ASSESSMENT OF COST-OPTIMALITY AND TECHNICAL SOLUTIONS IN HIGH PERFORMANCE MULTI-RESIDENTIAL BUILDINGS IN THE MEDITERRANEAN AREA

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Abstract

The European policy framework is focused on reducing energy consumption in the building sector. The recast of Energy Performance of Buildings (EPBD) Directive establishes that minimum energy performance requirements have to be set to achieve cost-optimal levels.

A methodology is developed to assess energy and cost effectiveness in new buildings located in the Mediterranean area. Several energy efficiency technical variants are applied to a multi residential reference building selected as a representative model of the national building stock. Primary energy consumption and global costs are evaluated in a number of configurations to derive the cost-optimal solution.

The paper shows how economical high efficient buildings can be obtained at a design stage for a warm climate. The selected configuration decreases primary energy consumption by 90% and CO_2 emissions by 88% with respect to the baseline building.

Results appear useful for comparison with other climates and building types. The paper also points out that the methodology is suitable to guide and support the choice of cost effective energy efficiency measures in compliance with EU requirements.

Keywords: EPBD; cost-optimality; Mediterrean climate; reference building; global cost; Zero Energy Building; energy efficiency; envelope; multi-residential; Primary energy.

1. Introduction

1.1 The European framework

The European Climate and Energy package foresees a 20% reduction of energy consumption in buildings by 2020. The Programme also foresees a 20% increase of renewable energy production and a 20% decrease of greenhouse gas emissions. The European Union (EU) promulgates specific measures to reduce energy consumptions in buildings with Energy Performance of Building Directive (EPBD) in 2002 [1], its recast in 2010 [2], Energy Efficiency Directive (EED) [3] and Renewable Energy Directive (RED) [4], in order to improve the energy performance of Member States (MS) building stock.

EPBD recast requires that cost optimality has to be taken into account in the establishment of energy performance requirements in buildings. According to Article 5, MS have to consider initial investment costs, running costs and replacement costs over a building's life cycle. National minimum standards should be set based on cost effectiveness for construction and operational costs in new buildings and buildings undergoing major renovation [5].

The assessment of cost optimality and high performance technical solutions are strictly connected to the implementation of nZEBs, as stated in [6]. Explanatory Guidelines of Delegated Regulation n.244/2012 of January 16, 2012 of the EC [7][8] describe a comparative methodological framework to derive a cost efficient configuration to be adopted in a building.

The overall aim of the calculation is to obtain a cost-optimal level to identify the solution that represents the lowest total costs without discriminating against or promoting any specific technology. A graph that reports global costs (€/m^2) on the ordinate and energy consumption (kWh/m^{2}y) on the abscissa is derived to identify cost-optimality. The point of the curve that belongs to the lower part is indicative of the optimal configuration. The shape of the cost-curve is influenced by several factors, such as building typology, variants definition, discount rate, energy price, and cost data. Sensitivity analysis is suggested to add robustness to calculations, especially when a relatively flat curve is obtained.

The EU framework on cost optimality leaves MS to decide on many important aspects, such as reference buildings, selection of packages of measures, construction costs, maintenance costs of building elements, lifetime of building elements, discount rates, energy price trends, and starting energy prices. The impact of input parameters on the results has been investigated by Leutgob et al [9]. An important factor influencing energy performance is also occupancy behaviour and auxiliary gains [10].

The first step of the cost-optimal methodology is the definition of reference building properties. A reference building represents a “typical building geometry and systems, typical energy performance for both building envelope and systems, typical functionality and typical cost structure", being representative of a country considering its climate and geographic location [8]. The methodological approach to be followed in the definition of reference buildings is still under discussion and it is an important field in the studies related to buildings energy performance [11] [12].

This paper aims at the assessment of cost-optimality in multi-residential reference buildings situated in the Mediterranean area (Lecce, South of Italy). As a first step, a conventional baseline building is described in terms of physical characteristics, envelope and systems. Several energy efficient technical measures are subsequently selected as possible variants for the reference building at the design stage. Energy performance and global costs are evaluated for all the obtained combinations. The cost-optimal solution is identified for the case study. The selected and the initial configurations are finally compared in order to derive potential energy and CO_2 savings.

1.2 Cost-optimal methodology implementation

Results on cost-optimal levels strongly depend on the selected reference buildings (size, shape, compactness, share of window area) and climatic conditions. Generally, in warm climates it is easier to meet the nZEB target, while in cold climates, it is more challenging. Kurnitski et al. identified a solution with a specific heat loss of 0.33 W/Km^2 and a district heating of around 140 kWh/m^{2}y as the cost-optimal level in office buildings located in the cold Estonian climate [13]. Labour costs, material costs, overheads, and value added tax (VAT) are included in energy performance calculations. In the same climate, the cost optimal solution was assessed at 110 kWh/m^{2}y primary energy for a detached house, compared to national minimum requirement of 180 kWh/m^{2}y [14]. Pikas et al. [15] furthermore develop this research considering alternative fenestration design solutions for offices. Among their findings about the most energy efficient and cost optimal solution over 20 years are included triple glazed argon filled windows with a small window to wall ratio, and 200 mm thick insulation on walls [16]. The authors affirm that cost optimality is likely to become more affordable in near future with increasing energy costs and reduction of construction costs of PV panels and/or windows with four panes.

A methodology for economic efficient design of Net ZEBs has been proposed by Kapsalaki et al. in three different climates [17]. The authors conclude that the differences between an economically efficient and economically inefficient NZEBs can be over three times both in terms of initial and life cycle costs.

The EPBD Concerted Action supports MS by the exchange of experiences along the path of implementing a cost optimal methodology [18]. This study reports how the current requirements were too lax compared with their calculated cost-optimal levels in some MS (e.g. Estonia, the Flemish region of Belgium and Lithuania) while in others (e.g. Slovenia) they were more demanding than the cost-optimal point. According to the survey, for each building typology in each climatic zone there is a different cost-optimal level. Moreover, where the reference building is far away from the cost-optimal level, the curve shows a clear optimum with about 10% of additional costs for obtaining a 30% increase in the energy performance in new buildings.

A comprehensive overview on the implementation of the cost-optimal methodology in EU countries has been published by the Buildings Performance Institute Europe (BPIE) [19]. The implication of discount rates, simulation variants, costs and energy prices have been highlighted by the study that reports calculation examples for Austria, Germany and Poland. In Austria current building requirements are very close to cost-optimal levels in multi-residential buildings as the global cost difference between actual building requirements and nZEBs do not exceed 0.15 €/m^2. In Germany additional global costs to reach the nZEB target range between 2 and 8 % with associated CO_2 emissions between 4.2 and 9.5 Kg/m^{2}y in multi-residential buildings. However, the study stresses the need of a further tightening of the current requirements to achieve cost-optimal levels.

Corgnati et al. [20] propose a general methodology for the definition of reference buildings in cost-optimal assessment. Dynamic energy simulations are done to calculate the energy performance of an Italian office building selected as a case study.

De Angelis et al. [21] explain the economic sustainability of different retrofitting strategies in an Italian social housing district. Several refurbishment alternatives are investigated and different funding systems and incentives are analysed. Refurbishment alternatives are also analysed in [22] [23].

Szalay et al. [24] illustrate a methodology to set requirements based on the analysis of a generated large sample of residential buildings located in Hungary. Hamdy et al. [25] conduct a multi-stage methodology to design a cost-optimal nZEB in single family houses in Finland. A simulation-based optimization method is shown and the optimal solution depends on the selected heating/cooling systems, variations of energy costs, energy saving measures and renewables.

Corrado et al. [26] derive energy performance and global cost calculations based on a sequential search-optimization technique. The authors show a cost optimization procedure applying different energy efficiency measures to a reference building of TABULA (Typology Approach for Energy Building stock Assessment) project. This project involved countries from thirteen MS and analysed the European residential housing stock within the Intelligent Energy Europe (IEE) EU Programme. A harmonized structure of European building typologies has been created in order to estimate the energy demand at a national level and predict the impact of energy efficiency measures in existing buildings. Furthermore, De Santoli [27] developed guidelines for energy efficiency in relation to cultural heritage.

TABULA classifies a building typology according to location, construction period, size and shape. Three main approaches towards reference building typologies are possible: Real Example Buildings (ReEx), Real Average Buildings (ReAv), and Synthetical Average Buildings (SyAv) [28].

As regards Italian typologies, eight classes are distinguished in relation to construction periods (from Class I - up to 1900, to Class VIII - after 2005). Each class reflects the characteristics of morphological, constructive, and technical systems of the national stock. Four further classes are defined according to geometry, number of apartments and floors: single-family house, terraced house, multi-family house, apartment block.

1.3 Italian building requirements

A debated issue at the EU level is how to combine harmonised energy performance and costs requirements. The EU legislative framework for buildings requires MS to adopt national definitions and policies for nZEBs implementation considering cost-optimality. The Italian Government implemented EPBD with Legislative Decree 192/05, and EPBD recast with Legislative Decree 63/13. Both Decrees introduce several novelties related to energy requirements, design methodology, and plants inspection.

Among other specific provisions, Legislative Decree 115/08, implementing Directive 2006/32/EC on energy end-use efficiency and energy services, establishes new requirements for the improvement of energy supply security and energy end-uses efficiency from a cost- benefit side. It also provides calculation methodologies related to Energy Certificates for buildings using the official Italian calculation methods UNI TS 11300. National Law 10/91 gives a comprehensive framework related to energy efficiency in buildings. It introduces specific regulations aimed at a more efficient use of energy sources in all end-use sectors. At national level, the Ministry for Economic Development is coordinating a working group, led by the National Energy Agency (ENEA) and mainly involving the Polytechnic University of Turin, for the application of cost-optimal methodologies. A report has been recently published with the main findings of this research that gives an overall guidance on cost-optimality for both new and existing residential as well as offices [29]. The measure of the Energy Performance (EPi) of a building indicates how much energy a building consumes during a year per square meter of treated floor area (TFA). The European average yearly heating consumption has been estimated between 150 and 230 kWh/m^2 in residential buildings [30]. The EPi value has been progressively reduced over time. In Italy, there is an evident difference between a building designed and built according to the current legislation and one constructed before. For example, the EPi of an existing building, built before the application of national Law 10/91, is commonly a value between 200 and 300 kWh/m^2y with fuel consumption between 10 and 30 l oil /m^2y [31]. A building designed and built according to current legislation has usually an EPi value between 15 and 130 kWh /m^2y, with fuel consumption between 1.5 and 13 l oil/m^2y.

An energy performance certificate includes the reference performance of a building as well as other reference values such as maximum energy performance requirements [Table 1]. Seven classes (from A to G) are distinguished in the national energy classification system in function of the energy needs of a building. A class A building requires less than 15 kWh/m^2y, while a Class G building consumes more than 160 kWh/m^2y.

Three high performance energy classes (Gold, A, and B) are identified by the KlimaHaus agency for buildings certification. The first class is the most ambitious, presenting a heating energy consumption of 10 kWh/m^2y, the second class can reach 30 kWh/m^2y consumption, the third includes buildings consuming less than 50 kWh/m^2y. Both classifications are considered as reference in this study.

2. Methods

The main steps followed in this research are: definition of reference buildings, establishment of technical variants, set up of combinations for energy performance assessment, and global cost evaluation.

Macro-economic and sensitivity analyses have been considered for the configurations that define the optimal-cost curve. The evaluation of primary energy consumption and the calculation of the global costs have been carried out using the software ProCasaClima 2015 that also derived heating, cooling, domestic hot water and lighting loads [32]. The software is able to perform energy calculations to evaluate buildings energy requirements in compliance with Directives 2010/31/EU and 2012/27/EU [35]. The Autonomous Province of Bolzano introduced a procedure for the assessment and the improvement of building energy performance using an energy rating system [33]. This tool applies hourly weather data provided by the Italian Heat Technology Committee to carry out dynamic simulations [34]. This approach permitted definition of combinations of energy efficiency measures, to calculate energy performance and costs of the combinations, and to derive the cost-optimal solution for the reference building.

2.1 Reference building description

Reference buildings represent as accurately as possible national building typologies in a given MS. They can be real or virtual. The former represents the most typical building designed with specific geometrical data and thermo-physical properties. The latter is created using statistical information and parameters.

TABULA project has been considered as a reference for the definition of multi-residential reference buildings, considered as a virtual case including traditional materials and systems. The reference building of this research in located in Lecce, where the climate is warm and temperate [36]. The Mediterranean climate is characterized by non-extreme winters (average temperature 13 °C over the last ten years) and high aridity in summer (average temperature 30.3 °C) [Table 2] [36][37].

The Italian territory is divided into six climatic zones (from A to F) based on the number of heating degree-days and Lecce, having up to 1153 heating degree-days, belongs to climatic zone C. The indoor design temperature of a building is 20 °C during the heating period and it is 26 °C during the cooling period [38].

The location of our case study (national climatic zone C, or “Mediterranean zone” according to the Tabula classification) has not been addressed either by the official national study, which focuses on national climatic zones B and E, nor by the Tabula project which focuses on the “Middle Climatic zone”, including municipalities with heating degree days between 2100 and 3000. The representativeness and the meaningfulness of the selected case-study is evidenced by the fact that its 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). Therefore, this study represents a supplementary application of the cost-optimal methodology in another climate characterized by different materials and systems. This assists development of cost-optimal calculations for other reference buildings in different climates, regulations, and conditions in order to test and spread the methodology in the heterogeneous building framework of Italy.

2.1.1 Multi-residential building

The multi-residential building selected as reference building is now described. The construction consists of six apartments disposed on three floors. The apartments on each floor are arranged symmetrically and have the same room disposition, as showed in Table 2 and Fig. 1. The stratigraphy of external walls and structures is shown in Fig.2.

Each apartment is suitable for a single family composed of four people. It consists of three bedrooms, a living room, a kitchen, a corridor, a bathroom and a service-room. The building includes two unheated spaces: an elevator shaft and a stairwell. The structure is simple and compact (S/V=0.56). The internal height of the building is 3.5 m and the treated floor area of each room is reported in Table 2.

Heating and DHW are provided by a condensing boiler with radiators. The cooling system consists of splits, and there are solar thermal and photovoltaic panels as RES [Table 3].

2.2 Energy performance

High energy efficiency measures both for the building envelope and the technical systems are taken into account to reduce the primary energy consumption of the reference building.

2.2.1 High performance envelope: external walls and windows

A multi-objective optimization analysis has been carried out to reach different types of highly energy efficient external walls for the Mediterranean climate, obtained through the combination of several materials using the software *Modefrontier* rel.4.3. To evaluate the dynamic performance of the different components *MatLab* rel.7.0 has been used. The full methodology of this research is presented in [38].

A configuration with five layers and a maximum thickness of 430 mm has been selected. The analysis has been carried out in reference to summer since winter is not a critical season in such a climate. However, obtaining a high energy performance in summertime does not guarantee compliance with the limits imposed by Italian Laws on wintertime. Therefore, a check related to the steady thermal transmittance and the hygrothermal performance test (Glaser) have also been carried out to search for the best configuration.

The analysis has been developed considering steady thermal transmittance, periodic thermal transmittance, decrement factor, time shift, areal heat capacity, thermal admittance, surface mass, and thickness according to the standard EN ISO 13786 [40].

The choice of number and type of layers has been made following a previous study [39, 41]. A multi-objective analysis has been performed to obtain several types of high energetic efficiency external walls in relation to the Mediterranean climate. Steady state thermal transmittance, periodic thermal transmittance, decrement factor, time shift, areal heat capacity, thermal admittance, surface mass, thickness, costs and eco-friendly score have been optimized considering combinations of various local materials.

A high thickness results in a decrement factor decrease, which implies a reduction in the amplitude of periodic oscillations. To achieve warmer internal temperatures at night, the time shift must be such that daytime temperature peaks are delayed in night hours towards the building internal side. Low values of the decrement factor combined with high values of internal areal heat capacity, and high values in the time shift of periodic thermal transmittance designate the best wall configuration when the aim is to decrease the effects of external thermal loads during summertime [42].

The most suitable four layer wall configuration [Fig.3] has been obtained to reduce external thermal loads during summer. Low values of the decrement factor, high values of internal areal heat capacity together with high values in the time shift of periodic thermal transmittance are the key elements to reach a reasonable configuration in a warm climate. To achieve a comfortable indoor temperature during night, the time shift guarantees that daytime temperature peaks are lagged during night hours towards the inside of the building

[41] **Error! Reference source not found.**[43]. The main physical characteristics and the composition of the different layers of external wall variants are reported in Table 3.

In such a climate, it is necessary to guarantee the energy balance of residential buildings taking into account the cooling performance of windows and their material life [44], so several fenestration systems are considered with different combinations of thermal transmittance, U-value and g-value, orientation and shading [Table 4]. Optical and thermal properties of conventional fenestration products make them more exposed components towards energy losses in comparison to opaque building elements [45].

2.2.2 Supply systems

The decision to introduce HVAC systems as variants derived from the necessity to reduce energy consumption maintaining a high level of comfort in all the building rooms. [46]

Three main HVAC systems are considered to satisfy heating, ventilation and air conditioning demand in residential buildings with a continuous use. All systems [Fig.4] are designed to achieve an internal temperature of 26 °C with 50% relative humidity (RH) in summer, and 20 °C with 50% RH in winter [46].

Furthermore two types of generation systems are considered, a heat pump with air and ground heat source and a variation of the number of PV panels (46-54 panels).

HVAC system 1 presents a AHU unit for centralized ventilation (pre-treatment) and fan coil units for cooling and heating (post-treatment). The production of DHW is combined with heating by the presence of a centralized heat pump. Renewables consist of an external tank (600 l), 9 solar collectors (η_k = 55%) and photovoltaic panels with an efficiency η_k = 17%.

HVAC system 2 consists of fan coils to fulfil the demand for heating and cooling, and VCM with static heat recovery for ventilation and indoor air purification, one for each apartment. The machine recovers energy from the extracted air of utility rooms and feeds purified air into the indoors. The generation system, DHW and renewable energy systems are equal to HVAC system 1.

As regards HVAC system 3, each floor has a VCM with dynamic heat recovery for purification, dehumidification and integration of DHW in the indoor environment. Radiant floor panels are useful to fulfil heating and cooling demand. The generation system comprises a centralized heat pump. The production of DHW is combined with the heating plant and integrated with an external tank (600 l). The solar thermal system includes 9 solar collectors (ηk yield = 55%), the PV panels have an efficiency of ηk = 17%.

Table 3 shows the main parameters of technical systems used for the simulations including the reference scenario.

2.3 Variants and combinations

In addition to defining reference buildings, MS should identify energy efficiency measures based on RES, combinations and variants of these measures [8]. A list that gives an indication of the measures is given and should be applied to building structures, systems and consolidated variants [Table 3] [Table 4]. The measures are grouped with the aim of defining a series of combinations that should be ten as a minimum number. Table 5 shows the obtained 144 combinations in this study.

2.4 Energy performance evaluation

Standard EN ISO 13790 has been used for the definition of the main procedures for the calculation of heating and cooling energy demand [47].

The calculation of the primary energy demand for all the simulated combinations, including the reference scenario has been performed through the software ProCasaClima2015 including the demand of heating, cooling, ventilation, DHW and lighting. The energy performance of a reference building is derived following some listed criteria. For example, in winter, the heating demand is calculated as the loss of energy through the envelope and the ventilation minus the internal and natural gains.

In addition, the provided indications state that the characterization of the seasonal efficiency of a system or a dynamic simulation has to be taken into account in the calculation of energy consumption of heating, cooling, domestic hot water (DHW), and energy production (electricity and thermal) from RES.

As regards energy consumption of final uses (heating, cooling, ventilation, DHW, lighting), the energy vector has been considered. The thermal energy from solar panels has to be subtracted from the primary energy associated with the provided energy. Once the energy performance calculations are done, global costs have been evaluated.

2.5 Global costs

UNI EN 15459 [48] has been used to estimate global costs, in terms of net present value for each combination of measures. Cost evaluation for measures, packages and variants have been carried out following the previously mentioned Guidelines [8]. Regulation suggests to carry out financial and macro calculations. The latter includes taxes, VAT, charges and subsidies.

The calculation of 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.

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

The final value Vf,τ (j) of a component is calculated by a straight-line depreciation of the initial investment until the end of the calculation period and referred to the beginning of the calculation period (τ = 30 years for residential and public buildings and τ = 20 years for non-residential commercial buildings).

$$V_{f,\tau}(j) = V_0(j) \times (1 + R_p/100)^{n_\tau(j) * \tau_n(j)} \times \left[\frac{(n_\tau(j) + 1 \times \tau_n(j) - \tau}{\tau_n(j)} \right] \times R_d(\tau) \tag{2}$$

Where:

$$V_0(j) \times (1 + R_p/100)^{n_\tau(j) * \tau_n(j)} \tag{3}$$

represents the last replacement cost, when taking into account the rate of development of the price for products (Rp);

$$\frac{(n_\tau(j) + 1 \times \tau_n(j) - \tau}{\tau_n(j)} \tag{4}$$

represents the straight-line depreciation of the last replacement cost (i.e. remaining lifetime at the end of the calculation period of the last replacement of component j divided by the lifespan of component j);

$$R_d(\tau) = \left(\frac{1}{1 + R_R/100} \right) \tag{5}$$

represents the discount rate at the end of the calculation period, and the real interest rate, depends on the market interest rate R and on the inflation rate Ri. A calculation period of 30 years has been considered for global costs evaluation [Table 6].

The optimal range should be evaluated on the basis of primary energy consumption [Fig.5] and global costs associated with the different measures analysed for the reference building. The optimal configuration is located at the lowest point of the curve [Fig.6] that indicates the cost assessment as a function of primary energy consumption. Minimum energy performance requirements are represented by the area of the curve that delivers the lowest cost. The area of the curve to the right of the economic optimum represents solutions that underperform from energy and performance aspects.

The global costs evaluation has been carried out using the software ProCasaClima 2015. Global costs have been estimated from a financial analysis including VAT. There are no tax breaks because the structures are new constructions in this study.

The Delegated Regulation No244/2012 of 16 January 2012 [7] proposes the macro-economic analysis for global costs evaluation, including CO_2 emission costs. The latter is the monetary value of the environmental damage caused by CO_2 emissions due to building energy consumption [49].

The optimal solution in terms of cost-optimal levels of energy performance requirements has been searched at the lowest point of the curve as previously described.

3. Results and discussion

Table 7 shows the results related to the calculation of primary energy demand in all the simulated combinations for the 144 scenarios.

As regards the energy performance national classification, the reference scenario of this study fall within class C, observing national law limits. The primary energy consumption is 99.34 kWh/m^2y, with gas emissions of 25 $kgCO_2/m^2y$ and a global cost of 389 €/m^2.

The different colours indicate the grouped combinations types of HVAC systems, including the variations of the heat pump and the number of PV panels. All the combinations provide a reduction of primary energy consumption ranging from 56% to 90% and the CO_2 emissions decrease up to 88% compared to the reference scenario [Table 7].

The histograms in Figure 5 show the primary energy demand for all combinations. The first group, HVAC system 1 (s1, s4, s7, s10) reach a primary energy reduction with a minimum value of 10.72 kWh/m^2y for Combo C-119 and a maximum value of 43.38 kWh/m^2y for Combo C-9.

The second group of HVAC system (s2, s5, s8, s11) presents a minimum value of primary energy of 10.41 kWh/m^2y (Combo C-125) and a maximum value of 30.71 kWh/m^2y (Combo C-21).

In the second group it is possible to find a minimum value of 13.00 kWh/m^2y (Combo C-101) and a maximum value of 30.03 kWh/m^2y (Combo C-33).

Figure 6 shows cost assessment as a function of primary energy demand, indicating on the ordinate the value of the global costs (€ $/m^2$) and on the abscissa the value of consumption (kWh/m^2y) of all combinations and describing the difference in costs and consumptions. Its location on the abscissa provides the cost-optimal level of minimum energy performance for a combination of packages.

The highest efficiency combinations C-122, C-124, C-53, C52 define the optimal curve [Figure 6], and the best configurations is Combo C-125 with a value of 10.41 kWh/m^2y of primary energy ad a cost of 237 €/m^2; it has the greatest reduction of CO_2 emissions (88% - 3 kg CO^2/m^2y) seen in the previous figure.

All the highest performance solutions that define the optimal cost curve, including the best configuration (C-125), have the same group: HVAC system 2 that consists of a fan coil for heating, cooling and dehumidification demand and CMV with static heat recovery for ventilation. The generation system is a centralized heat pump with the ground as heat source.

The combinations C-53, C-52, have a total number of 46 PV panels compared to the 54 panels of the Combo C-122, C-124. Although the costs increase, the primary energy requirement reduce. On the other hand, the best configuration (C-125) offers both energy and economic optimization, ranking the building at class A for CasaClima classification.

The histograms in Figure 7 show the values of heating, cooling, DHW, auxiliary and lighting for Combo C-0 and C-125 in terms of primary energy consumption against monthly demand. The cost-optimal configuration shows a balance between heating and cooling demand.

The sensitivity analysis reported in Figure 8 explains how total costs drop with the growth of the discount rate (2.52%, 3% and 4%), while it increases with rising energy price rate (2.80%).

4. Conclusions

According to the Guidelines provided by EPBD recast, a set of reference scenarios and a minimum energy performance requirements should be considered at a national or regional level in order to reach the best configuration in terms of cost-optimal levels. Reference buildings are becoming more and more important to assess energy performance and economic competitiveness in the built environment.

This paper shows the application of a methodology to identify cost-optimal levels in new residential buildings located in the Mediterranean area. The study is based on economic and cost assumptions that can change unpredictably. In particular, assumed fluctuations of energy costs and inflation rate during the calculation period need to be carefully evaluated. Sensitivity analyses can help in overcoming this uncertainty, making the outcomes of the study more reliable. Reducing the gap between energetic and economical optimal solutions is a challenge that requests future research in this topic. Furthermore, the continuous evolution of energy requirements can also have an impact on the methodology and interpretation of results.

Several combinations of high performance technological variants have been applied to the envelope and systems of the reference scenario to derive the cost-optimal configuration.

This case-study is an example of the application of the proposed methodology in the Mediterranean climate in relation to residential reference buildings and Italian requirements, technologies and energy costs. However, the methodology used can be followed and applied to other cases in different scenarios, climates, and requirements taking into account local materials and construction properties. In particular, the aim of this paper is to obtain a set of configurations among which the designer can choose the appropriate solutions for his application to support nZEBs design, facilitating the management of many variables.

The methodology used has been applied to different reference buildings, climatic conditions and requirements. As an example, [50] considered a mono-residential reference building located in the Mediterranean climate. [51] studied cost optimality for a single family house while [52] focuses on both new and existing (from two different construction periods: 1946-1976, and 1977-1990) residential buildings (single family, small and large multi apartment) and offices located in two Italian national climatic zones (B and E).

The selected cost-optimal configuration allows the building to reach a high energy performance with a primary energy reduction between 56% and 90%. The study highlights the potential improvement of cost-optimality with respect to baseline solutions and suggests further research effort on design and control optimization.

A heat pump with ground as heat source results in the highest efficiency generation solution among all configurations for a warm climate [53][54]. Constructions located in a warm climate can usually reach a high comfort level through the use of massive structures. These technologies are optimal solutions to improve energy efficiency, preserving indoor thermal comfort, especially for hot-summer Mediterranean zones [55][56].

The adopted measures have led to the definition of many combinations and results show that the superficial mass of the external wall is important to obtain the best performance in this climate. Lighter and thinner walls allow high performance in summertime, but the best solution must consider the costs. Therefore, the cost-optimal configuration is achieved by a combination of the W2 variant for the external walls (Ms = 178.3 kg/m^2, U = 0.12W/m^2K) and the F2 variant for the windows.

The analysed optimal solutions are technically feasible with a global costs between 237 €/m^2 and 332 €/m^2. The best configuration reached the highest reduction of 152 €/m^2 compared to the reference scenario, whose global cost is 389 €/m^2 .

In conclusion, this method can be useful as a comparison tool, supporting nZEBs design exploiting knowledge of many variables and selecting different configuration for new constructions.

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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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Table(s) with Caption(s) revised

List of tables

Nomenclature

Nomenclature			
$A_{t,n}$	treated floor area (m^2)		
V	volume at controlled temperature	PE	primary energy
S/V	shape factor	RES	renewable energy sources
EP	energy performance index	GC	global cost
R	thermal resistance (m^2K/W)	*Greek letters*	
T	period of the variations (s)	κ	areal heat capacity ($kJ/m^2 K$)
U	thermal transmittance under steady state boundary conditions (W/m^2K)	λ	design thermal conductivity (W/m K)
Y_{mm}	thermal admittance (W/m^2K)	ρ	density (kg/ m^3)
Y_{mn}	periodic thermal transmittance (W/m^2K)	η	efficiency
c	specific heat capacity (kJ/kgK)	τ	calculation period
d	thickness of a layer (m)	τ_n	lifespan
fd	decrement factor	τ_0	starting year
Δt	time shift: time lead (if positive). or time lag (if negative) (s or h)		
Ms	total surface mass (Kg/m^2)	*Subscripts*	
C_G	global costs	m,n	for the thermal zones
C_I	initial investment costs	a	air layer
C_a	annual costs	1	internal
R_d	discount rate	2	external
R_R	real interest rate	s	related to surface
R_p	rate of development of the price for products	w	winter
$V_{f, \tau}$	final (or residual) value	s.env	for the envelope in summer
n_{τ}	number of replacements	e	emission
HVAC	heating ventilation air conditioning	d	distribution
CMV	controlled mechanical ventilation	g	generation
DHW	domestic hot water	r	regulation
AHU	air handling unit	e,w	dhw emission
MS	member states	d,w	dhw distribution
PVC	polyvinyl chloride	s,w	dhw storage
q	air flow CMV	v,e	external air flow
SPF	specific power consumption	v,tot	total air flow
t_B	daily service time	Ɵw,d	winter thermal recovery
n	air change	Ɵs,d	summer thermal recovery
P	thermal capacity	Ɵx,wd	hygrometric recovery
$T_{h/w}$	design heating/ water temperature	k	panels
t_i	insulation thickness		
T_{st}	average storage temperature		
h_{st}	daily hours with accumulation in temperature		
COP	performance factor	*Symbols*	
SEER	seasonal energy efficiency ratio	^	complex amplitude
No	number of panels	-	mean value
P_{peak}	peak power		
f_s	azimuth		
f_n	zenith		

Table 1. Description of Italian requirements for building certification

REQUIREMENT	DESCRIPTION
EP_w	$EP_w < EP_{w,limit}$
$Ep_{s.env}$	$Ep_{s,\ env} \leq Ep_{s,env\ limit}$
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 the heating system.
Inertia	$Im,s \geq 290\ W/m^2$
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.
Shading	External screening systems are mandatory. These systems may be omitted in the presence of glass surfaces with solar factor (UNI EN 410) equal or less to 0.5.
Check T_{room}	Devices for the automatic control of room temperature have to be installed to avoid overheating as a result of solar and internal gains and free contributions.
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
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 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
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 generators of heat to the service of the individual heating system. expressed in kW.

Table 2. Design parameters and primary energy of the reference building

Town: Lecce (Southern Italy)	**Climatic area:** C	Degrees during the day: **1153**	Altitude: **49 m** Latitude: **40°21'** Longitude: **18°10'**
Class size of building: E1	**Period of construction:** after 2005	$\mathbf{EP_{w,env} < EP_{w,limit}}$ **33.30 < 38.20** $\mathbf{EP_{s,env} \leq EP_{s,env,limit}}$ **27.42 < 30**	**Energetic class:** B $\mathbf{EP_{global}}$ **: 36.9 kWh/m^{2}y**
V: 3074.2 m^3	**S/V:** 0.56 m^{-1}	**At,n :** 1767.6 m^2	**Apartments number:** 6 **Conditioned floor number:** 3
ROOF 1. Tuff (40 mm) 2. Dry send (100 mm) 3. Concrete (60 mm) 4. EPS (80 mm) 5. Concrete screed (50 mm) 6. Slab (200 mm) 7. Plaster (10 mm) **U = 0.324 W/m^{2}K**	**WALL** 1. Plaster (15 mm) 2. Tuff (200 mm) 3. EPS (80 mm) 4. Plaster (15 mm) **U = 0.382 W/m^{2}K**	**FLOOR** 1. Gravel (400mm) 3. Concrete screed (60 mm) 4. Bituminous membrane (5 mm) 5. XPS (80mm) 6. Concrete screed (120 mm) 7. Cement mortar (35 mm) 8. Tiles (20 mm) **U = 0.348 W/m^{2}K**	**WINDOW** Double glass with low emissivity (Argon) Thickness 20 mm Metal frame with thermal break **Uw = 1.65 W/m^{2}K**

Table 3. Variants of efficiency measures in multi residential building

Measure	*Reference scenario*	*Variant 1*	*Variant 2*	*Variant 3*	*Variant 4*	*Variant 5*
Wall	**W0**	**W1**	**W2**	**W3**	**W4**	
Layer1	Plaster 1	Concrete	Concrete	Concrete	Concrete	
Layer2	Tuff	Polyur. foam 1	Wood fiber hardb.	Polyur. foam 1	Fibreboard	
Layer3	EPS	Concr. exp. Clay	Wood fiber hardb.	Cross-laminated timber panels	Polythane exp.	
Layer4	Plaster 1	Polyur. foam 2	Polyur. foam 1	Polyur. foam 2	Cork panel exp.	
Layer5	-	Concrete	OSB	Plaster 2	Plaster 3	
U (W/m^2K)	0.382	0.131	0.118	0.273	0.125	
Y_{12} (W/m^2K)	0.044	0.006	0.008	0.015	0.037	
Y_{22} (W/m^2K)	1.4	10.06	2.01	2.5	1.37	
Y_{11} (W/m^2K)	5.4	5.97	5.35	5.93	5.9	
fd	0.114	0.047	0.066	0.055	0.294	
M_s (Kg/m^2)	5.04	474	183	309	225	
Dt (h)	9.17	15	18.18	15.21	10.5	
k1 (kJ/m^2K)	74.8	82.1	73.5	81.5	81.6	
k2 (kJ/m^2K)	19.8	138.4	27.6	34.3	19.1	
d (m)	0.31	0.42	0.355	0.303	0.345	
Window	**F0**	**F1**	**F2**	**F3**		
U (W/m^2K) 80x150	2.52	2.00	1.34	2.10		
U (W/m^2K) 120x150	2.59	2.10	1.39	2.30		
U (W/m^2K) 120x210	2.51	2.10	1.45	2.30		
U (W/m^2K) 180x210	2.43	1.90	1.38	2.10		
Heating/ Cooling	**H/C 0**	**H/C 1**	**H/C 2**	**H/C 3**		
$\eta_{e,h}$	95,0%	96,0%	96,0%	99,0%		
$\eta_{d,h}$	90,0%	95,0%	95,0%	95,0%		
$\eta_{r,h}$	94,0%	99,0%	99,0%	98,0%		
$\eta_{s,h}$	100,0%	100,0%	100,0%	100,0%		
Ventilation	**V0**	**V1**	**V2**	**V3**		
$q_{v,e}$	-	1100 m^3/h	1080 m^3/h	960 m^3/h		
$q_{v,tot}$	-	6600 m^3/h	-	-		
$\eta_{\Theta w,d}$	-	74%	86%	-		
$\eta_{\Theta s,d}$	-	50%	50%	-		
$\eta_{xw,d}$	-	58%	-	-		
SFP_d	-	0.31 Wh/m^3	0.46 Wh/m^3	0.46 Wh/m^3		
V_N	-	2062.2 m^3	2062.2 m^3	2062.2 m^3		
t_B	-	24 h/d	24 h/d	24 h/d		
n_w	-	0.24	0.24	0.24		
n_s	-	0.73	0.73	0.73		
Generation	**G0**	**G1**	**G2**	**G3**	**G4**	**G5**
Energy vector	Methane gas	Electricity	Electricity	Electricity	Electricity	Electricity
Heat source	-	Air	Air	Ground	Ground	Air
P_h	33.2 kW	25.8 kW	16.6 kW	25.3 kW	16.1 kW	2.1 kW
P_c	22.4 kW	24.1 kW	15.9 kW	22.1 kW	17.7 kW	1.0 kW
$T_{h,out}$	70 °C	45°C	35°C	45°C	35°	35 °C
$T_{w,out}$	60 °C	40°C	40°C	40°C	40 °C	40 °C
$\eta_{g,h}$/COP	94%	3.21	4.08	4.0	5.6	3.84
SEER	5.1	2.56	3.83	4.6	5.8	2.6
RES (SC/PV)	**SC0 / PV0**	**PV1**	**PV2**			
A_N	2 m^2 ; 1.5 m^2	1.5 m^2	1.5 m^2			
N_o	9 p. ; 24 p.	46	54			
P_{peak}	6 kW	11.5 kW	13.5 kW			
f_s	0°	0°	0°			
f_N	45° / 30°	30°	30°			
η_k	55% ; 17%	17%	17%			
DHW	**DW 0**					
$\eta_{e,w}$	95%					
$\eta_{d,w}$	93%					
$\eta_{s,w}$	91%					
V	600 l					
t_i	7 cm					
T_{st}	50 °C					
h_{st}	24 h					

Table 4. Summary of variants and symbols of the applied measures

Measure	*Variant*	*Symbol*
Wall	heavy wall 0	W0
	heavy wall 1	W1
	heavy wall 2	W2
	heavy wall 3	W3
	heavy wall 4	W4
Window	Metal frame - Glazing low emissivity (Argon)	F0
	Metal frame - Glazing low emissivity (Argon)	F1
	PVC frame - Glazing low emissivity (Argon)	F2
	Metal-wood frame - Glazing low emissivity (Argon)	F3
Conditioning	Wall radiators - Split	H/C0
	AHU - Fancoils	H/C1
	Fancoils	H/C2
	Radiant panels	H/C3
Ventilation	AHU	V1
	Passive Heat recovery CMV	V2
	Active heat recovery CMV	V3
Generation	Condensing boiler	G0
	Centralized Heat Pump (Air)	G1
	Centralized Heat Pump (Air)	G2
	Centralized Heat Pump (Ground)	G3
	Centralized Heat Pump (Ground)	G4
	Active Heat Recovery	G5
DHW	Heating production External tank	DW0
Renewable energy sources	Solar collectors	SC0
	Photovoltaic panels	PV1
	Photovoltaic panels	PV2

Table 5. Combinations of different technical variants

Package	*Combo*	*Wall*	*Frame*	*Cond.*	*Vent.*	*Gen.*	*RES*	*Package*	*Combo*	*Wall*	*Frame*	*Cond.*	*Vent.*	*Gen.*	*RES*
s1	**C-1**	W1	F1	H/C1	V1	G1	PV1 + SC0	**s7**	**C-73**	W1	F1	H/C1	V1	G1	PV2 + SC0
	C-2	W1	F2	H/C1	V1	G1	PV1 + SC0		**C-74**	W1	F2	H/C1	V1	G1	PV2 + SC0
	C-3	W1	F3	H/C1	V1	G1	PV1 + SC0		**C-75**	W1	F3	H/C1	V1	G1	PV2 + SC0
	C-4	W2	F1	H/C1	V1	G1	PV1 + SC0		**C-76**	W2	F1	H/C1	V1	G1	PV2 + SC0
	C-5	W2	F2	H/C1	V1	G1	PV1 + SC0		**C-77**	W2	F2	H/C1	V1	G1	PV2 + SC0
	C-6	W2	F3	H/C1	V1	G1	PV1 + SC0		**C-78**	W2	F3	H/C1	V1	G1	PV2 + SC0
	C-7	W3	F1	H/C1	V1	G1	PV1 + SC0		**C-79**	W3	F1	H/C1	V1	G1	PV2 + SC0
	C-8	W3	F2	H/C1	V1	G1	PV1 + SC0		**C-80**	W3	F2	H/C1	V1	G1	PV2 + SC0
	C-9	W3	F3	H/C1	V1	G1	PV1 + SC0		**C-81**	W3	F3	H/C1	V1	G1	PV2 + SC0
	C-10	W4	F1	H/C1	V1	G1	PV1 + SC0		**C-82**	W4	F1	H/C1	V1	G1	PV2 + SC0
	C-11	W4	F2	H/C1	V1	G1	PV1 + SC0		**C-83**	W4	F2	H/C1	V1	G1	PV2 + SC0
	C-12	W4	F3	H/C1	V1	G1	PV1 + SC0		**C-84**	W4	F3	H/C1	V1	G1	PV2 + SC0
s2	**C-13**	W1	F1	H/C2	V2	G1	PV1 + SC0	**s8**	**C-85**	W1	F1	H/C2	V2	G1	PV2 + SC0
	C-14	W1	F2	H/C2	V2	G1	PV1 + SC0		**C-86**	W1	F2	H/C2	V2	G1	PV2 + SC0
	C-15	W1	F3	H/C2	V2	G1	PV1 + SC0		**C-87**	W1	F3	H/C2	V2	G1	PV2 + SC0
	C-16	W2	F1	H/C2	V2	G1	PV1 + SC0		**C-88**	W2	F1	H/C2	V2	G1	PV2 + SC0
	C-17	W2	F2	H/C2	V2	G1	PV1 + SC0		**C-89**	W2	F2	H/C2	V2	G1	PV2 + SC0
	C-18	W2	F3	H/C2	V2	G1	PV1 + SC0		**C-90**	W2	F3	H/C2	V2	G1	PV2 + SC0
	C-19	W3	F1	H/C2	V2	G1	PV1 + SC0		**C-91**	W3	F1	H/C2	V2	G1	PV2 + SC0
	C-20	W3	F2	H/C2	V2	G1	PV1 + SC0		**C-92**	W3	F2	H/C2	V2	G1	PV2 + SC0
	C-21	W3	F3	H/C2	V2	G1	PV1 + SC0		**C-93**	W3	F3	H/C2	V2	G1	PV2 + SC0
	C-22	W4	F1	H/C2	V2	G1	PV1 + SC0		**C-94**	W4	F1	H/C2	V2	G1	PV2 + SC0
	C-23	W4	F2	H/C2	V2	G1	PV1 + SC0		**C-95**	W4	F2	H/C2	V2	G1	PV2 + SC0
	C-24	W4	F3	H/C2	V2	G1	PV1 + SC0		**C-96**	W4	F3	H/C2	V2	G1	PV2 + SC0
s3	**C-25**	W1	F1	H/C3	V3	G2+G5	PV1 + SC0	**s9**	**C-97**	W1	F1	H/C3	V3	G2+G5	PV2 + SC0
	C-26	W1	F2	H/C3	V3	G2+G5	PV1 + SC0		**C-98**	W1	F2	H/C3	V3	G2+G5	PV2 + SC0
	C-27	W1	F3	H/C3	V3	G2+G5	PV1 + SC0		**C-99**	W1	F3	H/C3	V3	G2+G5	PV2 + SC0
	C-28	W2	F1	H/C3	V3	G2+G5	PV1 + SC0		**C-100**	W2	F1	H/C3	V3	G2+G5	PV2 + SC0
	C-29	W2	F2	H/C3	V3	G2+G5	PV1 + SC0		**C-101**	W2	F2	H/C3	V3	G2+G5	PV2 + SC0
	C-30	W2	F3	H/C3	V3	G2+G5	PV1 + SC0		**C-102**	W2	F3	H/C3	V3	G2+G5	PV2 + SC0
	C-31	W3	F1	H/C3	V3	G2+G5	PV1 + SC0		**C-103**	W3	F1	H/C3	V3	G2+G5	PV2 + SC0
	C-32	W3	F2	H/C3	V3	G2+G5	PV1 + SC0		**C-104**	W3	F2	H/C3	V3	G2+G5	PV2 + SC0
	C-33	W3	F3	H/C3	V3	G2+G5	PV1 + SC0		**C-105**	W3	F3	H/C3	V3	G2+G5	PV2 + SC0
	C-34	W4	F1	H/C3	V3	G2+G5	PV1 + SC0		**C-106**	W4	F1	H/C3	V3	G2+G5	PV2 + SC0
	C-35	W4	F2	H/C3	V3	G2+G5	PV1 + SC0		**C-107**	W4	F2	H/C3	V3	G2+G5	PV2 + SC0
	C-36	W4	F3	H/C3	V3	G2+G5	PV1 + SC0		**C-108**	W4	F3	H/C3	V3	G2+G5	PV2 + SC0
s4	**C-37**	W1	F1	H/C1	V1	G3	PV1 + SC0	**s10**	**C-109**	W1	F1	H/C1	V1	G3	PV2 + SC0
	C-38	W1	F2	H/C1	V1	G3	PV1 + SC0		**C-110**	W1	F2	H/C1	V1	G3	PV2 + SC0
	C-39	W1	F3	H/C1	V1	G3	PV1 + SC0		**C-111**	W1	F3	H/C1	V1	G3	PV2 + SC0
	C-40	W2	F1	H/C1	V1	G3	PV1 + SC0		**C-112**	W2	F1	H/C1	V1	G3	PV2 + SC0
	C-41	W2	F2	H/C1	V1	G3	PV1 + SC0		**C-113**	W2	F2	H/C1	V1	G3	PV2 + SC0
	C-42	W2	F3	H/C1	V1	G3	PV1 + SC0		**C-114**	W2	F3	H/C1	V1	G3	PV2 + SC0
	C-43	W3	F1	H/C1	V1	G3	PV1 + SC0		**C-115**	W3	F1	H/C1	V1	G3	PV2 + SC0
	C-44	W3	F2	H/C1	V1	G3	PV1 + SC0		**C-116**	W3	F2	H/C1	V1	G3	PV2 + SC0
	C-45	W3	F3	H/C1	V1	G3	PV1 + SC0		**C-117**	W3	F3	H/C1	V1	G3	PV2 + SC0
	C-46	W4	F1	H/C1	V1	G3	PV1 + SC0		**C-118**	W4	F1	H/C1	V1	G3	PV2 + SC0
	C-47	W4	F2	H/C1	V1	G3	PV1 + SC0		**C-119**	W4	F2	H/C1	V1	G3	PV2 + SC0
	C-48	W4	F3	H/C1	V1	G3	PV1 + SC0		**C-120**	W4	F3	H/C1	V1	G3	PV2 + SC0
s5	**C-49**	W1	F1	H/C2	V2	G3	PV1 + SC0	**s11**	**C-121**	W1	F1	H/C2	V2	G3	PV2 + SC0
	C-50	W1	F2	H/C2	V2	G3	PV1 + SC0		**C-122**	W1	F2	H/C2	V2	G3	PV2 + SC0
	C-51	W1	F3	H/C2	V2	G3	PV1 + SC0		**C-123**	W1	F3	H/C2	V2	G3	PV2 + SC0
	C-52	W2	F1	H/C2	V2	G3	PV1 + SC0		**C-124**	W2	F1	H/C2	V2	G3	PV2 + SC0
	C-53	W2	F2	H/C2	V2	G3	PV1 + SC0		**C-125**	W2	F2	H/C2	V2	G3	PV2 + SC0
	C-54	W2	F3	H/C2	V2	G3	PV1 + SC0		**C-126**	W2	F3	H/C2	V2	G3	PV2 + SC0
	C-55	W3	F1	H/C2	V2	G3	PV1 + SC0		**C-127**	W3	F1	H/C2	V2	G3	PV2 + SC0
	C-56	W3	F2	H/C2	V2	G3	PV1 + SC0		**C-128**	W3	F2	H/C2	V2	G3	PV2 + SC0
	C-57	W3	F3	H/C2	V2	G3	PV1 + SC0		**C-129**	W3	F3	H/C2	V2	G3	PV2 + SC0
	C-58	W4	F1	H/C2	V2	G3	PV1 + SC0		**C-130**	W4	F1	H/C2	V2	G3	PV2 + SC0
	C-59	W4	F2	H/C2	V2	G3	PV1 + SC0		**C-131**	W4	F2	H/C2	V2	G3	PV2 + SC0
	C-60	W4	F3	H/C2	V2	G3	PV1 + SC0		**C-132**	W4	F3	H/C2	V2	G3	PV2 + SC0
s6	**C-61**	W1	F1	H/C3	V3	G4+G5	PV1 + SC0	**s12**	**C-133**	W1	F1	H/C3	V3	G4+G5	PV2 + SC0
	C-62	W1	F2	H/C3	V3	G4+G5	PV1 + SC0		**C-134**	W1	F2	H/C3	V3	G4+G5	PV2 + SC0
	C-63	W1	F3	H/C3	V3	G4+G5	PV1 + SC0		**C-135**	W1	F3	H/C3	V3	G4+G5	PV2 + SC0
	C-64	W2	F1	H/C3	V3	G4+G5	PV1 + SC0		**C-136**	W2	F1	H/C3	V3	G4+G5	PV2 + SC0
	C-65	W2	F2	H/C3	V3	G4+G5	PV1 + SC0		**C-137**	W2	F2	H/C3	V3	G4+G5	PV2 + SC0
	C-66	W2	F3	H/C3	V3	G4+G5	PV1 + SC0		**C-138**	W2	F3	H/C3	V3	G4+G5	PV2 + SC0
	C-67	W3	F1	H/C3	V3	G4+G5	PV1 + SC0		**C-139**	W3	F1	H/C3	V3	G4+G5	PV2 + SC0
	C-68	W3	F2	H/C3	V3	G4+G5	PV1 + SC0		**C-140**	W3	F2	H/C3	V3	G4+G5	PV2 + SC0
	C-69	W3	F3	H/C3	V3	G4+G5	PV1 + SC0		**C-141**	W3	F3	H/C3	V3	G4+G5	PV2 + SC0
	C-70	W4	F1	H/C3	V3	G4+G5	PV1 + SC0		**C-142**	W4	F1	H/C3	V3	G4+G5	PV2 + SC0
	C-71	W4	F2	H/C3	V3	G4+G5	PV1 + SC0		**C-143**	W4	F2	H/C3	V3	G4+G5	PV2 + SC0
	C-72	W4	F3	H/C3	V3	G4+G5	PV1 + SC0		**C-144**	W4	F3	H/C3	V3	G4+G5	PV2 + SC0

Table 6. Financial parameters and energy costs

Calculation period - [τ]	30 years
Inflation rate - [R_i] (*source: Istat 2012)*	3.0 %
Market interest rate - [R]	5.6 %
Real interest rate – [R_r] *(source: guidelines Reg.Del. UE 244/2012)*	2.52 %; 3%; 4%
Design payback period of building – [τ_building] *(source: guidelines Reg.Del. UE 244/2012)*	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 – [$R_{e,3}$]	2.4 %; 2.8%
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

Table 7. Primary energy and global cost evaluation

System	Combo	CO_2	PE	GC	Reduction			System	Combo	CO_2	PE	GC	Reduction		
		$kgCO_2/m^2y$	kWh/m^2y	€/m²	CO_2	PE	GC			$kgCO_2/m^2y$	kWh/m^2y	€/m²	CO_2	PE	GC
s0	C-0	25	99.34	€ 389	-	-	-	s0	C-0	25	99.34	€ 389	-	-	-
s1	C-1	10	34.23	€ 285	60%	66%	€ 104	s7	C-73	7	25.98	€ 278	72%	74%	€ 111
	C-2	9	32.52	€ 282	64%	67%	€ 106		C-74	7	24.28	€ 275	72%	76%	€ 114
	C-3	10	34.71	€ 288	60%	65%	€ 101		C-75	7	26.47	€ 281	72%	73%	€ 108
	C-4	9	33.53	€ 281	64%	66%	€ 108		C-76	7	25.28	€ 273	72%	75%	€ 115
	C-5	9	31.07	€ 277	64%	69%	€ 112		C-77	6	22.82	€ 270	76%	77%	€ 119
	C-6	10	34.02	€ 284	60%	66%	€ 105		C-78	7	25.78	€ 276	72%	74%	€ 112
	C-7	12	42.85	€ 328	52%	57%	€ 60		C-79	10	34.61	€ 321	60%	65%	€ 68
	C-8	12	41.06	€ 326	52%	59%	€ 63		C-80	9	32.81	€ 318	64%	67%	€ 71
	C-9	12	43.38	€ 332	52%	56%	€ 57		C-81	10	35.14	€ 324	60%	65%	€ 65
	C-10	9	31.13	€ 295	64%	69%	€ 93		C-82	6	21.82	€ 287	76%	78%	€ 102
	C-11	8	29.66	€ 293	68%	70%	€ 96		C-83	6	20.73	€ 285	76%	79%	€ 104
	C-12	9	31.57	€ 298	64%	68%	€ 90		C-84	6	22.16	€ 290	76%	78%	€ 99
s2	C-13	6	20.70	€ 261	76%	79%	€ 128	s8	C-85	4	15.03	€ 257	84%	85%	€ 132
	C-14	5	18.73	€ 258	80%	81%	€ 131		C-86	3	12.99	€ 254	88%	87%	€ 135
	C-15	6	21.26	€ 264	76%	79%	€ 125		C-87	4	15.61	€ 260	84%	84%	€ 129
	C-16	5	19.89	€ 256	80%	80%	€ 133		C-88	4	14.18	€ 252	84%	86%	€ 137
	C-17	5	17.92	€ 253	80%	82%	€ 136		C-89	3	12.15	€ 249	88%	88%	€ 140
	C-18	6	20.45	€ 259	76%	79%	€ 130		C-90	4	14.77	€ 255	84%	85%	€ 134
	C-19	8	30.11	€ 304	68%	70%	€ 84		C-91	7	25.05	€ 301	72%	75%	€ 87
	C-20	8	28.13	€ 301	68%	72%	€ 87		C-92	6	22.94	€ 298	76%	77%	€ 91
	C-21	9	30.71	€ 308	64%	69%	€ 81		C-93	7	25.69	€ 305	72%	74%	€ 84
	C-22	6	20.29	€ 274	76%	80%	€ 115		C-94	4	14.60	€ 270	84%	85%	€ 118
	C-23	5	18.31	€ 271	80%	82%	€ 118		C-95	3	12.56	€ 267	88%	87%	€ 122
	C-24	6	20.85	€ 277	76%	79%	€ 111		C-96	4	15.18	€ 274	84%	85%	€ 115
s3	C-25	6	20.48	€ 281	76%	79%	€ 107	s9	C-97	4	15.84	€ 279	84%	84%	€ 110
	C-26	5	18.53	€ 279	80%	81%	€ 110		C-98	4	13.90	€ 276	84%	86%	€ 113
	C-27	6	21.05	€ 285	76%	79%	€ 104		C-99	4	16.42	€ 282	84%	83%	€ 107
	C-28	5	19.63	€ 277	80%	80%	€ 112		C-100	4	15.00	€ 274	84%	85%	€ 114
	C-29	5	17.63	€ 274	80%	82%	€ 115		C-101	3	13.00	€ 271	88%	87%	€ 118
	C-30	6	20.21	€ 280	76%	80%	€ 109		C-102	4	15.57	€ 278	84%	84%	€ 111
	C-31	8	29.55	€ 325	68%	70%	€ 63		C-103	7	24.92	€ 323	72%	75%	€ 66
	C-32	8	27.70	€ 322	68%	72%	€ 66		C-104	6	23.07	€ 320	76%	77%	€ 69
	C-33	8	30.03	€ 328	68%	70%	€ 60		C-105	7	25.40	€ 326	72%	74%	€ 63
	C-34	5	20.02	€ 295	80%	80%	€ 93		C-106	4	15.39	€ 293	84%	85%	€ 96
	C-35	5	18.08	€ 292	80%	82%	€ 96		C-107	4	13.45	€ 290	84%	86%	€ 99
	C-36	6	20.62	€ 298	76%	79%	€ 90		C-108	4	15.99	€ 296	84%	84%	€ 93
s4	C-37	7	23.70	€ 262	72%	76%	€ 127	s10	C-109	4	15.93	€ 256	84%	84%	€ 133
	C-38	6	22.28	€ 260	76%	78%	€ 129		C-110	4	14.46	€ 253	84%	85%	€ 135
	C-39	7	24.10	€ 265	72%	76%	€ 124		C-111	4	16.35	€ 259	84%	84%	€ 130
	C-40	6	23.13	€ 258	76%	77%	€ 131		C-112	4	15.33	€ 251	84%	85%	€ 138
	C-41	6	21.63	€ 255	76%	78%	€ 134		C-113	4	13.78	€ 248	84%	86%	€ 140
	C-42	7	23.54	€ 261	72%	76%	€ 128		C-114	4	15.76	€ 254	84%	84%	€ 135
	C-43	9	30.81	€ 303	64%	69%	€ 86		C-115	6	23.27	€ 297	76%	77%	€ 92
	C-44	8	29.34	€ 301	68%	70%	€ 88		C-116	6	21.77	€ 294	76%	78%	€ 95
	C-45	9	31.24	€ 306	64%	69%	€ 83		C-117	7	23.72	€ 300	72%	76%	€ 89
	C-46	5	20.06	€ 272	80%	80%	€ 117		C-118	3	11.83	€ 264	88%	88%	€ 124
	C-47	5	18.79	€ 269	80%	81%	€ 119		C-119	3	10.72	€ 262	88%	89%	€ 126
	C-48	6	20.45	€ 274	76%	79%	€ 114		C-120	3	12.18	€ 267	88%	88%	€ 122
s5	C-49	4	16.21	€ 246	84%	84%	€ 143	s11	C-121	3	12.82	€ 245	88%	87%	€ 144
	C-50	4	14.49	€ 243	84%	85%	€ 146		C-122	3	11.10	€ 242	88%	89%	€ 147
	C-51	4	16.70	€ 249	84%	83%	€ 140		C-123	3	13.31	€ 248	88%	87%	€ 141
	C-52	4	15.50	€ 241	84%	84%	€ 148		C-124	3	12.12	€ 240	88%	88%	€ 149
	C-53	4	13.79	€ 238	84%	86%	€ 151		C-125	3	10.41	€ 237	88%	90%	€ 152
	C-54	4	15.99	€ 244	84%	84%	€ 145		C-126	3	12.60	€ 243	88%	87%	€ 146
	C-55	7	24.31	€ 287	72%	76%	€ 101		C-127	6	20.93	€ 286	76%	79%	€ 102
	C-56	6	22.60	€ 285	76%	77%	€ 104		C-128	5	19.21	€ 284	80%	81%	€ 105
	C-57	7	24.82	€ 290	72%	75%	€ 98		C-129	6	21.43	€ 290	76%	78%	€ 99
	C-58	4	15.85	€ 259	84%	84%	€ 130		C-130	3	12.46	€ 258	88%	87%	€ 131
	C-59	4	14.14	€ 256	84%	86%	€ 132		C-131	3	10.75	€ 256	88%	89%	€ 133
	C-60	4	16.34	€ 262	84%	84%	€ 127		C-132	3	12.95	€ 261	88%	87%	€ 127
s6	C-61	5	19.03	€ 273	80%	81%	€ 116	s12	C-133	4	15.64	€ 272	84%	84%	€ 116
	C-62	5	17.25	€ 271	80%	83%	€ 118		C-134	4	13.87	€ 270	84%	86%	€ 119
	C-63	5	19.56	€ 276	80%	80%	€ 113		C-135	4	16.17	€ 275	84%	84%	€ 113
	C-64	5	18.27	€ 269	80%	82%	€ 120		C-136	4	14.88	€ 268	84%	85%	€ 121
	C-65	4	16.44	€ 266	84%	83%	€ 123		C-137	3	13.05	€ 265	88%	87%	€ 124
	C-66	5	18.80	€ 272	80%	81%	€ 117		C-138	4	15.41	€ 271	84%	84%	€ 118
	C-67	8	27.00	€ 315	68%	73%	€ 73		C-139	7	23.62	€ 315	72%	76%	€ 74
	C-68	7	25.39	€ 313	72%	74%	€ 76		C-140	6	22.01	€ 312	76%	78%	€ 77
	C-69	8	27.41	€ 318	68%	72%	€ 70		C-141	7	24.03	€ 318	72%	76%	€ 71
	C-70	5	18.62	€ 287	80%	81%	€ 102		C-142	4	15.23	€ 286	84%	85%	€ 103
	C-71	5	16.85	€ 284	80%	83%	€ 105		C-143	4	13.46	€ 283	84%	86%	€ 105
	C-72	5	19.17	€ 290	80%	81%	€ 99		C-144	4	15.79	€ 289	84%	84%	€ 100

LIST OF FIGURES

Figure 01

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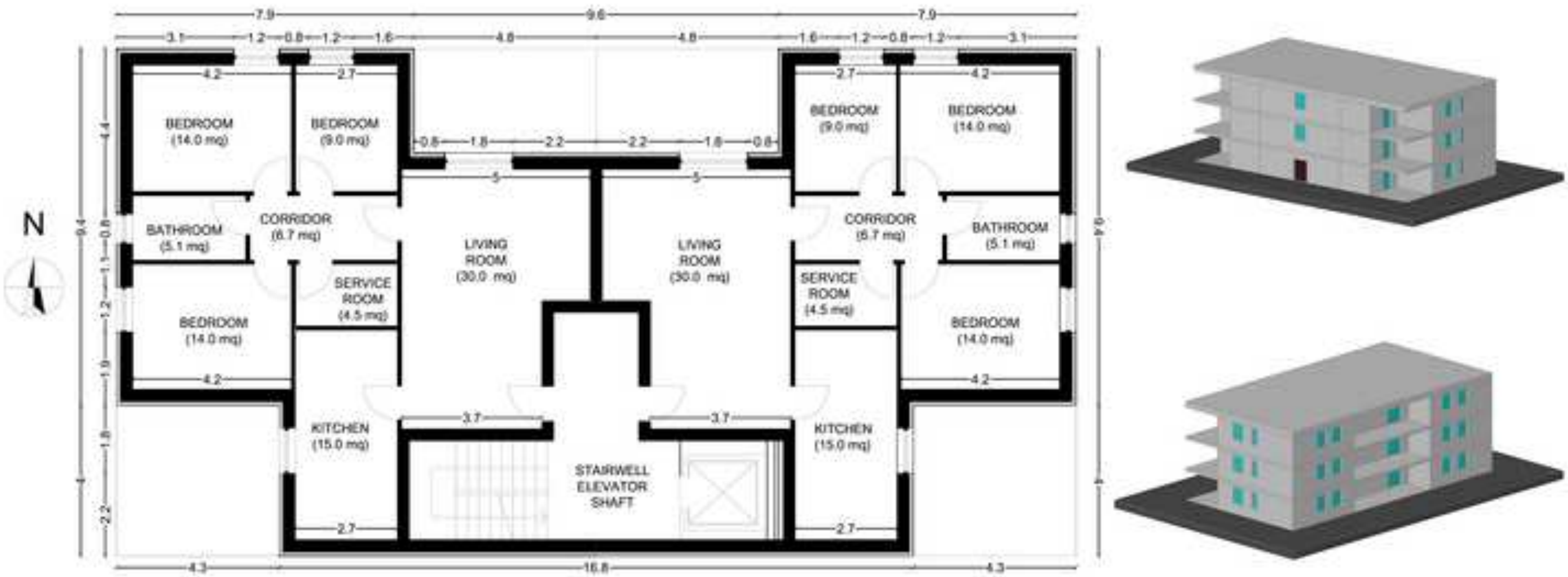

Figure 02

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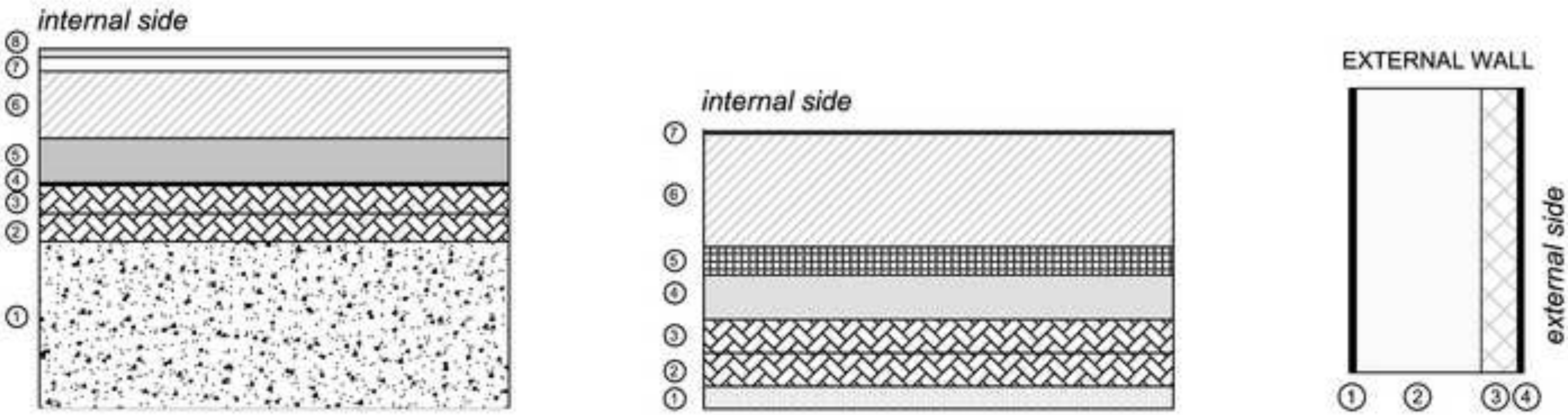

Figure 03
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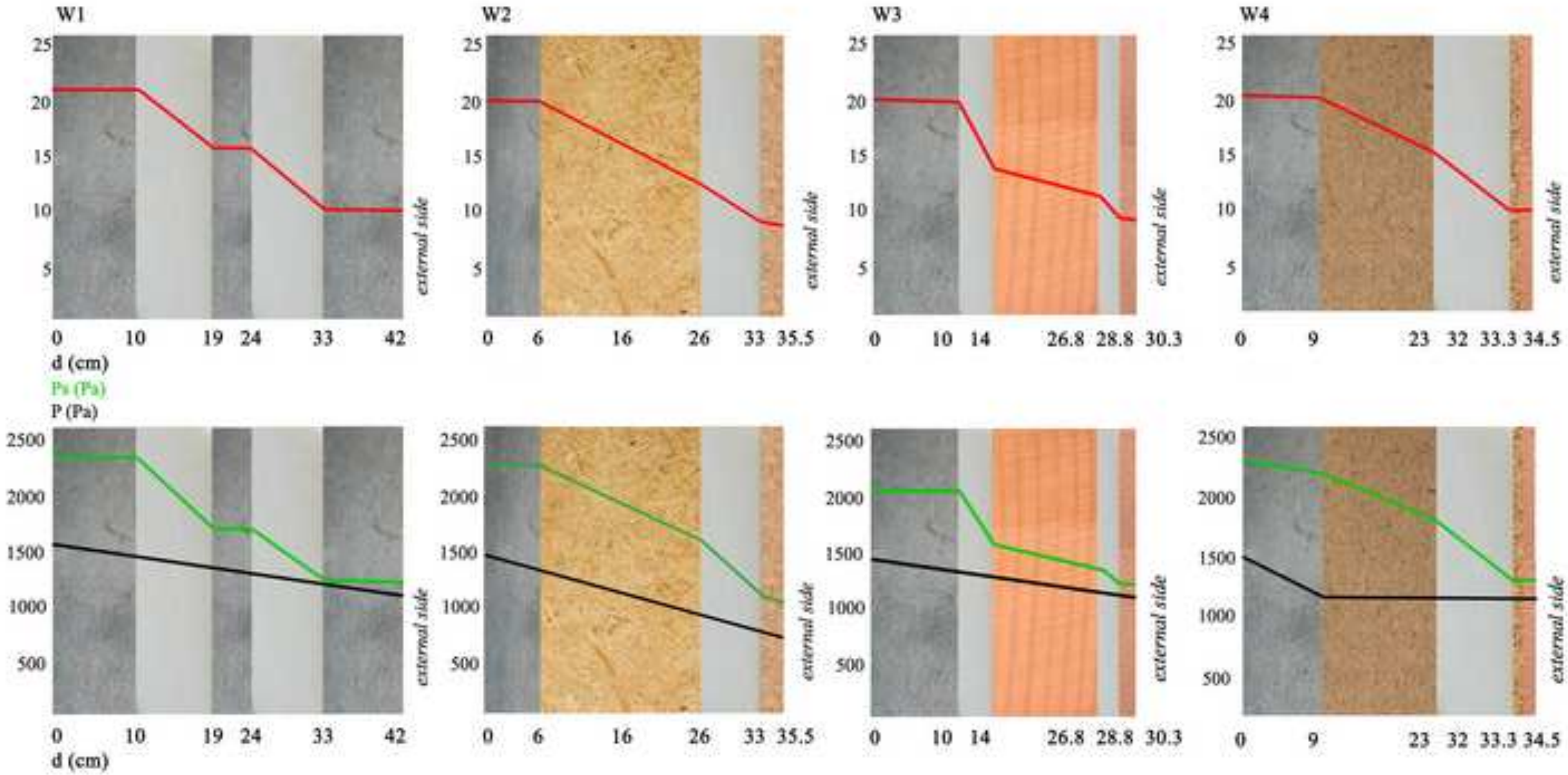

Figure 04
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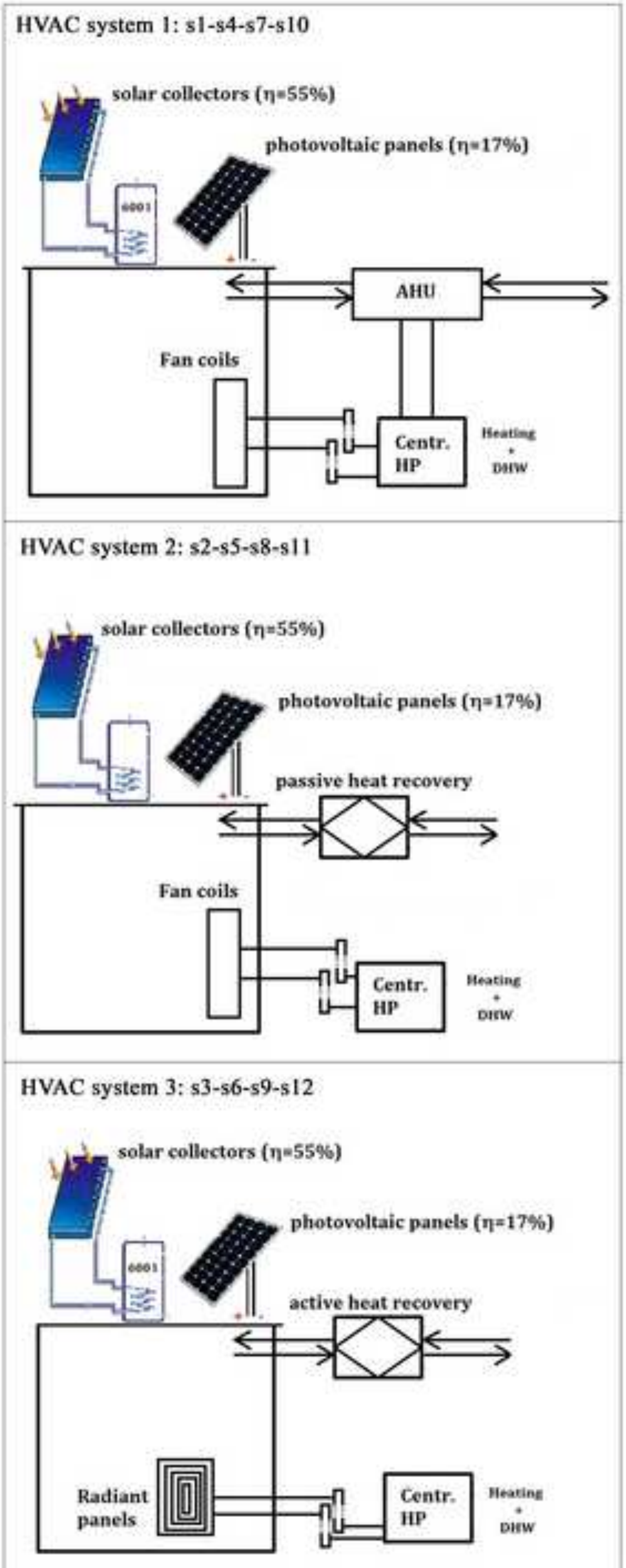

Figure 05
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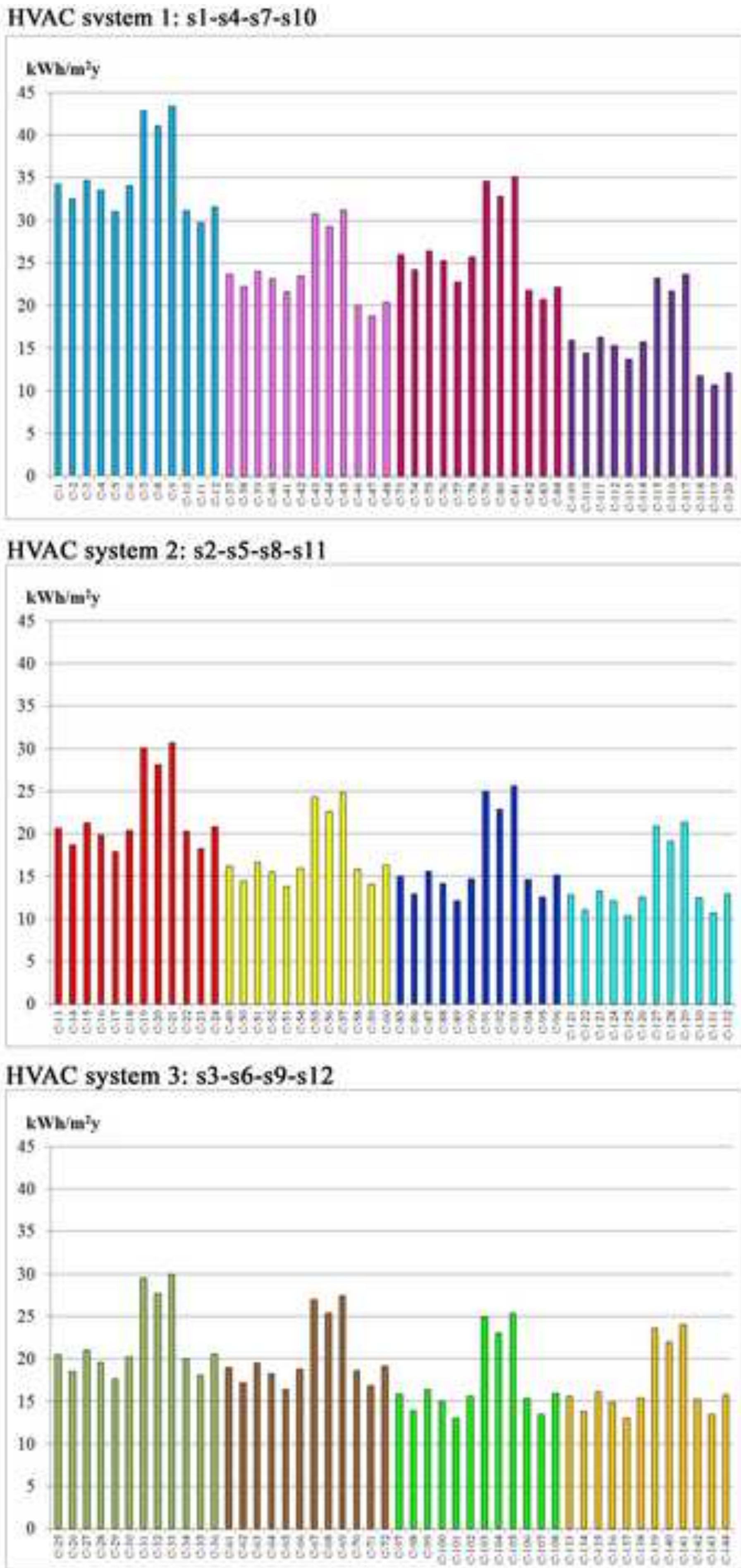

Figure 06
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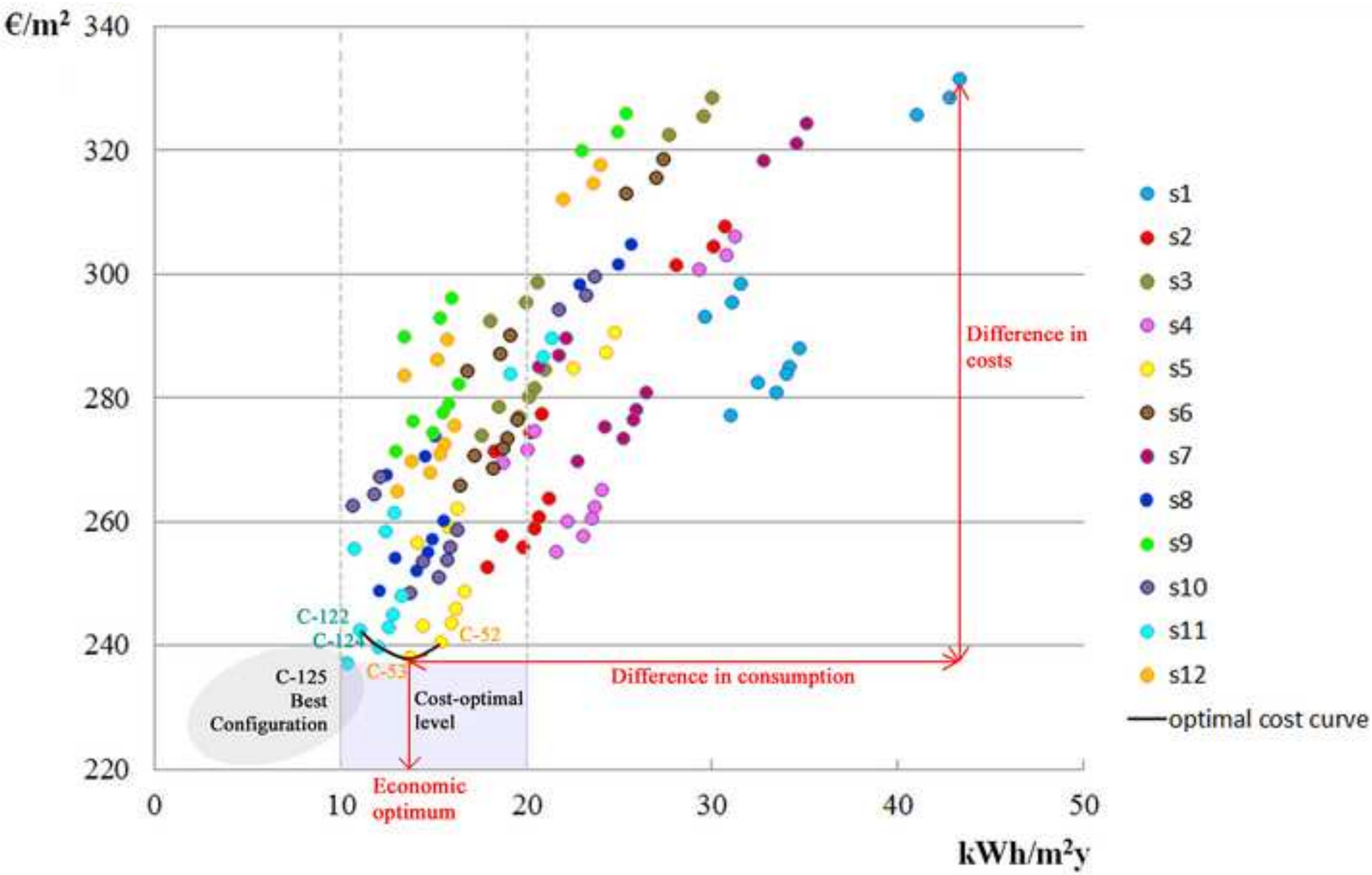

Figure 07

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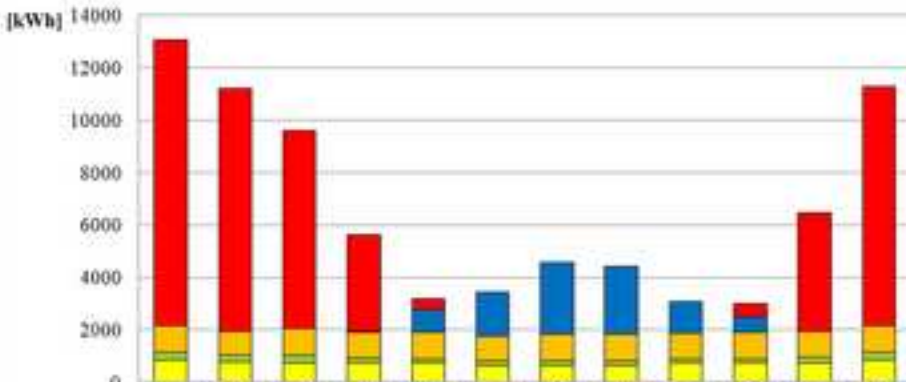
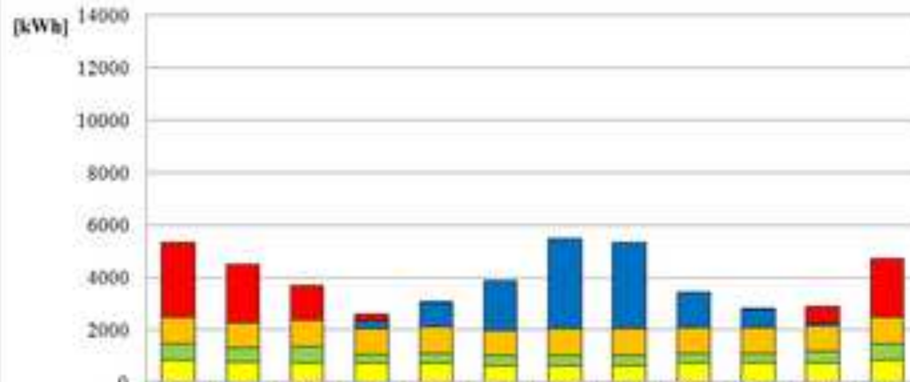
COMBO C-0



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
heating	10909	9273	7555	3681	397	0	0	0	0	513	4548	9139
cooling	0	0	0	55	869	1685	2751	2610	1221	603	0	0
dhw	1033	932	1027	987	1010	967	992	992	967	1009	986	1028
auxiliary	267	241	267	187	151	185	191	191	167	132	217	267
lighting	857	774	746	722	746	614	634	634	722	746	722	857

COMBO C-125



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
heating	2815	2223	1318	255	2	0	0	0	0	5	633	2226
cooling	0	0	0	290	931	1898	3433	3305	1362	687	107	0
dhw	1033	932	1027	978	1010	967	992	992	967	1009	986	1028
auxiliary	610	551	610	355	361	396	409	409	384	341	451	610
lighting	857	774	746	722	746	614	634	634	722	746	722	857

Figure 08

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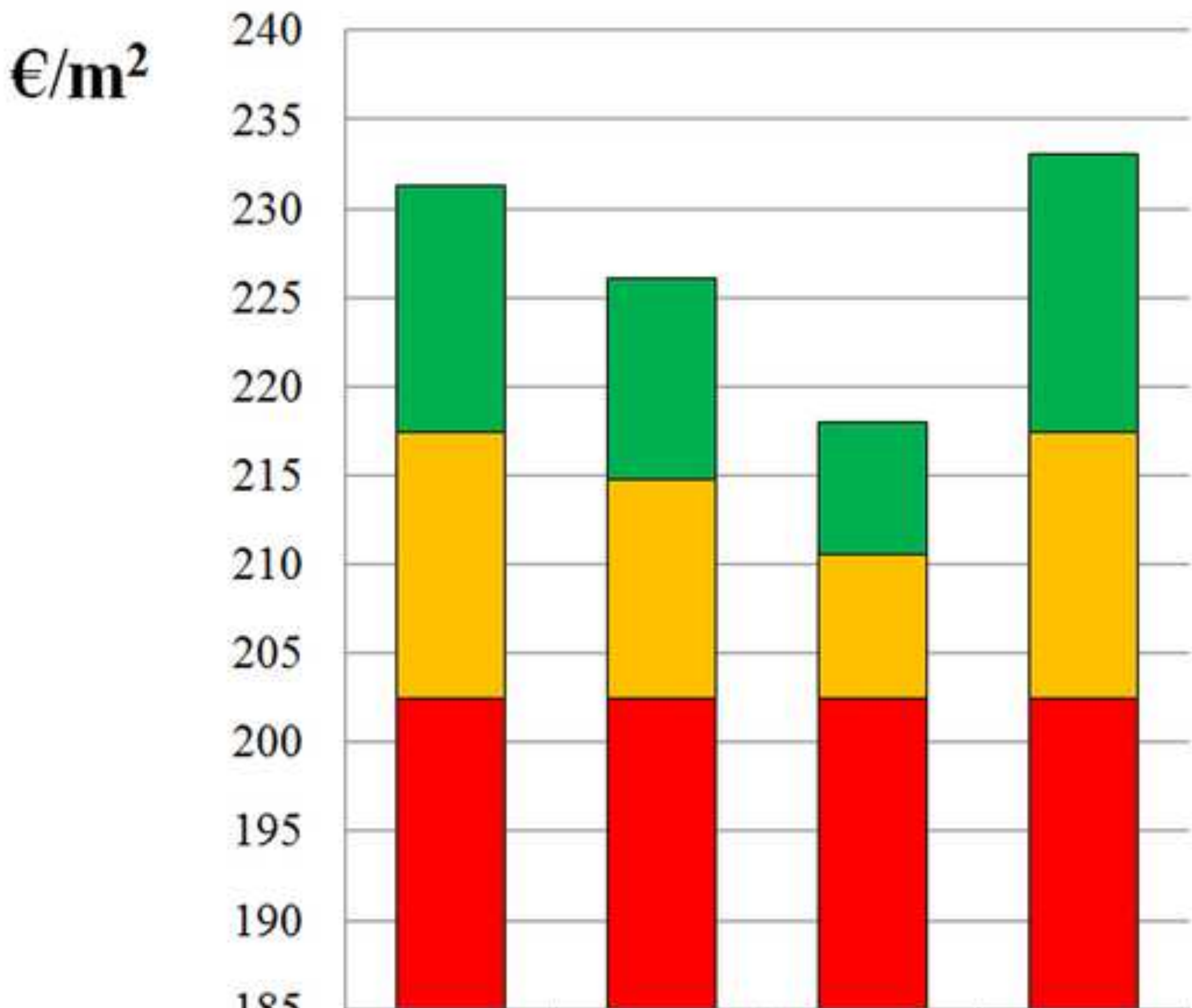

	2.52%	3%	4%	2.80%
Energy cost	€ 14	€ 11	€ 7	€ 16
Operating cost	€ 15	€ 12	€ 8	€ 15
Investment cost	€ 202	€ 202	€ 202	€ 202