COST-OPTIMAL DESIGN FOR NEARLY ZERO ENERGY OFFICE BUILDINGS LOCATED IN WARM CLIMATES

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Abstract

The improvement of energy efficiency and the integration of renewable energy in buildings are key elements of current European policies. According to the recast of the Directive on Energy Performance of Buildings (EPBD), Member States have to target nearly zero energy buildings (nZEBs) and minimum energy performance requirements within a cost-optimal framework by 2020.

This study reports the comparative methodological framework reported in EPBD, aimed at the establishment of cost-optimality in office buildings located in a warm climate. A number of energy efficiency measures have been selected and applied to the envelope and the systems of a virtual reference office building. Technical features and energy performance calculations have been assessed for the obtained configurations. Primary energy consumption and global costs have been derived to identify the cost-optimal configuration from a financial and macroeconomic analysis.

The paper shows the suitability of the methodology to support the design of cost-effective energy efficient solutions in new office buildings. Results show technical variants selection able to a decrease primary energy consumption by 39% and CO_2 emissions by 41% at the lowest cost. They also illustrate how to design cost-optimal nZEBs for a warm climate in compliance with EU Directives.

Keywords: ZEB; building; EPBD; cost-optimality; renewable; office.

1. Introduction

The building sector accounts for 40% of final energy consumption and 36% of CO_2 emissions in Europe. The European Union (EU) set up a policy framework focused on reducing this consumption and obtaining important savings from buildings. The renowned “20-20-20” targets, established by the Climate and Energy Package, aims at a 20% increase of energy from renewables, a 20% decrease of greenhouse gases emissions and a 20% reduction of primary energy consumption in buildings by 2020 [1].

Over the last decade, new legislation and methodologies have introduced technical and regulatory measures to promote a rational use of energy and assess the effectiveness of policies. One of the most important energy policy initiative is the recast of the Energy Performance of Building Directive (EPBD) [2]. According to Article 9 of the EPDB, all new buildings have to be nearly zero energy buildings (nZEBs) by December 31, 2020. In the last decade, achieving the nZEB target has become a priority not only for designers, architects, engineers and researchers dealing with building physics, but also policy makers, economists and environmental analysts. However, the establishment of a common nZEB definition is a long way off in Member States (MS) and the topic is still subject to discussion on suitable boundaries and calculation methodologies at international level [3].

The EPBD also requires that MS account for cost-optimality to establish minimum energy performance requirements leading to the lowest building costs. To this end, the Directive introduces a methodology to set benchmark requirements for national standards. The cost-optimal level is defined as “the energy performance level which leads to the lowest cost during the estimated economic lifecycle”. According to Article 5, energy-related investment costs, maintenance, operating costs and, where applicable, disposal and replacements costs, have to be considered in the analysis. Delegated Regulation No. 244/2012 and its Guidelines describe the methodology to be followed by MS to derive cost-effectiveness from a technical and economic perspective [4,5]. The methodological framework comprises both new and existing buildings undergoing major and non-major renovation of their structural and technical components.

According to the proposed approach, construction alternatives have to be included and compared in terms of costs [6] and energy performance [7] among the studied solutions. The cost-optimal configuration presents the lowest costs maintaining a high performance. It can be identified in the lower part of the curve that reports global costs (€/m^2) and energy consumption (kWh/m^2y) [Fig. 1].

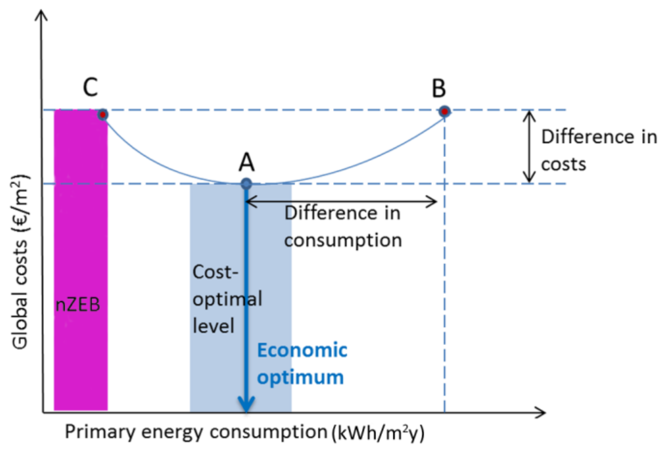

Fig. 1. Global cost curve (A= economic optimum, B= requirement in force, C= cost neutral compared to requirement in force)

Several parameters can alter the shape of the curve, among them geometrical building features, technical systems, data on energy price, discount rate, and costs. Therefore a sensitivity analysis can be performed to reduce variability within calculations. MS have compared the results of cost-optimality against minimum requirements and reported the outcomes to the Commission. Combining harmonised energy performance and costs requirements at the EU level is an open issue. A heterogeneous situation characterize European countries as each building type and climate present a different cost-optimal level [8]. Some of them, such as Estonia, the Flemish region of Belgium and Lithuania, have current national requirements comparable with calculated cost-optimal levels while others, such as Slovenia, have more demanding requirements. A broad overview on the implementation of the cost-optimal methodology in MS has been published by the Buildings Performance Institute Europe (BPIE) [9]. The study reports calculation examples for Austria, Germany and Poland as well as impact of discount rates, simulation variants, costs and energy prices.

The Ministry for the Economic Development coordinated an analysis on cost-optimality in the Italian framework. The study gives an overall guidance on cost-optimality for new and existing (from 1946 to 1976 and from 1977 and 1990) residential and office buildings of two national climatic zones (B and E). However, there is the need of developing cost-optimal calculations for other reference buildings and in relation with different climates, regulations, and conditions in order to pass from a usual construction perspective to a life cycle cost perspective.

The objective of this paper is the evaluation of cost-optimal and nearly zero energy requirements for office buildings located in Lecce (South of Italy). This area has a warm climate belonging to the climatic zone (C) that has not yet been addressed at national level. After the definition of a baseline reference building, several technical variants related to the envelope, supply systems, fenestration, and energy sources, have been selected and applied. Energy performance and global cost calculations have been then assessed for the obtained configurations. A financial and macroeconomic study has been carried out performing a sensitivity analysis to add robustness to the evaluation. Finally, the cost-optimal solution has been derived and discussed in terms of both physical and technical characteristics and potential savings.

1.1 Literature overview

Several projects have been carried out in MS to comply with EU energy policy requirements. Achieving the nZEB target seems to be feasible in many cases especially in relation to new buildings or where the contribution from renewable is more available. However, reaching a nearly-zero energy balance taking into account cost-optimality is still challenging and in most cases limited to demonstration studies or pilot projects.

Many input parameters can influence results, among them reference building properties and climatic conditions, as investigated by Leutgob *et al.* [10]. Kapsalaki *et al.* study a methodology for the design of cost efficient Net ZEBs in three climates [11]. According to the authors, economically efficient and inefficient ZEBs can present a factor of three difference in terms of initial and life cycle costs. Becchio *et al.* [12] state that a PV system plays a key role in nearly and net zero building energy balance.

In reference office buildings located in a cold climate, Kurnitski *et al.* identify cost-optimality with 140 kWh/m^2y district heating and 0.33 W/Km^2 envelope insulation level, including transmission and infiltration losses per unit heated floor area [13]. Pikas *et al.* further consider alternative fenestration design solutions for offices, finding the most energy efficient and cost-optimal solution in triple glazed argon filled windows with a small window to wall ratio, and 200 mm thick insulation on the walls [14]. The authors state that cost-optimality will be affordable in future with energy cost escalation, cost reduction of PV panels and windows with four panes [15].

The influence of control strategies on energy demand and comfort performance in offices have been investigated by Liu *et al*. [16]. The authors show that an intelligent glazed façade is capable of monitoring thermal, solar and mass transmittance by controlling shutters, blinds and openings. This technology can reduce by approximately 60% the annual primary energy demand in comparison with the same building with a static façade. Goia *et al*. [17] also assessed the advantages of an adaptive building envelope able to change its thermo-physical properties over conventional building systems in offices.

Krarti *et al.* [18] carry out a design comparative evaluation for office buildings in the US and France using a life cycle cost analysis approach. The authors found that optimizing life cycle costs resulted on average in 30% primary energy saving for office buildings located in the US and a 40% saving in France.

Zhou *et al.* [19] examine lighting energy consumption over various timescales, based on a statistical analysis of measured lighting energy use data from 15 large office buildings in China. They found that the 24-hourly variation in lighting energy use is mainly driven by the schedules of the building occupants.

Corgnati *et al.* illustrate a methodology for reference building definition using dynamic simulations to assess energy performance in an Italian office [20]. Office buildings have been also investigated by Aidan Parkinson *et al*. [21]. The authors explore the relation between building energy performance and real estate financial value. Suitable instruments are applied to a number of offices in the UK to show how energy management in buildings can be evaluated assessing a large sample of assets. Corrado *et al*. propose energy performance and global cost calculations using a sequential search-optimization considering discrete options [22]. They applied different energy efficiency measures to a reference building of the TABULA (Typology Approach for Energy Building stock Assessment) project [23].

De Angelis *et al.* focus on the economic sustainability of different retrofitting strategies in an Italian social housing district. The authors investigate several refurbishment alternatives and analyse different funding systems and incentives [24].

1.2 The Italian framework

The Italian legislative framework for increasing energy efficiency in buildings is quite varied and aimed implementing EU requirements at national level. The EPBD was adopted in Italy by Legislative Decree No 192/2005, while the EPBD recast was adopted by Decree Law No 63/2013, converted into Law No 90/2013. Both decrees are key acts that update the national regulatory framework and establish criteria and procedures for nZEBs. They introduce cost-optimality, methods for calculating the energy performance of buildings based on Standard UNI TS 11300 [7] as well as Energy Performance Certificate (EPC) requirements to be reported when selling or renting a property.

The energy that a building consumes during a year per square meter of treated floor area (TFA) is an indication of its Energy Performance (EPi). Thanks to the new legislation aimed at a more rational use of energy, the EPi value has been progressively reduced over time in Italy. The national energy classification system currently includes seven classes (from A to G) characterized by increasing primary energy consumption (for heating, cooling, dhw, ventilation, lighting and auxiliary) needs from class A to class G.

Italy submitted its final report on cost-optimal assessment in August 2013 [25]. Overall results from the application of the methodology are in line with the simulations carried out on the same sample of buildings by ENEA. Some assumptions still need further discussion, for example the contribution of surplus electricity produced on-site. Apart from residential buildings, this report analyses two office types, having a medium and small size, shape, type and structural features adapted to the Italian building stock in three cities of different climatic zones: Milan (climatic zone E), Rome (climatic zone D) and Palermo (climatic zone B) [26, 27].

1.3 The national non-residential building sector: office buildings

In Italy there are around 65,000 buildings entirely or largely used as offices [28]. Regarding location, 30% of office buildings are concentrated in 12 provinces, mainly Milan, Rome and Turin, and 50% are located in 26 provinces. Office buildings have a total floor area of 56.7 million m^2 and their volume is around 200 million m^3. Most buildings have a small size and about half do not exceed 350 m^2. A share of 32% of the total floor space and of volume (about 62 million m^3) is made up of less than 1,200 large buildings having more than 5,000 m^2.

Even if non-residential buildings represent only 13% of the national building stock, the energy savings that can derive from this sector through efficiency measures are considerable due to their typically high energy consumption. The average saving is estimated at around 60% for existing offices, but it is higher for public buildings built before 1980 that are characterized by a poor energy performance. Projects focused on promoting daily actions to reduce energy consumption in office buildings are growing in Italy. Among them, an initiative led by the Veneto Region and supported by the Ministry of the Environment to spread energy consumption awareness [29]. The information campaign advertises good practices on how to save energy when using printers, copy machines, personal computers, monitors, lifts, heating and lighting.

The importance of office buildings is also stressed by the amount of savings that are expected from this category. A total energy saving of 6,739 GWh/y, corresponding to 0.58 Mtoe/y, is estimated by 2020 from private and public office renovation, considering a yearly renovated floor area of 5,520,000 m^2 [28].

The ENEA report has made a comparison of energy performance indices of cost-optimal solutions in new office buildings [25]. The study is referenced to current regulatory limits in relation to the national climatic zone E, which has between 2,100 and 3,000 heating degree days. Results demonstrate that legal limits are stricter than cost-optimal levels for this climate. In particular, the cost-optimal primary energy performance is assessed at 16.1 kWh/m^3 in comparison with the 13.8 kWh/m^3 legal limit for an office having a ratio between envelope area and volume of 0.35 m^{-1}. In case of precast offices of similar geometry, the same index is assessed at 10 kWh/m^3 for cost-optimality in comparison with the legal limit of 5.86 kWh/m^3.

The comparison between envelope thermal transmittance (U) of cost-optimal solutions and national legal limits appear very close for new office buildings located in the climatic zone E. As example, the U wall value is 0.34 W/m^2K as legal limit and 0.29 W/m^2K as cost-optimal solution. The U window value corresponds to 2.2 W/m^2K in both cases, U floor is 0.33 W/m^2K as legal limit and 0.45 W/m^2K as cost-optimal solution, and U roof or ceiling is equal to 0.30 W/m^2K in both cases. This result was expected as national limits are referred to the standard of 2006, when national building requirements were higher and technological solutions were not as well performing as they currently are.

With a discount rate of 4%, the cost-optimal solution corresponds to a global cost of 608 € with EPi of 112 kWh/m^2 for that climatic zone. However, graphical results related to new office buildings are quite scattered and therefore the cost-optimal configuration can be hard to locate on the cost-energy curve.

The office building of this research references to the small size office of [25]. It has been adjusted in terms of geometry, materials and systems to be representative of its climatic zone (C) that has not yet been investigated at national level. These stresses the meaningfulness of the selected reference building to address cost-optimality in another climate and conditions in order to test the methodology in the heterogeneous building framework of Italy.

2. Methodology

The main steps of the methodology of this paper comprise:

• definition of the reference building (Section 2.1);

• identification of energy efficiency measures (Section 2.2);

• establishment of technical variants and combinations (Section 2.3);

• assessment of energy performance and global costs with sensitivity analysis (Section 2.4);

This has allowed the design of cost-optimal nearly zero energy office buildings located in a warm climate.

2.1 Definition of the reference building

The main aim of reference buildings is to represent the typical housing stock in a country. A reference building must be defined accurately in order to have comparable results from different analyses.

According to [4], two main approaches can be used in the definition of a reference building: real or virtual buildings. The first represents a typical building having a known floor area, shape factor, envelope, technical systems and a specific category according to occupancy pattern. The second includes common materials and technical systems for each parameter.

According to the EPBD recast, different sources and databases can be used to define reference buildings. For example, it is possible to refer to the previously mentioned TABULA project [30, 31] or the ASIEPI (Assessment and Improvement of the EPBD Impact) project [32]. One of the aims of these projects is to create a harmonized structure in relation to European building types, with a particular focus on the residential sector.

Each defined reference building has a specific size and a period of construction. Building types are used as a tool to derive energy performance and potential savings that can be achieved through high efficiency technical variants in each country. As this research focuses on non-residential buildings, the ENEA report has been considered as a reference. This paper presents the application of the cost-optimal methodology to an office building that corresponds to the small size office studied in [25].

Following are given details about the location where the reference building is placed. The architectural features, building type description, construction elements properties and technical systems details are shown.

2.1.1 Geographical location

The reference office building of this study is located in Lecce, a city in the South of Italy having 1153 degree-days as part of the climatic zone C. It is characterized by a Mediterranean climate with by non-extreme winters (average temperature 13 °C over the last ten years), high aridity in summer (average temperature 30.3 °C) and rainfall concentrated in autumn and winter [33, 34, 35, 36, 37].

In this area, the indoor design temperature of a building is 20 °C during the heating period, running from November15th to March 31st, and 26 °C during the cooling period [38]. This climate is common in the South of Italy and its main islands as well as in other MS (e.g. Cyprus, Greece, Spain, and Portugal). This research represents a supplementary application of cost-optimality in a not previously studied climate characterized by different materials and systems.

2.1.2 Geometrical features and construction elements properties

The office is designed to accommodate 32 employees according to the use of the building; in particular, the assessment comprises standard values for the steady calculation of internal heat gains (6 W/m^2) that include gains for users, equipment and lighting. For the dynamic simulations, the values are variable during the day (1 W/m^2 from 01:00 to 07:00 a.m., 4.5 W/m^2 at 08:00 a.m., 9 W/m^2 from 09:00 a.m. to 03:00 p.m., 4.5 W/m^2 at 04:00 p.m. and 1 W/m^2 from 05:00 to 00:00 p.m.). In this case study the users work from 8 to 10 hours, and the plant operation amounts to 12 hours. Following the building type described in [25]; it consists of four floors with a multi-pitched roof (S/V = 0.47) (Fig.2). The facades are linear and regular and the windows surfaces are evenly distributed. The shape is rectangular in plan view; the vertical surfaces with the greatest base length are oriented towards East and West, respectively. The indentation of the facades is in correspondence of the stairwell and elevator shaft.

The internal ceiling height of the building is 2.7 m and the treated floor area of each room is also shown in Figure 2. The ground floor consists of an entrance hall, an office room, while five offices and a meeting room are located in the other floors. In the South-East corner of the building there are four bathrooms. The glass area constitutes 12% of vertical surfaces.

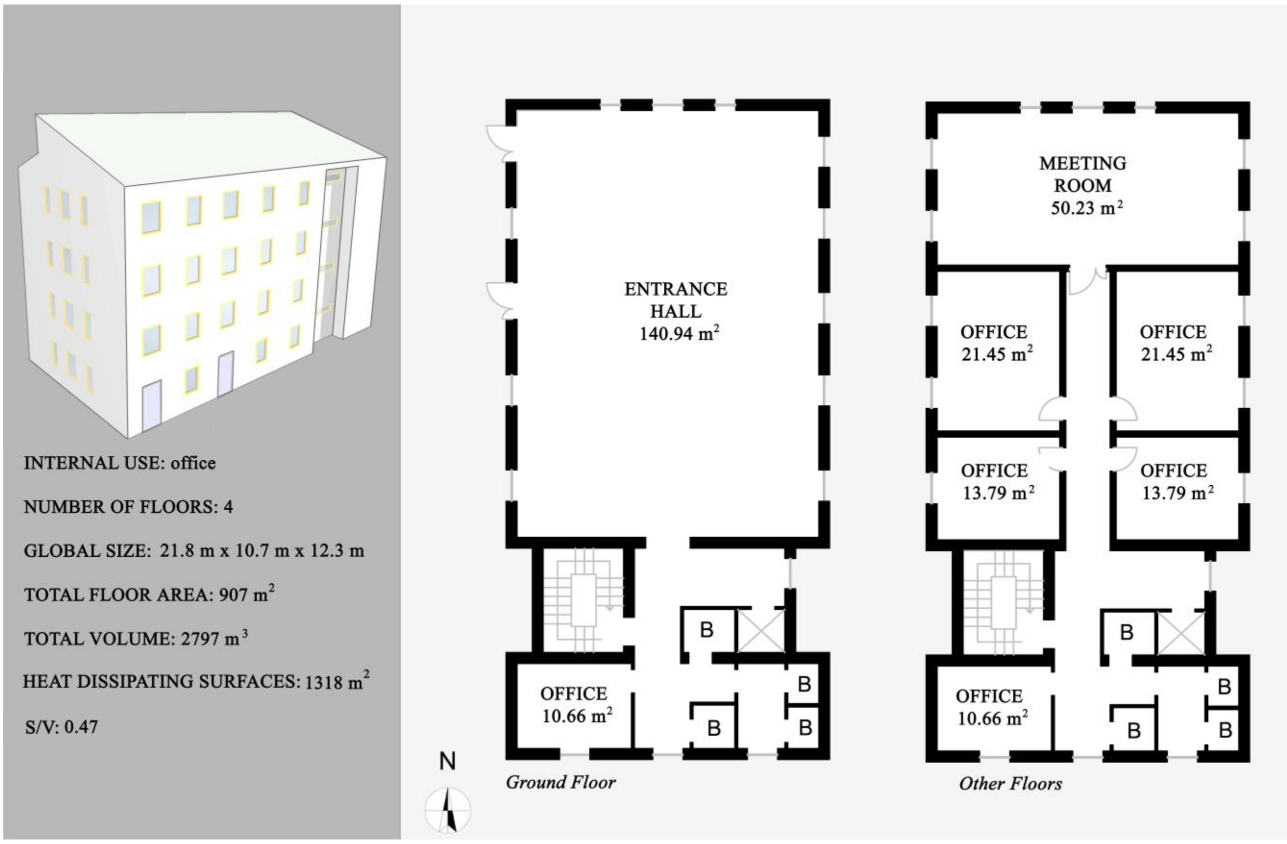

Fig. 2. Floor layout and geometrical parameters of reference building.

The building materials and elements (walls, roofs, floors) of the reference scenario are commonly used in the Italian context. The thermal parameters of the building, such as transmittance (U) and heat capacity per unit area, fall within typical national values. The case study is a new building that respects the limits of Italian laws, whose limitations are related to the climatic zone in which the building is located [Table 1]. Table 2 shows the thermal properties of the envelope of the reference scenario.

Table 1
Italian requirements for building certification

Requirement 1: EP_w	$EP_w < EP_{w,limit}$
Requirement 2: $Ep_{s,env}$	$Ep_{s,\ env} \leq Ep_{s,\ env\ limit}$ $Ep_{s,\ env}$: ratio between annual thermal energy for cooling (calculated taking into account the summer design temperature according to the UNI/TS 11300-1), and: - treated floor area for a residential building; - volume of the building for other building categories
Requirement 3: Dividing wall	$U_{dividing\ wall} \leq 0.8\ W/m^2K$ - For all dividing walls (vertical and horizontal) of separation between building or confined housing units; - For all opaque structures that delimit external environments not equipped with a heating system.
Requirement 4: Inertia	$Im,s \geq 290\ W/m^2$

Requirement 5: check air conditioning in summer	- Regularly control screening systems of glazed surfaces to reduce incoming solar radiation; - Exploit external conditions and internal spaces to strengthen natural ventilation; - use controlled mechanical ventilation if natural ventilation is not sufficient.
Requirement 6: Shading	External screening systems are mandatory. These systems may be omitted in presence of glass surfaces with solar factor (UNI EN 410) equal or less to 0.5.
Requirement 7: Check T_{room}	Devices for automatic control of room temperature have to be installed to avoid overheating as a result of solar and internal gains or free contributions.
Requirements 8: thermal renewable	a. 50% EPdhw e 20% (EPi + EPe+ EPdhw) from 31/05/2012 to 31/12/2013 b. 50% EPdhw e 35% (EPi + EPe+ EPdhw) from 01/01/2014 to 31/12/2016 c. 50% EPdhw e 50% (EPi + EPe+ EPdhw) from 01/01/2017
Requirement 9: electric renewable	It is obligatory to install an electrical power [kW] system powered by renewable sources installed in or on the building: $P=S/K$ where S is the floor area of the building at ground level (m2), and K is a coefficient (m2/kW) that has the following values: a. K = 80 from 31/05/2012 to 31/12/2013 b. K = 65 from 01/01/2014 to 31/12/2016 c. K = 50 from 01/01/2017
Requirement 10: average seasonal efficiency	Check: - Seasonal average global efficiency: $(\eta g)\geq(75+3\log Pn)\%$ if $Pn<1000$ kW $(\eta g)\geq 84\%$ if $Pn \geq 1000$ kW where logPn is the base-10 logarithm of the effective rated output of the generator or heat generator in service of an individual heating system, expressed in kW.

Table 2
Construction properties of the reference building: element data set

element	layer	material	t	λ	c	ρ	U	d
	(from internal to external side)		(m)	(W/mK)	(J/KgK)	(kg/m³)	(W/m²K)	(m)
Floor	1	linoleum	0.005	0.170	1400	1200	0.410	0.387
	2	light concrete screed	0.060	0.127	1000	400		
	3	concrete screed	0.200	1.060	1000	1900		
	4	vapour barrier	0.002	0.400	1500	360		
	5	extruded polystyrene foam	0.060	0.040	1450	35		
	6	concrete screed	0.060	1.060	1000	1900		
Internal slab	1	linoleum	0.005	0.170	1400	1200	1.030	0.265
	2	light concrete screed	0.050	0.127	1000	400		
	3	slab	0.200	0.743	1000	1800		
	4	plaster	0.010	0.900	840	1800		
Roof slab	1	plaster	0.010	0.700	840	1400	0.350	0.380
	2	slab	0.200	0.743	1000	1800		
	3	light concrete screed	0.050	0.580	1000	900		
	4	polyurethane foam	0.080	0.035	1450	35		
	5	concrete screed	0.040	1.060	1000	1700		
Sloped roof	1	plaster	0.010	0.900	840	1800	1.230	0.260
	2	slab	0.200	0.743	1000	1800		
	3	light concrete screed	0.050	0.127	1000	400		

The external walls, show in Figure 3 as “WALL 0”, are composed of perforated bricks (25 cm) and polyurethane foam (6 cm). They reach a steady thermal transmittance of 0.36 W/m^{2}K, satisfying the hygrothermal performance test (Glaser).

In Table 3 the thermal properties and the investment costs are reported for external walls, including the walls used in the reference scenario.

Table 3
Physical properties and investment costs of external walls

type	**description**	**layer**	**material**	**t**	**λ**	**c**	**ρ**	**cost**	**Cost + VAT**
			from internal to external side	**(m)**	**(W/mK)**	**(J/KgK)**	**(kg/m^3)**	**€/m^2 - €/m^3**	**€/m^2 - €/m^3**
		1	Perforated brick	0.250	0.281	1000	800	12.1	14.7
W0	**thick**	**2**	Polyurethane foam	0.060	0.035	1450	35	9.8	11.9
		1	Concrete	0.090	1.670	880	2200	120.0	146.4
		2	Wood fibre panel	0.080	0.046	2100	230	130.0	158.6
		3	Hemp fibres	0.040	0.030	2200	38	331.0	403.8
		4	Wood and hemp fibre panel	0.040	0.042	2100	190	130.0	158.6
W1	**thick**	**5**	Wood and hemp fibre panel	0.019	0.048	2100	230	130.0	158.6
		1	Concrete	0.090	1.670	880	2200	120.0	146.4
		2	Wood and hemp fibre panel	0.020	0.048	2100	265	130.0	158.6
		3	Wood fibre panel	0.120	0.042	2100	190	130.0	158.6
		4	Wood fibre panel	0.022	0.048	2100	270	130.0	158.6
W2	**thick**	**5**	Wood and hemp fibre panel	0.019	0.048	2100	230	130.0	158.6
		1	Concrete	0.050	1.670	880	2200	120.0	146.4
		2	Wood fibre panel	0.080	0.046	2100	230	130.0	158.6
		3	Polyethylene foam	0.004	0.048	2092	33	74.3	90.6
		4	Polyester fibres	0.020	0.024	1453	36	130.0	158.6
W3	**thin**	**5**	Wood and hemp fibre panel	0.040	0.042	2100	190	130.0	158.6
		1	Concrete	0.060	1.670	880	2200	120.0	146.4
		2	Wood fibre hardboard	0.060	0.039	2100	160	130.0	158.6
		3	Wood and hemp fibre panel	0.040	0.042	2100	190	130.0	158.6
		4	Wood fibre hardboard	0.020	0.039	2100	160	130.0	158.6
W4	**thin**	**5**	Wood fibre panel	0.020	0.039	2100	160	130.0	158.6

	U	**Y_{12}**	**Y_{22}**	**Y_{11}**	**fd**	**Ms**	**Δt**	**k_1**	**k_2**	**d**
type	**(W/m^{2}K)**	**(W/m^{2}K)**	**(W/m^{2}K)**	**(W/m^{2}K)**	**-**	**(Kg/m^2)**	**(h)**	**(kJ/m^{2}K)**	**(kJ/m^{2}K)**	**(m)**
W0	0.360	0.056	0.540	2.840	0.156	202.00	10.69	39.8	8.2	0.310
W1	0.215	0.040	1.209	5.833	0.185	229.89	13.38	80.6	16.8	0.269
W2	0.230	0.033	1.294	5.847	0.144	236.41	14.71	80.6	17.8	0.271
W3	0.263	0.093	0.990	5.014	0.356	136.85	10.05	70.2	14.8	0.194
W4	0.269	0.089	0.963	5.348	0.332	155.60	10.29	74.7	14.4	0.200

Windows are composed of a metal frame, F0 (U_f=2.3 W/m^{2}K), a double low emissivity glass with argon cavity (U_g=1.1 W/m^{2}K) and an aluminium spacer (16 mm, y_g=0.11 W/mK) [Table 4]. Windows placed to the West and East sides are equipped with blinds, while internal white curtains are placed in the South and North side.

Table 4
Physical properties and investment costs of windows

orientation		quantity	width	eight	window area	total window area	thermal transmittance			
							F0	**F1**	**F2**	**F3**
							U_f = 2.3 W/m^{2}K	**U_f = 1.2 W/m^{2}K**	**U_f = 1.3 W/m^{2}K**	**U_f = 1.8 W/m^{2}K**
							g = 0.60 - U_g = 1.10 W/m^{2}K			
							y_g = 0.11 W/mK	**y_g = 0.08 W/mK**		
							τ_n = 25	**τ_n =30**	**τ_n =20**	**τ_n =30**
		n.	**L**	**H**	**A_W**	**$A_{W,tot}$**	**$U_{W,F0}$**	**$U_{W,F1}$**	**$U_{W,F2}$**	**$U_{W,F3}$**
O1	**O2**	**-**	**m**	**m**	**m^2**	**m^2**	**(W/m^{2}K)**	**(W/m^{2}K)**	**(W/m^{2}K)**	**(W/m^{2}K)**
south	east	12	1.00	1.5	1.5	6.00	1.70	1.4	1.4	1.50
west	south	18	1.00	1.5	1.5	27.00	1.70	1.4	1.4	1.50
west	south	4	0.50	2.5	1.3	1.25	1.90	1.5	1.5	1.60
east	north	24	1.00	1.5	1.5	30.00	1.70	1.4	1.4	1.50
north	west	8	1.00	1.5	1.5	12.00	1.70	1.4	1.4	1.50
north	west	4	0.70	1.5	1.05	4.20	1.80	1.4	1.4	1.50
window 1.00x1.50						cost (€)	746.10	586.50	490.50	844.00
						cost+VAT (€)	820.70	645.20	539.60	928.40
window 0.50x2.50						cost (€)	471.25	432.00	393.00	602.00
						cost+VAT (€)	518.40	475.20	432.30	662.20
window 0.7x1.50						cost (€)	522.27	478.00	414.00	788.00
						cost+VAT (€)	574.50	525.80	455.40	866.80

2.1.3 Technical systems

The air conditioning system consists of a AHU useful to satisfy the thermo-hygrometric conditions of the environments of the building located in a warm climate area. Heating and cooling coils integrate a unit for heat recovery useful to guarantee an indoor air quality. The air reaching the ventilation unit undergoes a pretreatment in order to reduce the demand of the coils useful to reach the thermal conditions. The generation system consists of a centralized air-source heat pump useful for heating, cooling and domestic hot water demand. DHW is provided by an external tank of 500 l and it is combined with a heating system. There are four solar collector panels having an area of 2 m^2 for each one, with an efficiency of 55%, and 24 monocrystalline PV panels having a total area of 36 m^2 with 17% efficiency and 6 kW peak power.

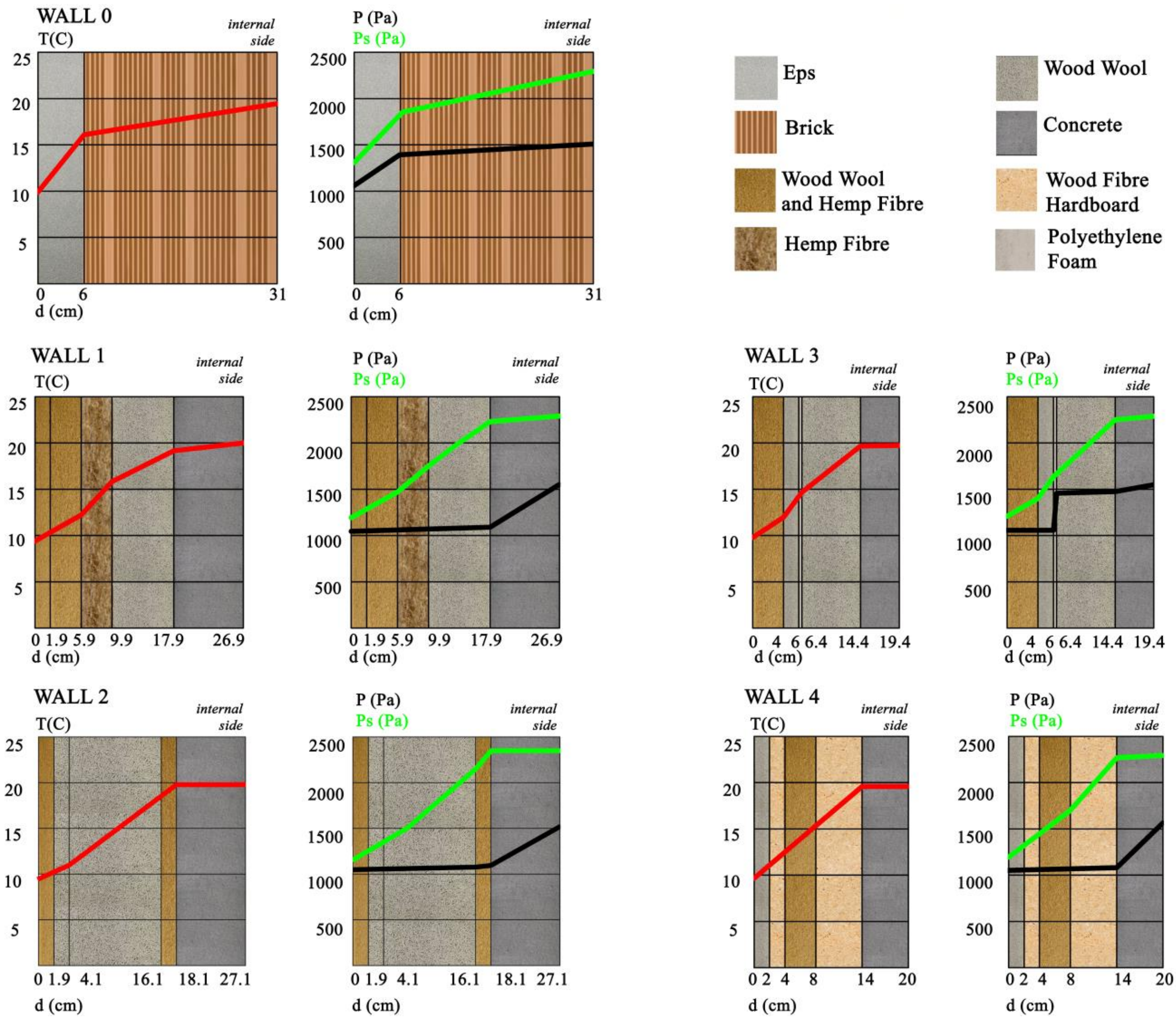

Fig. 3. Variants of the external walls and Glaser test.

Lighting is designed with high-efficiency lamps provided with an automatic control system. Control and efficient lamps have been chosen to obtain a lighting consumption lower than standard values. In particular, the three different variants related to lighting are calculated through the rapid method suggested by UNI EN 15193 [39]. This one offers an estimation of yearly energy lighting consumption corresponding to different building types. The annual energy requirement is the sum of W_L (energy demand to satisfy lighting and final uses) and W_P (annual parasitic energy). The calculation is carried out using default reference values that are reported in Appendix F (Table F.1) of [37]. The rapid method gives LENI (lighting energy numerical indicator) values higher than those obtained with the complete method using the same software. Related to office use this value is equal to 35.3 kWh/m^{2}y for non-steady automatic control and 32.2 kWh/m^{2}y for steady automatic control.

2.2 Identification of energy efficiency measures

Energy efficient technological measures have to be properly applied to the reference building with the aim of reducing its energy demand. Different types of walls, windows and technical systems (heating and cooling, ventilation, generation and PV panels) have been considered as variants to obtain high efficient combinations to be compared in terms of energy performance.

Primary energy consumption is closely linked to greenhouse gases production, therefore a reduction of energy demand can decrease CO_2 emissions. An energy performance improvement can be obtained using eco-friendly materials that have a lower environmental impact. Prefabricated units are showing good results in this field.

Precast walls have been chosen as variants to obtain a highly efficient envelope, considering the important benefits that this technology presents in comparison with walls realized *in situ*. Among the advantages that this choice offers there is a decrease of waste, water consumption, construction time and processing. Furthermore, the office work space that result is clean and safe [40, 41]. Several construction materials have been combined to obtain different types of highly efficient precast walls for a warm climate [42,43].

The dynamic performances of the different components have been evaluated through a multi criteria analysis performed using *Modefrontier rel.4.3.* optimization tool [44] and *MatLab rel.7.0* [45]. The full methodology of this research is available in [46, 47].

In accordance with the standard EN ISO 13786 [48], the analysis has been carried out in terms of steady thermal transmittance, periodic thermal transmittance, decrement factor, time shift, heat capacity per unit area, thermal admittance, surface mass, and total thickness. A database of materials containing design thermal conductivity, specific heat capacity, density and thickness has been considered.

The optimization has been implemented taking into account thermal efficiency as well as costs and eco-friendly features of the whole package. In particular, the latter is evaluated following the Itaca Protocol (Institute for Innovation and Transparency of Contracts and Environmental Sustainability). The most important properties of eco-friendly building materials are that they are not toxic, reusable, renewable, recycled and locally available [49]. Table 3 and Figure 3 show the selected highly efficient external precast walls: W1, W2, W3, W4. The first two ones are thick walls (25-28 cm) while the last two ones are thin (18-20 cm).

A check related to steady thermal transmittance values in agreement with national limits and the hygrothermal performance test (Glaser) have also been carried out.

The use of eco-friendly elements allows a reduction of primary energy and costs. Windows are included as variants, in order to reach a high performance with the right window design that considers the climate [50, 51]. As windows account for approximately 30-50% of transmission losses through the envelope, an improvement of their energy performance lead to a decrease of the building energy demand [52]. This can be achieved upgrading the thermal features of the framework, the glazing and the effects due to their interaction. For this reason, a careful choice of window position and type is crucial to avoid thermal losses through the envelope [Table 4]. Windows present mobile screening with the variants of overhang (L=1.5 m for each floor).

2.3 Establishment of technical variants and combinations

MS should identify energy efficiency measures based on RES, packages and variants [5]. In particular, the latter ones should be applied to building structures, systems and consolidated variants.

The interaction between systems (i.e. external insulation affect capacity and size of building systems) has to be taken into account when defining packages and variants. Therefore, as suggested in [4], measures have been combined to find those that perform better than single measures. Optimizing energy consumption of HVAC systems and using renewable are a useful way to reduce greenhouse gases, global costs and pollution. High efficiency elements, such walls and windows, together with high performing heating, ventilation and air conditioning systems as well as RES, are the main considered variants of this research. Therefore, a selection of technical systems has been considered. The first type consists of a HVAC system with fan coils to satisfy heating, cooling and dehumidification. A static heat recovery for ventilation is present at each floor. The generation option is a centralized geothermal heat pump with ground heat source. A variation of number and peak power values of PV panels has been taken into account. Table 5 and Table 6 report the variants of the measures, their efficiencies and investment costs. Building orientation has been also considered variable with the position of the side having the steepest roof passing from West to South.

The summary of the variants related to walls, windows, conditioning and ventilation, production, DHW, and renewable sources are grouped in packages to establish a series of combinations.

Table 5
Technical system variants

Generation

type	description	energy carrier	heat source	unit number	P_h	P_c	$T_{h.out}$	$T_{w.out}$	COP	SEER
					(kW)	(kW)	(°C)	(°C)		
G0	centralized heat pump	electricity	air	1	25.8	24.0	45	40	2.89	2.33
G1	centralized heat pump	electricity	ground	1	25.3	22.1	45	40	4.04	5.14

Emission

type	description	unit number		η_e	η_d	η_r	η_s
		n.		(%)	(%)	(%)	(%)
H/C0	air handling unit	1		94	95	98	100
H/C1	fancoil	44	4	96	95	98	100

Ventilation

type	description	unit number	$q_{v,e}$	$q_{v,tot}$	$\eta_{\Theta w,d}$	$\eta_{\Theta s,d}$	SFP_d	V_N	t_B	n_w	n_s
		n.	(m^3/h)	(m^3/h)	(%)	(%)	(Wh/m^3)	(m^3)	(h/d)	-	-
V0	heat recovery	1	1280	7680	83	70	0.7	2077	12	0.15	0.94
V1	CMV	4	320	350	88	50	0.88	519	12	0.14	0.31

Domestic hot water

type	description	$\eta_{e.w}$	$\eta_{d.w}$	$\eta_{s.w}$	V	t_i	T_{st}	h_{st}
DW0	external tank + heating combination	(%)	(%)	(%)	(l)	(cm)	(°C)	(h)
		95	96	67	500	7	50	24

Renewable energy sources

type	description	A_N	N_o	P_{peak}	f_s	f_N	η_k
		(m^2)	-	(kW)	degrees	degrees	(%)
SC0	solar collector panels	2	4	-	90	30	55
SC1		2	4	-	0	30	55
PV0	photovoltaic panels	1.5	24	6.00	90	30	17
PV1		1.5	36	9.00	90	30	17
PV2		1.5	24	6.00	0	30	17
PV3		1.5	36	9.00	0	30	17

The European Commission has shown that the minimum number of combinations should not be less than 10 variants or packages, in addition to the reference scenario [4, 5], to obtain an accurate cost-optimal solution; 256 combinations (4 walls * 4 frames * 2 generations * 2 heating/cooling systems * 4 PV systems = 256 combinations) of design variants have been considered for the reference building of this study.

Table 6
Lifespan and investment costs of technical system

description			lifespan	cost	cost+VAT
				€/u.-€/m	€/u.-€/m
conditioning - ventilation (H/C0-V0)	cell (4 ranks)	u	20	3870.00	4257.00
	plenum with vents	u	20	228.80	251.68
	plenum with grid and filter	u	20	1163.71	1280.08
	grid	u	30	502.51	552.76
	filter	u	15	367.95	404.75
	post-heating cell	u	20	1651.79	1816.97
	heat exchanger	u	20	3862.00	4248.20
	distribution duct 1	m	30	281.33	309.46
	distribution duct 2	m	30	115.52	127.07
	distribution duct 3	m	30	27.4	30.14
	vent	u	20	18.95	20.85
conditioning (H/C1)	unit emission	u	15	250.00	275.00
	regulation	u	20	90.00	99.00
	distribution pipe	m	30	10.85	11.94
	collector	u	20	350.00	385.00
	hp collector	u	20	350.00	385.00
ventilation (V1)	grid	u	20	72.00	79.20
	regulation	u	15	36.00	39.60
	distribution pipe	m	30	11.74	12.91
	cmv pipe	u	30	26.39	29.03
	distribution box	u	30	66.00	72.60
	cmv	u	20	915.00	1006.50
Generat. and RES	heat pump (G0)	u	15	12323.00	13555.30
	heat pump (G1)	u	15	7952.00	8747.20
	geothermal probe (G1)	m	30	40.91	45.00
	pv panel	u	20	300.00	330.00
	inverter	u	20	790.00	869.00

2.4 Assessment of energy performance and global costs with sensitivity analysis

The demand of heating, cooling, ventilation, DHW and lighting of the combinations applied to the reference scenario, has been calculated using ProCasaClima2015 for each combination. The calculation tool shows a clear sensitivity of the climate data compared to the most popular dynamic software [53].

The software performs dynamic simulations using hourly weather data provided by the Italian Heat Technology Committee. UNI TS 11300 (part1, part2) have been included in the calculation tool to estimate thermal energy demand in summer and winter [7]. The heat exchange with the ground (UNI EN ISO 13370 [54]) can be also assessed as well as global efficiency of building-plants and CO2 emissions. The results of the dynamic simulation allow to classify the comfort of the indoor environment according to the UNI EN 15251 [55].

A dynamic calculation method has been used for the evaluation of energy consumption of all main uses according to Standard EN ISO 13790 in relation to heating and cooling energy requirements [56].

The calculation tool estimates the global cost by the application of UNI EN 15459 [6] where the global costs is defined in terms of net present value.

The global costs (C_G) has been carried out considering an initial investment CI and an annual cost for every year *i* (referred to the starting year) for each component or system *j*, and a final value according to the Regulation, with a calculation period (τ) of 20 years.

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j) \right] \quad (1)$$

Investment costs refer to the prices drafted by the Puglia Region and a market survey. The goal is to encourage the local market and decrease emissions from transport.

The calculation of primary energy consumption is carried out in accordance with the specified conversion factor values: 1.00 for natural gas, 2.17 for the electricity network and 1.00 for renewable sources. The CO2-eq emission factors considered for the calculation are 0.249 $kgCO_2/kWh$ for methane gas and 0.647 $kgCO_2/kWh$ for electricity [57, 58].

The Regulation [5] gives the possibility to evaluate global costs for the whole building, or only renovated components. It also establishes two possible procedures presenting a financial and macro calculation approach. The first takes into account taxes, VAT, charges and subsides, while the second includes the costs of released greenhouse gases, defined as the monetary value of the environmental damage caused by CO_2 emissions related to a building energy consumption. NREAP (National Renewable Energy Action Plan) provides the cost data for calculations until 2045 [25].

The reference scenario of this research is a non-residential building (office), so a calculation period of 20 years is taken into account to estimate the global costs of the established configurations. Furthermore, a variation of the discount rate and the development rate of the energy price has been considered to give an *ex-ante* evaluation of cost-optimality through a sensitivity analysis [Table 7].

Table 7
Financial parameters and energy costs

Calculation period - [τ]	20 years		
Inflation rate - [R_i]	3.0 %		
Market interest rate - [R]	5.6 %	6.1%	7.1%
Real interest rate – [R_r]	2.52 %	3.00 %	4.00 %
Design payback period of building – [$\tau_{\_building}$]	50 years		
Rate of development of the price for products – [R_p]	0.0 %		
Rate of development of the price for human operation – [R_o]	0.0 %		
Rate of development of the price for fossil energy – [$R_{e,1}$]	2.8 %		
Rate of development of the price for biomass – [$R_{e,2}$]	2.0 %		
Rate of development of the price for electricity – [$R_{e,3}$]	2.40 %	2.80 %	
Rate of development of the price for maintenance – [R_m]	0.0 %		
Rate of development of the price for added costs	0.0 %		
Cost of natural gas (methane)	0.093 €/kWh		
Cost of electricity	0.25 €/kWh		

3. Results and discussion

The paper presents a set of 256 combinations showing a variation of primary energy compared to the reference scenario. The assessment of the energy demand of the reference building shows that the office fall within class B with a primary energy consumption of 125.72 kWh/m^{2}y, 37 kgCO_2/ m^{2}y of greenhouse gas emission and a global cost of 350.82 €/ m^2. Figure 4 shows the primary energy and CO_2 gas emissions values for all combinations. In particular, it is possible to note that the results of combinations are represented in seven different ranges. The best performing combinations constitute 6.25% of all solutions with the lowest primary energy consumption between 76.4 and 77.6 kWh/m^{2}y, and 41 % CO_2 emission reduction compared to the reference building. The good results of this group has been obtained through the combination of variants that have high performance for a warm climate, such as the transmittance of the external walls and windows, the high efficiency of geothermal heat pump and the good orientation of the panels for RES. However, the lower reduction of primary energy values (from 121.5 kWh/m^{2}y to 123.1 kWh/m^{2}y) and CO2 gas emissions (36 KgCO_2/m^{2}y), compared to the reference case, constitutes the same percentage, 6.25%; in the middle, 37.50% of combinations present a primary energy value between 97.6 and 100.4 kWh/m^{2}y with a reduction of CO_2 emissions of 22%.

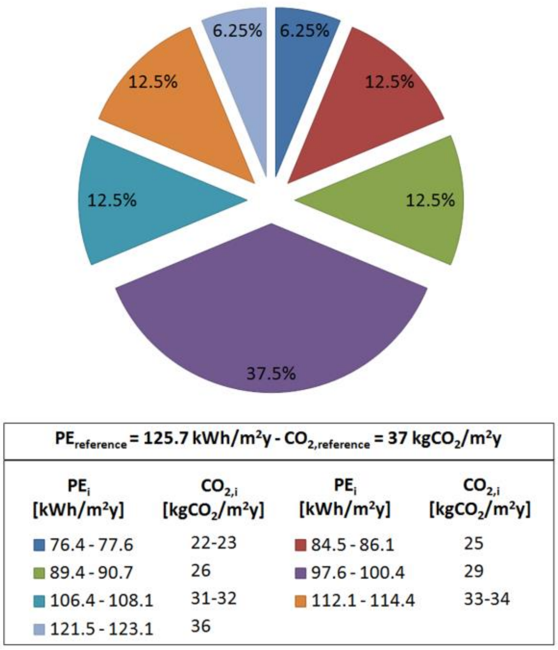

Fig. 4. Ranges value of primary energy consumption and CO_2 gas emission.

Figure 5 shows the cost-optimal solutions derived from a financial analysis carried out for the 256 combinations. Seven intervals of primary energy consumption have been identified and different symbols and colours for wall and window combinations have been used to better visualize the composition in terms of cost. The different kinds of variants define the intervals of primary energy consumptions. Table 8 reports for each range of primary energy consumption and CO_2 gas emissions the combinations of technical systems adopted. As shown in figure 5, all point of the intervals are characterized by different kind of envelope (windows and external walls). The best range of solutions includes the combination of photovoltaic panels orientation through the South and total number of 36 (PV3-OV2) with the geothermal probes for generation system (G1).

Table 8
Technical system variants of each PE and CO2 range

Total number of simulations (%)	PE range (kWh/m^2y)	CO_2 emission $kgCO_2/m^2y$	Technical system variants						
6.3	76.4 - 77.6	22-23	OV2	G1	H/C1	V1	DH0	SC1	PV3
12.5	84.5 - 86.1	25	OV2	G1	H/C0	V0	DH0	SC1	PV3
			OV2	G0	H/C1	V1	DH0	SC1	PV3
12.5	89.4 - 90.7	26	OV1	G1	H/C1	V1	DH0	SC0	PV1
			OV2	G1	H/C1	V1	DH0	SC1	PV2
37.5	97.6 - 100.4	29	OV1	G1	H/C1	V1	DH0	SC0	PV0
			OV1	G1	H/C0	V0	DH0	SC0	PV1

			OV1	G0	H/C1	V1	DH0	SC0	PV1
			OV2	G1	H/C0	V0	DH0	SC1	PV2
			OV2	G0	H/C1	V1	DH0	SC1	PV2
			OV2	G0	H/C0	V0	DH0	SC1	PV3
12.5	106.4 - 108.1	31-32	OV1	G1	H/C0	V0	DH0	SC0	PV0
			OV1	G0	H/C1	V1	DH0	SC0	PV0
12.5	112.1 - 114.4	33-34	OV1	G0	H/C0	V0	DH0	SC0	PV1
			OV2	G0	H/C0	V0	DH0	SC1	PV2
6.3	121.5 - 123.1	36	OV1	G0	H/C0	V0	DH0	SC0	PV0

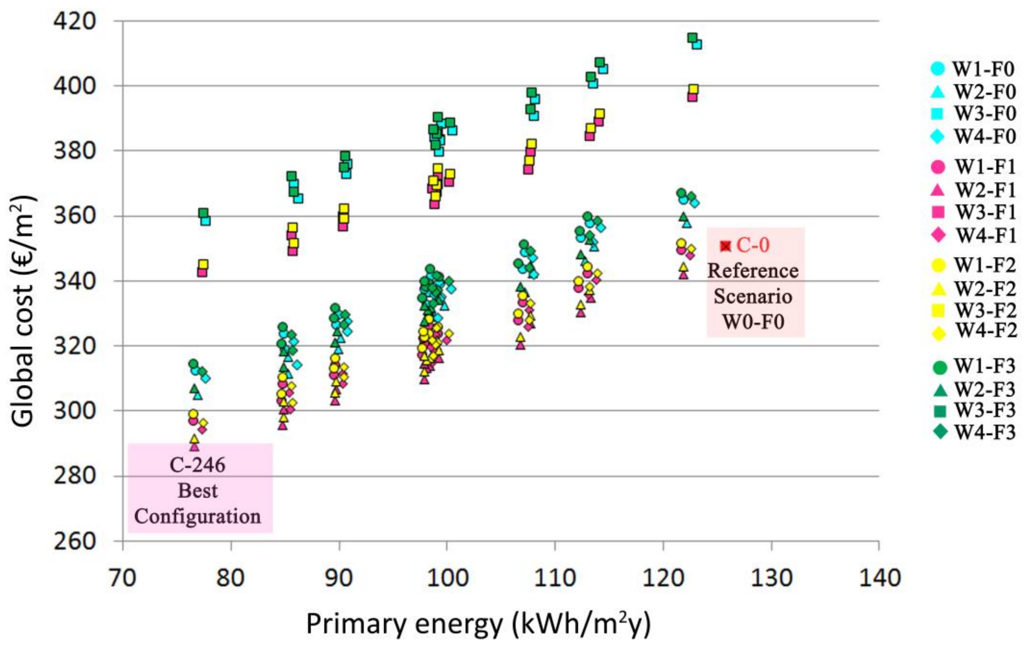

Fig. 5. Global cost-optimal values of all combinations.

Figures 6 and 7 show the cost-optimal curve and the sensitivity analysis obtained for the most performing combination range (primary energy between 76.4 and 77.3 kWh/m^{2}y) using a financial and macro analysis respectively.

Both ranges of values include the same type of technical systems variants, centralized geothermal heat pump for generation (G1), fancoil for heating and cooling (H/C1), CMV for ventilation (V1), solar collectors (SC1) and photovoltaic panels (PV3) oriented towards the south [Table 9].

Table 9

Combinations and output values of best configurations

combo	wall	window	overhang	generation	emission	ventilation	dhw	RES		CO_2	PE	Class	GC-f	GC-m	CO_2	PE
C-00	W0	F0	OV0	G0	H/C0	V0	DH0	SC0	PV0	37	125.72	B	350.82	334.73	-	-
C241	W1	F0	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.67	A	312.91	292.22	40.54%	39.02%
C242	W1	F1	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.37	A	297.42	278.54	40.54%	39.26%
C243	W1	F2	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.39	A	299.59	280.08	40.54%	39.24%
C244	W1	F3	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.39	A	315.00	294.08	40.54%	39.24%
C245	W2	F0	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.78	A	305.32	286.00	40.54%	38.93%
C246	W2	F1	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.47	A	289.83	272.32	40.54%	39.17%
C247	W2	F2	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.5	A	292.00	273.86	40.54%	39.15%
C248	W2	F3	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	76.55	A	307.44	287.92	40.54%	39.11%
C249	W3	F0	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.59	A	358.93	331.04	37.84%	38.29%
C250	W3	F1	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	77.26	A	343.04	316.55	40.54%	38.54%
C251	W3	F2	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.29	A	345.27	318.58	37.84%	38.52%
C252	W3	F3	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.34	A	361.12	332.99	37.84%	38.48%
C253	W4	F0	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.6	A	310.33	291.67	37.84%	38.28%
C254	W4	F1	OV2	G1	H/C1	V1	DH0	SC1	PV3	22	77.28	A	294.48	277.12	40.54%	38.53%
C255	W4	F2	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.3	A	296.70	278.70	37.84%	38.51%
C256	W4	F3	OV2	G1	H/C1	V1	DH0	SC1	PV3	23	77.3	A	312.43	293.01	37.84%	38.51%

The best combination (Combo C-246) has a primary energy value of 76.47 kWh/m^{2}y. It has a global cost of 289.83 €/ m^2 and 272.32 €/ m^2 in financial and macro terms respectively. A sensitivity analysis has been reported for the cost-optimal combination established with a variation of investment, operating and energy costs, changing discount rate and development rate of energy price both in financial and macro analysis.

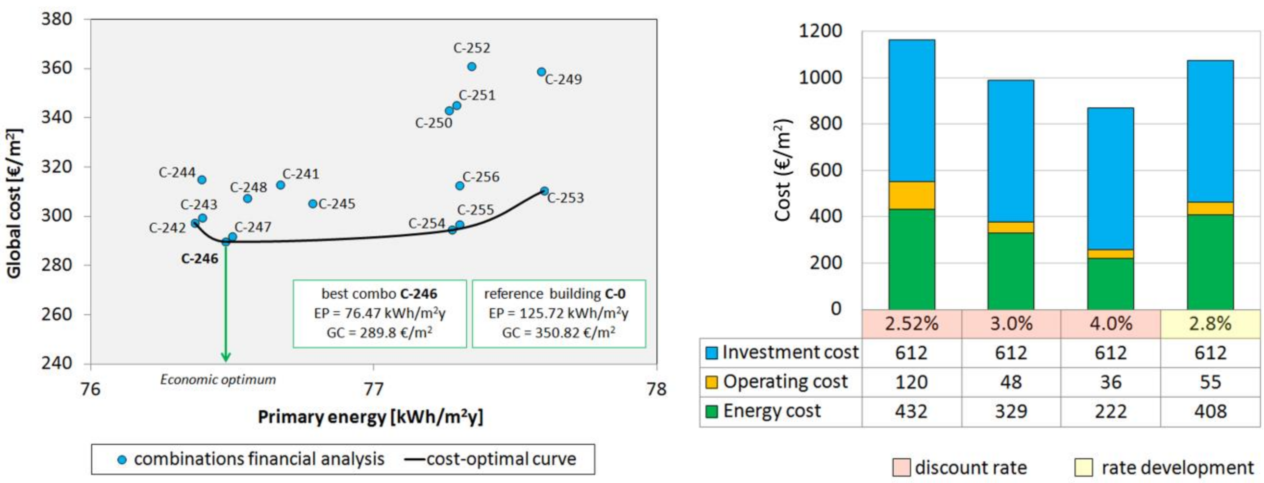

Fig. 6. Cost-optimal curve for the best sixteen configurations and sensitivity analysis of the best one – financial analysis.

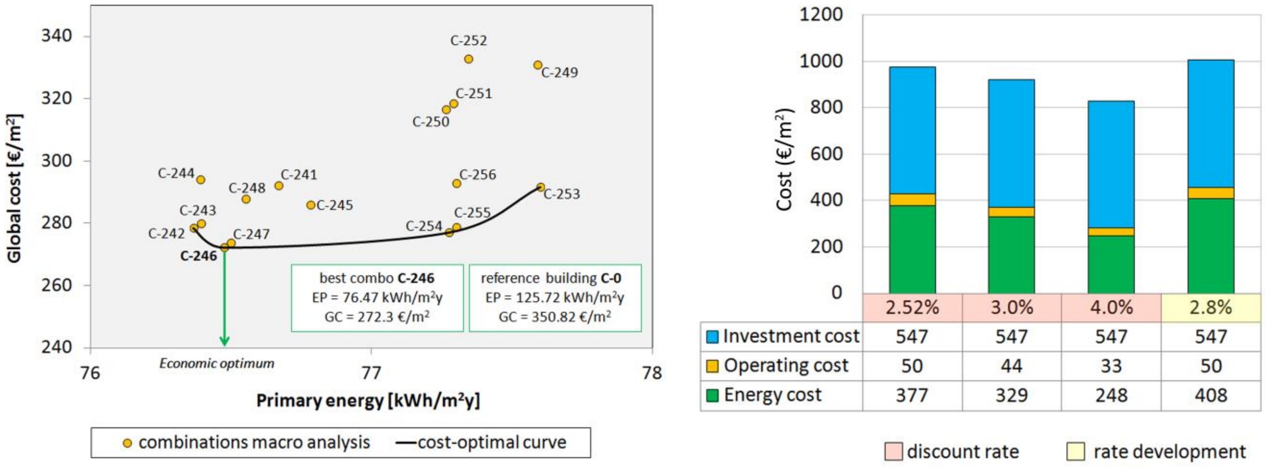

Fig. 7. Cost-optimal curve for the best sixteen configurations and sensitivity analysis of the best one – macro analysis.

A direct comparison has been made between the best configuration and the other combinations, by changing one parameter at a time. The cost-optimal result of all tested combinations for a warm climate is an envelope consisting of precast external walls with a high eco-friendly score and a low cost, and windows with wooden frames. The best performance of the external walls can be reached, in the warm climate, by the superficial mass and internal areal heat capacity. In particular, the internal side is characterized by high surface mass, the middle layers by eco-friendly insulating materials and the outer layer by common insulating materials. This configuration constitutes the best solution for precast walls in order to obtain high performance also in the summertime. The wall of the best solution (W2, thick wall) has a very low value of transmittance compared to the law limits, and a high surface mass with an optimal time shift ($U = 0.23$ W/m^{2}K, $M_s =$ 236.41 kg/m2, $\Delta t = 14.61$ h, d= 27.10 cm). The wooden frame (F1) helps to reduce energy consumption due to its properties ($U_f = 1.2$ W/m^{2}K); it is a material through which achieve balance between quality and costs. The comparison between the best solution and the combinations obtained by this one changing only the walls (comparison between C-246 and C-242, C-250, C-254), shows a steady reduction about 39% of primary energy consumption, and a different reduction in terms of global costs compared to the reference building. The global costs reduction of the best solution is about 61 €/m^2, while the worst among the four combinations only about 8 €/m^2. The different types of frame have shown (combinations C-245, C-246, C-247 e C-248) a steady reduction both for primary energy consumption and global costs. Therefore, the walls have a larger impact on global costs.

As regard plant systems, the variation of the air heat pump (G0) with a geothermal heat pump (G1), (C-230, C-246), has been shown a greater reduction of primary energy and global costs values for the best solution as well as CO_2 gas emission compared to the reference building. For combination C-230, the reduction of PE is about of 33% as well as for CO_2 emission, while a percentage about 39% and 41% for C-246, defining a gap of 6-8%. The implementation of geothermal probes decrease the energy consumption by the good conditions of the ground temperature that facilitates the decrease of air temperature fluctuations, keeping the behavior of the heat pump stable [59].

A minimum difference of output values is found between the solutions (C-214 and C-246) that have different types of emission systems (H/C0-V0; H/C1-V1). The high emission efficiency of fancoil and the integration of controlled mechanical ventilation, define a gap between the combinations of 8.11% for the reduction of CO_2 emission, 6.57% for the reduction of primary energy consumption and 11.33 €/m^2 for the global costs. The implementation of CMV for each floor demonstrates that the heat recovery increase the performance of the building through to the pre-treatment of air reducing the primary energy consumption related to heating and ventilation.

A comparison between combination C-118 (PV1-SC0, west orientation of the panels) e C-246 (PV3-SC1, south orientation of the panels) has been shown that the values for these two kind of solutions differ of 10.47% as regards the primary energy reduction, of 17.23 €/m^2 as regards global costs and 10.81% as regards the reduction of CO_2 gas emissions. In particular, PV plant covers a maximum of about 30% of the total electricity demand required when the orientation of the panels is directed towards the south. Only a portion of energy is covered because the energy requirement are significant for use destination, so there isn't a surplus of energy produced on-site.

These results confirm that, for warm climate, the measures that have most influence on the reduction of primary energy are the heat pump with geothermal probes [59, 60] and orientation of the panels to the south, while the walls affect the global costs. About the efficiency, the combinations with geothermal heat pump provide higher performance and lower global cost than those with air-source heat pumps. The integration of photovoltaic system with self-consumption allows a greater reduction of both costs and energy consumptions ($PE_{reduction}$ = 39.17%, $CO_{2,reduction}$ = 40.54%, $GC_{reduction}$ = 60.89 €/m^2), as well as the use of fan coil for heating, cooling and dehumidification and CMV with static heat recovery for ventilation. In particular, in winter, the geothermal system reduces the power required by the generator for heating. Moreover, the CMV allows the renewal of air and the recovery of heat from stale air, reducing heating requirements. In summer, the implementation of the electricity as energy carrier is useful to facilitate and exploit the use of renewable energy sources that have an high performance for the southern Italy, a warm climate zone.

Furthermore, there are combinations that have higher values of global cost than the reference building despite there is an evident reduction of primary energy consumption (Figure 5).

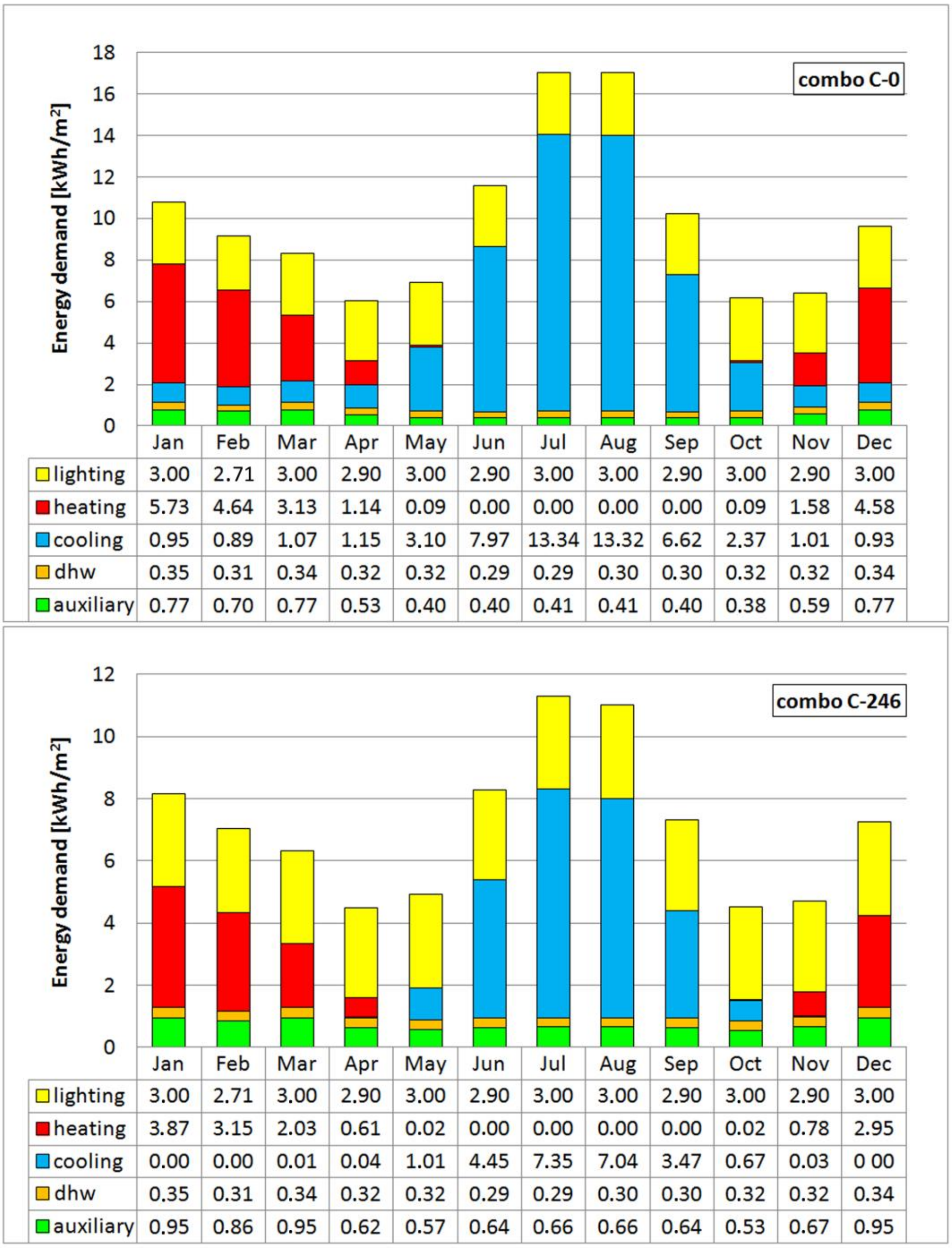

Fig. 8. Energy demand for the reference building and cost-optimal configuration.

The energy requirements of the building, referred to electrical uses, have been obtained for each combination, including the reference scenario. In particular, for the base case the highest values are referred to the cooling and lighting demand (52.71 kWh/m^2, 35.28 kWh/m^2 respectively).

The best range shows an average value of cooling energy requirement of 23.92 kWh/m^2, while the auxiliary energy requirement grows in average of 2.23 kWh/m^2. This last value not influence the total energy reduction, that passes from a 118.92 kWh/m^2 for the reference building to an average value of 86.06 kWh/m^2 for the best range.

Histograms in figure 8 show the energy requirements in relation to final uses for the reference and the best configuration during each month. There is an evident decrease of cooling and heating demand compared to the reference building.

4. Conclusions

The merge between the implementation of nZEBs and the assessment of cost-optimality represents one of the major challenges that the EU will face in near future. As established by the EPBD, the nZEB target has to be achieved in new and existing buildings undergoing renovation. According to Delegated Regulation No 244/2012 and its Guidelines, minimum energy performance requirements corresponding to cost-optimal levels have to be derived in MS from a technical and economic perspective.

This paper presents the application of the comparative methodological framework reports in EPBD to identify cost-optimal solutions in a new non-residential building used as an office in a warm climate. The main achieved goal regards the establishment of high performance buildings presenting cost-optimal and nearly zero energy requirements.

Common building manufacturing, materials and technical systems are used. The established 256 combinations have shown varying primary energy and CO_2 emissions. In particular, a ranges value of primary energy consumption and CO_2 gas emissions have been reported in order to give the different weight of the measures. The results show that the best performing solutions range is between 76.4 and 77.3 kWh/m^2y of primary energy consumption with 22 kgCO_2/m^2y compared to the reference scenario (125.72 kWh/m^2y, 37 kgCO_2/ m^2y, 350.82 €/ m^2). This range has been achieved due to the implementation of heat pump with geothermal probes (G1), fancoil for heating, cooling and dehumidification (H/C1), CMV for ventilation (V1), orientation towards the south for solar collectors (SC1, n = 5) and the photovoltaic panels (PV3, n = 36). The best configuration (Combo C-246) reaches a reduction of primary energy consumption of 39% and 41% of CO_2 gas emissions, ranking in average energy consumption level for this type of climate zone (for office, placed in Madrid, is equal to 74.27 kWh/m^{2}y) [61]. This level has been achieved through the implementation of precast external walls (W2) with a high eco-friendly score and a low cost, and windows with wooden frames (F1).

The cost-optimal configuration obtained from a financial analysis presents 60.99 €/ m^2 cost reduction from the reference building. The cost-optimal configuration deriving from a macroeconomic analysis shows a global cost lower than 62.4 €/ m^2.

Results also show that the superficial mass of external walls is important to obtain the best performance in a warm climate. The research suggests to move the layer with a high thermal internal capacity towards the inner side and to place an insulating coat towards the outer side. Furthermore, different solutions can be defined to maximise the contribution from renewable sources in a warm climate. Among them, the use of high efficiency window frames, efficient generation and HVAC systems, and RES.

This study is useful to support the design of nZEBs, to guide the investment decisions according to national requirements, and to identify the cost-optimal solutions in terms of high energy performance and global costs for warm climate. In particular, it permits to reduce the cooling demand improving thermal internal conditions and using local resources. In addition, this study is useful to define a method with several parameters in the different climate, not only for a building located in a Mediterranean area.

Author Contributions

All authors participated in preparing the research from the beginning to ends, such as establishing research design, method and analysis. All authors discussed and finalized the analysis results to prepare manuscript according to the progress of research.

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