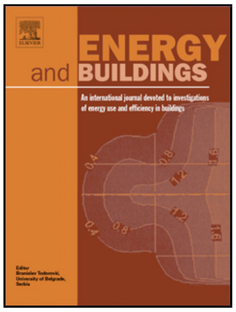

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Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia

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HIGHLIGHTS

- Cost effective evaluation for energy renovation of residential buildings
- Energy, comfort and economic criteria for choosing energy efficiency measures
- Building simulation including detailed characterization of the user interaction
- Effect of passive strategies as natural ventilation and solar protections

ABSTRACT

This paper presents the results of a detailed method for developing cost-optimal studies for the energy refurbishment of residential buildings. The method takes part of an innovative approach: two-step evaluation considering thermal comfort, energy and economic criteria. The first step, the passive evaluation, was presented previously [1] and the results are used to develop the active evaluation, which is the focus of this paper. The active evaluation develops a cost-optimal analysis to compare a set of passive and active measures for the refurbishment of residential buildings. The cost-optimal methodology follows the European Directives and analysed the measures from the point of view of non-renewable primary energy consumption and the global costs over 30 years. The energy uses included in the study are heating, domestic hot water, cooling, lighting and appliances. In addition, the results have been represented following the energy labelling scale. The paper shows the results of a multi-family building built in the years 1990-2007 and located in Barcelona with two configurations: with natural ventilation and without natural ventilation. The method provides technical and economic information about the energy efficiency measures, with the objective to support the decision process.

KEYWORDS: cost effective; energy renovation; residential building; passive strategies; global cost

Nomenclature

EPBD	Energy Performance of Building Directive
nZEB	nearly Zero Energy Buildings
C2	Barcelona climate
LDP	Long-term Percentage of Dissatisfied
OH	Overheating hours
VENT	dwelling with natural ventilation
nVENT	dwelling without natural ventilation
BC	Base case
INT	Internal insulation
EXT	External insulation
RW	Mineral wool
EPS	Expanded polystyrene
DHW	Domestic hot water
AC	Air conditioning split
η	Efficiency of the boiler
EER	Energy efficiency ratio of the cooling system
E_{ng}	Final energy consumption of natural gas
E_{ele}	Final energy consumption of electricity
Q_C	Cooling demand
Q_{DHW}	Domestic hot water demand
Q_H	Total heating demand
Q_h	Heating demand
$Q_{l,em}$	Heat losses due to emitter system
$Q_{l,ctr}$	Heat losses due to control system
PV	Photovoltaic
C_i	Initial investment cost

C_r	Running costs
C_p	Replacement costs
V_f	Final value of the component
T	Economic calculation period
R_D	Discount rate
R	Market interest rate
RI	Inflation rate
R_R	Real interest rate
R_E	Energy evolution rate
RX_E	Energy cost evolution
R_{CO2}	Environmental evolution rate
RX_{CO2}	CO2 cost evolution
$RX_{E,ele}$	Electricity cost evolution
$RX_{E,ng}$	Natural gas cost evolution
$E_{R,label\ i}$	Energy label scale
LIG_{BC}	Lighting consumption for the base case dwelling
APP_{BC}	Appliance consumption for the base case dwelling
$E_{T,label\ i}$	Total energy labelling scale
CO	Cost optimal measure
DR	Deep renovation scenario
SD	Standard dwelling
UD	Under roof dwelling

1. Introduction

Within the European regulatory framework, the nations and regions have an essential role in decision-making to reach the 20/20/20 targets, applying the Energy Performance of Building Directive (EPBD, recast) [2] and the Energy Efficiency Directive [3]. To promote the refurbishment of residential buildings, which present rates of energy renovation very low (0.2% dwellings per year [4] in Catalonia), the countries and regions must define retrofit strategies implementing cost-effective solutions following the EPBD approach. In this context, several studies have implemented the cost-effective methodology to evaluate both, new and existing building, and define the cost-optimal energy efficiency measures. These studies cover different climates, types of buildings and energy efficiency strategies, to evaluate the effectivity of the method and the most appropriated measures for each scenario.

Brandão et al. [5] developed the cost-optimal evaluation for a residential building of Portugal. They studied around 35,000 combinations of passive measures to evaluate which was the most suitable strategy for the envelope renovation. They used EnergyPlus for the primary energy calculation. The work concluded that the rehabilitation of the roof produces the greatest variation in terms of primary energy consumption and the combination of thermal envelope measures creates synergy effects that lead to better results than single measures. Stocker et al. [6] implemented the cost-optimal method for the renovation of school buildings in the Alps. The objective of the study was to reduce the heating energy consumption and they implemented measures to improve the envelope performance as well as, the efficiency of the heating system. Additionally, they developed a sensitivity analysis in order to evaluate the impact of some parameters used for the calculation. They obtained that the variation on the energy price, the measure cost and the interest rate are the most influential in the results. Similar results were obtained in ECOFYS study [7], where analysed the link and consistency between the nearly zero energy buildings definition and the cost-optimal levels of the minimum energy requirements. One of the aspects that they evaluated was the gap in the global cost calculation, mainly related to the variability of some parameters over the period calculation: technology costs, energy costs and primary energy factors for electricity or district heating. They performed some scenarios to quantify the impact of this variability into the cost-optimal analysis, obtaining significant changes in the optimum levels (from 25% to 50% of variability, depending on the scenario).

Aelenei et al. [8] implemented the methodology for the refurbishment of public buildings toward nearly Zero Energy Buildings (nZEB). The analysis was applied to a reference building of an existing office building in five different countries: Italy, Portugal, Romania, Spain and Greece. The evaluation tool used a new cost optimization procedure based on a sequential search optimization technique considering discrete options [9], which was implemented before in a cost-optimal study in residential buildings in Italy. The results were presented in terms of optimal "package of measures", primary energy consumption and global costs, as well as a cross-country comparison. The study presented by Hambdy et al. [10] introduced an efficient, transparent, and time-saving simulation-based optimization method. The method was applied to find the cost-optimal and nZEB energy performance levels for a study case of a single-family house in Finland. They proposed a multi-stage optimization: in the first stage they selected the optimal passive strategies in terms of heating demand and total investment costs; followed by the second stage where the active systems were evaluated from the primary energy consumption and Life Cycle Cost point of view; to finalize with the renewable energy design in order to improve the results obtained in the second stage. Moreover, they used two different optimization technics in the different stages of the study (genetic and deterministic algorithms). Asadi et al. [11] wanted to demonstrate the potentiality of the cost-effective evaluation to provide decision support. For that, an optimization methodology was developed based on combining TRNSYS, GenOpt and a multi-objective optimization algorithm in MatLab. The optimization approach was applied to a case study to evaluate all available combinations of alternative retrofit actions.

At Spanish level, the Spanish Ministry of Development [12] analysed the current building code to determine if it is possible to achieve the minimum energy performance requirement with cost-optimal solutions, obtaining that in most of the building typologies and climates, the current building regulation goes further than the cost-optimal measures. In addition, there are also several scientific studies developed in Spain [13-16]. They cover different regions, the northern [13, 15] and the southern [14], and all of them are focused on residential sector. However, not all the studies implement the cost-optimal method but, they proposed other variables of decision: [15] included the payback period as additional parameter for the economical evaluation; [14] used the construction costs and the CO_2 emissions to analysed the impact of different building legislations; and [13, 16] implemented the Life Cycle Cost and the Life Cycle Impact Assessment.

Then, it is clear that there is a wide range of possibilities to develop this type of studies, from the point of view of the criteria and parameters and, from the point of view of the tools. In that sense, Tadeu et al. [17] compared the cost-optimal evaluation with the return of investment. The results from the real options perspective enabled to conclude that the global cost is not enough for the investors and must be complemented with additional information (as the value of operational flexibility and other strategic factors), and the return of investment must be evaluated in a long-term rather than in the short-term perspective. Other point of view of the same discussion is described by Becchio et al. [18]. They introduced the need to incorporate some additional benefits to the global cost calculation, in order to achieve more interesting results for all the actors involved, including investors and final users. They proposed a method for quantify qualitative benefits in monetary terms, as the increase of the real estate market value, the enhancement of the indoor comfort, the reduction of CO_2 emissions.

To put on overall context, the present paper describes a cost-optimal analysis of a residential building of Catalonia. The work covers some aspects that have been described in the introduction. The study propose a cost-effective evaluation divided in two steps (Figure 1): first a passive evaluation, presented previously [1], where the envelope performance is improved using thermal comfort and initial investment costs as a criteria of decision; and a second step, active evaluation, where the passive and actives measures are combined and evaluated using the global cost and the non-primary energy consumption to find the cost-optimal scenario. Additionally, the study proposes a translation of the results to the energy labelling, in order to disseminate the results easily around the policy makers and the final users. An extended description of the active evaluation is done including the implementation of the energy systems and their use in the building model, as well as, the definition of the energy efficiency measures and the cost-optimal evaluation. The paper is divided in the following sections: Section 2 describes the method and the assumptions proposed in the study. Section 3 analyses and discuss the results. Finally, the most important conclusions are outlined in Section 4.

2. Methodology

The main objective of the method is to provide the cost-optimal measures for the energy renovation of residential buildings, considering three main criteria: thermal comfort, primary energy use and global costs., which was introduced previously in [19]. The analysis is done using dynamic building simulations, where the building and its interaction with the user are characterized in detail with TRNSYS [20]. The simulation evaluates the three criteria for the base case, i.e. the existing building, and for the building with different combination of energy efficiency measures (passive and active measures).

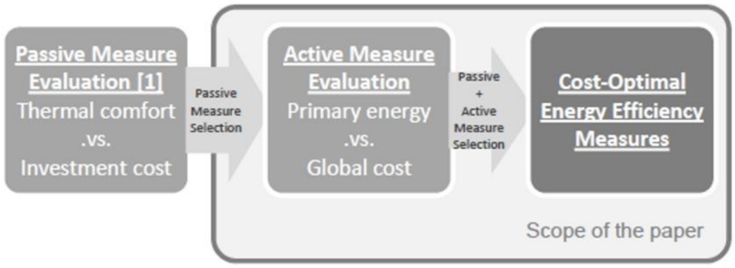


Figure 1 Overview of the two-step evaluation process

A co-simulation process is done to carry out each evaluation step, using SDLPS as a management tool and TRNSYS as a calculus engine for the energy simulation. SDLPS [21, 22] is a general purpose software infrastructure that makes possible to manage the main simulation process, running all the scenarios and collecting the results. The Brute-Force approach was used since the objective is to obtain a complete characterization of the problem [23, 24]. This approach consists on run the simulation with all the possible combinations i.e no optimization algorithm is used. The complete process of simulation implies around 6,000 simulation for the passive evaluation and 2,000 simulations for the active evaluation. Figure 2 represents the scheme of building simulation, where the software (solid lines), the methods (dashed lines) and the results (dotted lines) are remarked. Following sections describes how the different parts of the building model are implemented.

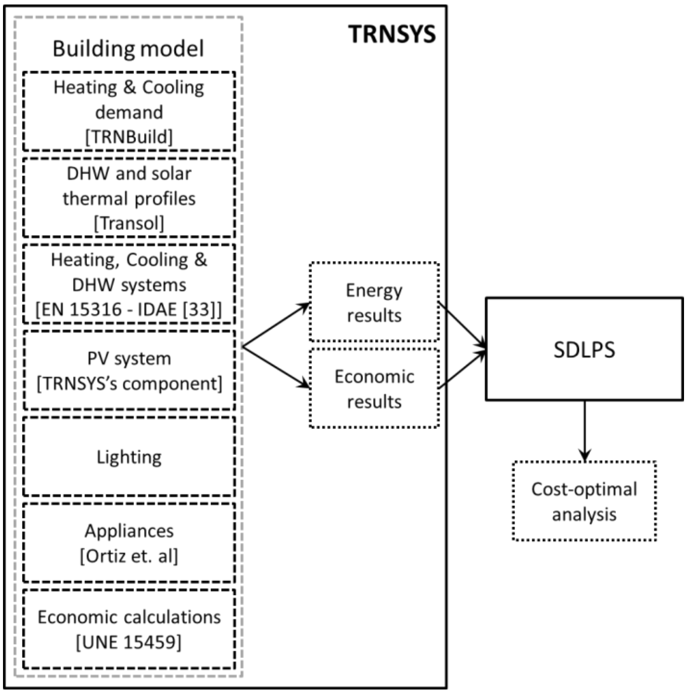


Figure 2 Software and methods implemented for the active measure evaluation to develop the cost-optimal analysis (solid line: software; dashed line: method; dotted line: results)

2.1. Starting point: passive measure evaluation

To carry out the passive measure evaluation, a detailed building model was developed, improving aspects of the building features, occupancy behaviour and passive strategies. The building characterization implemented in the model permits to establish the relation between the simulation parameters and the actual state of the building. The occupancy has been conceived as the main element of the simulation: the occupancy is needed for the activation of the different elements of the simulation (natural ventilation and solar protections). The building was analysed in Barcelona climate (C2). C2 corresponds to a representative climate of Spain, following the classification from the Spanish Building Regulation (Código Técnico de la Edificación [25]). For the evaluation, the building was simulated without the use of the heating and cooling system (free running mode) and the comfort model used was the ASHRAE adaptive model [26]. The purpose was to explore to what extent the passive measures were able to reduce the discomfort conditions without the use of the mechanical systems. Moreover, the paper evaluated the impact of the natural ventilation, simulating the building with and without natural ventilation (VENT and nVENT, respectively).

The comfort index used were the Long-term Percentage of Dissatisfied (LDP) for the annual, warm and cold period, and the hours of overheating (OH), which are explained in detail in [1, 27]. The LDP index was calculated using the operative temperature as a short comfort index, following the ASHRAE adaptive model. The results of the passive evaluation are summarized in Figure 3, Table 1 and Table 2. The data represent the base case (BC) and the selected passive measures, which tries to find an equilibrium between the different criteria: a) to select the measures that achieves a comfort improvement with the minimum investment cost; b) to reduce the hours of overheating below the threshold comfort (this situation makes possible to avoid the cooling system, because there is not overheating problems in the household); c) to reduce the cold thermal comfort (the heating demand is the large demand of dwellings, for that reason, if the combination of measures reduce the cold thermal comfort, then the heating demand will be lower).

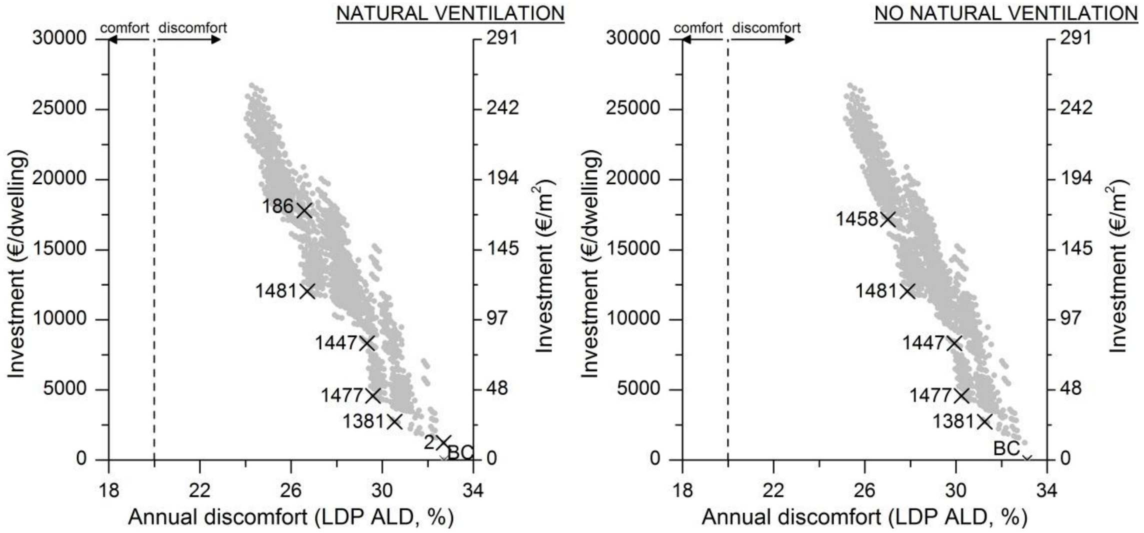


Figure 3 Passive measure selection, following comfort and economic criteria for Barcelona climate. Left: with natural ventilation; Right: without natural ventilation

Table 1 Passive measure selection, following comfort and economic criteria for Barcelona climate with natural ventilation

Passive (u-value) /(g-value)	**Façade (W/m^{2}K)**	**Roof (W/m^{2}K)**	**Window (W/m^{2}K) /(%/100)**	**Solar Prot.**	**Annual LDP %**	**Cold season LDP %**	**Warm season LDP %**	**Over-heating OH Hours**
BC	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	32.7	54.7	8.9	45
2	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Awning	32.7	54.7	8.8	41
1381	INT–RW 6 (0.339)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	30.6	51.2	8.2	40

1477	INT–RW 8 (0.294)	INT–RW 8 (0.275)	Base case (5.7)/(0.85)	Internal blinds	29.6	49.5	8.1	51
1447	INT–RW 8 (0.294)	EXT–EPS 8 (0.259)	Base case (5.7)/(0.85)	Internal blinds	29.3	49.2	7.9	36
1481	INT–RW 8 (0.294)	INT–RW 8 (0.275)	4/16/4PVC (2.8)/(0.75)	Internal blinds	26.7	44.3	7.6	62
186	EXT–EPS 8 (0.273)	Base case (0.546)	4/16/4PVC (2.8)/(0.75)	Awning	26.6	44.4	7.3	39

LDP <20% represent comfortable conditions. OH < 41 hours represent comfortable conditions in the climate of Barcelona

Table 2 Passive measure selection, following comfort and economic criteria for Barcelona climate without natural ventilation

Passive (u-value) /(g-value)	**Façade (W/m^{2}K)**	**Roof (W/m^{2}K)**	**Window (W/m^{2}K) /(%/100)**	**Solar Prot.**	**Annual LDP %**	**Cold season LDP %**	**Warm season LDP %**	**Over-heating OH Hours**
BC	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	33.1	54.7	9.8	120
1381	INT–RW 6 (0.339)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	31.3	51.2	9.7	202
1477	INT–RW 8 (0.294)	INT–RW 8 (0.275)	Base case (5.7)/(0.85)	Internal blinds	30.2	49.5	9.4	182
1447	INT–RW 8 (0.294)	EXT–EPS 8 (0.259)	Base case (5.7)/(0.85)	Internal blinds	29.9	49.2	9.1	109
1481	INT–RW 8 (0.294)	INT–RW 8 (0.275)	4/16/4PVC (2.8)/(0.75)	Internal blinds	27.9	44.3	10.1	390
1458	INT–RW 8 (0.294)	EXT–EPS10 (0.229)	4/16/4PVC (2.8)/(0.75)	Awning	27.0	43.5	9.2	217

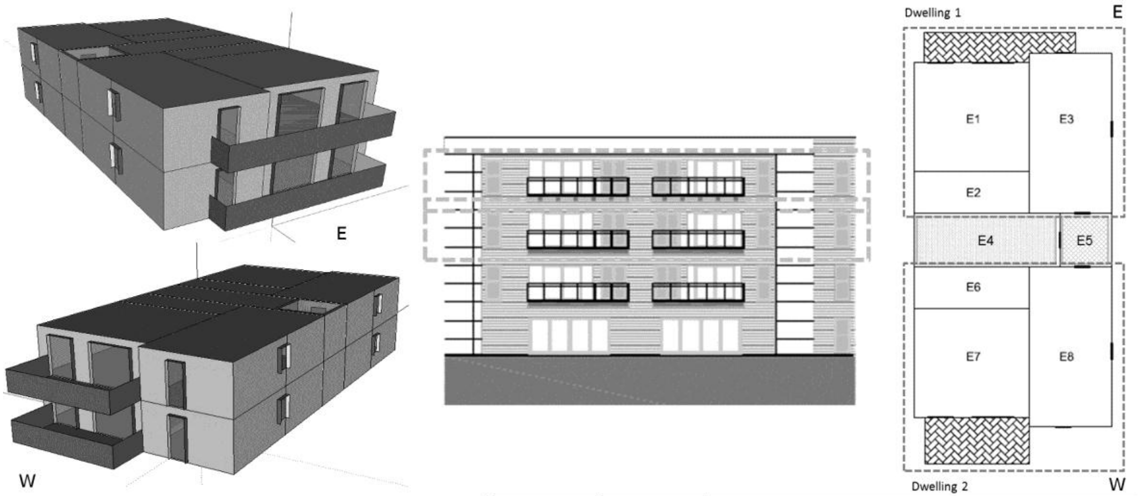
LDP <20% represent comfortable conditions. OH < 41 hours represent comfortable conditions in the climate of Barcelona

2.2. Detailed building simulation

2.2.1. Building features

To select the building typology, a research was done by the Catalan Housing Agency and Estudi Ramon Folch (AHC and ERF) in the framework of the MARIE project [28], in order to characterize and improve the information of the building stock from Catalonia. They defined the constructive features, the equipment and the user characteristics. The results obtained were consistent with the typologies defined in Catalonia by Garrido-Serrano et al. [29]. After the stock characterization, the most representative building typologies were chosen, in order to carry out the cost-optimal study. The building typology selected for the study is a block of apartments constructed during 1991-2007 under the second building regulation (NRE-AT-87, [30]).

The building geometry (Figure 4) is introduced in the simulation by a multizone 3D model, using the plugin Trnsys3D for Google SketchUp [31]. Only two floors are included in the simulation, in order to simulate the building with more detail: the standard floor and the under roof floor. There are two dwellings per floor and each one is divided following two zonification criteria: night and day use. The building model includes the external environment and its corresponding shadings. The building performance is described in the base case (BC) of the Table 1 for natural ventilation and Table 2 for no natural ventilation.



I	Area (m^2)	Day Zone	Night Zone	Corridor	Courtyard
Dwelling 1	103.1	E1,E2	E3	E4	E5
Dwelling 2	103.4	E6,E7	E8		

Figure 4 Building typology: block of apartments 1991-2007

In the simulation, the occupancy has been defined as the main driver of the use of the building (heating, cooling, natural ventilation, solar protection and lighting use). For that reason, one of the main objectives is to use realistic profiles of the occupants. This profile has to reproduce the variability of the real occupants and, at the same time, their behaviour has to be representative of the average occupant. The stochastic profiles are based on Time Use Data survey of Spain [32]. Then, an annual profile is created through statistical analysis of the raw data, assigning a state of each occupant: outside of home, passive at home, and active at home. Figure 5 illustrates two week profiles, winter and summer, of the occupancy used in the model. The details of the approach used are explained in [1].

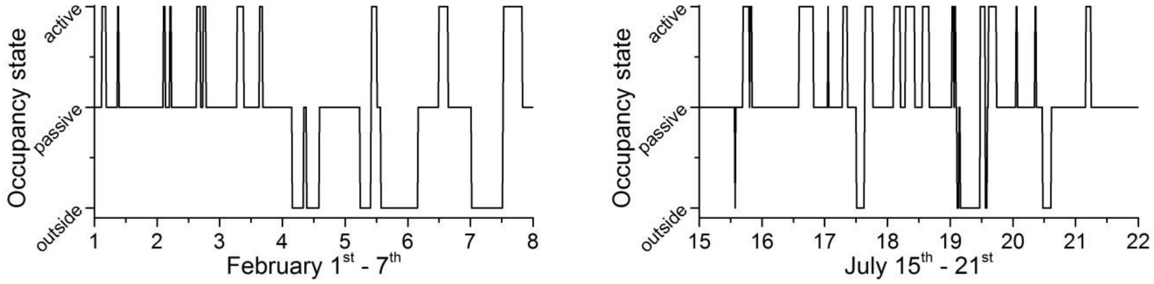


Figure 5 Example of the occupancy profile used in the simulation. Left: winter week; Right: summer week.

Vernacular strategies from Mediterranean climates have been included in the simulation as the main strategy to cool the household during the warm season. The control strategies of the natural ventilation and the use of solar protections have been defined with the objective to model the actual behaviour of the users. The details of the approach used in the simulations are explained in [33]. The building model has been configured with the option to simulate the building with or without natural ventilation. The objective is to compare the buildings that can use natural ventilation or not due to its surrounding (possible noise problems, pollution and/or security).

2.2.2. Heating, domestic hot water and cooling system

The definition of the active systems and their use is based on the survey results of the MARIE project [28]. Around 60% of the households have a natural gas boiler to cover the heating and domestic hot water (DHW) demand, using water radiators as emitters. For the cooling system, around 50% of the households have an air conditioning split (AC) in one or two zones of the household. The characteristics of the systems considered in the BC and the systems proposed as a measure are described in Table 3. In addition, when the building is simulated with natural ventilation there are some packages of measures (2, 1381, 1447 and 186) that achieve comfortable condition without the use of cooling systems, as Table 1 shows (OH < 41hours). In these cases, an additional measure has considered: remove the cooling system.

Table 3 Characteristics of the heating, domestic hot water and cooling systems

System	**Power**	**Base case**	**EE measure**
Natural gas boiler (η)	24 kW	Conventional (0.7)	Condensing (1.09)
AC (EER)	5 kW	Conventional (2)	Efficient (4.55)

The energy systems have been defined using a simplified method based on the efficiency of the different parts of the system: generation, emission and control. The efficiency of generation is calculated using [34], which proposes a set of equations to correct the performance of the equipment depending on the partial load, and the indoor and outdoor temperature.

Regarding to the efficiency of the emitters and the control of the heating system, the methodology implemented follows the European standard EN 15316 [35]. The method takes in consideration different factors that affect the efficiency of the system: intermittent operation, radiative effect, stratification effect due to heating system and type of external walls, losses through external elements, type of control and hydraulic equilibrium. Table 4 shows the values used for the BC and for the system after improving the performance of the installation through a programmable thermostat and thermostatic radiator valves.

Table 4 Parameter to estimate the efficiency of the emitters and the control system [35]

Parameter	**Base case**	**EE measure**
Factor for intermittent operation	0.97	0.97
Factor due to the radiative effect	1.00	1.00
Efficiency due to stratification (temperature)	0.93	0.93
Efficiency due to stratification (type of wall)	0.95	0.95
Efficiency due to loses through external walls	1.00	1.00
Efficiency due to temperature control in the room	0.88	0.97
Factor for hydraulic equilibrium	1.03	1.00

The equations 1, 2 and 3 represent how the heating, DHW and cooling system has been implemented in the building model. The heating and the cooling demand are obtained directly from the dynamic simulation and the DHW is introduced in the simulation as an input data, obtained by Transol [36, 37],using the following reference daily profile [38].

$$E_{ng} = \frac{Q_H + Q_{DHW}}{\eta} \tag{1}$$

$$Q_H = Q_h - Q_{l,em} - Q_{l,ctr} \tag{2}$$

$$E_{ele} = \frac{Q_C}{EER} \tag{3}$$

Where E_{ng} represent the final energy consumption of natural gas and E_{ele} the final energy consumption of electricity, in kWh. Q_C is the cooling demand, Q_{DHW} is the domestic hot water demand and Q_H is the total heating demand, including the losses related to the emission ($Q_{l,em}$) and the control system ($Q_{l,ctr}$), in kWh. Q_h represents the heating demand of the dwelling. η is the efficiency of the boiler and EER is the energy efficiency ratio of the cooling system.

In addition, the surveys provide information about the use of the systems. Figure 6 shows that the use of the heating and cooling system follows different patterns. Regarding to the heating system use: 20% of the households use the heating system for the whole cold season; 28% use the system only when is very cold; 27% use the system when there is occupancy for the day-time, switching off for night; 17% use the heating system depending on the situation, without follow any schedule; and the 8% use the heating system when there is occupancy. The setpoint of the heating system is between 21-23ºC (44%) and lower or equal than 20ºC (42%). The information about the use of the systems has been translated in the building model, as Table 5 describes. The heating system is used when there is occupancy in the dwelling with two setpoints, depending on the hour of the day (20ºC and 15ºC, day and night respectively).

During the warm period, the cooling system is used basically when the temperature is hot (57%) and the setpoint of the cooling system varies between 24-25ºC (42%). These results are consistent with the hypothesis that the main strategy to reduce the temperature in summer is the natural ventilation, and the cooling system is used only when the weather conditions are extremes. Then, the use of the cooling system has been implemented in the model following the same rationale, prioritizing the natural ventilation (Table 5).

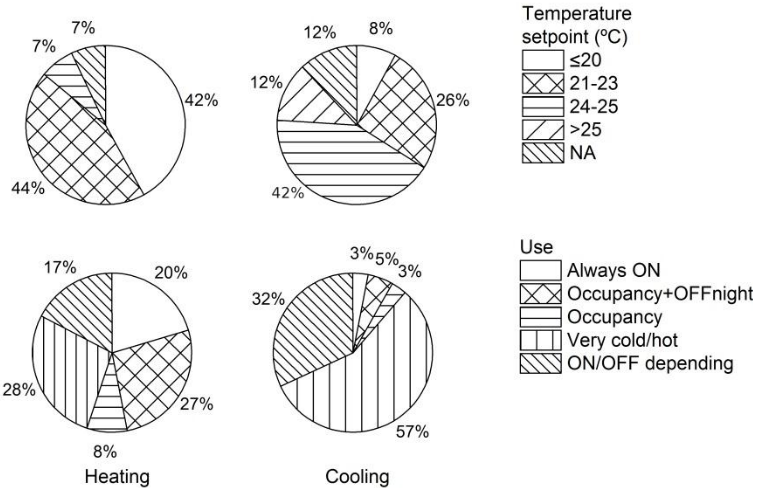


Figure 6 Use of the heating and cooling system obtained from the surveys

Table 5 Use of the heating and cooling system implemented in the building model

System	Use	Setpoint
Heating	Occupancy =0	OFF
	Occupancy>0	20ºC during day 15ºC during night
Cooling	Occupancy =0	OFF

	Occupancy >0 & T<28ºC	OFF
	Occupancy >0 & T>28ºC & Tint > Tout	24.5ºC

Regarding to the setpoint from both systems, the temperature to have comfort conditions has been calculated, assuming a comfort Category II for new and renovated buildings (Predicted Mean Vote = ±0.5). For the calculation it has been considered: the mean radiant temperature equal to the air temperature, indoor air relative humidity of 50%, air velocity of 0.1 m/s, metabolic rate of 1.2 met, clothing insulation of 1 clo and 0.5 clo, for cold and warm periods respectively, and an external work of zero met. The objective of that is to ensure that the setpoint used in the simulation are coherent with Fanger comfort model [39] (comfort model used in buildings with mechanical heating and cooling systems). The comfort range temperatures obtained are 19.2ºC - 23.7ºC and 23.0ºC - 26.2ºC for cold and warm periods. In conclusion, the temperatures used in the building simulation are inside the comfort range, according to the Category II of the Fanger model.

2.2.3. Artificial lighting and appliances

The artificial lighting and the appliances consumption are not usually included in the studies of residential building. One of the reasons is the high dependence to the occupancy behaviour, which is one of the main sources of uncertainty. However, as the building improves their performance, the energy consumption related to the equipment becomes more and more important.

The consumption of the artificial lighting depends on the occupancy, the availability of daylighting and the hour of the day (night, from 24h to 7h, and day, from 7h to 24h). The estimation of the daylighting is explained in [1]. Table 6 describes the control strategy for the artificial lighting implemented in the model.

Table 6 Control strategy of the artificial lighting

General rules of control	Condition	Use of artificial lighting
Occupancy = 0		NO
If the occupancy > 0		
Hour of the day & Irradiance (I)	Day (7-24h) & I<150lux	YES
	Day (7-24h) & I>200lux	NO
	Night (24-7h)	Only active occupancy

The characteristics of the lighting system are described in Table 7. The selection of the type of light bulb has been done in coherence with the results of the surveys: 63% of the households have installed efficient lamps in the main rooms of the household. In addition, the table shows the characteristics of the LED lamps, which are considered as a measure of improvement.

Table 7 Characteristics of the lighting system

Lighting system	**Power install**	**Luminous efficiency**
Fluorescent compact lamp	2 W/m^2	60%
LED lamp	1.5 W/m^2	80%

Regarding to the appliances consumption, the stock of equipment has been obtained from the surveys and is listed in Table 8. The characteristics of the appliances follows the characterization of an average household of a multifamily building in the Mediterranean region, which are detailed in [40]. The energy consumption profile of the appliances has been obtained through a stochastic model presented in [40].

Table 8 Stock of appliances based on the survey results

Equipment	**Percentage of households (%)**
Refrigerator	100
Washing machine	100
Television	99
Microwave	97
Electric Oven	87
Dishwasher	86
Computer	66
Electric stove	62
Drier	62

Finally, one of the measures that have been considered in the study is the implementation of an awareness campaign in order to change the behaviour of the users and reduce their energy consumption. The campaign consists in a training session about how can save energy at home, and an installation of smart metering in each dwelling to provide information of their consumption. The smart metering visualizes the electric consumption in real-time as well as via web-server. This measure provides a reduction of 13% of the lighting and appliances consumption according to the results obtained from the local project “Smart Metering” in Sabadell [41]. The project developed an awareness campaign installing smart metering’s in 100 households, obtaining positive results after six months of actuation.

2.2.4. Renewable energy system

The BC of the building typology does not have installed renewable energy systems. However, the building model has two renewable energy systems implemented in the simulation, in order to be considered as retrofitting measures.

Solar thermal is one of the renewable energy systems considered in the study to cover partially the DHW demand. In this case, the heat produced by the system has been calculated through Transol [36, 37], generating different profiles depending on the surface of the system. The solar thermal system is designed for the whole building and includes a centralized storage tank. The other renewable energy is a photovoltaic (PV) system. In this case, the system has been implemented in the building model through a group of TRNSYS's components. The PV system has been designed at building level, then, the production must be divided between the dwellings of the building. Table 9 describes the characteristics of both systems.

Table 9 Characteristics of the renewable energy systems

Renewable energy system	**Characteristics**
Solar thermal	16 m^2 / building + 1500 l storage tank
Photovoltaic	20 m^2 / building – 240 Wp / module (12 modules)

2.3. Economic evaluation: global cost method

The economic approach used to estimate the global cost is described in the European standard EN 15459 [42]. The global cost calculation method is the calculation of a present value of all the costs during a long period, taking into account the residual values of components with longer lifetimes. Figure 7 represents the costs that are included in the global cost indicator. Basically, the costs can be divided in three main groups: energy costs, investment costs and running costs. Each of these costs is calculated for the calculation period established in the study, in this case 30 years.

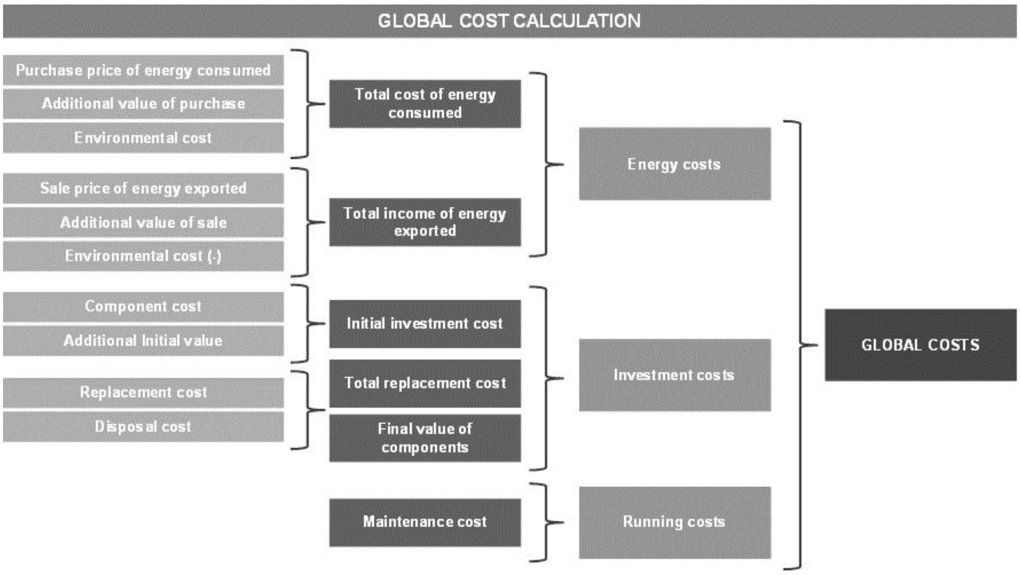


Figure 7 Global costs calculation scheme

The energy costs are composed of two terms: costs related to the consumed energy by the building (purchased energy) and the costs related to the produced energy in the building (sold energy). In both terms, the included costs can be: energy cost (€/kWh), additional values for purchase/sale (€/yr, as for example power fix term of the electrical contract), and environmental costs (€/CO_2emission). In this study, the environmental cost is not included because the perspective of the evaluation is microeconomic.

The investment cost of each retrofit option includes three terms: the initial investment cost, the replacement cost and the final value of the component. The total replacement cost and the final value of the component are related to the lifespan of the retrofit measures. Figure 8 describes the relationship between the initial investment cost (C_i), the total replacement cost (C_p), the final value (V_f) and the lifespan of the component. In the example, the calculation period (T) is 30 years and the lifespan of the component is 8 years. At initial conditions (Year=0), the initial investment cost is considered and every 8 years the component is replaced by a new one, being replaced several times over the calculation period. At the end of the period, the final value of the component is calculated, in order to take into account the cost of the remaining active service of the component (in the example, remains 2/8 years).

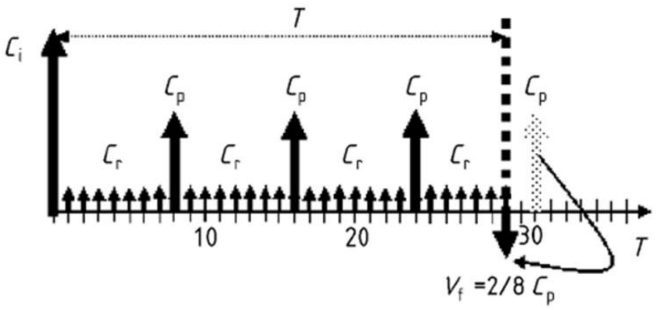


Figure 8 Representation of the investment cost calculation. C_i: initial investment cost; C_r: running costs; C_p: replacement costs; V_f: final value of the component; T: economic calculation period. Source: [42]

Finally, the running cost includes the annual cost for the maintenance of the building and their systems, which is considered every year of the calculation period.

Figure 9 represents the sequence of calculation that is implemented in TRNSYS to obtain the global costs. The first step is to obtain the information about the reference year: energy consumption, energy costs and environmental costs. In the reference year (year=0), the initial investment cost is considered. After the reference year, the energy costs, environmental costs and the component costs are included every year being modified according to their corresponding evolution rate. Finally, at the end of the period, the final value of the components is calculated.

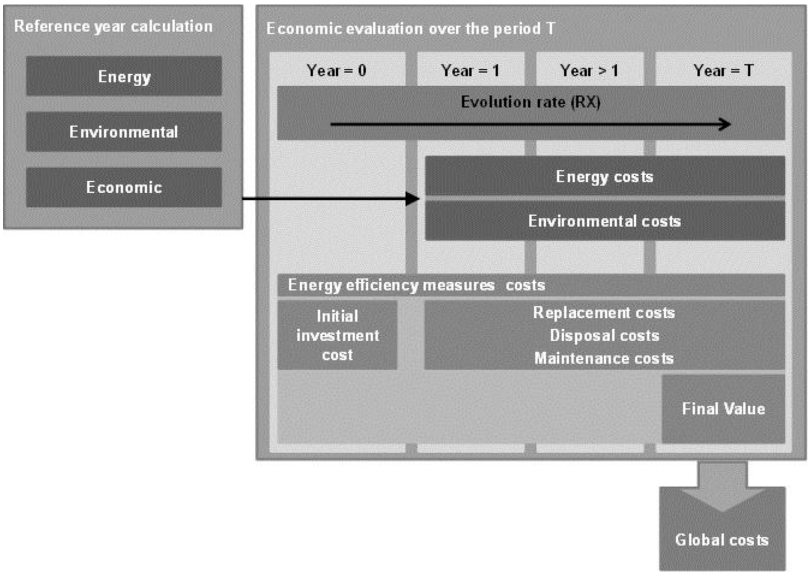


Figure 9 Global costs calculation procedure

Figure 9 shows that the costs are estimated according to an evolution rate. This figure represents how the cost of an element (energy, emissions, components…) will change over the years. However, not all the elements follow the same evolution rate. Table 10 describes the different evolutions rates used in the cost calculation:

- Discount rate: it is the rate used to compare the money value in different years. The discount rate is implemented in all the elements that follow the market evolution.
- Energy evolution rate: it is the rate used to compare the energy cost in different years. The energy evolution rate is implemented for each different energy source, applying in each case its corresponding value.

Table 10 Description of the evolution rates implemented in the global cost calculation

Economic term	Evolution rate calculation	Equation	
Replacement cost Disposal cost Maintenance cost Additional values for purchase/sale energy	Discount rate (R_D): Market interest rate (R) Inflation rate (RI) Real interest rate (R_R)	$R_R = \frac{R-RI}{1+(RI/100)}[\%]$ $R_D = \frac{1}{1+(R_R/100)^t}[-]$	(4) (5)
Energy cost	Energy evolution rate (R_E) Energy cost evolution (RX_E)	$R_E = (1+RX_E/100)^{t-1}[-]$	(6)

t is the year of calculation

Three main groups of data are needed: economic, energy and environmental, and energy efficiency measures. Regarding to the economic assumptions needed for the global cost calculation, there are basically two parameters: inflation rate and market interest rate. Table 11 shows the values used in the present study, which are consistent with the values proposed in [42].

Table 11 Economic hypotheses

Parameter	Hypothesis
Inflation rate (RI)	2%
Market interest rate (R)	4.5%
Discount rate (R_D)	2.5%

The energy and environmental hypotheses depend on the energy system of each country. Table 12 shows the hypotheses and their corresponding sources. Finally, Table 13 describes the parameters needed for the energy efficiency measures evaluation. In this case, the investment and the maintenance costs are obtained from [28] and the lifespan from [42]. The perspective of the evaluation is microeconomic (i.e. energy bills), for that reason the costs must include taxes.

Table 12 Energy and environmental hypotheses

Parameter	**Catalonia (2014)**	**Source**
Electricity		
Energy cost (€/kWh)	0.1315	[28]
Additional values for purchase (€/kW·yr)	40.58	[28]
Energy cost evolution, $RX_{E,ele}$ (%)	2.50	[28]
Conversion factor from final energy to primary energy (kWh_p/kWh_f)	2.464	[12]
Conversion factor from final energy to CO_2 emissions (g_{CO2}/kWh_f)	248	[12]
Natural gas		
Energy cost (€/kWh)	0.0527	[28]
Additional values for purchase (€/yr)	106.56	[28]
Energy cost evolution, $RX_{E,ng}$ (%)	2.00	[28]
Conversion factor from final energy to primary energy (kWh_p/kWh_f)	1.070	[12]
Conversion factor from final energy to CO_2 emissions (g_{CO2}/kWh_f)	201	[12]

*Prices not include the VAT

Table 13 Description of the component costs and lifespan

Measure	**Code**	**Description**	**Investment cost (€/dw)**	**Replacement cost (€/dw)**	**Maintenance cost (€/yr)**	**Lifespan (years)**
Passive package	BC	Base case	-	-	-	-
	2	Solar protection: awning	1,235	-	-	15
	1381	Façade: internal insulation	2,734	-	-	40
	1477	Façade: internal insulation Roof: internal insulation	4,580	-	-	40 30
	1447	Façade: internal insulation Roof: external insulation	8,315	-	-	40 30
	1481	Façade: internal insulation Roof: internal insulation Window: improve window performance	12,029	-	-	40 30 30
	1458	Façade: internal insulation Roof: internal insulation Window: improve window performance Solar protection: awning	17,162	-	-	40 30 30 15
	186	Façade: external insulation Window: improve window performance Solar protection: awning	17,809	-	-	40 30 15
Heating and DHW system	H00	Base case. Conventional natural gas boiler	-	1,815	145	20
	H01	Condensing boiler + Improve installation performance	2,737	2,737	109	20
Cooling system	C00	Base case. Conventional AC-Split	-	1,379	48	15
	C01	Efficient AC-Split	1,379	1,379	48	15
	C02	No cooling system	-	-	-	-
Lighting system	L00	Base case. Fluorescent compact lamp	-	200	-	5
	L01	LED lamps	546	546	-	20
Awareness campaign	A00	Base case	-	-	-	-
	A01	Awareness campaign and monitoring	290	290	24	20

		system				
Solar thermal system	T00	Base case. No system	-	-	-	-
	T01	Solar thermal system	2,200	2,200	10	15
PV stem	P00	Base case. No system	-	-	-	-
	P01	PV system	895	895	73	20

*Prices include the VAT

2.4. Energy labelling

The results obtained from the building simulation are in terms of energy (energy demand, final energy and primary energy) and global costs. However, it is interesting to translate these results to the energy labelling, in order to have a high impact on the results implementation. This section explains how the results have been adapted.

In Spain, the energy label legislation [43] establish that for residential buildings the primary energy consumption must include the energy consumption of: heating, cooling and domestic hot water. As it has been explained before, in this study, the energy consumption includes also the consumption of lighting and appliance. For that reason, an adaptation of the energy label scale is needed.

Basically the steps followed for this adaptation are represented in Equation (8). First, the energy label scale ($E_{R,label-i}$) has been obtained for each climate following [44, 45]. Then, the energy consumption of lighting ($E_{LIG,BC}$) and appliances ($E_{APP,BC}$) of the BC has been added to the scale in order to take into consideration these energy uses in the labelling. After the adaptation, the energy labelling represents the total energy consumption of a dwelling: total energy labelling scale ($E_{T,label-i}$).

$$E_{T,label-i} = E_{R,label-i} + (E_{LIG,BC} + E_{APP,BC}) \tag{8}$$

3. Results and discussion

3.1. Main results: cost-effective energy efficiency measures

This first analysis is focused on the building located in Barcelona climate with natural ventilation. The results represent a mean dwelling of the building, which has been calculated as the weighted average between the results of the standard dwelling and the results of the under roof dwelling. Figure 10 shows the results obtained in terms of annual primary energy consumption (x-axis) and global costs over 30 years (y-axis). In addition, the left graph represents the total energy labelling scale as a background of the graph. Each dot on the graph represents the results of one simulation. BC represents the base case (the building without any measure); CO the cost optimal measure; and DR the deep renovation scenario, which provides the maximum energy saving with the lowest global cost. The right graph of the figure represents the global cost distribution of the Pareto frontier measures. The global costs are divided in energy, investment, replacement and maintenance costs. The x-label represents the code of the measures implemented in each scenario (passive-active), which are described in Table 1, Table 2, Table 13 and Table 14.

The graphs show that the BC has an E label (198 kWh/m^2·yr) with a global cost of 453€/m^2 over 30years. Since the building and their systems improve the performance, the primary energy consumption decreases, achieving an A-label. Regarding to the global cost, most of the measures imply an increase of the global cost; however, there is a set of combinations that reduces the cost below the BC (the points below the horizontal line of the left graph). The CO measure is able to decrease the energy consumption until a B-label (123 kWh/m^2·yr) and the global cost until 355€/m^2, implying a reduction of the 38% and 22%, respectively. For the DR measure, the energy reduction is about 59% and the global cost increases by 18% (98 kWh/m^2·yr and 535€/m^2). Analysing the distribution of the global costs, it is possible to observe that the investment costs increase as long as the energy consumption decreases. The energy costs can be reduced by 42% comparing the DR respect the BC scenario.

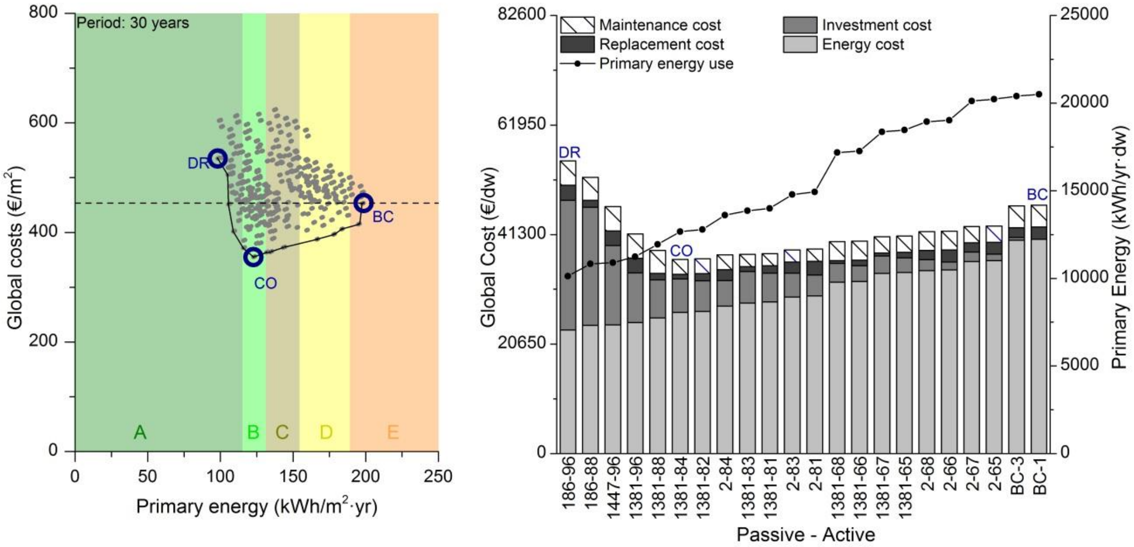


Figure 10 Cost-energy evaluation: primary energy consumption vs. global cost over 30 years (colour background: energy label scale of Total consumption of dwelling). Building located in Barcelona (C2) with natural ventilation. Right: Energy efficiency measures of the Pareto frontier, detailing the global cost distribution: energy cost, investment cost, replacement cost and maintenance cost. Passive measure description in Table 1 and active measure in Table 14.

Figure 11 complements the information of the Pareto frontier measures, giving details about the distribution of the energy demand (left) and the final energy consumption (right). The general trend of the measures is to reduce mainly the heating demand, making the appliances demand more significant over the whole need of the household. The energy efficiency measures not always provide the same impact over the primary energy consumption and over the energy demand. This fact is reflected in several cases of the Pareto frontier and the main reason for this behaviour is the type of measure implemented. For example, the measure 2-81 and the measure 1381-68 have a similar primary energy consumption, being slightly lower the first one (Figure 10); however, they energy demand is quite different presenting the opposite behaviour. The first combination of measures (2-81) is composed mainly by the active systems improvement (condensing boiler) with small intervention on the solar protection strategy. On the other hand, the measure 1381-68 adds insulation to the façade reducing the heating demand, improves the lighting system and reduces the electrical consumption through the awareness campaign.

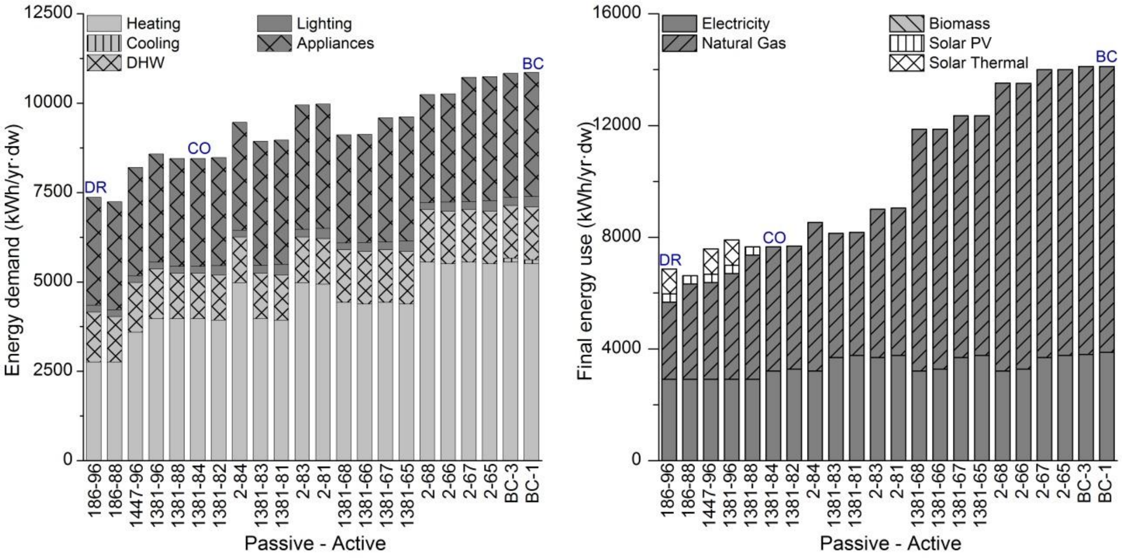


Figure 11 Energy efficiency measures of the Pareto frontier for the Barcelona climate with natural ventilation. Left: Distribution of the energy demand: heating, cooling, DHW, lighting and appliances. Right: Distribution of the final energy use: electricity, natural gas, biomass, solar PV and solar thermal. Passive measure description in Table 1 and active measure in Table 14.

The right graph of the Figure 11 represents the distribution of the energy consumption in terms of final energy. The main consumption of energy comes from natural gas. There is a quantitative leap on the natural gas consumption after the measure 1381-68 and represents the change of the conventional boiler to condensing boiler. The effects over the electricity consumption are low and the main reason is that there are not specific measures to improve the efficiency of the appliances, which are the main responsible of this consumption.

The packages of measures with lower primary energy consumption incorporate some renewable energy; however, their contribution is small in terms of final energy. In particular, the solar thermal contribution represents around the 60% of the DHW demand, as the Spanish Building Regulation requires.

Table 14 Description of the energy efficiency measures of the Pareto frontier for climate C2 and the use of natural ventilation (YES or NO).

Code	**Heating + DHW system**	**Cooling system**	**PV system**	**Lig. system**	**Awar. campaign**	**Natural ventilation**
0	Conventional NG boiler	Conventional AC	NO	CFL	NO	YES & NO
2	Conventional NG boiler	Conventional AC	NO	CFL	YES	NO
3	Conventional NG boiler	Conventional AC	NO	LED	NO	YES & NO
4	Conventional NG boiler	Conventional AC	NO	LED	YES	NO
9	Conventional NG boiler	Efficient AC	NO	CFL	NO	NO
10	Conventional NG boiler	Efficient AC	NO	CFL	YES	NO
11	Conventional NG boiler	Efficient AC	NO	LED	NO	NO
12	Conventional NG boiler	Efficient AC	NO	LED	YES	NO
25	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	CFL	NO	NO
26	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	CFL	YES	NO
27	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	LED	NO	NO
28	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	LED	YES	NO
32	Condensing NG boiler Improve efficiency installation	Efficient AC	YES	LED	YES	NO
48	Condensing NG boiler Improve efficiency installation Solar thermal system	Efficient AC	YES	LED	YES	NO
65	Conventional NG boiler	NO	NO	CFL	NO	YES
66	Conventional NG boiler	NO	NO	CFL	YES	YES
67	Conventional NG boiler	NO	NO	LED	NO	YES
68	Conventional NG boiler	NO	NO	LED	YES	YES
81	Condensing NG boiler Improve efficiency installation	NO	NO	CFL	NO	YES
82	Condensing NG boiler Improve efficiency installation	NO	NO	CFL	YES	YES
83	Condensing NG boiler Improve efficiency installation	NO	NO	LED	NO	YES
84	Condensing NG boiler Improve efficiency installation	NO	NO	LED	YES	YES
88	Condensing NG boiler Improve efficiency installation	NO	YES	LED	YES	YES
96	Condensing NG boiler Improve efficiency installation Solar thermal system	NO	YES	LED	YES	YES

3.1.1. Standard dwelling vs. under roof dwelling

Figure 12 represents the cost-effective analysis for the two types of dwellings: standard and under roof, left and right respectively. It is observed that the base case of the under roof dwelling (BC-UD) has a higher primary energy consumption than the standard dwelling (BC-SD). This effect has a direct repercussion on the global cost, which follows the same trend. This difference is quite important representing an increase of 7% of primary energy and 4% of global costs due to the higher heating and cooling demand. However, that difference is reduced as long as the building performance is improved, up to 4% and 3% in terms of primary energy and global costs respectively. In both cases, the starting point is an E-label, achieving a B-label with CO measures and A-label with the DR. In addition, the potential of improvement of the UD is higher and there are more cost effective measures in comparison with the standard floor.

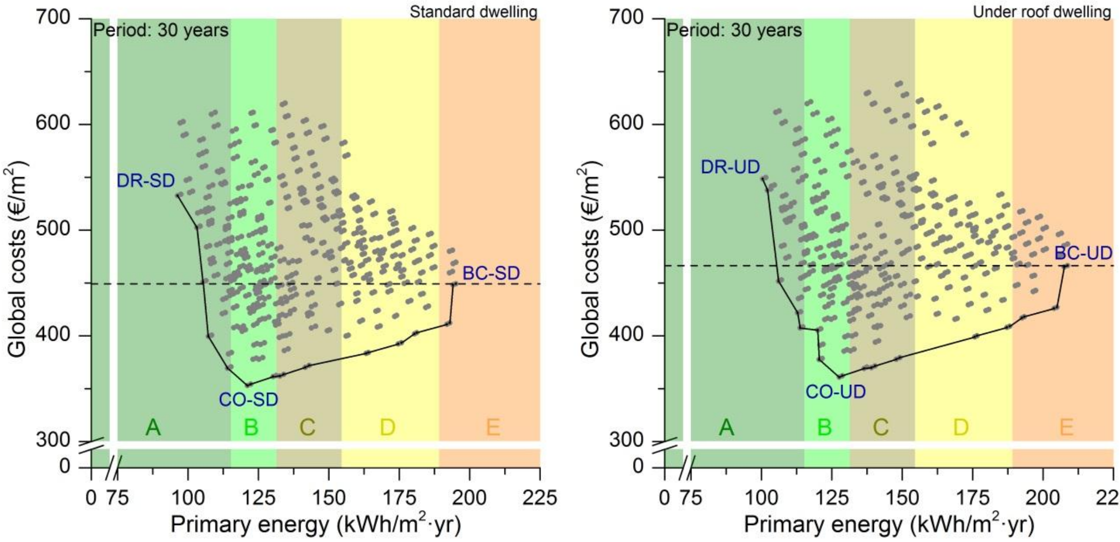


Figure 12 Comparison of the cost effective evaluation between a standard household and an under roof household

3.2. Effect of measures

In this section, the impact of the different measures is evaluated. Figure 13 represents the cost effective evaluation for a dwelling with natural ventilation located in Barcelona, where the Pareto frontier of the different measures are highlighted in each graph: passive measures (a), heating and DHW system (b), cooling system (c), lighting system (d), integration of PV system (e) and implementation of awareness campaigns (f).

In Figure 13-a different patterns can be distinguished, depending on the investment cost of the measure and the impact of passive measure for reducing the overheating hours. The passive measure 2, which supposes an improvement on the solar protection strategy, has a small impact over the primary energy consumption; however, the improvement of the solar protection strategy reduces the risk of overheating and makes possible to remove the cooling system, and then save the money of the cooling consumption, the replacement and maintenance of the equipment. A similar situation shows the measure 1381 and 1447, but in this case the passive measure has a significant impact on the energy demand due to the implementation of insulation on the façade. These measures (1381 and 1447) are able to achieve an A-label in combination with several active measures. The measure 2 and 1381 are the measures that, in combination with the active ones, provide more cost effective solutions. On the other hand, the measures 1481 and 186 are the measures with the highest energy impact; however, their global costs increase over the BC scenario in most of the cases. Finally, the measure 1477, which has a good impact over the energy consumption and at the same time has an acceptable investment cost (4,600 €/dw), is penalized due to the need to have air conditioning in the dwelling to guarantee comfortable condition. For that reason, the results of this measure are in general trends worse than the others. The results are very sensitive to the overheating threshold, having a direct consequence over the costs. The research related to define proper criteria to characterize the overheating are ongoing and there is not a consensus among the experts.

Regarding to the heating and DHW system, Figure 13-b represents four different areas according to the different possibilities. The solar thermal system implies a slight higher global cost in comparison with the BC. Although, it reduces the primary energy consumption (7%), providing some cost effective combination of measures. The effect of the condensing boiler is considerable in both aspects: energy reduction and global cost savings (26% and 9%). The condensing boiler represents the most cost effective solution. Finally, the combination of the condensing boiler and the solar thermal system helps to reduce more the primary energy consumption.

Analysing the effect of the cooling system (Figure 13-c), there is a clear difference between the two strategies: reduce the overheating with passive measures and, the use of the cooling system to guarantee comfortable condition in the warm period. As the passive measure analysis has shown, the solutions that avoid the cooling system are more cost effective than the ones that needs the active system. Comparing the dwelling with the cooling BC and the measures with the efficient cooling system, the differences between them are small, mainly due to the low cooling demand.

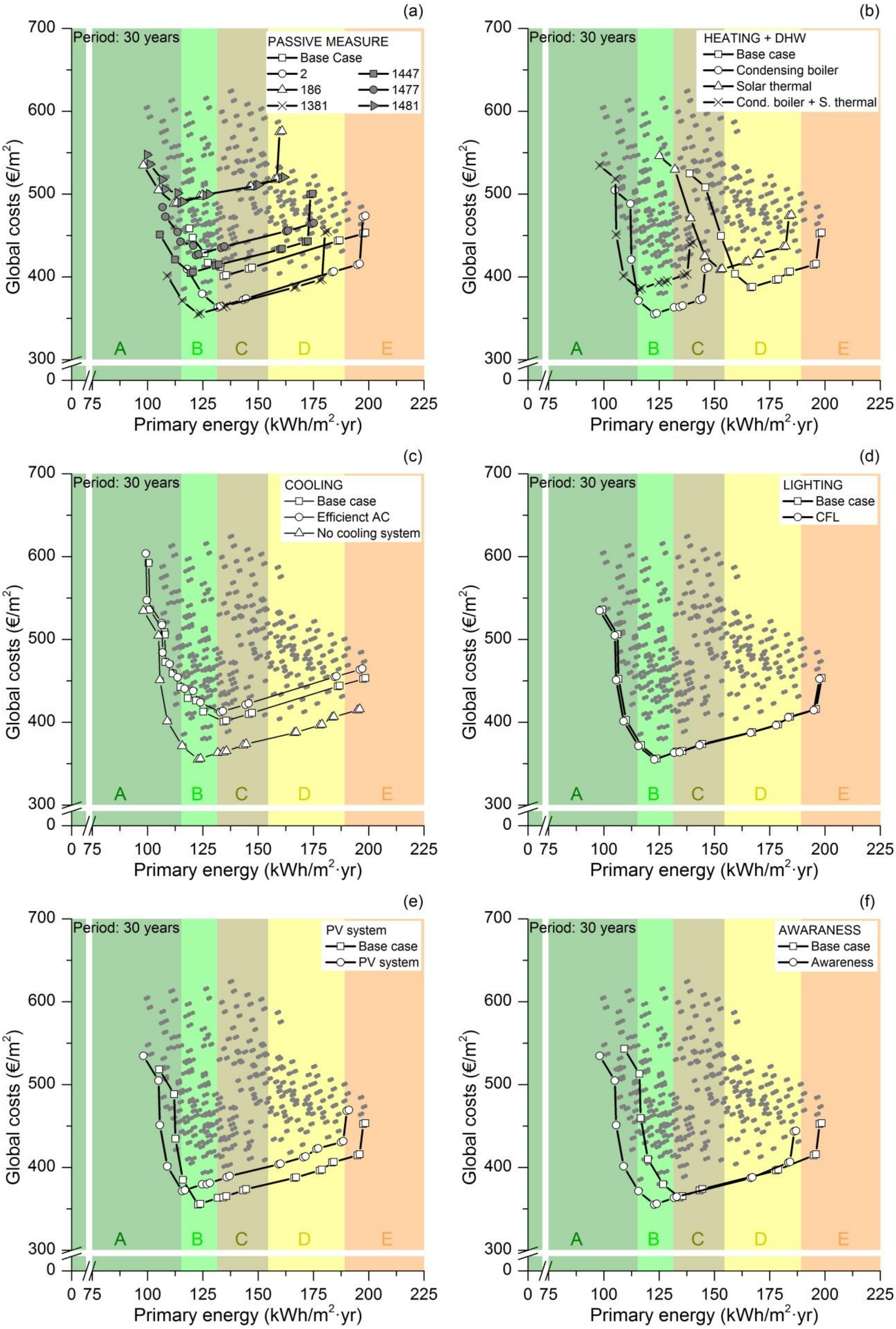


Figure 13 Cost effective evaluation of the mean dwelling in Barcelona (C2) with natural ventilation: comparison of the effect of the measures regarding to the primary energy consumption (x-axis) and the global cost (y-axis), emphasising: type of passive measure (a), type of heating and DHW system (b), type

of cooling system (c), type of lighting system (d), integration of PV system (e) and implementation of awareness campaign (f)

The effect of lighting system (Figure 13-d) improvement is not significant in global terms, reducing only 1% the primary energy consumption of the dwelling. The reason is that the use of the artificial lighting has been implemented in the model considering the daylighting availability. This configuration provides an optimal use of the artificial lighting and small energy consumption, representing only 3% of the primary energy consumption. However, the impact of the LED system is positive, providing savings without an increase of the global cost.

The implementation of the PV system (Figure 13-e) reduces the primary energy consumption, however, the system that has been proposed does not generate enough energy (covers only the 8% of the electric consumption of the dwelling) to cover the expenses (investment, replacement and maintenance costs). A better sizing of the system is needed in order to be a cost optimal solution. Nevertheless, the PV system, in combination with the passive measures that avoid the cooling system, provides cost effective solutions. From another point of view, if the objective is to achieve an A-label or better, the use of the PV system, as well as the solar thermal system, is needed in most of the cases.

Finally, the implementation of the awareness campaign has a positive effect reducing the primary energy consumption by 6% in comparison with the BC (Figure 13-f).

3.3. Effect of natural ventilation

To finalize the analysis of the results, the possibility to use natural ventilation or not are compared. Figure 14 reflects that the effect of the natural ventilation is decisive on the results, in terms of energy consumption and also in global costs. In both cases, with natural ventilation (VENT) and without natural ventilation (nVENT), the BC corresponds to an E-label; but in BC-VENT the dwelling is near the boundary D-E, while in BC-nVENT is near the boundary E-F, implying a 33% more of primary energy consumption and a 21% of global costs. These differences make that the dwelling with natural ventilation achieves a B-label for the CO-VENT measure and an A-label for the DR-VENT, in comparison with the D-label and B-label achieved by the dwelling without natural ventilation. Also the global costs are higher, mainly due to the cooling consumption and the costs related to the cooling system; because the system is needed to achieve comfortable conditions, as a difference of most cases of natural ventilation scenario.

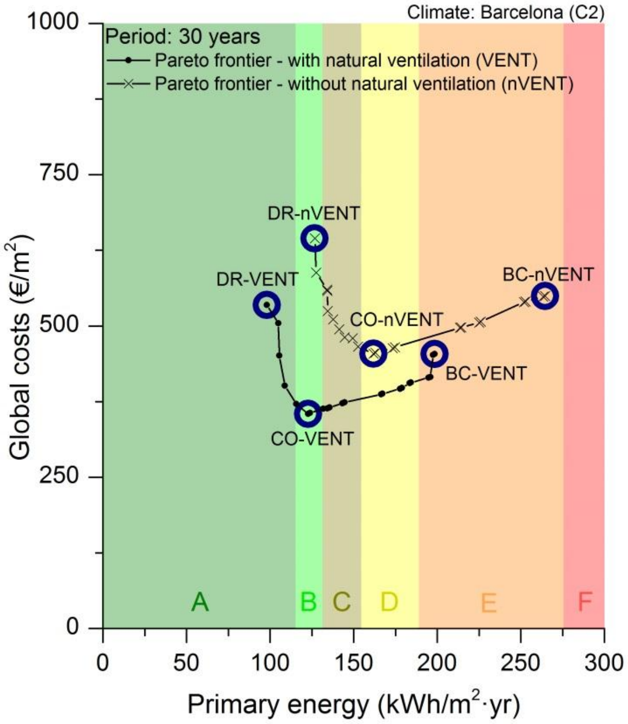


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Figure 14 Cost effective evaluation. Comparison between dwelling with or without natural ventilation (VENT and nVENT, respectively)

Table 15 summarizes the results of this comparison, where it is possible to visualize easily the main differences. The CO measures achieve an improvement of 3-labels in the dwelling with natural ventilation and only 1-label when there is no natural ventilation. For the DR strategy, the improvement is about 4-labels and 3-labels, respectively. Moreover, if focus the analysis on the measures that are included in both cases, it is possible to observe that the CO-nVENT does not include an improvement of the envelope, as a difference of the CO-VENT. The reason is that in the case of nVENT, the passive measures do not improve the thermal comfort above the thresholds, as Table 2 shows, and consequently, there is not the option to avoid the cooling system. This fact makes that in the case of nVENT the passive measures are not a cost optimal option. However, it is important to remark, that the passive measures are cost effective measures, reducing the global cost of the BC-nVENT.

Table 15 Summary of the impact of the cost optimal and deep renovation scenarios for the dwelling located in Barcelona (C2) and with or without natural ventilation (VENT and nVENT, respectively).

EE measure		**Natural ventilation**	**Energy Label**	**Label Improve BC**	**Primary Energy**	**Energy Savings**	**CO_2 emissions reduction**	**Initial Invest.**	**Global cost**	**Economic compar.**
Passive/Active					kWh/yr·dw	%	%	€/dw	€/dw	%
BC	0/0	VENT	E	-	20,501	-	-	-	46,828	-
	0/0	nVENT	E	-	27,315	-	-	-	56,750	-
CO	1381/84	VENT	B	3	12,677	38	45	6,307	36,642	22%
	0/28	nVENT	D	1	16,715	39	42	4,953	46,909	17%
DR	186/96	VENT	A	4	10,134	51	59	24,477	55,206	-17%
	1468/48	nVENT	B	3	13,084	52	58	25,210	66,589	-17%

Finally, Figure 15 compares the energy demand distribution for the different scenarios. Analysing the BC, the higher energy demand is the heating, followed by the appliance demand. The DHW represents around 14% of the energy demand and the lighting only the 3%. While the building improves its performance, the heating demand tends to be lower to the point that the appliance demand becomes the most important energy demand of the dwelling. This result remarks the need to include the appliances consumption in the cost-optimal studies and refurbishment analysis, in order to start to implement measures to reduce them.

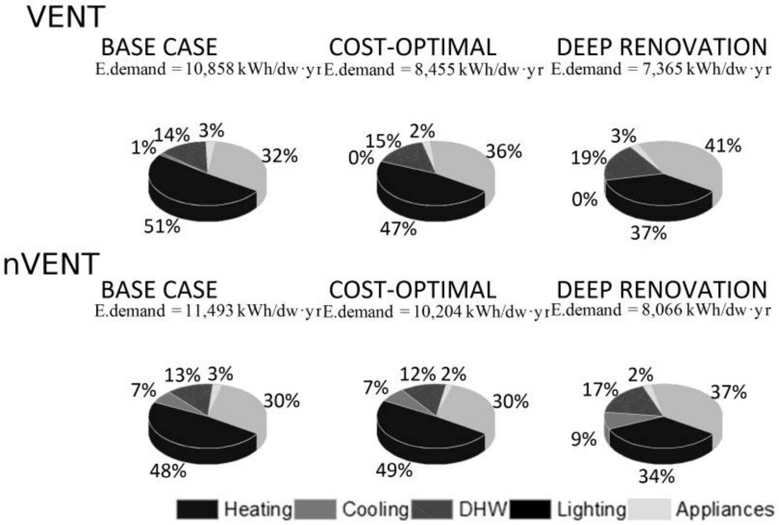

Figure 15 Comparison in terms of energy demand of the dwelling with or without natural ventilation (VENT and nVENT, respectively).

4. Conclusions

The paper presents the results of a cost-optimal analysis to evaluate energy efficiency measures for a residential building in Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs. The method is divided in two stages. The first stage is named the passive evaluation and the passive measures are evaluated using the thermal comfort and the investment cost. This first part is deeply described in [1] and applied to a block of apartments built in 1990-2007. The second part of the methodology, called the active evaluation, all the energy efficiency measure are analysed using the global cost and the primary energy consumption. The active evaluation is presented in this paper. Therefore, it is applied to the same building typology, over a selected number of solutions which are the result of the first stage of the method.

The method proposed for implementing the heating, DHW and cooling systems in the building simulation provides a good compromise between detail and simulation effort. The method includes the performance variation due to the weather condition and the actual use of the system. At the same time, the characteristics of the systems and their operation are based on surveys done around Catalonia, including a more realistic configuration of the systems. Moreover, the study includes the energy consumption due to lighting and appliances, obtaining results of the total energy consumption of the dwelling. This fact makes an easier comparison with the household energy bills, which could be useful for future studies. In additional, the study relates the results with the energy labelling scale (which has been adapted to be comparable with the results, which includes heating, cooling, DHW, lighting and appliances consumption), providing comprehensive information for the final users.

The natural ventilation represents an important impact in the results. Where is possible to implement natural ventilation, results show that cost-optimal measure can achieve a B-label, improving 3-labels in comparison with the base case. The cost-optimal measure reduces around 40% of the primary energy consumption and 22% of savings in the global costs. If the dwelling does not use natural ventilation then, the situation is worse. The base case is also an E-label; however the cost-optimal measure achieves only a D-label. The main difference between both cases is that the dwelling with natural ventilation can avoid the cooling system in most of their combination of measures, thanks to the positive effect of passive measures, which reduces the overheating hours below the discomfort level. On the contrary, the dwellings without natural ventilation include the cooling consumption and the costs related to the cooling system making of the primary energy consumption and the global costs higher than the case when natural ventilation is applied.as well as the global costs.

The Deep Renovation scenario has been also evaluated, where the measures with high energy saving are analysed. In this case, the dwellings with natural ventilation reach an A-label in comparison with the dwellings without natural ventilation that achieves a B-label. In those cases, the passive and actives measures are also combined with renewable energy systems.

In addition, a comparison between the under roof dwelling and standard dwelling is presented. The results show that the under roof dwellings has a higher primary energy consumption and global costs than the standard dwelling. However, this situation provides to the under roof dwelling a higher potential of improvement and more cost effective measures compared to the standard dwelling.

From the set of strategies that can be simulated in order to reduce the energy consumption, only some options are found to be cost effective measures, from the micro-economic approach followed to compute the global costs. The cost effective strategies are:

- The implementation of passive strategies to reduce the heating demand and provide comfortable conditions for the warm period without the use of cooling systems (when it is possible). It makes one of the big differences between cases, making possible to avoid the cooling system and save its related costs. However, further research is needed related with the overheating indices and their thresholds in order to obtain robust criteria to take decisions. In addition, the implementation of passive solutions reduces the heating demand, which has an impact over one of the highest energy uses of the dwelling.
- To improve the heating system, using efficient technologies on the market (condensing boiler, in this case). As it has said before, the heating consumption is one of the most important consumption of the dwelling, and it is important the use of efficient systems.
- To improve the lighting system with LED technologies. The lighting consumption represents a low fraction of the total energy consumption of the household. However, the implementation of LED systems in the dwelling provides a positive impact in both, energy and global cost savings.
- The development of awareness campaigns has a high potential to reduce the energy consumption. The awareness campaign represents the most effective measure, in terms of energy savings by euro invested.
- To achieve A-labels, the integration of renewable systems is needed (PV and solar thermal system, in this case).

Finally, the results show that it is important to takes in consideration the lighting and appliances consumption, since these energy uses becomes more and more important as long as the performance of the building and systems are improved. In the case of the deep renovation, the appliances consumption becomes the greatest energy use of the dwelling.

In conclusion, the method provides technical and economic information to help taking decisions of the users, experts and politicians, considering not only economic and energy aspects, but also comfort parameters.

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