, the technical building system configuration that leads to the compliance with the RER_{H+W} limit value is characterised by a centralised heat pump for space heating (EEM8/EEO3-4) and generators for individual DHW production (EEO9/EEO1-2). On the other hand, neither the ventilation typology nor the photovoltaic system size, which covers the electricity demand of the auxiliaries and the mechanical ventilation, are determining for the compliance with the *RER* requirements. Nevertheless, all the technical building system configurations positively affect the energy performance, guaranteeing lower $EP_{gl,nren}$ values than the *reference case.*

As regards the economic feasibility, the results are shown in Figure 5b, in which each point describes one of the tested configurations, while the red line represents the cost-effectiveness limit with respect to the *reference case*. Among the tested combinations, 32.6% are cost-effective (i.e. *GC* lower than the *reference case*), but only 40 out of 1100 combinations (3.6%) also comply with the *RER* requirements. The EEMs package that guarantees the lowest global cost ($\Delta GC = -27.2$ €·m^{-2} compared to the *reference case*, in the *Pareto front*), but not the compliance with the *RER* requirements (35% and 20% for RER_H and RER_{H+W} respectively), belongs to the first configurations group (*Series 1* in Figure 5). This is characterised by a centralised and individuals low temperature boilers for heating and DHW production respectively, natural ventilation and the lowest level of efficiency for the photovoltaic system (i.e. installed peak power of 9.5 kW).



Detailed charts' legend:

	Heating system type	DHW system type	Solar system ($A_{coll,sol}$)	PV system (P_{PV})	Ventilation type
● ***Reference case (RF)***	Individual (boilers)		Absent	Absent	Natural
● **Series 1 (S1)**	Centralised (boilers)	Individual (boilers)	20 m²	7.6 - 19 kW	Natural / Mechanical
	Individual (boilers)				
● **Series 2 (S2)**	Centralised (boilers)	Individual (boilers)	30 m²	7.6 - 19 kW	Natural / Mechanical
	Individual (boilers)				
● **Series 3 (S3)**	Centralised (boilers)	Individual (boilers)	50 m²	7.6 - 19 kW	Natural / Mechanical
	Individual (boilers)				
● **Series 4 (S4)**	Centralised (boilers)	Individual (boilers)	70 m²	7.6 - 19 kW	Natural / Mechanical
	Individual (boilers)				
● **Series 5 (S5)**	Centralised (boilers)	Individual (boilers)	90 m²	7.6 - 19 kW	Natural / Mechanical
	Individual (boilers)				
● **Series 6 (S6)**	Centralised (heat pumps)	Individual (boilers)	20 m²	7.6 - 19 kW	Natural / Mechanical
● **Series 7 (S7)**	Centralised (heat pumps)	Individual (boilers)	30 m²	7.6 - 19 kW	Natural / Mechanical
● **Series 8 (S8)**	Centralised (heat pumps)	Individual (boilers)	50 m²	7.6 - 19 kW	Natural / Mechanical
● **Series 9 (S9)**	Centralised (heat pumps)	Individual (boilers)	70 m²	7.6 - 19 kW	Natural / Mechanical
● **Series 10 (S10)**	Centralised (heat pumps)	Individual (boilers)	90 m²	7.6 - 19 kW	Natural / Mechanical

Figure 5: *RER* evaluation and cost-optimal analysis (without cooling system).

In Figure 6, each *Series* that includes EEMs packages in compliance with the *RER* requirements is plotted as to discuss the economic implications. Generally, the solar thermal system size and, more, the typology of the DHW production generators are crucial for the cost-effectiveness of the solutions, while neither the heat pump efficiency nor the PV size are incisive. As regards the combinations implementing the second EEO for the thermal solar system (i.e. *Series 7*, $A_{coll,sol} = 30$ m^2, Figure 6a), the cost-effective solutions are characterised by the low temperature boiler for the DHW production and both natural ventilation (NV) and mechanical ventilation (MV).

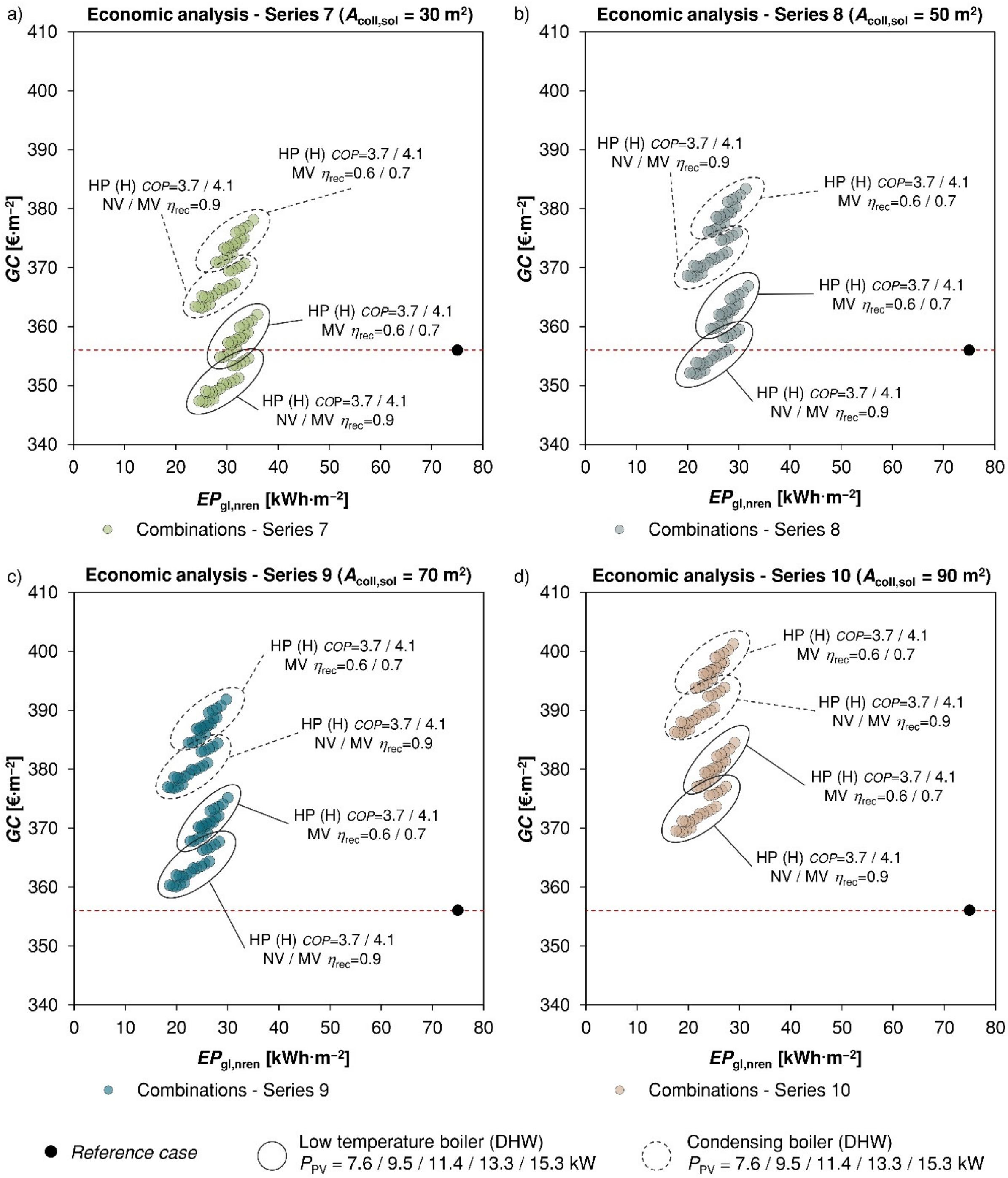


Figure 6: Cost-effectiveness evaluation of the EEMs packages in compliance with the *RER* requirements (without cooling system).

Specifically, the most cost-effective combinations are characterised by a heat pump with a *COP* of 4.1 and a heat recovery system for mechanical ventilation with 0.9 efficiency, and presents a variation of the global cost compared to the *reference case* (ΔGC) of −9 €·m^{-2}. The solutions implementing the natural ventilation present, instead, ΔGCs of −5.5 €·m^{-2}, and of −1 €·m^{-2} for the combinations characterised by a heat recovery system with 0.7 efficiency. Furthermore, the heat pump with a *COP* of 3.7 presents slightly higher ΔGCs equal to −2.5 and −7.3 €·m^{-2} with the natural ventilation and a heat recovery system with 0.9 efficiency respectively.

On the other hand, the solutions implementing the condensing boilers, characterised by a generation efficiency close to the low temperature ones, but higher costs (105 €·kW^{-1} with respect to 35 €·kW^{-1} of the low temperature boiler), are not cost-effective. The increasing of the thermal solar system size (i.e. *Series 8*, $A_{\mathrm{coll,sol}}$ = 50 m^2, Figure 6b) negatively affects the performance of some solutions which slightly become cost-ineffective, such as the ones implementing the MV (η_{rec} = 0.7) and the most efficient heat pump (*COP* = 4.1) – which presents ΔGCs around 3.8 €·m^{-2} – or the ones characterised by a 3.7 *COP* heat pump and the natural ventilation (2.3 €·m^{-2}). Furthermore, the high costs of the solar system technology with respect to the effective DHW energy need coverage imply the economic unfeasibility of all the solutions implementing more than 50 m^2 of solar collectors (*Series 9* and *10*, respectively in Figure 6c and 6d).

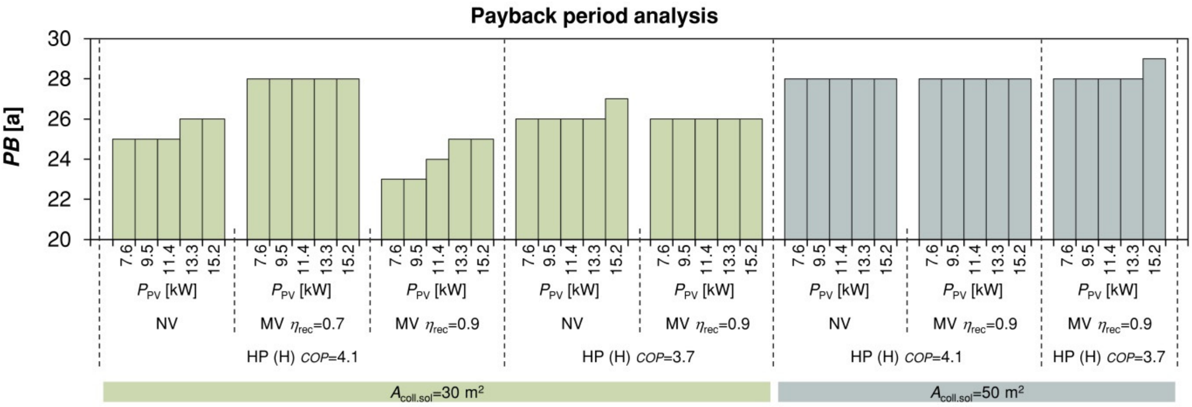
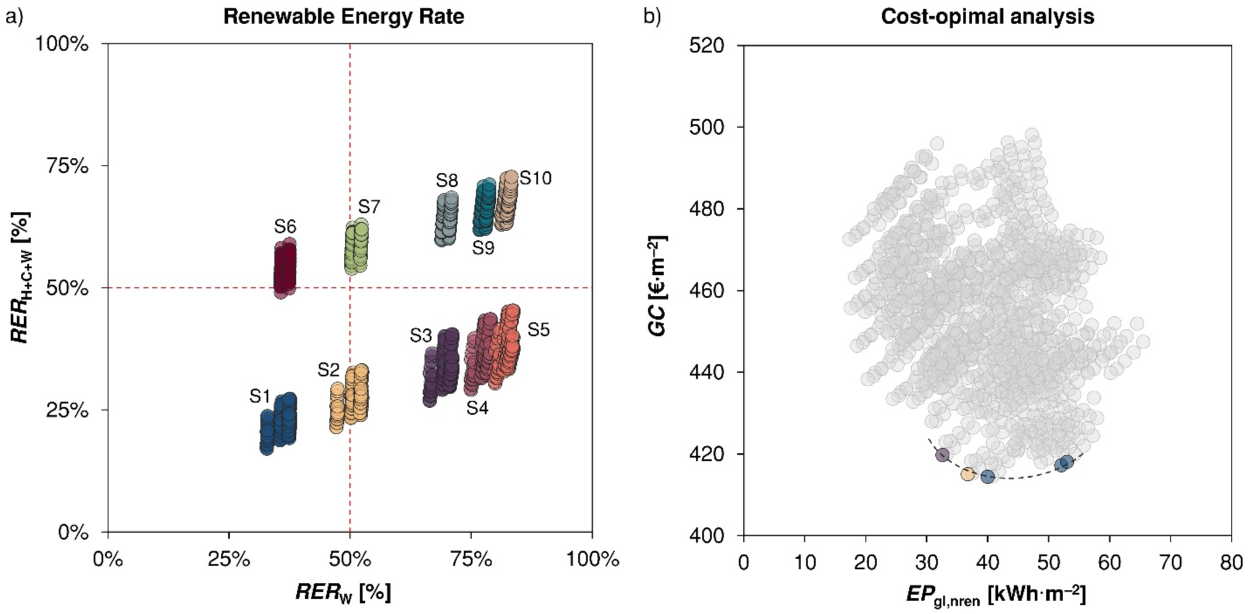


Figure 7: Payback periods for the cost-effective technologies in compliance with the *RER* requirements.

The payback periods, shown in Figure 7, are consistent with the global cost trends. The payback periods of the cost-effective solutions range from 23 to 29 years. All the other combinations in compliance with the *RER* requirements, not represented in Figure 7, have *PB* values over the building lifetime (30 years). The combinations that have *PB* values lower that 23 years, however, do not comply with the requirements related to RES.

4.2.2 Technical building system configurations with the cooling system

In a second stage, the parametric analysis was performed including the cooling systems (EEM7) and the results are shown in Figure 8.



Detailed charts' legend:

<table>
<tr><th></th><th>Heating system type</th><th>DHW system type</th><th>Solar system ($A_{coll,sol}$)</th></tr>
<tr><td rowspan="2">Series 1 (S1)</td><td>Centralised (boilers)</td><td>Individual (boilers)</td><td rowspan="2">20 m²</td></tr>
<tr><td colspan="2">Individual (boilers)</td></tr>
<tr><td rowspan="2">Series 2 (S2)</td><td>Centralised (boilers)</td><td>Individual (boilers)</td><td rowspan="2">30 m²</td></tr>
<tr><td colspan="2">Individual (boilers)</td></tr>
<tr><td rowspan="2">Series 3 (S3)</td><td>Centralised (boilers)</td><td>Individual (boilers)</td><td rowspan="2">50 m²</td></tr>
<tr><td colspan="2">Individual (boilers)</td></tr>
<tr><td rowspan="2">Series 4 (S4)</td><td>Centralised (boilers)</td><td>Individual (boilers)</td><td rowspan="2">70 m²</td></tr>
<tr><td colspan="2">Individual (boilers)</td></tr>
<tr><td rowspan="2">Series 5 (S5)</td><td>Centralised (boilers)</td><td>Individual (boilers)</td><td rowspan="2">90 m²</td></tr>
<tr><td colspan="2">Individual (boilers)</td></tr>
<tr><td>Series 6 (S6)</td><td>Centralised (heat pumps)</td><td>Individual (boilers)</td><td>20 m²</td></tr>
<tr><td>Series 7 (S7)</td><td>Centralised (heat pumps)</td><td>Individual (boilers)</td><td>30 m²</td></tr>
<tr><td>Series 8 (S8)</td><td>Centralised (heat pumps)</td><td>Individual (boilers)</td><td>50 m²</td></tr>
<tr><td>Series 9 (S9)</td><td>Centralised (heat pumps)</td><td>Individual (boilers)</td><td>70 m²</td></tr>
<tr><td>Series 10 (S10)</td><td>Centralised (heat pumps)</td><td>Individual (boilers)</td><td>90 m²</td></tr>
<tr><td colspan="4">In all series:
Cooling system type: Individual (multisplit)
PV system (P_{PV}): 7.6 – 19 kW
Ventilation type: Natural / Mechanical</td></tr>
</table>

Figure 8: *RER* evaluation and cost-optimal analysis (with cooling system).

As far as the use of renewable energy sources is concerned (see Figure 8a), similar conclusions to the parametric analysis results presented in Section 4.2.1 can be drawn. In fact, also in this case 29.1% of the tested combinations complies with both the requirements of RER_{W} and RER_{H+C+W}. These are characterised by a centralised heat pump for space heating (EEM8/EEO3-4), generators for individual DHW production (EEO9/EEO1-2) and an installed solar collector size of 30 m^2 or more (EEO11/EEO2-5). In contrast to the previous analysis (Section 4.2.1), the variability of the photovoltaic system size has a greater impact in the amount of the Renewable Energy Ratio for heating, cooling and DHW. In fact, RER_{H+C+W} is 10% higher passing from EEM12/EEO1 (i.e. P_{PV} = 7.6 kW) to EEM12/EEO5 (i.e. P_{PV} =

15.2 kW).

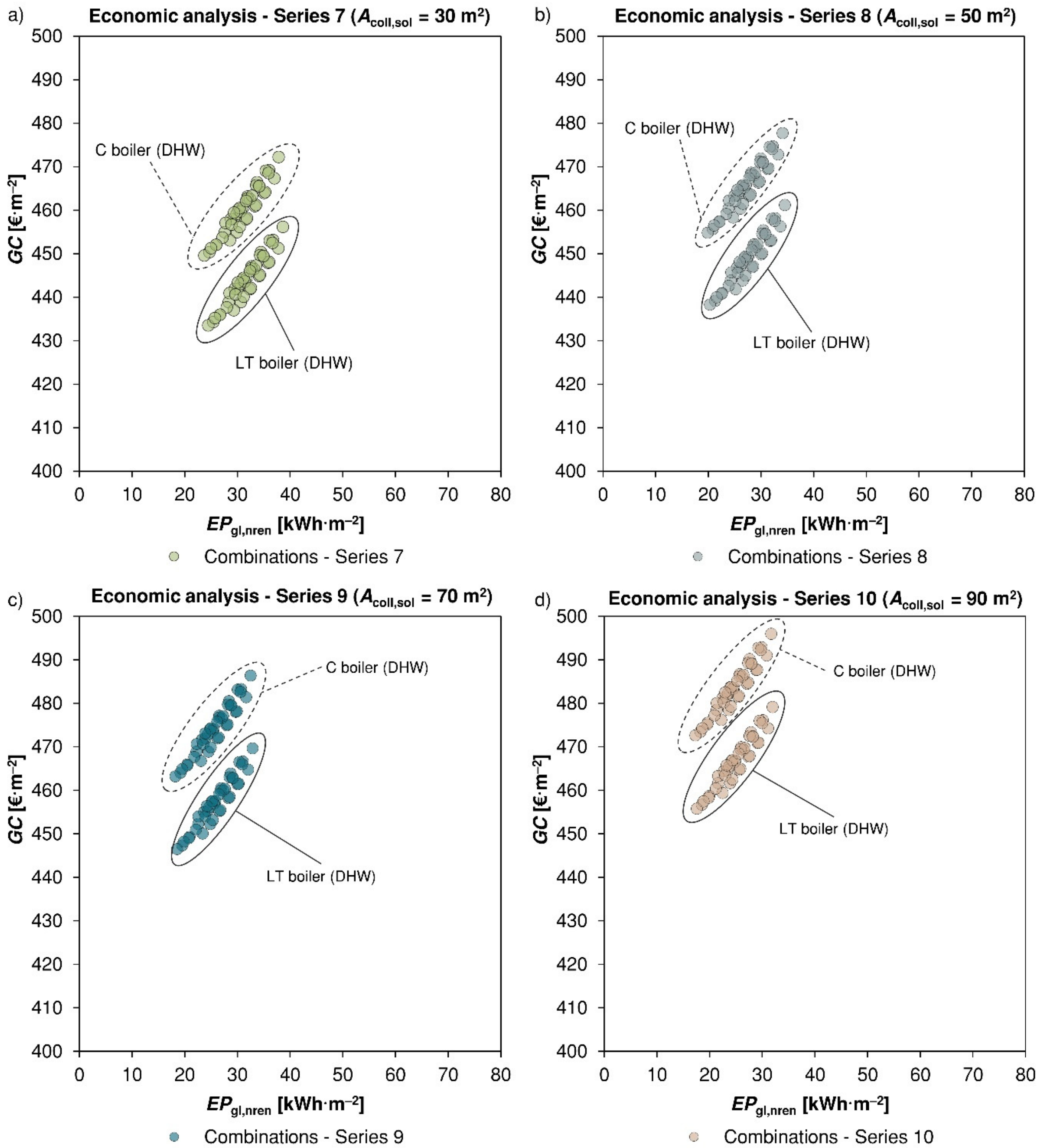


Figure 9: Global cost evaluation of the EEMs packages in compliance with the *RER* requirements (with cooling system).

As regards the economic evaluation (Figure 8b), the EEM packages that guarantee the lowest global costs are characterised by centralised and individuals low temperature boilers for heating and DHW production respectively, different EEOs for the solar thermal system (EEM11/EEO1-3), high levels of the PV power (EEM12/EEO4-5) and both natural and mechanical ventilation (EEM13/EEO4). However, despite the presence of both thermal solar and photovoltaic systems, none of the combinations belonging to the *Pareto front* is in compliance with the *RER* requirements.

In Figure 9, each *Series* of Figure 8 that includes EEMs packages in compliance with the *RER* requirements is plotted as to discuss the economic implications. Whereas the ventilation typology, natural or mechanical, enables the identification of several clusters in the analysis without cooling (see Figure 6, Section 4.2.1), in the present analysis neither the ventilation typology nor the photovoltaic system size enables a specific cluster identification. For the other EEMs, the same considerations already addressed in Section 4.2.1 can be drawn.

5. Discussion

As far as the envelope design is concerned, a mismatch between the cost-optimal package of measures and the minimum legal requirements is pointed out. In-situ installation of external thermal insulation systems is generally expensive and cost-ineffective, as well as windows replacement. Nevertheless, these measures are necessary to comply with the required values of the mean overall heat transfer coefficient by thermal transmission and to achieve the NZEB target. The need arises for a review of the legal thermal requirements of the envelope, with the aim of achieving the cost-optimal balance between the investments involved and the energy costs saved.

As regards the analysis of the partial energy performance related to different energy services, the main effect of the high level of insulation required for a NZEB is to reduce the thermal energy need for heating, which in turn boosts the relative weight of domestic hot water (see Table 5).

Turning to the technical building systems, the main design constraint is represented by the strict requirements on renewable energy share, RER_{W} and $RER_{\mathrm{H+C+W}}$; especially the latter index requirement often determines the technical non-feasibility of several systems solutions. This is clearly shown in Figures 5a and 8a, respectively referred to configurations without and with cooling systems, in which only a fraction of the proposed technologies (S7, S8, S9, and S10) comply with both *RER* requirements. More specifically, the only generation system that allows to comply with the *RER* requirements is the centralised heat pump, either used for space heating or for both heating and cooling as reversible machine, coupled with a PV system. This appears as a shortcoming of the Italian legislation for the promotion of the use of energy from renewable sources, because it highlights the rigidity of the prescriptive approach in establishing market barrier for some technologies.

The installation of thermal solar systems appears expensive; therefore, the only cost-effective solution is to have a low area of solar collectors sized to comply with *RER* requirements.

Both parametric analyses, with and without the cooling system, show a predominant role of the domestic hot water in the differentiation of the global costs for the solutions in compliance with the *RER* requirements (see, for instance, Figure 9). The overall primary energy from non-renewable sources ($EP_{\mathrm{gl,nren}}$) is strictly dependent on the typology of the domestic hot water generator as well, since the DHW need not covered by RES is attributed to non-renewable energy sources (e.g. boilers fuelled with natural gas). Thus, considering an equal thermal solar system size, the variation in the global cost only relies on the DHW generator cost. In particular, the installation of a slightly less efficient, but cheaper, boiler proves to be more cost-effective than the provision of a condensing boiler, because the energy cost savings resulting from the condensing boiler are not sufficient to recover the investment costs.

A possible policy implication of the obtained results is the need of promoting technologies that have a strong impact on the building energy performance but are hindered by market barriers, such as high efficiency DHW generators and thermal solar systems.

6. Conclusions

The present work, through the analyses carried out on the case study and their main findings, allowed to answer to the research questions introduced in Section 1.3. The mismatch between the compliance with NZEB requirements according to the Italian legislation and the cost-optimal package of energy efficiency measures in major renovations of buildings was highlighted. This mismatch is not intended to be specific to social housing, but it is a broader problem, as there are no legislative differences between social and private residential buildings. The intersection between legal compliancy and cost-effectiveness narrows the field of applicable solutions. This conclusion can be explained on the one side by the most stringent legal limits on *RER*, on the other side by the high cost of some technologies and measures, such as insulation coating and windows replacement.

As regards the technical building systems, the stringent limits on *RER* effectively oblige to adopt electric heat pumps and PV systems. The association of these systems demonstrated to be also cost-effective in residential buildings if coupled with small solar collectors. The global cost of the NZEB presents high sensitivity both to the solar collector size – that anyhow determines a significant increase of RER_{W} – and to the type of DHW generator. In general terms, care should be taken when setting strict *RER* limits because it could yield significant market disturbance.

A strength of this work is that it refers to the databases of reference buildings officially defined by the Italian Government in accordance with Annex III to Directive 2010/31/EU [5] (cost-optimal calculations). Therefore, the case study represents the typical and average residential building stock in Italy and the most representative technologies in this country. This makes the conclusions highly generalizable. Furthermore, the scientific rigor and the neutrality of the adopted methodology makes it possible to extend it to different countries and contexts.

It is necessary to remember that some technologies, such as absorbing heat pump and geothermal heat pumps, have been excluded from this study for their high cost that would have determined cost-ineffective solutions. Besides, biomass systems have been excluded as well because their use in urban areas is not allowed in many areas of the Italian territory, due to regional provisions on the reduction of air pollution and protection of air quality. Future works will investigate innovative technologies in relation with the effect of possible incentive schemes. Other building use categories will be considered as well.

The results of the study underscore the need for tough policy efforts aimed at promoting those measures for which a gap between financial and macroeconomic perspectives is shown. That should include both direct subsidies and tax deductions, but new forms of energy performance contracting as well. Any policy measure should anyway be preceded by the application of proper assessment methodologies and sensitivity analyses for identifying the best trade-off between energy efficiency and RES exploitation fit to preserve market equilibrium and minimise global costs.

Acknowledgement

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