COST-OPTIMAL ANALISYS AND TECHNICAL COMPARISON BETWEEN STANDARD AND HIGH EFFICIENT MONO RESIDENTIAL BUILDINGS IN A WARM CLIMATE

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Abstract

The recast of EU Directive on Energy Performance of Buildings (EPBD) requires nearly zero energy buildings (nZEBs) as the building target from 2018 onwards and the establishment of cost-optimal levels of minimum energy performance requirements in buildings.

This paper presents the results of the application of a methodology to identify cost-optimal levels in new residential buildings located in a warm climate. Mono-residential buildings have been considered as virtual reference buildings in this study. Different energy efficiency measures have been selected for the envelope and the systems.

A combination of technical variants has been then applied to the reference case in order to obtain several configurations to be compared in terms of primary energy consumption and global costs. The cost-optimal solution is identified assessing technical features and energy performance. Standard and high efficiency buildings are analysed to show how the selected configuration allows a decrease in primary energy consumption and CO_2 emissions at the lowest cost. Results are useful for comparison with other climates and building types. They also show the feasibility of the methodology to comply with EU requirements and to support the choice of economically efficient nZEBs solutions at the design stage.

Keywords: Reference building, nZEB, EPBD, cost-optimal analysis, warm climate, energy efficiency.

1. Introduction

Energy consumption in buildings is one of the most urgent concerns in Europe. In recent years the construction sector has considerably increased the exploitation of natural resources in industrialized countries. It is estimated that this sector is responsible for the consumption of around 40% of electricity (with peaks around 70%) and 12% of potable water [1].

The recast of European Directive on Energy Performance of Buildings (EPBD) introduces some remarkable concepts to reverse the current trend related to building consumption [2]. Article 9 states that new buildings and properties occupied by public authorities have to be nearly zero energy buildings (nZEBs) by December 31, 2018 and that all new buildings have to be nZEBs by December 31, 2020. According to Article 2, a nZEB is a building that "has a very high energy performance with a low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". EPBD also introduces the "cost-optimal" concept, defined as "the energy performance that leads to the lowest cost during the estimated economic life cycle". Moreover, it enlarges this concept to cost effectiveness that has to be adopted in Member States (MS) to establish minimum energy performance requirements in buildings. Starting with the definition of reference buildings, the Directive further provides a comparative methodology framework which enables measures to improve energy efficiency and obtain cost-optimal levels in buildings [3], [4]. Delegated Regulation No. 244/2012 and its Guidelines defines a reference building as 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. However, the process of reference building definition is still under discussion [5].

According to the methodological approach of cost-optimal calculations, alternatives must be considered when buildings are designed, including envelope, fenestration, energy sources, and building systems. Cost-optimality means the choice of energy efficient solutions with minimal life cycle cost. The introduction of this concept is innovative, as there are many studies that focus on reducing energy consumption in buildings achieving a ZEB target [6] [7] [8] [9], but fewer that also consider cost-optimality [10][11][12][13].

The proposed methodology can be carried out defining energy efficiency measures and/or measures based on renewable energy sources (RES). The procedure of measures selection for improving energy efficiency in buildings is also treated in the Regulation. These measures should consider both external and internal conditions, and cost-effectiveness [14]. Energy flows have to be taken into account in performance calculations as schematized in Fig.1. System boundaries are considered as in EN 15603 [15] with the inclusion of on-site renewable energy production in compliance with EPBD requirements. The Guidelines explain that renewable technologies are in direct competition with the solutions of the demand. The reference to RES and the request of a low energy demand are in accordance to the EPBD definition of nZEBs. Energy performance and global cost calculations have to be then performed according to UNI/TS 11300, parts 1-4 [16] and UNI EN 15459 [17], respectively.

Cost-optimal results strongly depend on the selected reference buildings (size, shape, compactness, share of window area) and climatic conditions. In a warm climate the nZEB target has a greater chance to match the cost-optimality area in comparison with cold climates. Kurnitski et al. identify cost-optimality with a heat loss of 0.33 W/Km^2 and a district heating of 140 kWh/m^2y in office buildings located in the cold Estonian climate [18]. In the same climate, the cost-optimal solution is assessed at 110 kWh/m^2y primary energy for a detached house, compared to national minimum requirement of 180 kWh/m^2y [19]. This research has been further developed by Pikas et al. [20]. The authors 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 walls [21]. According to the authors, cost-optimality will become more affordable in near future with energy escalation and reduction of construction costs of PV panels and/or windows with four panes.

The aim of this paper is to evaluate cost-optimal levels of minimum energy performance requirements in mono-residential reference building located in Lecce, a city of Southern Italy. Once the characteristics of the envelope and the systems are defined, a set of different energy efficient technical variants is selected and applied to the baseline case. Energy performance calculations are then performed for all the obtained combinations of measures. Global costs are finally derived for each combination in order to identify and evaluate the cost-optimal solution.

1.1 The Italian policy framework

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. National Law 10/91 gives a comprehensive framework related to energy efficiency in buildings providing explicit regulations for a more efficient use of energy sources in all end-use sectors. It sets out specific energy efficiency measures, rules for design, installation and operation of thermal systems, technical criteria for public and private buildings, and inspection of boilers.

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). In Italy, the EPi of an existing building built before national Law 10/91 is commonly a value between 200 and 300 kWh/m^{2}y with fuel consumption between 10 and 30 l oil/m^{2}y while a building designed and built according to current legislation has typically a EPi value between 15 and 130 kWh/m^{2}y, with fuel consumptions between 1.5 and 13 l oil/m^{2}y [22].

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]. According to the national energy classification system, seven classes (from A to G) are possible. A class A building requires less than 15 kWh/m^{2}y, while a Class G building consumes more than 160 kWh/m^{2}y. The CasaClima agency for buildings certification identifies three high performance energy classes (Gold, A, and B): the first class has up to 10 kWh/m^{2}y heating consumption, the second class can reach 30 kWh/m^{2}y, the third includes buildings with less than 50 kWh/m^{2}y consumptions. Both classifications are taken into account as reference in this research.

1.2 The reference buildings in literature

In the view of achieving EU requirements and implementing them at a national level, several studies and pilot projects have been recently launched. A general methodology for the definition of reference buildings for cost-optimal calculations is explained by Corgnati et al. [23]. Dynamic energy simulations are carried out to calculate the energy performance of an Italian office building selected as a case study.

Corrado et al. [24] propose a cost optimization procedure applying different energy efficiency measures to a reference building of TABULA (Typology Approach for Energy Building stock Assessment) project. The authors derived energy performance and global cost calculations based on a sequential search-optimization technique considering discrete options. De Angelis et al. [25] show the economic sustainability of different retrofitting strategies in an Italian social housing district. Several refurbishment alternatives have been investigated analysing different funding systems and incentives.

Zsuzsa Szalay et al. [26] illustrate a methodology to set requirements based on the analysis of a generated large sample of residential buildings located in Hungary. The suggested method appears suitable for developing building energy regulation threshold values, certification schemes or benchmarking values.

A debated issue is how to combine harmonised energy performance and costs requirements at the EU level. The Buildings Performance Institute Europe published a comprehensive overview on the implementation of the cost-optimal methodology in EU countries [27]. Aidan Parkinson et al. [28] explore the relationship between expectations of building energy performance and financial value of real estate. They argue that improvements in facility quality such as energy performance are expected to reduce costs for occupiers and hence increase asset values. Appropriate instruments are identified and applied in a case study of a number of offices in the UK showing how energy management in buildings can be appropriately evaluated through assessing a large sample of assets.

Hamdy et al. [29] conduct a multi-stage methodology to design a cost-optimal nZEB. A simulation-based optimization method is proposed for single family houses in Finland. The optimal solution depends on the selected heating/cooling systems as well as variations of energy costs, energy saving measures and renewables.

Two recent projects are renowned for the definition of reference buildings: ASIEPI project (ASsessment and Improvement of the EPBD Impact), aimed at improving regulation effectiveness on energy performance of buildings [30], and TABULA project [31]. This project involved thirteen countries to analyse the European residential housing stock within the Intelligent Energy Europe (IEE) EU Programme. The main aim of the project has been to create a harmonized structure for European building typologies in order to estimate the energy demand at a national level and predict the impact of energy efficiency measures in existing buildings.

A building typology is mainly classified in TABULA according to location, construction period, size and shape. The project illustrates the following main approaches towards the definition of different buildings of interest:

• Real Example Building (ReEx): a building type identified by means of experience and experts' inquires when no statistical data are available;

• Real Average Building (ReAv): a building type having average characteristics based on statistical analysis of a large bundling sample;

• Synthetical Average Building (SyAv): a building type identified as an "archetype", a virtual building characterized by a set of properties detected within a bundling category.

As regards Italian building typologies, eight classes have been defined in relation to different 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 classes have been defined according to geometry, number of apartments and floors: single-family house (a detached or semi-detached single dwelling of one or two floors), terraced house (a single dwelling of one or two floors bordering with other dwellings), multi-family house (a building with up to 15 apartments and 2-5 floors, or 16-20 apartments and 2-4 floors), apartment block (a larger building with a higher number of apartments).

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 methodology. A report has been recently published with the main findings of this research that gives an overall guidance on cost-optimality [32]. The study 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). 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.

2. Methodology

The methodology of this research has been carried out following these main steps:

1) Definition of the reference building (section2.1) and characterization of its envelope and systems (section 2.3);

2) Establishment of technical variants and combinations (section2.3) for energy performance assessment (section2.5);

3) Global costs calculations (section2.6).

This allowed the identification of measures able to optimize the energy performance of the selected reference building. Cost-optimal and cost effective levels are finally derived and discussed for the case study.

2.1 Reference building definition

The main objective of the use of reference buildings is to represent a typical and average housing stock in a given MS, since it is impossible to derive optimal solutions in terms of costs and energy efficiency for each building. Reference buildings can be obtained choosing a real or a virtual example. The first one should represent the most typical building within a specific category defined by the type of use in reference to occupancy pattern, floor area, geometrical features, thermo-physical properties of the envelope, or technical plants. The second one is a virtual building created using statistical information and surveys for each relevant parameter. TABULA project has been considered as a reference for the definition of a virtual building in this study: a mono-residential building consisting of a single family unit [Table 2].

Even if the Italian building typology is rather heterogeneous, the most frequent type is a small building. In particular, mono-residential buildings constitute about the 60% while multi-apartments are about 39% of the national building stock [32]. As regards the Italian building panorama, there are around twelve million residential buildings (11714262) over a total of fourteen million buildings (14176371). In particular, about five million buildings (4954362) are located in the North, about two million (1970519) in the Centre and about five million (4789381) in the South, including the main islands. The rate of new construction is around 2% per annum. Therefore, the case-study of this paper can be assessed as a representative building of the Italian context.

This type of reference building include commonly used material and systems. It is located in the city of Lecce, characterized by a Mediterranean climate with by non-extreme winters (average temperature 13 °C over the last ten years) and high aridity in summer (average temperature 30.3 °C). Rainfall is usually concentrated in autumn (240 mm seasonal average value) and winter (190 mm seasonal average value), while spring and summer have lower levels (average seasonal rainfall of 105 mm and 60 mm respectively) [33].

The geographical location of this case is part of the national climatic zone C, division based on the number of heating degree-days 1153. According to TABULA classification, our study-site falls within the “Mediterrean zone” which includes locations having up to 2100 heating degree-days. The majority of these locations are in the South of Italy and its main islands. However, due to a lack of consistent data on building typology in other climatic zones, only the “Middle Climatic zone”, including municipalities with heating degree days between 2100 and 300, has been analysed within the project [5], while the official national study takes into account the national climatic zones B and E [34]. This stresses the representativeness and the meaningfulness of the selected reference building to address cost-optimality in another climate. The indoor design temperature of a building located in the Mediterrean area is assumed to be 20 °C during the heating period running from November15th to March 31st, and 26 °C during the cooling period running from March 31st to November 15th.

The reference building of this paper is based on solutions defined within TABULA project. However, it is not exactly the same building in as its geometry, materials and systems have been adjusted to be more representative of the climatic zone in which is located. The case-study is suited for a single family composed by four people. It consists of three bedrooms, a living room, a kitchen, a ante-bathroom, a bathroom and a service-room. The structure is simple and compact (S/V =0.72 - 2 floors). The internal height of the building is 2.7 m and the treated floor area of each room is reported in Table 2.

The heating system consists of a standard boiler with radiators, while the cooling system consists of splits. Domestic hot water (DHW) is combined with a heating system. As regards RES, there is a solar thermal system consisting of two panels having an area of 2 m^2 and an external tank (200 l). The photovoltaic system consists of ten panels with a peak power of 2.5kW covering a total area of 15 m^2 [Table 3].

The building does not show the proper characteristics of a high efficient building, as it will be found during the energy performance assessment.

2.2. The calculation tool

In this research, heating and cooling loads are obtained using the software *ProCasaClima2015*. The Autonomous Province of Bolzano has been the first Italian municipality to introduce an energy rating system for buildings. The introduction of this procedure was aimed at the assessment and the improvement of the energy performance of the Bolzano area building stock [35].

The developed tool uses hourly weather data provided by the Italian Heat Technology Committee to implement dynamic simulations. This software is able to perform energy calculations to evaluate buildings energy requirements in compliance with Directives 2010/31/EU and 2012/27/EU. In particular, it estimates heating, cooling, domestic hot water and lighting loads [16]. *ProCasaClima2015* is equipped with many technical functions to evaluate a building from energetic, environmental and economic approaches.

It is necessary to enter the characteristics of the building site, envelope and systems to obtain numerical and graphical outputs, such as winter and summer energy demand for CasaClima certification or thermal energy demand in summer and winter (UNI TS 11300-1, UNI TS 11300-2).

The heat exchange with the ground (UNI EN ISO 13370) can be also assessed as well as global efficiency of building-plants and CO_2 emissions. Furthermore, *ProCasaClima2015* can derive costs and benefits of possible interventions (UNI EN 15459). It is possible to check the comfort dynamically (UNI EN ISO 13791, UNI EN ISO 15251). Energy requirements for cooling and dehumidification can be derived with the estimation of indoor comfort without active cooling and dehumidification.

2.3 Envelope and systems characterization

A proper selection of energy efficiency technological measures are able to reduce considerably the energy needs of a building. Building envelope is a key element to decrease the energy demand. Efficient external walls are characterized as obtained by an optimization modelling reported in Section 2.3.1. Windows are then defined in Section 2.3.2. Specifications of selected building technical systems are given in Section 2.3.3.

2.3.1 Highly energy efficient external walls

A multi-objective optimization analysis has been performed to obtain different types of highly energy efficient external walls for a warm climate, achieved through the combination of various materials. The analysis has been carried out during summertime since wintertime is not a critical period in such a climate. A check related to the steady thermal transmittance and the hygrothermal performance test (Glaser) have been also carried out to search for the optimal configuration.

The definition of external walls as an optimized multilayer package has been obtained through the integration of a multi-criteria optimization analysis carried out using the software *Modefrontier rel.4.3* [36]. The calculation procedure, further developed in *MatLab rel.7.0* [37], has allowed to evaluate the dynamic performance of the different components. The full methodology of this research is available in [35].

The analysis has been performed in terms of 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 [39].

The highly efficient external walls obtained for the climate under investigation are shown in Table 4. The aim of the optimization is to decrease the effects of external thermal loads during summer, so that low values of the decrement factor combined with high values of internal areal heat capacity, as well as high values in the time shift of periodic thermal transmittance, contribute to designate the optimal wall configuration. Instead of achieving warmer internal temperatures during the night, the time shift ensures that daytime temperature peaks are delayed during night hours towards the inside of the building [40][41][42].

Table 4 synthetically reports the external walls variants (W1, W2, W3, W4) with their main physical characteristics and the composition of the different layers of which they are made of. This study determines that a configuration with only five layers and a maximum thickness of 430 mm is preferable to simplify the analysis and to identify a suitable external wall configuration in terms of cost and easy-assembling at the building site.

2.3.2 Windows

Windows are a relevant component in sustainable buildings for the impact linked to both their material life cycle and their contribute to the energy performance of a building over its service life [43].

Heat transfer through windows represents a significant proportion of the energy used to cover both heating and cooling requirements, since optical and thermal properties of conventional fenestration products make them more “vulnerable” components towards energy losses in comparison to opaque building elements [44].

Therefore it is necessary to take into account the cooling performance of windows for residential buildings built in a warm climate. The cooling energy performance is estimated for different fenestration systems considering various combinations of thermal transmittance, U-value in different conditions, orientation, and shading. The solar transmittance of the whole window depends on the area of the transparent element, as presented in Table 5.

2.3.3 Supply systems

Conditioning and ventilation systems are evaluated to satisfy the demand of thermal comfort, ventilation and DHW production. Table 6 shows technical systems for building configurations, each one including RES. All systems are designed to obtain an internal temperature of 26 °C with 50% relative humidity (RH) in summer, and 20 °C with 50% RH in winter.

The first type of HVAC system consists of AHU for heating, cooling, dehumidification and ventilation demand. The second one is a fancoil system (heating, cooling and dehumidification) combined with static heat recovery for air exchange. Another system consists of a CMV with a dynamic heat recovery for heating and ventilation and a channelized split for cooling. The last system is composed of radiant panels (heating), fancoils (cooling and dehumidification) and a CMV with static heat recovery.

Electricity is preferred to other energy vectors because it can be largely covered by RES production. As the building is situated in a warm climate, heat pumps, solar thermal systems and photovoltaic panels are used for generation.

In particular, solar thermal collectors are used to satisfy DHW request for four users. A first water distribution system uses three solar panels with an external tank of 200 l and a resistor of 1 kW. A second one consists of a combination of hot water with heating system (heat pump), two solar panels and an external tank 200 l. A variant of the number of photovoltaic panels is considered too [Table 6].

In Table 7 the symbols for the combinations of technical systems useful to identify all the variants are shown.

2.4 Establishment of technical variants and combinations

MS should identify energy efficiency measures based on RES, packages and variants [4]. In particular, these ones should be applied to building structures, systems and consolidated variants. An approach to combine the possible measures in packages is also provided.

The measures have been grouped in packages for defining a series of 168 cases, resulting by the combination of walls, windows and technical systems variants [Table 8]. 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, to obtain a more accurate optimal solution.

2.5 Energy performance assessment

The procedure for the evaluation of the primary energy demand resulting from the application of measures to a reference building has been performed following [3]. This calculation includes the demand of heating, cooling, ventilation, DHW and lighting as concerned the Guidelines EN ISO 13790, including the regulation CEN for the choice of methods [45].

The previously described software *ProCasaClima2015* has been used for the calculation of the primary energy demand in all the simulated scenarios, including the base case.

As regards energy consumption of final uses, the energy vector has to be considered together with the characteristics of production, distribution, emission and control. Thermal energy from RES generated and utilized in situ (for example from solar collectors) has to be subtracted. The primary energy evaluation is derived from the primary energy associated with the provided energy (derived using the national conversion factors) minus the primary energy associated to the primary energy exported to the market (from RES). The conversion factors for the calculation of primary energy are valued according to the UNI EN 15603 [46] (Energy performance of buildings - Overall energy use and definition of energy ratings). The conversion factors are 1.36 for natural gas, 2.18 for the electricity network, 1.00 for renewable sources.

2.6 Global costs calculation

Global costs for each combination of measures related to the defined reference building are calculated following UNI EN 15459 [17]. Global costs are defined in terms of net present value. The costs that remain the same for all measures/packages/variants, as well as costs related to building elements that have no influence on the energy performance of a building, can be omitted to determine global costs. Regulation encourages the choice between a financial calculation and a macro calculation. The first differs from the second because it includes taxes, VAT, charges and subsidies.

Macro calculation includes costs for greenhouse gases emissions, the monetary value of the environmental damage caused by CO_2 emissions related to energy consumption in a building.

The calculation of global costs 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.

Investment costs refer to the prices drafted by the Puglia Region and a market survey. The goal has been to encourage the local market and to decrease the pollution from transport vehicles.

Global cost (C_G) considers the duration of the calculation period τ according to the following formula:

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

The final value Vf,τ (j) of a component is determined 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.

As reported in [4], section 8 of paragraph 4.2 "General principles for the calculation of costs", MS shall use a calculation period of 30 years for residential and public buildings, and a calculation period of 20 years for non-residential commercial buildings.

If the calculation period τ exceeds the lifespan τn (j) of the considered component (j), the last replacement cost is considered for the straight-line depreciation as:

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

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 9].

The optimal range should be evaluated on the basis of primary energy consumption and global costs associated to the different measures analysed for a reference building. Fig.2 shows costs assessment as a function of primary energy consumption, indicating on the ordinate the value of the global costs (€ /m^2) and on the abscissa the value of consumption (kWh/m^2y). The point of the curve that belongs to the lower border is indicative of the optimal configuration. Its location on the abscissa provides the cost-optimal level of minimum energy performance for a combination of packages.

The software *ProCasaClima2015* has been used for global costs calculation. Table 10 shows the global costs estimated from both a financial analysis including VAT and a macro-economic analysis including CO_2 emission costs. The last one is the monetary value of the environmental damage caused by CO_2 emissions due to building energy consumption [47]. There are no fiscal incentives because the structures are new constructions in this study.

3. Results and discussion

3.1 Primary energy evaluations

As regards energy performance national classification, the reference scenario of this study falls within class B, observing national law limits. It requires a primary energy demand of 59.06 kWh/m^2y and a global costs (in financial terms) of 495.6 €/m^2. Compared with the reference scenario, the 168 combinations have shown a significant reduction of the building primary energy. As shown in Figure 3, some of them have reached a very high performance. The figure reports the EPi values divided in intervals as obtained from the tested combinations. In particular, a reduction of primary energy demand between 90% and 95% has been obtained in 35% of the combinations. These configurations have a primary energy demand of less than 6 kWh/m^2y. 44% of the combinations show a primary energy reduction between 80% and 89% with a EPi value from 6 kWh/m^2y to 12 kWh/m^2y. A reduction of the energy demand between75% and 79% is seen in 15% of the configurations, showing an energy consumption between 12 kWh/m^2y and 15 kWh/m^2y. Finally, only 6% of the combinations have a reduction of EPi between 68% and 74% with an energy requirement of less than 19 kWh/m^{2}y.

Figure 4 shows the yearly building primary energy demand in relation to final uses (heating, cooling, humidification, DHW, lighting and auxiliary). Histograms show the requirements of the optimal configurations obtained from a financial (combo C-29) and macroeconomic (combo C-137) analysis.

3.2 Financial analysis

Figure 5 shows the cost-optimal level of the 168 configurations. Among the analyzed scenario, the optimal configuration (combo C-29) requires a primary energy demand of 8.99 kWh/m^{2}y and a global cost of 342.79 €/m^2, falling within class Gold of CasaClima classification.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 the hot-summer Mediterranean climate [46][49]. It is possible to reach high performance in summertime also by lighter and thinner walls, but the optimal solution must consider the costs. A combination of the W2 variant for the external walls (Ms = 178.3 kg/m2, U = 0.12W/m2K) and the F2 variant for the windows guarantee the cost-optimal configuration. This solution is provided with a CMV with a dynamic heat recovery system for heating, cooling, dehumidification, and ventilation. The system has also a channelized split for cooling integration. The production unit is a heat pump and there is a solar thermal system consisting of 3 solar collector panels, an external tank of 200 l with a resistance of 1 kW for DHW and a photovoltaic system of 12 panels with a peak power of 3 kW and an efficiency of 17%. Figure 6 shows the actualized costs for the optimal configurations. Investment, operating and energy costs are shown with a varying discount rate and energy price rate development. The sensitivity analysis illustrates how total costs drop with the growth of the discount rate, while it increases with the rise of the energy price rate development.

3.3 Macroeconomic Analysis

The global cost is evaluated through both a financial and a macroeconomic analysis. Therefore it was necessary to calculate the cost of CO_2 emissions. The assumptions made on the costs have been carried out in compliance with the data provided by NREAP in the view of a perspective of calculation until 2045 [50].

Figure 7 shows the cost-optimal level and a sensitivity analysis for the optimal configuration in macroeconomic terms (combo C-137). The configuration requires a primary energy demand of 3.28 kWh/m^{2}y and a global cost of 309.47 €/m^2. The combination consists of a AHU system for heating, cooling, dehumidification and ventilation. DHW production is combined with heating and two solar collectors. The PV system consists of 16 panels with a peak power of 4 KW. As for the previous configuration, the envelope is made of a window with a PVC frame (F2) and a lighter thinner wall (W2).

4. Conclusions

EPBD recast requires MS to create a set of reference scenarios and define minimum energy performance requirements in buildings and building components at a national or regional level, with the aim to reach the cost-optimal levels.

This paper has shown the application of a methodology to identify a cost-optimality in mono-residential building located in the Mediterranean area. The application of different high performance technological options to the envelope and systems of the baseline scenario has enabled several configurations of efficiency measures to be derived.

Primary energy consumptions and global costs have been calculated and compared for all the configurations. The cost-optimal solution shows that primary energy consumption can be reduced between 68% and 95% compared with the reference scenario. In particular, the optimal configuration obtained from a financial analysis reduces the primary energy by 85%, showing a cost reduction of 150 €/m^2 from the reference scenario. The optimal combination derived from a macroeconomic analysis shows an EPi reduction of 94% with a global cost of less than 135 €/m^2 compared to the reference building. The analysed optimal solutions are technically feasible but, having global costs between 309.47€/m^2 and 342.79 €/m^2, a system of national or regional incentives could help making nZEBs a more affordable and cost effective building target. A forward looking perspective to guide investment decision is fundamental to promote nZEBs beyond demonstration projects. Overcoming barriers like uncertainness in innovative technology and unforeseen costs, difficulty in accessing public funds or loans, unknown timeframe for investment return, are a priority to fully exploit potential energy savings that nZEBs can provide.

The study suggests the need for further research on design and control optimization to reach cost-optimal levels. In particular, the reduction of the gap between energy and economical optimal solutions is a challenge that requests future research in this topic. Another interesting development is related to sensitivity analysis on economic assumptions, especially in relation to fluctuation of energy costs and inflation rate during the assumed calculation period.

The results of this work refer to Mediterranean residential reference buildings in relation to Italian requirements, technologies and energy costs. However, the methodology used is general and can be applied to other cases. This approach can be useful to support nZEBs design and decision making, facilitating the management of many variables and the selection of different configuration options in new constructions.

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Author Contributions

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

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LIST OF FIGURES

Nomenclature

Nomenclature

$A_{t.n}$	treated floor area (m^2)
V	volume at controlled temperature
S/V	shape factor
EP	energy performance index
R	thermal resistance (m^2K/W)
T	period of the variations (s)
U	thermal transmittance under steady state boundary conditions (W/m^2K)
Y_{mm}	thermal admittance (W/m^2K)
Y_{mn}	periodic thermal transmittance (W/m^2K)
c	specific heat capacity (J/kgK)
d	thickness of a layer (m)
fd	decrement factor
Δt	time shift: time lead (if positive). or time lag (if negative) (s or h)
Ms	total surface mass (excluding coats) (Kg/m^2)
C_G	global costs
C_I	initial investment costs
C_a	annual costs
R_d	discount rate
R_R	real interest rate
R_p	rate of development of the price for products
$V_{f,\tau}$	final (or residual) value
n_τ	number of replacements
HVAC	heating ventilation air conditioning
CMV	controlled mechanical ventilation
DHW	domestic hot water
AHU	air handling unit
MS	member states
PVC	polyvinyl chloride

Greek letters

κ	areal heat capacity ($J/m^2 K$)
λ	design thermal conductivity (W/m K)
ρ	density (kg/m^3)
η	efficiency
τ	calculation period
τ_n	lifespan
τ_0	starting year

Subscripts

m.n	for the thermal zones
a	air layer
1	internal
2	external
s	related to surface
w	winter
s.env	for the envelope in summer
e.h	heating emission
d.h	heating distribution
g.h	heating generation
r.h	heating regulation
e.w	dhw emission
d.w	dhw distribution
s.w	dhw storage
t.v	thermal recovery
I.v	hygrometric recovery

Symbols

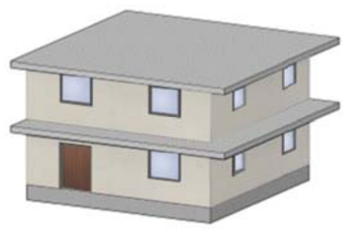
^	complex amplitude
-	mean value

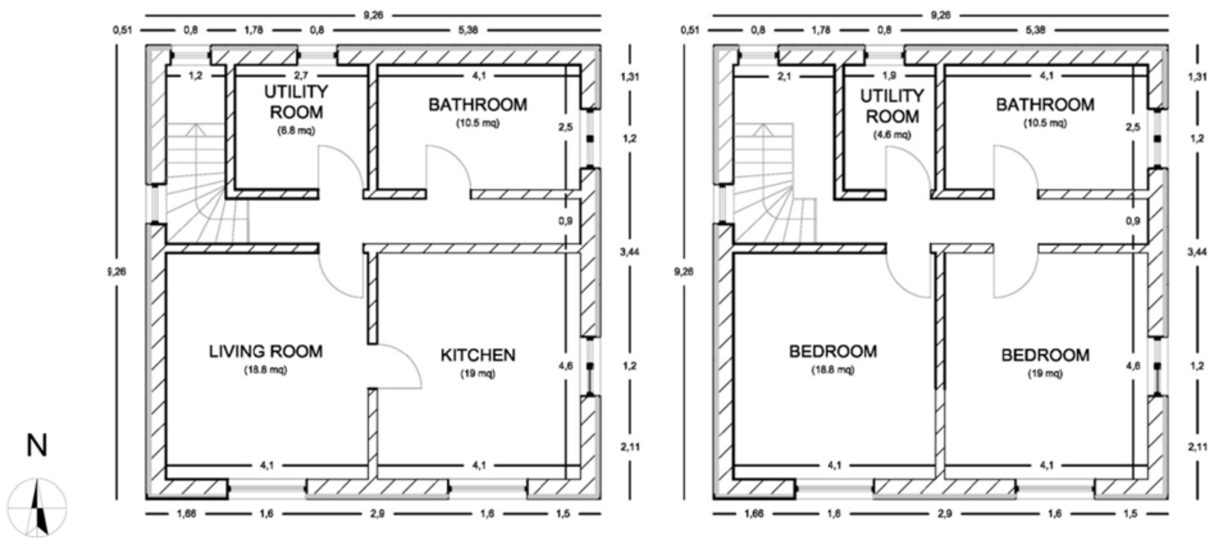
Table 1 Italian requirements for building certification.

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 Definition of the mono-residential reference building.

Climatic zone	C
Class period of construction	8 (after 2005)
Class size of building	E1 (1) – residential building with continuous use
Energy Class	B
EP_{global}	59.06 kWh/m^2y





V [m^3]	**S/V[m^{-1}]**	**At.n [m^2]**	**Apartments number**	**Conditioned floor number**
603.3	0.72	133.74	1	2

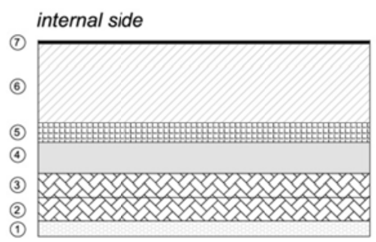
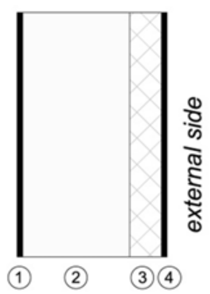
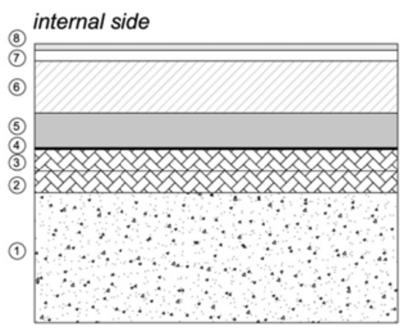
ROOF	**EXTERNAL WALL**	**FLOOR**	**WINDOW**
			Double glass with low emissivity (Argon) Thickness 20 mm Metal frame with thermal break
1. Tuff (40 mm) 2. Dry send (60 mm) 3. Concrete (60 mm) 4. EPS (80 mm) 5. Concrete screed (50 mm) 6. Slab (200 mm) 7. Plaster (10 mm)	1. Plaster (15 mm) 2. Tuff (300 mm) 3. EPS (80 mm) 4. Plaster (15 mm)	1. Gravel (300mm) 2. Concrete screed (100 mm) 4. Bituminous membrane (5 mm) 5. XPS (80mm) 6. Concrete screed (120 mm) 7. Cement mortar (25 mm) 8. Tiles (15 mm)	80x150 120x150 160x150 160x210
U (W/m^2K)	**U (W/m^2K)**	**U (W/m^2K)**	**Uw (W/m^2K)**
0.335	0.374	0.355	2.52 2.59 2.58 2.50

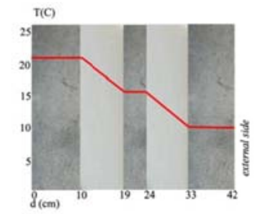
Table 3 Technical systems of the reference building.

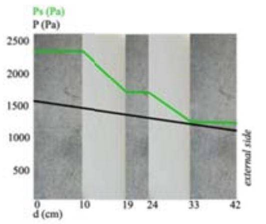
Domestic Hot Water	combined heating + tank		
supply	$\eta_{w.su}$	%	95
distribution	$\eta_{w.di}$	%	96
storage	$\eta_{w.st}$	%	74
volume (external tank)	V	l	200
insulation thickness	t_i	cm	7
storage average temperature	T_{st}	°C	50
daily hours storage	h_{st}	h	24
Heating	radiators		
emission	η_e	%	95
distribution	η_d	%	95
regulation	η_r	%	93
storage	η_s	%	100
Colling	split		
electric power	P_{ku}	kW	4.00
Seasonal energy efficiecy ratio	SEER	-	5.1
Generation	standard boiler		
energy vector	natural gas		
nominal thermal power	$P_{t.n}$	kW	21
minimum thermal power	$P_{t.m}$	kW	9.6
heat production efficiency (heating)	$\eta_{gn.h}$	%	87
heat production efficiency (water)	$\eta_{gn.w}$	%	89

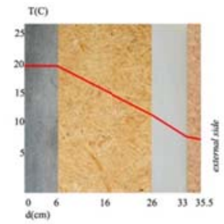
Solar system			solar collectors	PV panels
net area element	A_N	m^2	2	1.5
number of elements	N_o	-	2	2
peak power	P_{peak}	kW	-	2.5
azimuth	f_s	°	0	0
zenith	f_N	°	45	30
efficiency	η_k	%	55	17
coverage	GRcp	%	85	97
utilization	GRut	%	95	74

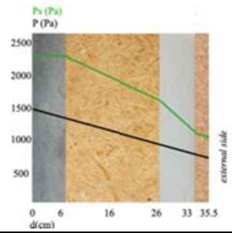
Table 4 Physical properties of heavy and light high performance external walls.

WALL	W1	W2
Layer1	Concrete	Concrete
Layer2	Polyurethane foam 1	Wood fiber hardboard
Layer3	Concrete exp. Clay	Wood fiber hardboard
Layer4	Polyurethane foam 2	Polyurethane foam 1
Layer5	Concrete	OSB
U (W/m^2K)	0.13	0.12
$\mathbf{Y_{12}}$ (W/m^2K)	0.0061	0.0111
$\mathbf{Y_{22}}$ (W/m^2K)	10.06	1.87
$\mathbf{Y_{11}}$ (W/m^2K)	5.97	5.35
fd	0.047	0.088
$\mathbf{M_s}$ (Kg/m^2)	474.4	178.3
$\mathbf{\Delta t}$ (h)	15.00	16.75
$\kappa 1$ (J/m^2K)	82.0	73.50
$\kappa 2$ (J/m^2K)	138.4	25.6
d (m)	0.42	0.33

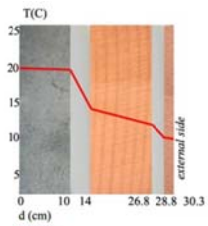


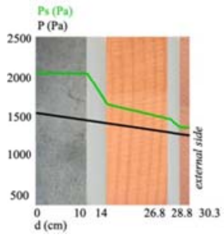


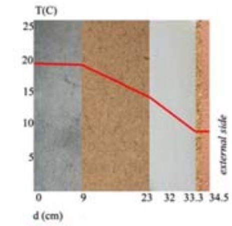




WALL	W3	W4
Layer1	Concrete	Concrete
Layer2	Polyurethane foam 1	Fibreboard
Layer3	Cross-laminated timber pane	Polyurethane exp.
Layer4	Polyurethane foam 2	Cork panel exp.
Layer5	Plaster	Plaster
U (W/m^2K)	0.27	0.12
$\mathbf{Y_{12}}$ (W/m^2K)	0.0151	0.0130
$\mathbf{Y_{22}}$ (W/m^2K)	1.92	1.84
$\mathbf{Y_{11}}$ (W/m^2K)	5.92	5.85
fd	0.055	0.104
$\mathbf{M_s}$ (Kg/m^2)	282.3	224.7
$\mathbf{\Delta t}$ (h)	15.09	15.23
$\kappa 1$ (J/m^2K)	81.5	80.58
$\kappa 2$ (J/m^2K)	26.3	25.3
d (m)	0.30	0.35







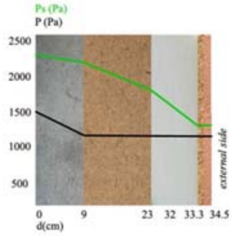


Table 5 Geometrical and thermal properties of external windows.

80x150 cm Double glazing low emissivity (argon)		**120x150 cm** Double glazing low emissivity (argon)		**160x150 cm** Double glazing low emissivity (argon)		**160x210 cm** Double glazing low emissivity (argon)	
F1	U_w = 2.00 W/m^{2}K	**F1**	U_w =2.10 W/m^{2}K	**F1**	U_w =2.10 W/m^{2}K	**F1**	U_w =1.90 W/m^{2}K
F2	U_w =1.34 W/m^{2}K	**F2**	U_w =1.39 W/m^{2}K	**F2**	U_w =1.34 W/m^{2}K	**F2**	U_w =1.90 W/m^{2}K
F3	U_w =2.10 W/m^{2}K	**F3**	U_w = 2.30 W/m^{2}K	**F3**	U_w =2.10 W/m^{2}K	**F3**	U_w =2.10 W/m^{2}K

F 1 = Metal frame
F 2 = Pvc frame
F 3 = Metal-wood frame

Table 6 Definition of technical systems for the building configurations.

Ventilation			AHU	static VMC
using			winter summer	winter summer
external air flow rate	$q_{v.e}$	m^3/h	180	180
thermal efficiency-heat recovery (winter)	$\eta_{\Theta w.d}$	%	85	84
thermal efficiency-heat recovery (summer)	$\eta_{\Theta s.d}$	%	50	50
hygrometric efficiency-heat recovery (winter)	$\eta_{xw.d}$	%	40	-
specific power consumption	SFP_d	Wh/m^3	0.40	0.46
volume-controlled ventilation	V_N	m^3	361	361
time daily service	t_B	h/d	24	24
air exchange - winter	n	1/h	0.17	0.18
air exchange - summer	n	1/h	0.25	0.25
bypass			yes	no
Generation			**Electrical Heat pump**	**Active heat recovery**
heating electric power	$P_{el.h}$	kW	3.04	1.90
cooling electric power	$P_{el.c}$	kW	3.74	1.78
design heating temperature	$q_{h.out}$	°C	40	40
design water temperature	$q_{w.out}$	°C	40	-
SCOP			3.8	3.67
SEER			2.6	2.41

Domestic Hot Water			
type of production	**generator: dedicated DHW/heating system**		
supply	$\eta_{w.su}$	95	%
distribution	$\eta_{w.di}$	96	%
storage	$\eta_{w.st}$	78	%
volume (external tank)	V	200	l
insulation thickness	t_i	7	cm
storage average temperature	T_{st}	50	°C
daily hours storage	h_{st}	24	h
electrical resistance	R	1.00	kW

Heating/cooling			AHU	Fancoil	Active heat recovery	Radiant Panels
emission	η_e	%	94	96	94	99
distribution	η_d	%	99	99	99	99
regulation	η_r	%	99	99	99	98
storage	η_s	%	100	100	100	100

Solar system			Solar collectors		PV panels	
net area element	A_N	m^2	2		1.5	
peak power	P_{peak}	kW	-		3.5	4.0
number of elements	N_o		2	3	12	16
azimuth	f_s	°	0		0	
zenith	f_N	°	45		30	
efficiency	η_k	%	55		17	
coverage	GRcp	%	92	98	88	95
utilization	Grut	%	88	74	87	78

Table 7 Symbols and description of the technical systems of the combinations.

System	HVAC system	Generation system	Solar thermal system	PV system
s1	AHU	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	12 PV panels - 3 kWp
s2	Fancoils + VMC (static)	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	12 PV panels - 3 kWp
s3	VMC (dynamic) + Channelized split	Active heat recovery	3 Solar collectors + External tank 200 l + 1kW (resistance)	12 PV panels - 3 kWp
s4	Radiant panels + Fancoils + VMC (static)	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	12 PV panels - 3 kWp
s5	AHU	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	12 PV panels - 3 kWp
s6	Fancoils + VMC (static)	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	12 PV panels - 3 kWp
s7	Radiant panels + Fancoils + VMC (static)	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	12 PV panels - 3 kWp
s8	AHU	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	16 PV panels - 4 kWp
s9	Fancoils + VMC (static)	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	16 PV panels - 4 kWp
s10	VMC (dynamic) + Channelized split	Active heat recovery	3 Solar collectors + External tank 200 l + 1kW (resistance)	16 PV panels - 4 kWp
s11	Radiant panels + Fancoils + VMC (static)	Heat pump (heating)	3 Solar collectors + External tank 200 l + 1kW (resistance)	16 PV panels - 4 kWp
s12	AHU	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	16 PV panels - 4 kWp
s13	Fancoils + VMC (static)	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	16 PV panels - 4 kWp
s14	Radiant panels + Fancoils + VMC (static)	Heat pump (heating + dhw)	2 Solar collectors + External tank 200 l	16 PV panels - 4 kWp

Table 8 Combinations of technical variants and EPi demand in mono-residential buildings.

Combo	Variants			EPi kWh/m²y	Combo	Variants			EPi kWh/m²y	Combo	Variants			EPi kWh/m²y	Combo	Variants			EPi kWh/m²y
C-01	W1	F1	S1	14.55	**C-43**	W3	F1	S4	12.53	**C-85**	W1	F1	S8	4.69	**C-127**	W3	F1	S11	7.55
C-02	W1	F2	S1	13.65	**C-44**	W3	F2	S4	10.42	**C-86**	W1	F2	S8	3.19	**C-128**	W3	F2	S11	5.87
C-03	W1	F3	S1	14.86	**C-45**	W3	F3	S4	13.15	**C-87**	W1	F3	S8	5.12	**C-129**	W3	F3	S11	8.03
C-04	W2	F1	S1	14.42	**C-46**	W4	F1	S4	8.51	**C-88**	W2	F1	S8	4.48	**C-130**	W4	F1	S11	4.17
C-05	W2	F2	S1	13.61	**C-47**	W4	F2	S4	7.01	**C-89**	W2	F2	S8	3.06	**C-131**	W4	F2	S11	2.67
C-06	W2	F3	S1	14.75	**C-48**	W4	F3	S4	8.98	**C-90**	W2	F3	S8	4.91	**C-132**	W4	F3	S11	4.63
C-07	W3	F1	S1	17.76	**C-49**	W1	F1	S5	14.74	**C-91**	W3	F1	S8	7.74	**C-133**	W1	F1	S12	4.80
C-08	W3	F2	S1	15.97	**C-50**	W1	F2	S5	13.68	**C-92**	W3	F2	S8	6.10	**C-134**	W1	F2	S12	3.30
C-09	W3	F3	S1	18.31	**C-51**	W1	F3	S5	15.13	**C-93**	W3	F3	S8	8.23	**C-135**	W1	F3	S12	5.23
C-10	W4	F1	S1	14.29	**C-52**	W2	F1	S5	14.60	**C-94**	W4	F1	S8	4.37	**C-136**	W2	F1	S12	4.59
C-11	W4	F2	S1	13.47	**C-53**	W2	F2	S5	13.65	**C-95**	W4	F2	S8	2.98	**C-137**	W2	F2	S12	3.28
C-12	W4	F3	S1	14.59	**C-54**	W2	F3	S5	15.00	**C-96**	W4	F3	S8	4.79	**C-138**	W2	F3	S12	5.03
C-13	W1	F1	S2	9.24	**C-55**	W3	F1	S5	18.21	**C-97**	W1	F1	S9	4.82	**C-139**	W3	F1	S12	7.88
C-14	W1	F2	S2	7.62	**C-56**	W3	F2	S5	16.26	**C-98**	W1	F2	S9	3.17	**C-140**	W3	F2	S12	6.22
C-15	W1	F3	S2	9.78	**C-57**	W3	F3	S5	18.76	**C-99**	W1	F3	S9	5.31	**C-141**	W3	F3	S12	8.37
C-16	W2	F1	S2	9.02	**C-58**	W4	F1	S5	14.41	**C-100**	W2	F1	S9	4.59	**C-142**	W4	F1	S12	4.48
C-17	W2	F2	S2	7.44	**C-59**	W4	F2	S5	13.50	**C-101**	W2	F2	S9	2.96	**C-143**	W4	F2	S12	2.99
C-18	W2	F3	S2	9.55	**C-60**	W4	F3	S5	14.79	**C-102**	W2	F3	S9	5.07	**C-144**	W4	F3	S12	4.91
C-19	W3	F1	S2	13.12	**C-61**	W1	F1	S6	9.58	**C-103**	W3	F1	S9	7.96	**C-145**	W1	F1	S13	4.96
C-20	W3	F2	S2	10.86	**C-62**	W1	F2	S6	7.78	**C-104**	W3	F2	S9	6.23	**C-146**	W1	F2	S13	3.31
C-21	W3	F3	S2	13.76	**C-63**	W1	F3	S6	10.12	**C-105**	W3	F3	S9	8.45	**C-147**	W1	F3	S13	5.45
C-22	W4	F1	S2	8.86	**C-64**	W2	F1	S6	9.36	**C-106**	W4	F1	S9	4.49	**C-148**	W2	F1	S13	4.73
C-23	W4	F2	S2	7.33	**C-65**	W2	F2	S6	7.58	**C-107**	W4	F2	S9	2.87	**C-149**	W2	F2	S13	3.10
C-24	W4	F3	S2	9.38	**C-66**	W2	F3	S6	9.89	**C-108**	W4	F3	S9	4.96	**C-150**	W2	F3	S13	5.21
C-25	W1	F1	S3	11.51	**C-67**	W3	F1	S6	13.63	**C-109**	W1	F1	S10	7.38	**C-151**	W3	F1	S13	8.10
C-26	W1	F2	S3	9.32	**C-68**	W3	F2	S6	11.31	**C-110**	W1	F2	S10	5.26	**C-152**	W3	F2	S13	6.37
C-27	W1	F3	S3	12.22	**C-69**	W3	F3	S6	14.26	**C-111**	W1	F3	S10	7.98	**C-153**	W3	F3	S13	8.59
C-28	W2	F1	S3	11.16	**C-70**	W4	F1	S6	9.21	**C-112**	W2	F1	S10	7.04	**C-154**	W4	F1	S13	4.63
C-29	W2	F2	S3	8.99	**C-71**	W4	F2	S6	7.46	**C-113**	W2	F2	S10	4.93	**C-155**	W4	F2	S13	3.00
C-30	W2	F3	S3	11.86	**C-72**	W4	F3	S6	9.72	**C-114**	W2	F3	S10	7.63	**C-156**	W4	F3	S13	5.10
C-31	W3	F1	S3	17.06	**C-73**	W1	F1	S7	9.19	**C-115**	W3	F1	S10	11.28	**C-157**	W1	F1	S14	4.63
C-32	W3	F2	S3	13.92	**C-74**	W1	F2	S7	7.43	**C-116**	W3	F2	S10	9.14	**C-158**	W1	F2	S14	3.02
C-33	W3	F3	S3	17.96	**C-75**	W1	F3	S7	9.71	**C-117**	W3	F3	S10	11.88	**C-159**	W1	F3	S14	5.10
C-34	W4	F1	S3	11.01	**C-76**	W2	F1	S7	8.97	**C-118**	W4	F1	S10	6.94	**C-160**	W2	F1	S14	4.40
C-35	W4	F2	S3	8.89	**C-77**	W2	F2	S7	7.24	**C-119**	W4	F2	S10	4.84	**C-161**	W2	F2	S14	2.82
C-36	W4	F3	S3	11.71	**C-78**	W2	F3	S7	9.49	**C-120**	W4	F3	S10	7.54	**C-162**	W2	F3	S14	4.87
C-37	W1	F1	S4	8.84	**C-79**	W3	F1	S7	13.03	**C-121**	W1	F1	S11	4.49	**C-163**	W3	F1	S14	7.70
C-38	W1	F2	S4	7.30	**C-80**	W3	F2	S7	10.78	**C-122**	W1	F2	S11	2.88	**C-164**	W3	F2	S14	5.45
C-39	W1	F3	S4	9.37	**C-81**	W3	F3	S7	13.65	**C-123**	W1	F3	S11	4.96	**C-165**	W3	F3	S14	8.17
C-40	W2	F1	S4	8.63	**C-82**	W4	F1	S7	8.82	**C-124**	W2	F1	S11	4.26	**C-166**	W4	F1	S14	4.31
C-41	W2	F2	S4	7.11	**C-83**	W4	F2	S7	7.12	**C-125**	W2	F2	S11	2.74	**C-167**	W4	F2	S14	2.72
C-42	W2	F3	S4	9.15	**C-84**	W4	F3	S7	9.32	**C-126**	W2	F3	S11	4.73	**C-168**	W4	F3	S14	4.77

	Epi < 6 kWh/m²y
	6 < Epi < 12 kWh/m²y
	12 < Epi < 15 kWh/m²y
	15 < Epi < 19 kWh/m²y
	Best configurations

Table 9 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 10 Global costs of combinations.

Combo	Global costs (financial) €/m^2	Global costs (macro) €/m^2	Combo	Global costs (financial) €/m^2	Global costs (macro) €/m^2	Combo	Global costs (financial) €/m^2	Global costs (macro) €/m^2	Combo	Global costs (financial) €/m^2	Global costs (macro) €/m^2
C-01	384.68	341.64	**C-43**	532.04	473.13	**C-85**	377.89	333.85	**C-127**	534.03	474.10
C-02	371.82	329.80	**C-44**	516.65	457.03	**C-86**	363.97	320.60	**C-128**	519.40	460.52
C-03	395.31	351.36	**C-45**	543.52	483.67	**C-87**	388.73	343.43	**C-129**	545.24	484.38
C-04	377.24	336.01	**C-46**	498.97	444.31	**C-88**	370.18	327.93	**C-130**	502.09	446.41
C-05	364.31	324.15	**C-47**	484.85	431.22	**C-89**	356.13	314.95	**C-131**	487.97	433.33
C-06	388.11	345.98	**C-48**	510.06	454.46	**C-90**	381.24	338.09	**C-132**	513.15	456.55
C-07	422.81	374.69	**C-49**	378.92	333.33	**C-91**	415.54	366.39	**C-133**	372.01	328.32
C-08	407.99	360.90	**C-50**	365.79	321.64	**C-92**	401.02	352.90	**C-134**	358.07	315.40
C-09	434.16	385.09	**C-51**	389.69	343.25	**C-93**	426.80	376.70	**C-135**	382.85	338.24
C-10	391.92	347.91	**C-52**	371.35	327.74	**C-94**	384.92	339.90	**C-136**	364.18	322.29
C-11	379.02	336.06	**C-53**	358.16	315.84	**C-95**	370.99	327.01	**C-137**	350.32	309.47
C-12	402.70	357.77	**C-54**	382.37	337.72	**C-96**	395.92	349.97	**C-138**	375.24	332.42
C-13	431.02	382.89	**C-55**	417.39	366.26	**C-97**	433.95	384.83	**C-139**	409.56	360.73
C-14	416.88	369.78	**C-56**	402.27	352.53	**C-98**	419.75	371.65	**C-140**	394.98	347.20
C-15	442.05	393.04	**C-57**	428.73	376.67	**C-99**	444.89	394.88	**C-141**	420.81	371.05
C-16	424.33	377.94	**C-58**	385.95	339.68	**C-100**	427.29	379.90	**C-142**	378.94	334.26
C-17	409.98	364.68	**C-59**	372.90	327.77	**C-101**	412.86	366.55	**C-143**	364.83	321.17
C-18	435.57	388.30	**C-60**	396.88	349.54	**C-102**	438.43	390.15	**C-144**	389.94	344.32
C-19	471.60	418.29	**C-61**	425.54	374.63	**C-103**	471.70	418.93	**C-145**	428.11	378.63
C-20	455.92	403.66	**C-62**	411.07	361.74	**C-104**	458.54	405.26	**C-146**	413.92	365.50
C-21	483.11	428.87	**C-63**	436.58	384.98	**C-105**	484.48	429.22	**C-147**	439.05	388.66
C-22	438.75	389.63	**C-64**	418.75	369.73	**C-106**	441.80	391.68	**C-148**	421.34	374.32
C-23	424.56	376.48	**C-65**	404.03	356.46	**C-107**	427.46	378.36	**C-149**	406.91	360.93
C-24	449.92	399.87	**C-66**	429.99	380.08	**C-108**	452.89	401.83	**C-150**	432.48	384.53
C-25	366.40	333.80	**C-67**	466.27	409.98	**C-109**	369.83	333.70	**C-151**	467.26	413.27
C-26	351.24	317.11	**C-68**	450.49	395.39	**C-110**	354.82	319.70	**C-152**	452.55	399.61
C-27	377.74	341.68	**C-69**	477.78	420.55	**C-111**	380.98	343.93	**C-153**	478.49	413.34
C-28	358.20	325.02	**C-70**	433.19	381.47	**C-112**	361.73	327.54	**C-154**	435.88	386.08
C-29	342.79	310.65	**C-71**	418.61	368.29	**C-113**	346.43	313.29	**C-155**	421.51	372.75
C-30	369.76	335.65	**C-72**	444.36	391.69	**C-114**	373.09	337.97	**C-156**	446.96	396.24
C-31	408.34	368.30	**C-73**	484.79	428.43	**C-115**	408.85	367.78	**C-157**	487.47	433.26
C-32	391.04	352.03	**C-74**	470.41	415.49	**C-116**	393.39	353.36	**C-158**	473.35	420.73
C-33	420.33	379.34	**C-75**	495.80	438.53	**C-117**	420.30	378.29	**C-159**	498.39	443.27
C-34	372.92	336.91	**C-76**	479.17	424.37	**C-118**	376.53	339.51	**C-160**	481.88	429.26
C-35	357.67	322.68	**C-77**	464.54	411.24	**C-119**	361.30	325.31	**C-161**	467.52	415.94
C-36	384.43	347.49	**C-78**	490.38	434.71	**C-120**	387.85	349.90	**C-162**	493.00	439.45
C-37	490.27	436.69	**C-79**	526.72	464.61	**C-121**	493.31	438.74	**C-163**	528.04	468.42
C-38	476.26	423.70	**C-80**	511.05	450.31	**C-122**	479.20	425.65	**C-164**	512.39	453.81
C-39	501.27	446.78	**C-81**	538.20	475.15	**C-123**	504.23	448.75	**C-165**	539.25	478.69
C-40	484.75	432.78	**C-82**	493.36	435.98	**C-124**	487.83	434.85	**C-166**	496.16	440.79
C-41	470.52	419.64	**C-83**	478.86	422.87	**C-125**	473.59	421.69	**C-167**	481.87	427.52
C-42	495.96	443.12	**C-84**	504.50	446.08	**C-126**	498.95	445.10	**C-168**	507.22	450.92

LIST OF FIGURES

Figure 01
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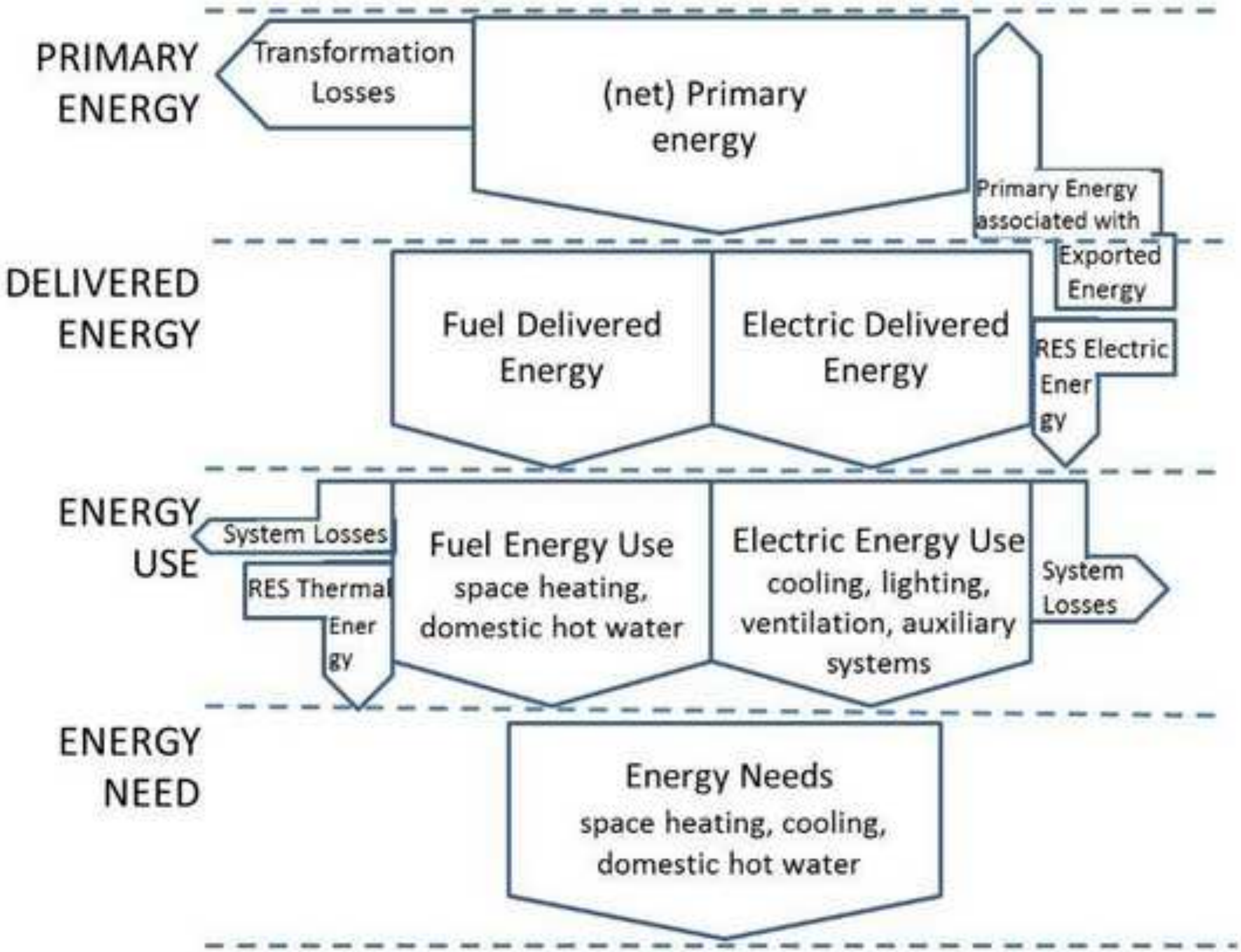

Figure 02
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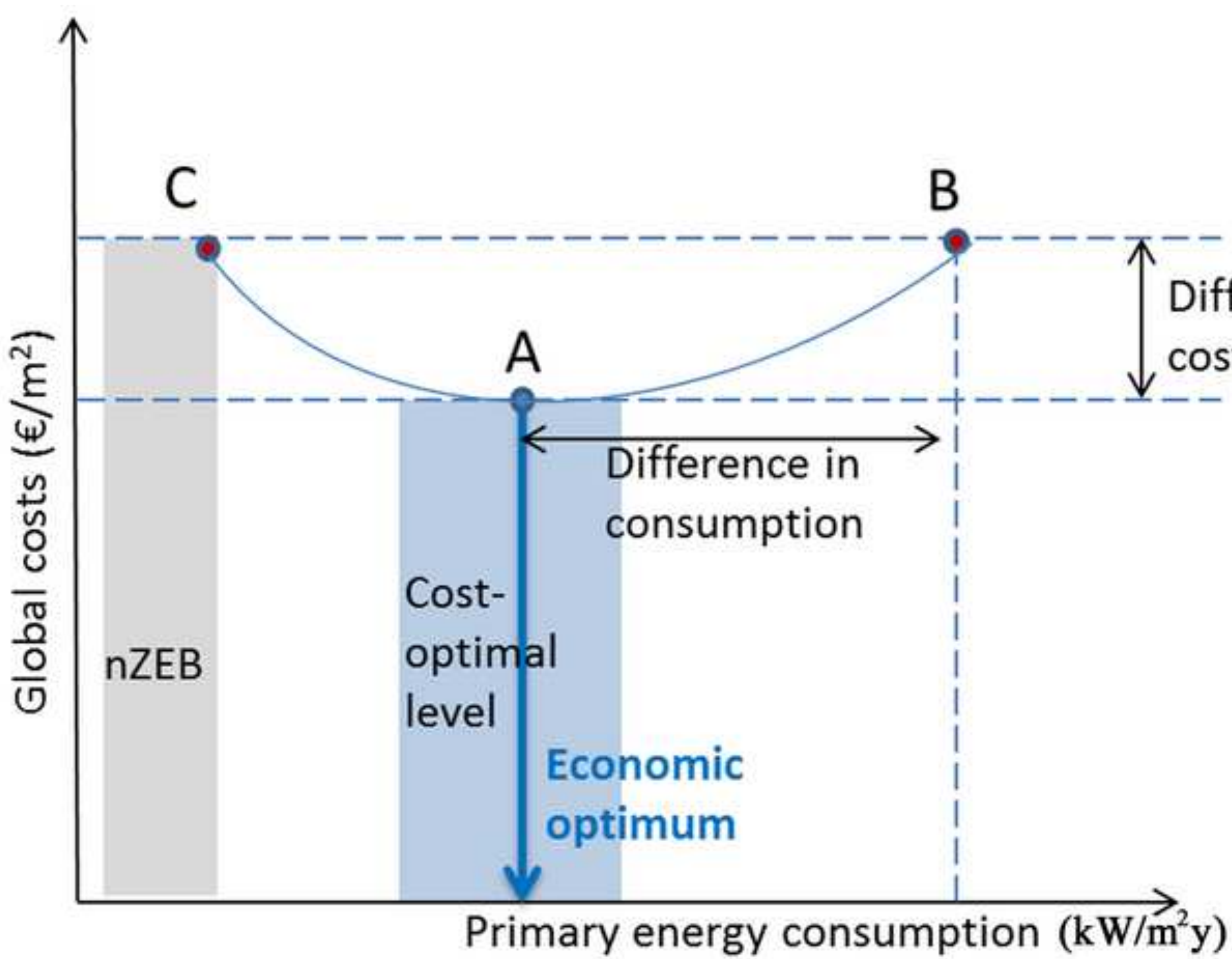

Figure 03
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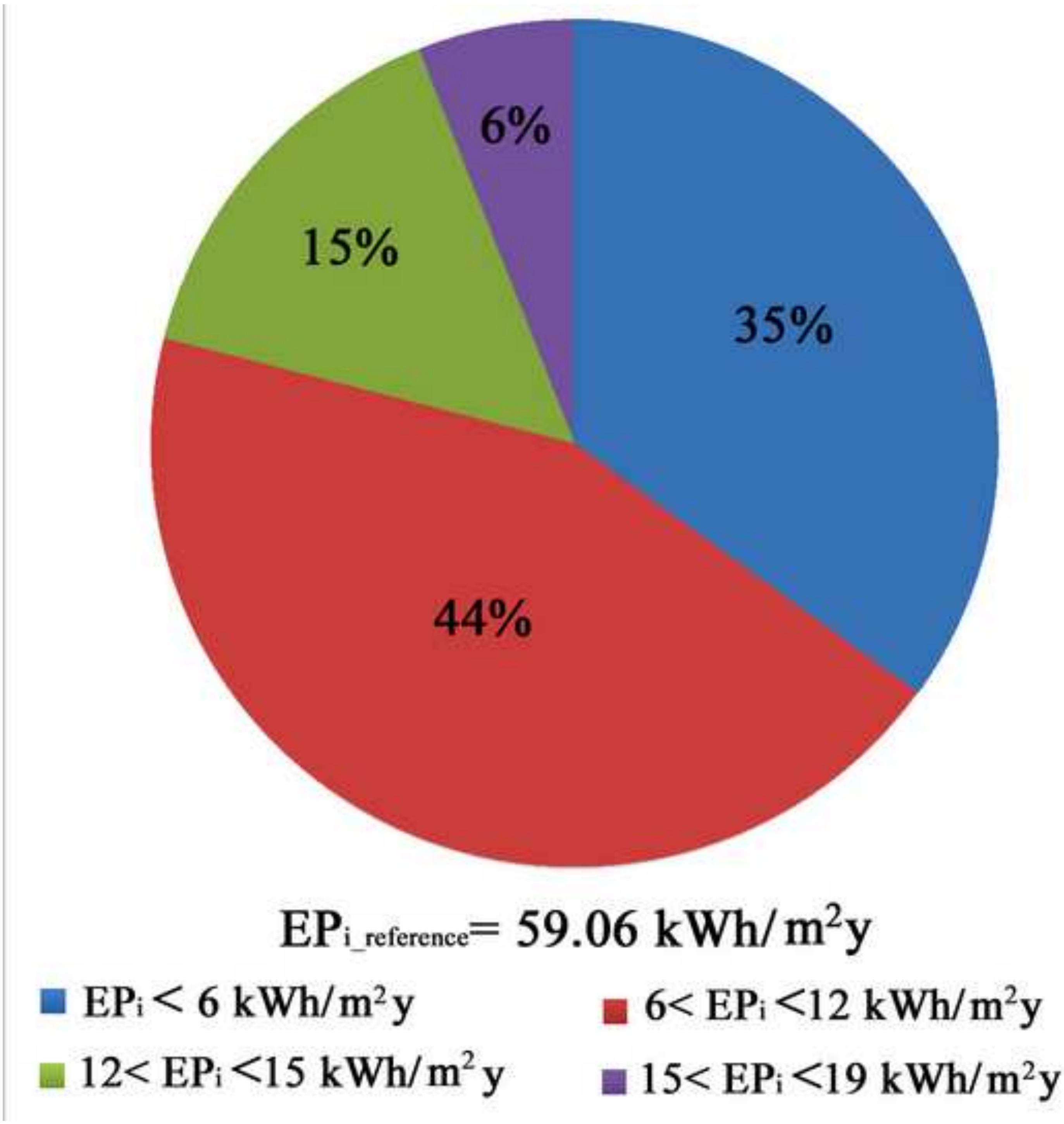

Figure 04

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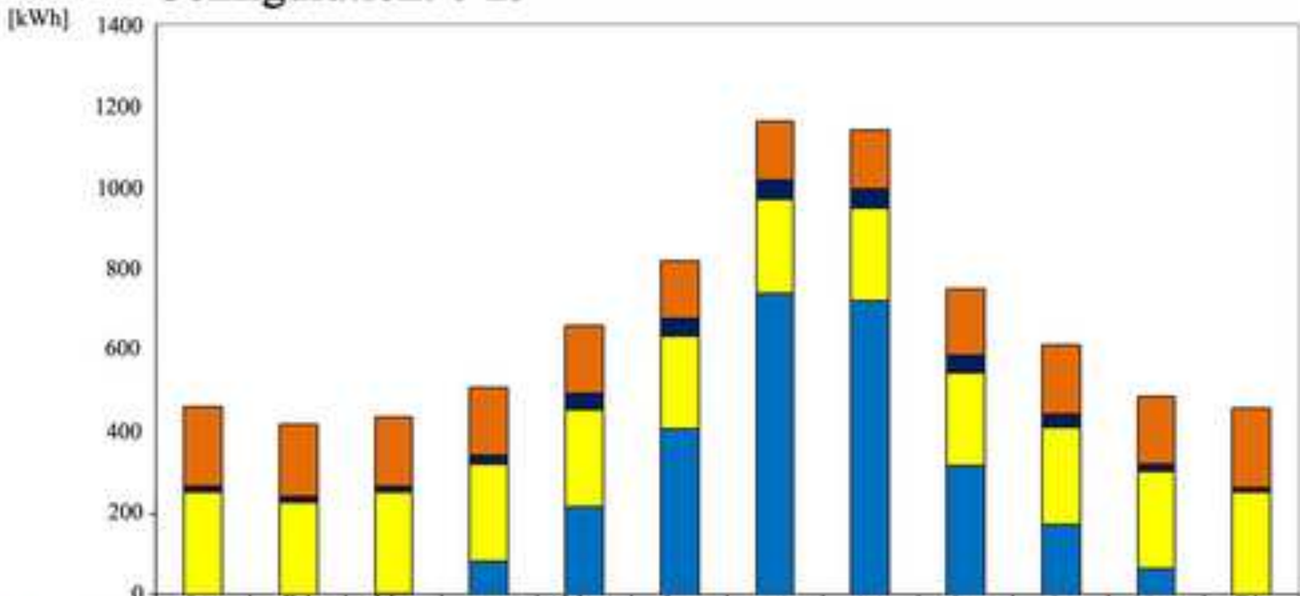
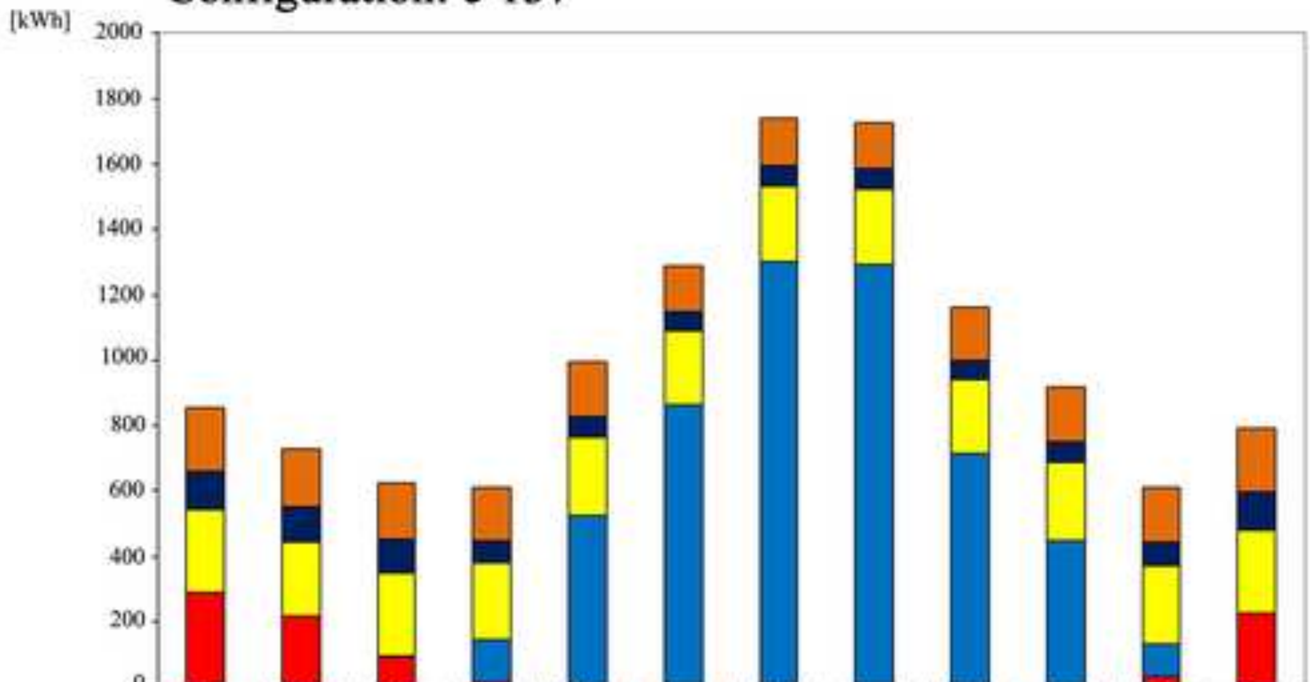
Configuration: c-29



	Jen	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dic
Lighting	195	176	169	164	169	139	144	144	164	169	164	195
Auxiliary	14	12	14	22	37	45	47	47	45	33	20	14
Humidification	0	0	0	0	0	0	0	0	0	0	0	0
DHW	254	229	251	238	240	226	230	230	226	240	238	252
Cooling	0	0	3	84	216	409	741	721	318	173	65	0
Heating	0	0	0	0	0	0	0	0	0	0	0	0

Configuration: c-137



	Jen	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lighting	195	176	169	164	169	139	144	144	164	169	164	195
Auxiliary	116	105	106	64	61	61	63	63	61	60	73	116
Humidification	0	0	0	0	0	0	0	0	0	0	0	0
DHW	254	229	251	238	240	226	230	230	226	240	238	252
Cooling	0	0	3	129	525	862	1302	1292	713	450	101	0
Heating	291	217	93	15	0	0	0	0	0	0	34	229

Figure 05

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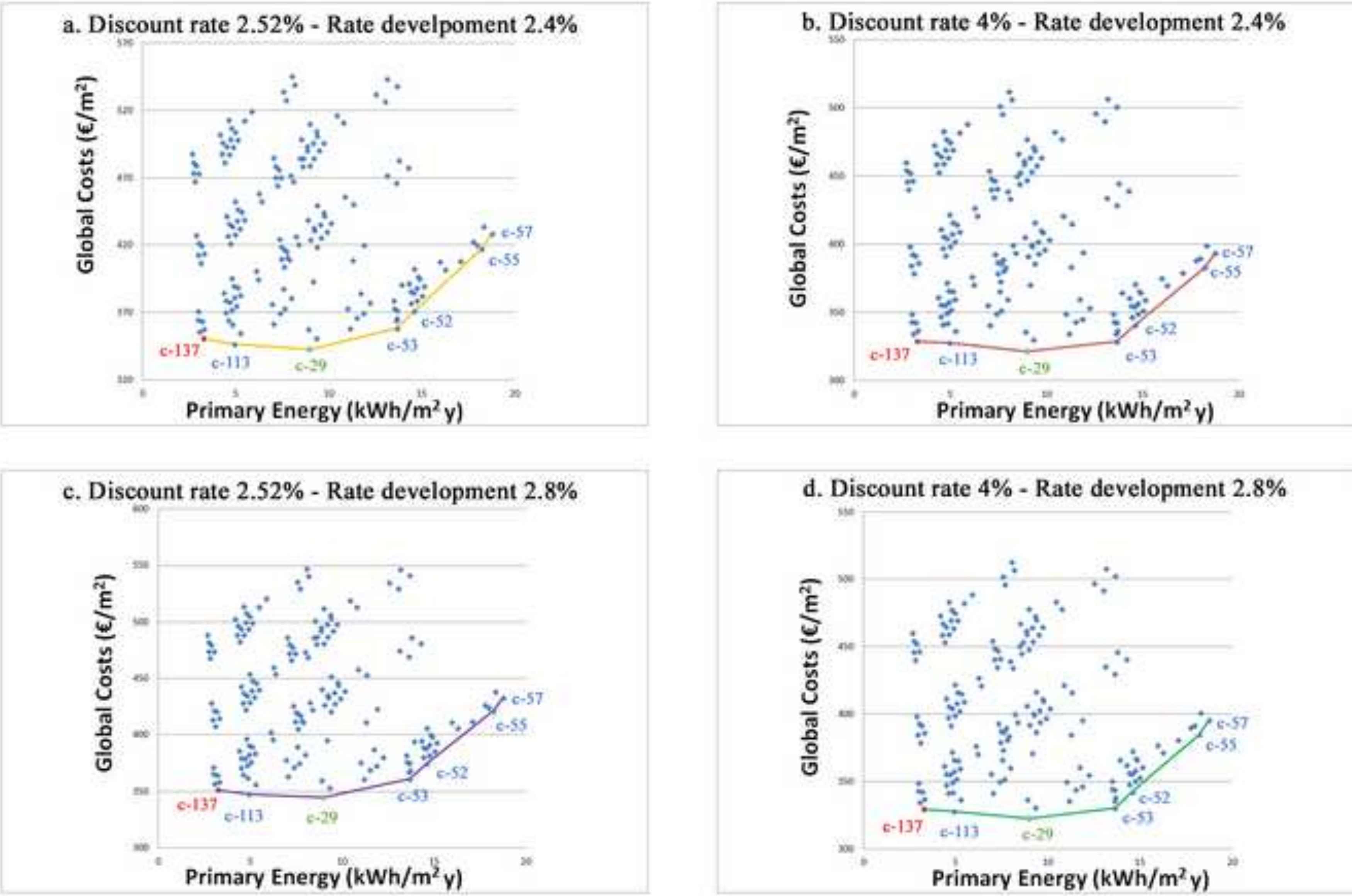

Figure 06
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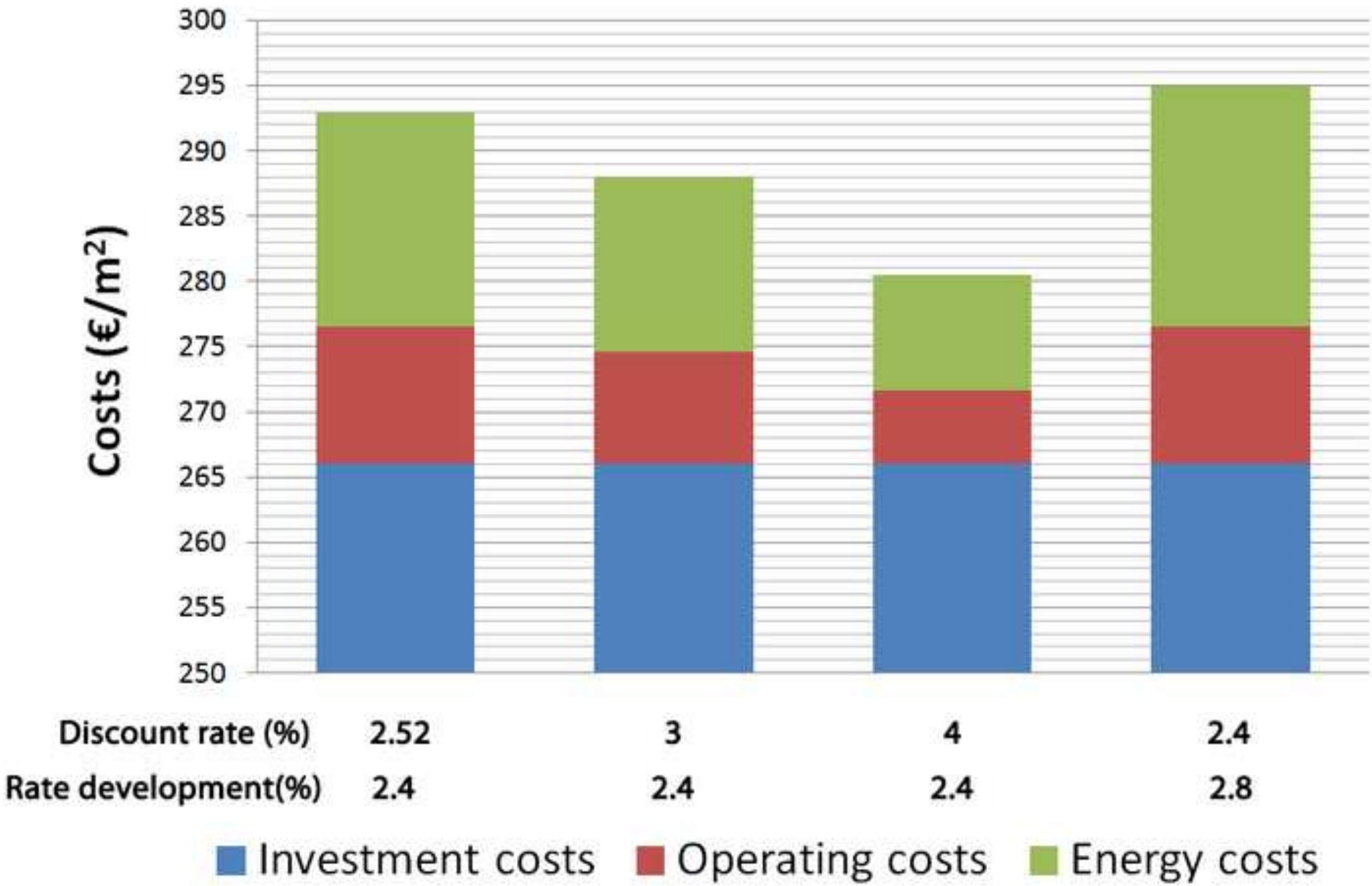

Figure 07
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