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Optimal renovation of buildings towards the nearly Zero Energy Building standard

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ABSTRACT

In this paper, a Mixed-Integer Linear Programming model is proposed for the design of the energy renovation of existing buildings, considering both Energy Supply Systems and the adoption of Energy Saving Measures to reduce the demand of buildings in retrofitting towards the nearly Zero Energy Building standard. The method is applied to an existing building located in Bilbao (northern Spain), getting the optimal design, i.e. lower annual net cost, for different limits of non-renewable primary energy consumption. The demand reduction produced by the Energy Saving Measures is included as an input from previously validated dynamic simulations and a simple method is presented for its specific distribution in reference days. This simple method, based on degree-days, allows reference days to be generated that, through an Energy Saving Measure based base temperature, consider the weather, the use and the thermal properties' dependency on the distribution of the demand. The optimization method is used to provide the design selection and operation strategy of the renovation of buildings to meet different

non-renewable primary energy consumption limits and to provide designs for different constraints: economic, space availability, etc.

Keywords: Building renovation; *Energy Supply System; Energy Saving Measure; nZEB; optimization; MILP*.

1 Introduction

Nowadays, the world energy scenario is strongly characterized by fossil fuel scarcity and the climate change driven by their use. This reality requires an energy transition consisting of lowering primary energy consumption, increasing energy efficiency and promoting renewable energy sources. In this context, the European Union (EU) is playing a major role towards this transition, enforcing several Directives that seek the reduction of the energy consumption of different sectors. Amongst these sectors, buildings are responsible for 40% of the overall primary energy consumption of the EU [1], and the Directive 2010/31/EU on the energy performance of buildings (EPBD) [2] aims to cut this consumption. In line with this goal, the EPBD requires all new buildings and part of the existing stock to be nearly Zero Energy Buildings (nZEB).

An nZEB is defined as a building of very high energy performance and the nearly zero amount of energy required should be covered to a very significant extent by energy from renewable sources. In this context, a Zero Energy Building (ZEB) would be an nZEB with no net Non-Renewable Primary Energy (NRPE) consumption. The specific definition of nZEB is intended for independent implementation by EU Member States according to a maximum Non-Renewable Primary Energy (NRPE) consumption value defined by the analysis of the cost optimality concept.

Thus, the design of nZEBs will be based on optimization routines that will give rise to best designs constrained to certain legal and technical specifications. These designs will arise from the evaluation of different combinations of technologies and their associated operation strategy. Specifically, building design optimization can be split into two levels: (i) load level, acting on the envelope and ventilation by Energy Saving Methods (ESM); or (ii) consumption level, acting on the Energy Supply Systems (ESS).

Regarding the load level, Huang and Niu presented a comprehensive review on the optimization of building envelope [3]. Different optimization techniques were identified, genetic algorithms, direct search and neural networks being the most used approaches. In relation to consumption level optimization, Attia et al. [4] reviewed the existing literature and concluded that simple genetic algorithms are the most adequate and widespread technique for solving multiple design, operation and control optimization problems with relative ease.

As can be seen from the literature reviews presented above, while many authors have carried out optimization work at one of these two levels, the combined optimization (i.e. considering both envelope and energy supply systems) is less common. Some of the most relevant studies dealing with this integral optimization analysis couple genetic algorithms with state-of-the-art building energy simulation programs. Ferrara et al. used a computing environment that combines TRNSYS, a building simulation environment, with GenOpt®, a generic optimization program, to get cost-optimal designs for a case study situated in France [5]. Analogously, Ascione et al. analyzed the optimal energy retrofit of a hospital, situated in southern Italy, using genetic algorithms through the combination of EnergyPlus and MATLAB [6]. Also worth mentioning is the approach presented by Hamdy et al. [7]. This consists of an optimization scheme that, at the same time, combines a genetic algorithm with detailed simulation programs, divides the whole process into three stages showing the effect of the optimal and speeds up the exploration by avoiding the unfeasible design-variable combinations and using pre-simulated results. More recently, D'Agostino et al. [8] developed a framework for cost-optimal nZEBs based on energy and cost simulations using a sequential search. However, these approaches require a detailed definition of the building and the solutions to be previously defined *ad-hoc* by the user, i.e. system configuration and operation strategy. In this sense, Hamdy et al. [9] comprehensively compared the performance of seven evolutionary optimization algorithms and they conclude that algorithm selection and settings might involve trial and error. Therefore, simulation-based approaches could get computationally costly when the whole parameter tuning process is considered. To reduce the computation expense, Gilles et al. used a Kriging model surrogate NZEB performance criteria during the optimization process and a genetic algorithm is considered efficient to find the global optimal solutions [10].

An alternative to overcome these disadvantages are exact optimization models, such as Mixed-Integer Linear Programming (MILP). MILP-based optimization problems have largely been applied to the optimal design and operation of energy supply systems in building at different levels. Mehleri et al. presented a MILP model for the optimal design of distributed energy generation systems for neighborhoods, which allowed the optimal selection of the system components among several candidate technologies, including the optimal design of a heating pipeline network, that allows heat exchange among the different nodes [11]. Omu et al. created a MILP model for the design of a distributed energy system that meets the electricity and heating demands of a cluster of commercial and residential buildings while minimising annual investment and operating cost [12]. Analogously, Milan et al. developed a MILP-based cost optimization model for the design of 100% renewable residential energy supply systems [13]. A number of recent papers have considered MILP-based approaches to optimize more specific configurations such as power and heat interchanges [14] or on-site renewable technologies with storage [15]. However, there is a lack of research applying these techniques to envelope optimization and, even less, integral optimization of envelope and energy supply systems. This is mainly explained by the high nonlinearity introduced into the optimization problem by different envelope solutions. Ashouri et al. presented a model for ESSs that also considers a building's thermal mass as an additional storage option [16]. However, it used constant thermal loads that were computed before the optimization was executed, not allowing a proper optimization of the envelope. Milic et al. [17] analyzed the performance of an in-house LCC optimization software, OPERA-MILP. The aim is fulfilled through comparison with building energy simulation software IDA ICE before and after cost-optimal energy renovation. MILP modelling has been also used for the simultaneous design and operation of urban energy systems considering a flexible value web framework for representing integrated networks of resources and technologies [18]. A very interesting solution to this problem has recently been proposed by Schütz et al. [19], who proposed a building model suitable for MILP, based on ISO 13790 and validated according to ASHRAE 140.

The authors recently presented a simple method dealing with the ESS optimization of buildings [20]. The method was based on a general superstructure that made it possible to include any existing or future technologies, covering heating, Domestic Hot Water (DHW), cooling and electricity. The model was linked to a Mixed Integer Linear Programming (MILP) problem that allowed the selection of equipment and its operation for a given set of load profiles. The operation included the unit commitment of technologies with limited load regulation capacity through binary control and the time horizon was discretized in a set of independent reference days, allowing the model to be optimized by state-of-the-art solvers within acceptable calculation times. The model allowed the annual cost minimization based on the net present value for a set of constraints imposed by the designer, such as NRPE consumption limits.

The main objective of this paper is to extend the optimization model to allow an optimization that considers both Energy Supply Systems and Energy Saving Measures alternatives for certain NRPE consumption limits. Thus, the method presented here contributes to the need for simple and reliable tools toward nZEB design and operation. The proposed envelope alternatives will be treated as virtual technologies that produce, at no energy cost, the heating demand reduction caused by their implementation. For this purpose, the different yearly demands are previously defined as inputs to the method, which were obtained from the simulation of a validated TRNSYS model. As previously stated, the MILP method presented by the authors discretized the aggregated thermal demand into a set of reference days. In this paper, the distribution of the input loads into reference days of the different envelope alternatives is obtained from a degree-days based method, using a variable base temperature.

The method is applied to achieve the optimal integral renovation of an existing building located in Bilbao (Northern Spain). A set of 7 envelope retrofitting solutions or ESMs were considered, while the main technologies available in the market have been included in the model using self-tailored cost estimation models. Then, the optimal ESS configuration and ESM solution, which minimize the annual cost, have been obtained for three NRPE consumption limits: cost optimal and two Zero Energy Building scenarios, depending on whether the electric consumption of the users is accounted (ZEB) or not (ZEB'). Only heating, DHW and electricity loads are considered in the case study, which are the typical loads in northern Spain. Cooling load would be included in the same way, but the application of the method to buildings under hot weather conditions will be analyzed by further research.

The rest of the paper is organized in 4 sections, as follows: Section 2 deals with the energy and economic modeling of the building renovation and presents the optimization method. This model is applied to the case study covered by Section 3, giving rise to the optimal configuration and operation in terms of energy and economic performance, as appears in Section 4. Finally, the main contributions of the paper and future research are summarized in Section 5.

2 Materials and Methods

This section presents the method for the optimal renovation of buildings considering, from an energy and economic perspective, both ESMs and ESSs.

2.1 Energy model

The renovation of buildings consists of the selection of ESMs and the design and operation of the ESS. Thus, the optimization method should cover the coupled energy modelling of these two issues as described below.

2.1.1 Energy supply systems

The modelling of ESSs was developed by the authors in a previous paper and the reader is referred to this paper for a detailed description [20]. In this section, a brief description of the model is presented.

Fig. 1. Schematic view of the energy supply system model

The energy model consists of a general superstructure comprising all the potential cases that could be found in a building (Fig. 1a). The superstructure includes 5 interlinked modules (electricity, cooling, high temperature heating, medium temperature heating and low temperature heating), which together provide the energy needs of the space heating, DHW, cooling and electricity. The superstructure aims to include any possible Energy Supply System configuration from the existing and future technologies for any of the defined modules.

The different building loads are outputs from different modules. Thus, the cooling and electricity are outputs, respectively, from the cooling and electricity modules. Analogously, the DHW is an output from the MT heat module and the heating from the LT heat module, which is a common trend nowadays considering the promotion of low temperature heating systems. Nevertheless, this superstructure could be adjusted to old existing buildings by placing the heating demand in the MT module. Fuels are divided into two groups: manageable and non-manageable. Renewable sources, such as solar and wind, belong to the second group, since their operation cannot be optimized.

The modules are interrelated, enabling the outputs of some modules to be the inputs of other modules. The temperature level between the heat modules is reduced by means of heat exchangers (HX). The heat flow between the medium temperature module and the cooling module is represented as bidirectional, since the heat can be sent from the cooling module as refrigeration heat, or from the MT heat module as, for instance, the input for a single-effect absorption chiller.

All the modules present a bidirectional connection with the environment, allowing the energy to be bought from a source (i.e., electricity network) or sold to a sink (i.e., district heating or cooling network). Additionally, HT and MT modules also present a bidirectional connection with the electricity module, that accounts for the electricity production or consumption of the technologies included in these modules. However, LT and Cooling modules only have unidirectional connection with the electricity module, since these technologies do not produce electricity.

Each module includes all the technologies with the same main product. Additionally, they may include any storage device that allows production and load decoupling (Fig. 1b). Thus, the energy balance for each module at every interval h of every reference day d is described by Equation (1).

$$\sum_{k\in K} e_{s,k,d,h}^{OUT} + e_{s,d,h}^{BUY} - \sum_{k\in K} e_{s,k,d,h}^{IN} - e_{s,d,h}^{SELL} - e_{s,d,h}^{STO} = L_s^{d,h} \quad \forall s \in S, d \in D, h \in H_d \qquad (1)$$

The manageable peak power is constrained by a minimum value imposed by load design (Equation (2)). Additionally, the storage system presents its own energy balance (Equation (4)), where the storage power is upper bounded by the storage capacity (Equation (6)) and the storage system is considered as fully discharged at the first and last interval of a certain period (Equation (3) and (5)).

$$\sum_{k\in K_{MAN}} E_{s,k}^{MAX} \cdot n_k \geq L_s^{PEAK} \qquad \forall s \in S \qquad (2)$$

$$q_s^{d,0} = 0 \qquad \forall s \in S, d \in D \qquad (3)$$

$$q_s^{d,h} + e_{s,d,h}^{STO} = \eta_s^Q q_s^{d,h+1} \qquad \forall s \in S, d \in D, h \in H_d | 0 < h < |H_d| \qquad (4)$$

$$q_s^{d,|H_d|} + e_{s,d,|H_d|}^{STO} = 0 \qquad \forall s \in S, d \in D \qquad (5)$$

$$q_s^{d,h} \leq Q_s^{MAX} \cdot n_{TES_s} \qquad \forall s \in S, d \in D, h \in H_d \qquad (6)$$

Technologies included in the s modules relate their outputs to their inputs, as depicted in Fig. 1c. Each technology presents a main product (p_k), so the rest of the inputs and outputs can be defined in relation to it by specific ratios.

$$e_{p_k,k,d,h}^{OUT} = \eta_{s,k}^{OUT} \cdot e_{s,k,d,h}^{OUT} \qquad \forall s \in S , k \in K, d \in D, h \in H_d \qquad (7)$$

$$e_{p_k,k,d,h}^{OUT} = \eta_{s,k}^{IN} \cdot e_{s,k,d,h}^{IN} \qquad \forall s \in S, k \in K, d \in D, h \in H_d \qquad (8)$$

$$e_{p_k,k,d,h}^{OUT} = \eta_{f,k}^{MAN} \cdot e_{f,k,d,h}^{MAN} \qquad \forall f \in F_{MAN} , k \in K, d \in D, h \in H_d \qquad (9)$$

$$e_{p_k,k,d,h}^{OUT} = \eta_{f,k}^{NMAN} \cdot E_{f,k,d,h}^{NMAN} \qquad \forall f \in F_{NMAN}, k \in K, d \in D, h \in H_d \qquad (10)$$

In addition to these, a set of constraints is included limiting the maximum power delivered by technology (Equation (11)). The model provides the possibility of including technologies that do present limited load regulation (Equation (12)), which implies including a decision variable known as commitment binary variable (Equation (13)).

$$e_{s,k,d,h}^{OUT} \leq E_{s,k}^{MAX} \cdot n_k \qquad \forall s \in S, k \in K_{FR}, d \in D, h \in H_d \qquad (11)$$

$$E_{s,k}^{MIN} \cdot u_k^{d,h} \leq e_{s,k,d,h}^{OUT} \leq E_{s,k}^{MAX} \cdot u_k^{d,h} \qquad \forall s \in S, k \in K_{RR}, d \in D, h \in H_d \qquad (12)$$

$$u_k^{d,h} \leq n_k \leq 1 \qquad \forall k \in K_{RR}, d \in D, h \in H_d \qquad (13)$$

With this approach, any kind of system could be modeled. For instance, as shown in Fig. 2, a natural gas boiler converts manageable fuel (e^{MAN}) into medium or low temperature heat (e^{OUT}) as a function of its thermal efficiency (η^{MAN}); η^{OUT}, η^{IN} and η^{NMAN} being null in that case. Analogously, a compressor chiller unit converts electricity from the electricity module (e^{IN}) into two outputs: cooling and low temperature heat (e^{OUT}) by its EER (η^{IN}) and the cooling to heat release ratio (η^{OUT}); resulting in η^{MAN} and η^{NMAN} being null values in this case. Thus, η^{OUT}, η^{IN}, η^{MAN} and η^{NMAN} are generic ratios that can represent the performance of different technologies to be included within the model.

Fig. 2. Technology level energy balance examples

2.1.2 Energy Saving Measures

Energy Saving Measures contribute to a reduction in the heating or cooling load to be met by any specific ESS at any time interval. Instead of aggregated renovation actions, ESMs are considered as a single combination of individual actions on roof, walls and windows.

To be consistent with the above presented model for ESSs, ESMs are included following the same approach presented above, considering different Energy Saving Measures as virtual technologies integrated into the module of the load they contribute to with respect to the reduction. Specifically, each virtual technology k produces, at each time interval, as much energy as it saves in that interval in relation to a prior renovation reference case, with no need of energy input. Following the technology representation in Fig. 1c, any energy saving measure could be schematically depicted as in Fig. 3.

Fig. 3. Energy Saving Measure as virtual technology

The virtual production corresponding to each ESM will contribute to the energy production of the module from which the space heating or cooling load is provided. This production is non-manageable by the user and its magnitude is initial-state dependent, i.e., the marginal effect of an ESM k at any time interval d, h over the module s $\left(E_{s,k,d,h}^{ESM}\right)$ needs to be assessed (see Equation (14)).

$$e_{s,k,d,h}^{OUT} = E_{s,k,d,h}^{ESM} \qquad \forall s \in S, k \in K_{ESM}, d \in D, h \in H_d \qquad (14)$$

Analogously, the implementation of any Energy Saving Measure will also result in a reduction of the peak load of manageable technologies to be installed. To do so, Equation (2) is replaced by the more general Equation (15), where the maximum after-renovation load is considered.

$$\sum_{k\in K_{MAN}} E_{s,k}^{MAX} \cdot n_k \geq \max_{d,h}\left(L_s^{PEAK} - \sum_{k\in K_{ESM}} n_k \cdot E_{s,k,d,h}^{ESM}\right) \qquad \forall s \in S \qquad (15)$$

Finally, as stated before, any ESM should be understood as an action on the envelope that comprises combined actions on the roof, walls and windows. Thus, the selection of an ESM will imply the rejection of the others; in other words, only one action on the envelope can be selected, as set by Equation (16).

$$\sum_{k\in K_{ESM}} n_k \leq 1 \qquad (16)$$

2.1.3 Load distribution

Load reduction caused by the adoption of a specific ESM is usually provided either by detailed simulation or other estimations. As defined by the model, demand is distributed into time intervals, which should include both short term (daily) and long term (annual) variations. The overall number of intervals will increase the time needed for optimization, and a compromise should be obtained between the level of detail and simplicity. This explains why many authors simplify load curves, relying on sets of reference days to deal with this kind of optimization problems as in [21] or [22].

Here, a degree-day (DD) based simple method is proposed for this aim, considering that the new load resulting from the implementation of an ESM will distribute differently to that of the reference case. This DD based simple method is developed for both domestic space heating or cooling, but to clarify, only heating is considered in the formulation.

According to Erbs et al. [23], the temperature profile for each monthly reference day can be built from the monthly mean temperature (T_M^d), the monthly mean of the daily maximum temperatures (T_{MAX}^d) and the monthly mean of the daily minimum temperatures (T_{MIN}^d), as presented in Equation (17).

$$T^{d,h} = T_M^d + (T_{MAX}^d - T_{MIN}^d) \cdot \sum_{j=1}^{4} a_j \cdot \cos(j \cdot \tau^t - b_j) \qquad (17)$$

where τ^t is the angular time of day (15° per hour from 180° to -180°) and a_j and b_j are constants defined by Erbs [23] as presented in Table 1.

Table 1. a_k and b_k coefficients proposed by Erbs et al. [23]

From this temperature profile, the daily degree-days distribution can be easily obtained. It should be noticed that this approach would lead to a load peak during the night with the lowest outdoor temperature, but users are normally sleeping at that time. One way to avoid this situation is to define a different temperature set point (T_{SP}) for the day and night periods. Thus, the hourly degree days* are defined by equation (18), this being the monthly or annual degree days obtained by the integration of those periods.

$$DD^{d,h} = (T_{SP} - T^{d,h})\, {C_{log}}^{d,h} \quad (18)$$

where C_{log} is a control variable equal to 1 when the outdoor temperature is below T_B or 0 when equal to or above it; defining T_B as the base temperature for the building, i.e., the empirical outdoor temperature below which it is necessary to supply heating [24]. This approach has some limitations (for instance, effects of the thermal mass), but it is considered accurate enough for a rough distribution of the load or load reduction. Assuming direct proportionality between load and degree days, the overall heating thermal load can be distributed by months and then, by hourly intervals per each reference day.

$$L_{LT}^{d,h} = L_{Heating}^{d,h} = \frac{DD^{d,h} . \frac{N_d}{24}}{DD} \bar{L}_{LT} \quad (19)$$

where $\bar{L}_{LT}$ is the annual heating load ($\bar{L}_{LT} = \sum_{d \in D} \sum_{h \in H_d} L_{LT}^{d,h}$) and DD the annual degree-days ($DD = \sum_{d \in D} \sum_{h \in H_d} DD^{d,h} \cdot \frac{N_d}{24}$). In this expression, in order to maintain consistency of units, as hourly degree days are defined by Equation (18), they should be divided by 24 to relate them to the annual degree-days in the denominator.

The application to cooling load distribution would be identical, calculating the cooling degree days as the difference between the outdoor ambient and the cooling temperature set point for all those moments when the ambient temperature is higher than the cooling base temperature. This is valid for those cases with low latent heat gains, as it is the case of the residential building sector in Europe.

2.2 Economic model

Building renovation implies an economic impact consisting of fixed and variable costs. In this paper, the methodology proposed by the Buildings Performance Institute Europe (BPIE) is followed [25]. This methodology is based on the net present value method defined by the standard En 15459 [26]. Thus, the annual cost (C^{annual}), considering a lifespan (LS), is defined by Equation (20):

$$C^{annual} = \frac{1}{LS}[C^{INI} + \sum_{i=0}^{LS} (C_i^{OP} \cdot R_i) - V] \quad (20)$$

* Hourly degree-day term is used here since "degree-day" is a widely used concept. However, as it is defined here on an hourly basis, it would be more appropriately defined as degree-hour.

where:

$$C^{INI} = \sum_{k\in K} C_k^{INV} \cdot n_k \cdot \left(1 + f_k^{O\&M}\right) \quad (21)$$

$$C_i^{OP} = \sum_{d\in D} N_d \sum_{h\in H_d} \left[\sum_{s\in S} \left(C_s^{BUY} \cdot e_{s,d,h}^{BUY} - C_s^{SELL} \cdot e_{s,d,h}^{SELL}\right) + \sum_{f\in F_{MAN}} \sum_{k\in K} C_f^{MAN} \cdot e_{f,k,d,h}^{MAN}\right] \quad (22)$$

$$R_i = (1 + r)^{-i} \quad (23)$$

$$V = \sum_{k\in K} C_k^{INV} \cdot n_k \cdot \left(\frac{LS_k}{LS} - 1\right) \cdot \frac{1}{(1+r)^{LS}} \quad (24)$$

where C^{INI} is the initial investment, which is the sum of the annual amortization of the technologies (ESS or ESM), C_k^{INV}, multiplied by the number of installed units, n_k, of the corresponding technology. The operation and maintenance cost is added as a percentage of the investment of each technology ($f_k^{O\&M}$).

C_i^{OP} are the yearly variable costs of each technology and consider the costs and incomes of the system operations throughout the time horizon, in this case discretized in reference days d and intervals h. It is calculated by adding the energy bought in each module, $e_{s,d,h}^{BUY}$, multiplied by the corresponding price, C_s^{BUY}, subtracting the income obtained from the energy sold, $e_{s,d,h}^{SELL}$, multiplied by its price, C_s^{SELL}, and finally, by adding the consumed manageable fuel, $e_{f,k,d,h}^{MAN}$, multiplied by the corresponding price of each fuel, C_f^{MAN}.

Finally, R_i is the discount factor for year i and V, the final value of technology j at the end of the lifespan of the project, which assigns an extra cost or benefit when the lifespan of the technology, LS_k, is lower or higher than the lifespan of the project.

2.3 Optimization problem

Next, the optimization problem is presented by the objective function and the bounds for the variables used in the model. The optimization problem is subjected to the constraints defined by equations (1) to (16), where the energy balance of the different elements of the superstructure is covered.

- **Objective function:**

The objective function (25) minimizes the annual cost of satisfying the load of each system module. Therefore, the optimization problem integrates the energy model and the economic models holistically:

$$\min C^{annual} \quad (25)$$

subject to:

Energy supply system constraints (1) to (6)

Technology energy balance constraints (7) to (13)

Energy saving measure constraints (14) to (16)

Variable bounds (26) to (31)

- **Variable bounds:**

The variable n_k counts the number of installed units of each technology; therefore, it is integer and non-negative, see (26). The binary variable $u_k^{d,h}$ defines the commitment status of a unit, see (27). The variable $e_{s,d,h}^{STO}$ keeps track of the energy transferred towards the storage unit and can be positive (charge) or negative (discharge), see (28). The rest of the variables are continuous and non-negative, see constraints (29) to (31).

$$n_k \in \mathbb{Z} \text{ , } n_k \geq 0 \qquad \forall k \in K \qquad (26)$$

$$u_k^{d,h} \in \{0,1\} \qquad \forall k \in K, d \in D, h \in H_d \qquad (27)$$

$$e_{s,d,h}^{STO} \in \mathbb{R} \qquad \forall s \in S, d \in D, h \in H_d \qquad (28)$$

$$e_{s,k,d,h}^{OUT},\ e_{s,k,d,h}^{IN} \geq 0 \qquad \forall s \in S, k \in K, d \in D, h \in H_d \qquad (29)$$

$$e_{s,d,h}^{BUY}, e_{s,d,h}^{SELL}, q_s^{d,h} \geq 0 \qquad \forall s \in S, d \in D, h \in H_d \qquad (30)$$

$$e_{f,k,d,h}^{MAN} \geq 0 \qquad \forall f \in F_{MAN}, k \in K, d \in D, h \in H_d \qquad (31)$$

3 Case study

The proposed method is applied to a multi-family building located in a district of Otxarkoaga, in the city of Bilbao (northern Spain). The district was built in 1959-1961 and can be considered representative of the existing building stock in the region. The building comprises 36 dwelling units, each of which has a net floor area of 55 m², giving rise to an overall area of 1980 m² [27]. A picture of the building and its surroundings are presented in Fig. 4.

Fig. 4. Views of the multi-family building located in Otxarkoaga (Spain)

The external walls of the dwelling are composed of two layers of hollow bricks separated by an air gap. The indoor surfaces of the walls consist of plaster over gypsum. Two different kinds of window –single and double glazed- could be found in the majority of the dwellings, all with aluminum frames without a thermal break. Regarding heating systems, natural gas boilers have been installed in some dwellings recently, but in the majority of the cases, electric heaters are used to warm the dwellings in winter periods. The building has a total roof area of 418 m^2, but only 40 % is considered net available area for facilities, which means 167 m^2. The thermal behavior of the building was evaluated in a previous study [27] and this analysis is used as a basis for the analysis presented in this paper. In mentioned research piece, a detailed monitoring study was carried out and the obtained data was used for calibrating and adjusting the TRNSYS simulation model.

For the analysis presented in this paper, only heating, DHW and electricity loads were considered in the case study; cooling facilities are unusual in residential buildings in Bilbao, due to the temperate climate in northern Spain. The building is grid-connected, but there is no connection for the sale or purchase of thermal energy (i.e. district heating), and only heat release is eventually considered as energy sold at 0 €/kWh (see Fig. 1b). The variable costs associated to the purchase and sale of energy are presented in Table 2.

Table 2. Variable costs under consideration

The building was modeled, monitored and validated by the authors in a previous work [27]. The total heating load of the studied building is 94,667 kWh/y (47.82 kWh/m^2.y), which, as mentioned above, was obtained from a TRNSYS simulation. DHW and electricity loads are respectively 33.62 kWh/m^2.y and 35 kWh/m^2.y [28]. No cooling load is considered in the case study, as it is not commonly installed in dwellings in northern Spain. Loads are hourly, distributed into 12 reference days, one per month. The criteria followed for the load distribution, as well as the resulting profiles, are presented in detail in [6], except for the heating load that is presented in Section 3.1.2. Annual maintenance and operating costs were included as 2.5% of the plant cost, while a discount factor of 2.5% per year and a lifetime of 20 years were considered for ESS technologies and 50 years for the ESMs.

3.1 Energy renovation options

Amongst all the possible renovation options, the main ESSs and ESMs available in the Spanish building sector are considered in the case study, as it is described as follows.

3.1.1 Energy Supply Systems

In this paper, the set of technologies developed in [20] are considered eligible options for the design of the ESS, as listed in Table 3. These technologies appear grouped in the module levels defined before. Cost and efficiency values for each technology are included, using cost and efficiency estimation models obtained from a self-tailored top-down analysis of the Spanish market. To deal with the nonlinearities of these expressions for the integration into MILP programming, the cost and efficiency correlations for each technology were discretized into a finite set of equipment sizes. The discretization was made by setting a lower power bound of 0 kW and an upper bound equal to the already defined peak power. Thus, 6 equally distributed sizes were taken for each technology. In the case of the solar technologies, the discretization base was the number of panels.

Table 3. ESS technologies under consideration

Combined Heat and Power (CHP) units should present a Primary Energy Save (PES) over a specific given limit by power and technology [29]; this limits the heat release and was included in the model as an additional constraint. It has been considered that all the technologies can regulate their load capacity from 0 to 100%, except CHP units, which can only regulate from 60% to 100%.

3.1.2 Energy Saving Measures

As presented before, ESMs are introduced in the energy model of the building system as virtual technologies that produce a certain amount of heat, corresponding to the demand reduction obtained when they are applied. This virtual production is not equally distributed but depends on the indoor and outdoor conditions of each time interval. In this section, a set of typical ESMs are proposed as part of the case study; the demand reduction corresponding to each ESM is calculated by TRNSYS simulations; and a method is proposed and applied for distributing the demand reduction on the reference demand previously calculated.

- **Description of the Energy Saving Measures**

In the work previously published by Terés-Zubiaga et al. [27], 64 different ESMs were proposed and evaluated using TRNSYS for that purpose. Amongst them, the most interesting 8 ESMs were selected as options in the present optimization work. They are considered as the most interesting (amongst the 64 options evaluated in the previous paper) since they are representative of the different levels of potential improvements in façade, roof and windows (the baseline scenario and three levels of improvement which were defined in [27]: “Business as usual”, “improved scenario” and “high standard renovation”). These consist of a specific combination of insulation (EPS) on walls and roof, as well as window updates as summarized in Table 4; both thermal properties of the updates and required investment are included (prices based on the Spanish market). The lifespan of the ESMs was set at 50 years and no maintenance cost was considered.

Table 4. ESM solutions under consideration

ESMs under consideration can be classified in two main groups: those where windows are not changed and those where they are substituted by a better option. This is because window renovation implies a substantial investment regarding the achievable savings and, therefore, the window update is usually motivated by other factors apart from the higher energy efficiency, such as acoustic comfort or security. These other motivations could be introduced in the method presented here as user requirements.

- **Virtual production of Energy Saving Measures**

The adoption of a specific ESM implies a reduction in the space heating demand of the building that is treated as a virtual thermal energy production. This is determined on a yearly basis by dynamic simulations of the different renovation options through TRNSYS software [30]. The main features of this simulations are described in detail in [27]. The yearly space heating demands are outlined in Table 5.

Table 5. Yearly space heating demand reductions by ESMs

- **Load distribution**

As stated before, optimization is very time consuming and therefore, solutions aimed to speed up the process without sacrificing the reliability of the results should be found. As building behavior, specifically domestic, is highly season-dependent, monthly reference days on an hourly basis is a commonly adopted measure to reduce the number of variables of the problem.

The distribution of the different ESM cases (including the reference case) is carried out applying the degree-days based method presented in Section 2.1.2. The abovementioned TRNSYS simulations [27] have been used to determine T_B for each ESM solution. Fig. 5 graphically depicts the temperatures at which the heating system is switched-on and switched-off for the reference situation (Case #0). The base temperature is defined as the mean of these values for the whole year.

Fig. 5. Representation of the on-off temperatures and the corresponding base temperature for the reference case

Following the same approach, T_B was calculated for ESM and included in Table 4. For the load distribution, a different T_{SP} was defined for day and night periods, being respectively 20 (from 08.00 to 23.00) and 17°C (rest of the day).

Fig. 6. Case dependency of the different ESMs for the January and May reference days

The effect of the new base temperature in the heating load distribution is shown in Fig. 6, where January and May are selected for analysis purposes. How the insulation level affects not only the space heating load, but its distribution over time can be observed. Thus, lower base temperatures reduce the hours when the heating load is required and soften the load variations over time, which could result in less need for load regulation or power fractioning.

Considering all the assumptions and simplifications in ESS and ESMs presented here, the optimization problem will provide suboptimal results. However, simplifications follow the European Directive's approach, considering the climatic zone where the building is located and the stage of development of the available technologies; so the results can be understood as a useful indicator of the actual potential of the building renovation under different NRPE consumption limits.

4 Results and discussion

The model has been generated and solved with CPLEX v12.6.2 [31] within MatLab R2014a [32]. A computer with Intel Core i5-2430M CPU @ 2.40 GHz processor and 8 GB of RAM was used for the resolution. The problem consists of 58,858 constraints, 37,440 continuous variables, and 6,970 integer variables, from which 6,919 are binary ones. Elapsed time is case dependent. The following stop criterion was taken: simulations were run until a gap of 1% or, alternatively, 2 hours of operation were reached. In no case was the gap larger than 2% and no significant influence was seen in the resulting configuration and operation.

The optimization method was applied to the case study with the aim of getting the optimal ESM and ESS configuration and its hourly operation for two different cases: (a) cost optimal solution and (b) Zero Energy Building (ZEB). However, different criteria exist for the definition of NRPE. Usually, official definitions only include the electricity consumption due to lighting and do not consider the consumption associated to other electrical appliances [33]. To analyze the implications, two NRPE limits were introduced; one without considering the domestic electricity consumption (NRPE) and the other considering it (NRPE').

Table 6 presents the design of the renovation for the 3 scenarios covering the selection of ESS technologies and ESMs. Regarding ESMs, for the optimal case, the BAU renovation was selected (22.32% heating load reduction), based on 6 cm of insulation in both walls and roof. However, for both ZEB and ZEB' cases, optimization sets the improved renovation (27.9% heating load reduction), increasing the insulation up to 8 cm for facades and 14 cm for the roof. In none of the cases was the windows upgrade selected, as it would require a high investment with respect to the heating saving potential. Regarding the ESS, the optimal cost and ZEB cases included an internal combustion engine-based cogeneration, together with a 1000 l storage tank at medium temperature and a conventional natural gas boiler to meet the peak load. On the other hand, the ZEB' case included a biomass boiler instead of the cogeneration unit and, since the boiler allows partial load regulation, managed without the thermal energy storage tank. Otherwise, the ZEB' case also presented a conventional natural gas boiler to meet peak load. It was observed that, as the NRPE consumption limit decreased, a higher number of PV panels were required. Thus, whereas the optimal cost case did not require any, the ZEB' case required more space for their installation than was available on the roof, so some of them (more than 2/3) would have to be installed nearby.

Table 6. Configuration of the optimal ESS and ESM designs.

Table 7 summarizes the operation of the ESS for the 3 selected cases. A different selection of ESMs makes the heating load demand different for the different cases, the lowest being that of the ZEB' case. In the optimal cost and ZEB cases, thermal demand is mainly met by the cogeneration unit, whereas the conventional boiler is only used for the peaks. In both cases, although the same units are installed, the boiler operates for a higher number of hours, increasing the amount of heat released and, therefore, the PES is reduced. On the other hand, it produces more electricity, which justifies higher economic savings due to the higher price of electricity in relation to that of the heat produced. In the ZEB' case, the thermal demand is exclusively met by the biomass boiler.

Table 7. Operation results for the three analyzed cases

Electricity demand is the same in the 3 cases and is met by different operation strategies according to the specific NRPE consumption limit. In the optimal cost case, electricity demand is met by the cogeneration engine plus electricity imported from the grid, since this case does not include any PV panels. In the ZEB case, additional PV panels are included, which are a non-manageable source of electricity. This reduces the hours of operation of cogeneration which, additionally, runs more efficiently, avoiding releasing as much heat as in the cost optimal case. Lastly, in the ZEB' case, the electricity needs are produced by the photovoltaic panels and, when needed, imported from the grid.

The electricity surplus is exported to the electricity distribution grid; the ZEB' case being the one that exports a higher amount of production. However, this is also the one with a higher rate of imported electricity. This is a consequence of the fact that electricity is produced by the PV panels and cannot be managed; thus, the electricity is produced when the solar resource is available, regardless of the instantaneous electricity demand of the building. It can be seen that, in the optimal cost case, the self-consumption ratio exceeds 70%; whereas, in the ZEB case, it remains below 66% and, in the case of the ZEB', it is around 41%.

Next, the economic analysis is presented. The required investment for each of the 3 cases is presented in Fig. 7, where it has been disaggregated into renovation components, both ESS and ESMs. The photovoltaic plant represents the highest contribution to investment in those cases where it is selected. The investment associated to the ESMs is relatively low in relation to the ESS. This is because the lifespan is 50 years, more than twice that of the ESSs and only a partial contribution of this cost is considered in this analysis, as defined by Equation (20).

Fig. 7. Total investment for each of the cases disaggregated by components

The economic analysis has been carried out comparing the investment with the economic savings. Thus, the economic feasibility has been evaluated by simple Payback. Table 8 presents the results.

Table 8. Economic results for the three analyzed cases.

Variable costs correspond to the fuel and electricity inputs, as well as the maintenance costs. Annual cost includes, on a yearly basis, the variable cost plus annual amortization of both ESS technologies and ESMs. Annual savings have been calculated by comparing the annual costs to those of a reference case, consisting of a non-renovated building with a 200 kW natural gas boiler that imports all its electricity needs from the grid. The payback period shows a variation trend in relation to the NRPE consumption like that of the total investment presented in Fig. 7.

Parametrically solving the optimization problem constrained to different NRPE consumption limits, the optimal cost curve has been obtained, as presented in Fig. 8, which has a minimum corresponding to the optimal cost case. There, the ZEB and ZEB' cases are highlighted, as well as the case presenting the roof limit. The area of the economically feasible cases has been marked in grey, that is, those cases with a payback lower than the analysis period of 20 years.

Fig. 8. Minimum annual cost for different NRPE consumption values

It can be seen that, when the NRPE consumption limit is lower than -4 kWh/m^{2}y (or NRPE'<87.1 kWh/m^{2}y), minimum cost solutions are not economically feasible, since the Payback period exceeds the limit of 20 years. Thus, whereas the ZEB case can be reached under market conditions, the ZEB' requires a Payback of more than 55 years. Fig. 8 also contains the case in which the roof availability for solar technologies is met, which occurs for an NRPE of -18.6 kWh/m^{2}y (or 87.1 kWh/m^{2}y if the NRPE' is taken into account). Minimum costs solutions for lower NRPE consumption limits imply a nearby location of renewables, due to lack of space on the roof.

4.1 Sensitivity analysis

In order to assess the impact of potential disturbances from the base case scenario, two key parameters are considered, specifically, the natural gas and electricity costs, and the shape of the electricity load profile. The former aims to evaluate the impact from future variations on the price of the most relevant fuels, while the latter, seeks to forecast the impact that variations in the domestic use of electricity may induce, which could be caused, in particular, due to a massive introduction of electric vehicles. For the sake of simplicity, only the ZEB case is considered.

4.1.1 Fuel price variation

Two additional cases are considered here: (a) ZEB case with a fixed 10% increase on the natural gas and a 10% decrease on the electricity price and (b), ZEB case with a fixed 10% decrease on the natural gas and a 10% increase on the electricity price. Then, the configuration of the ESSs and ESMs resulting from the optimization are summarized in Table 9.

Table 9. Configuration of the optimal ESS and ESM designs under fuel price variations.

Little differences are found when the electricity price increases and the natural gas price decreases (ZEB (b)). These mainly consist of the installation of additional PV panels for a higher rate of self-consumption, reducing the amount of electricity purchased to the utility. In this case, a thinner insulation is proposed, since the economic saving of a natural gas consumption reduction is now lower.

When the electricity cost decreases and the natural gas cost increases (ZEB (a)), the size of the PV installation is reduced, since the benefits from the self-consumption are reduced accordingly. Higher prices of natural gas recommend substituting the CHP by biomass, with the natural gas boiler acting as a peak power reservoir. The economic analysis of the three cases is presented in Table 10.

Table 10. Economic results for the three analyzed cases under fuel price variations.

From the sensitivity analysis, it is observed that a decrease of the electricity and an increase of the natural gas price (ZEB (A)) allow getting the ZEB performance with half of the investment needed at the current prices (ZEB). Considering the expected trends, this is a foreseeable scenario where electricity price is reduced due to the higher penetration of new renewable technology and natural gas price is increased due to a higher scarcity and taxes on CO_2 emissions. However, this should be understood as a rough estimation where the variation is considered constant for the whole life cycle while the price of pellets remains at current prices.

4.1.2 Electricity load profile variation

Based on the ZEB case, two additional cases are defined for the electricity load profile. Specifically, the electricity load demand considered up to now is modified given rise to two additional scenarios (c) an electricity load profile with a lower contrast between peak and off-peak periods (in dark grey) and (d) its inverse, showing a peak at night (in light grey). These profiles are depicted in Fig. 9 for the winter and summer season.

Fig. 9. Electricity load profiles considered for the sensitivity analysis (winter and summer)

From the optimization of ESSs and ESMs, it is observed that the method proposes the same configuration for the three of them, while some differences are found regarding the operation as it can be seen from the economic results (Table 11). These differences are mainly caused by the fact that different imported/exported electricity ratios are got, which produces slight variations on the economic feasibility of the project (Payback variations are lower than 5%). Thus, no significant variations are expected from other electricity profiles different from the considered ones.

Table 11. Economic results for the three analyzed cases under electricity load profile variations.

5 Conclusions

The energy renovation of buildings is expected to play a key role in reducing energy dependency and mitigating climate change, especially due to the great stock of existing low efficiency buildings. Even though the nZEB concept has recently been introduced for new buildings, the dominant urgency of changes will require its application to be extended to the renovation of existing ones. In this paper, a method has been proposed for the design of energy renovation, considering ESSs and the adoption of ESMs to reduce the demand. Thus, this paper has shown how the method previously developed by the authors [20] has been updated and extended for the design of energy renovation, demonstrating the potential of the developed method to evaluate optimum solution for energy renovation in buildings taken into account not only energy systems but also different passive measures and the interaction between them. The main challenge was the introduction of ESMs as virtual technologies that produce, at the relevant time intervals, the amount of energy they save.

The method has been successfully applied to an existing building located in Bilbao (northern Spain), to get the optimal design that minimizes the annual net cost for different limits of NRPE consumption. Specifically, the demand reduction produced by the ESMs has been included as an input from previously done and validated TRNSYS simulations, but a simple method is presented for its distribution in reference days. The model, based on degree-days, allows synthetic reference days to be generated that considers, through a variable base temperature, the dependency of the distribution of the demand on the weather, use and the building thermal characteristics.

The optimization method provided the design selection and operation strategy of the renovation of buildings to meet different NRPE consumption limits, providing feasible and not feasible designs for different constraints: economic, space availability, etc. The method applied in the selected case study showed its potential for energy planning and fast estimation of the impact of different systems on the goals of reducing the NRPE consumption towards the nZEB definition of existing buildings.

Even though they cannot be directly extrapolated to other situations, some interesting points can also highlighted taken into account the results obtained in the case study, both related to the economical and physical constrains for achieving ZEB' cases, that is, ZEB building considering the domestic consumption of the users. In this manner, from the economical point of view, whereas ZEB case could be reached under market conditions through a deep energy renovation, achieving ZEB' case involves a payback period close to 60 years. As far as physical constrains are concerned, results have shown that roof availability can determine the limits of NRPE reductions in a cost-effective way, showing that minimum cost solutions for lower NRPE consumption involves a nearby location for installing renewable energy systems, due to the lack of space of the roof. A sensitivity analysis was carried out, it was obtained that the ZEB can be get for lower investments as the prices of the electricity decrease and those of the natural gas increase. However, no appreciable differences were found after variations of the electricity load profile.

It should be noticed that he method has been applied to a case study whose loads include heating, DHW and electricity demand, neglecting cooling as it is common in northern Spain. Even though its inclusion does not imply any additional challenge, the implications of taking cooling into account in energy renovation of buildings can offer interesting conclusions and will be cover by further research.

Additionally, future research areas include the extension of the model to stochastic optimization by incorporating uncertainty in the macro-parameters of the building [34] and the energy scheduling [35]. These two features should increase the size of the optimization model, which can be challenging to solve even for state-of-the-art solver. Therefore, based on the previous work by the authors [36], the development of a decomposition algorithm remains for further investigation.

Acknowledgements

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Appendix A- Nomenclature

Sets and indices:

Set	Index	Description
K	k	Technologies
K_{ESM}	k	Energy Saving Measures as virtual technologies ($K_{ESM} \subseteq K$)
K_{MAN}	k	Manageable technologies ($K_{MAN} \subseteq K$)
K_{FR}	k	Technologies with full load regulation ($K_{FR} \subseteq K$)
K_{RR}	k	Technologies with restricted load regulation ($K_{RR} \subseteq K$)
S	s	Modules
	p_k	Principal output module of a technology ($p_k \in S$)
S_{NE}	k	Modules, excluding electricity ($S_{NE} \subseteq S$)
F_{MAN}	f	Manageable fuels
F_{NMAN}	f	Non-manageable fuels
D	d	Reference days
H_d	h	Intervals in a reference day
J	j	Facility location

Decision variables:

Symbol	Description
n_k	Number of installed units of a technology
$u_k^{d,h}$	Commitment state of a unit

$e_{s,k,d,h}^{OUT}$ Total produced energy (kWh/h)

$e_{s,k,d,h}^{IN}$ Total consumed energy (kWh/h)

$e_{s,d,h}^{BUY}$ Energy bought by the system (kWh/h)

$e_{s,d,h}^{SELL}$ Energy sold by the system (kWh/h)

$e_{s,d,h}^{STO}$ Energy transferred to storage (kWh/h)

$e_{f,k,d,h}^{MAN}$ Manageable fuel input (kWh/h)

$q_s^{d,h}$ Stored energy at the beginning of the interval (kWh)

Constant parameters:

Symbol	Description
N_d	Yearly number of days of a reference day
$L_s^{d,h}$	Load (kWh/h)
L_s^{PEAK}	Maximum load (kW)
$\bar{L}_{LT}$	Annual heating load (kWh)
DD	Annual degree days
$DD^{d,h}$	Hourly degree days
T_{SP}	Temperature set point (°C)
T_B	Base temperature for the building (°C)
$T^{d,h}$	Hourly temperature (°C)
C_{log}	Binary control variable
$E_{s,k}^{MAX}$	Production at maximum power (kW)
$E_{s,k}^{MIN}$	Production at minimum power (kW)
$E_{s,k,d,h}^{ESM}$	Contribution of an Energy Saving Measure as virtual technology $k \in K_{ESM}$ (kWh/h)
$Q_{s,k}^{MAX}$	Maximum storage capacity (kWh)

$NRPE^{LIM}$ Non-renewable primary energy consumption limit, excluding electricity (kWh/y)

$NRPE'^{LIM}$ Non-renewable primary energy consumption limit, including electricity (kWh/y)

A_j^{MAX} Available area in a facility location (m²)

$A_{j,k}$ Facility location area used by a technology unit (m²)

W_s Module based primary energy weighting factors

$W_{s,k}$ Module and technology based primary energy weighting factors

$E_{f,k,d,h}^{NMAN}$ Non-manageable fuel input (kWh/h)

η_s^Q Storage efficiency

$\eta_{s,k}^{OUT}$ Production ratio with respect to the principal

$\eta_{s,k}^{IN}$ Consumption ratio with respect to the principal

$\eta_{f,k}^{MAN}$ Manageable fuel input ratio with respect to the principal

$\eta_{f,k}^{NMAN}$ Non-manageable fuel input ratio with respect to the principal

C_k^{INV} Initial investment cost (€)

C_s^{BUY} Purchase cost (€/kWh)

C_s^{SELL} Sale income (€/kWh)

C_f^{MAN} Purchase cost of manageable fuels (€/kWh)

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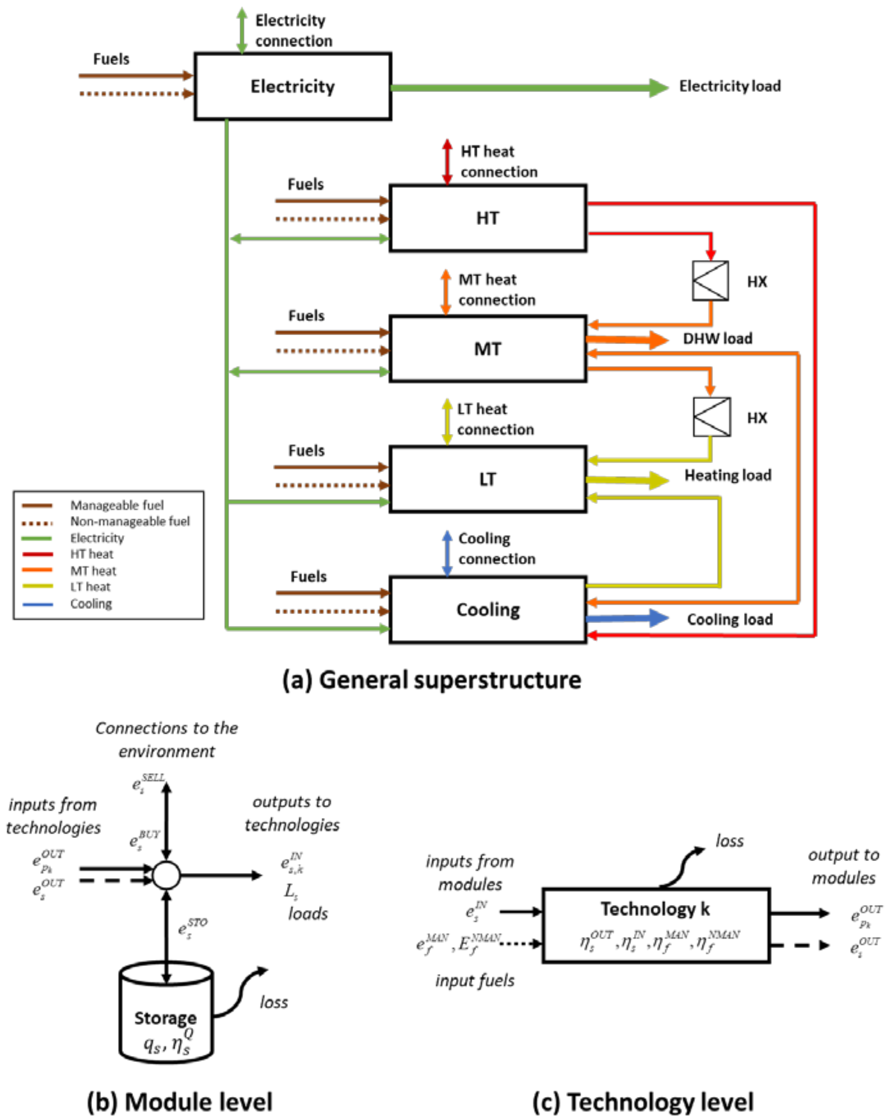

Fig. 1. Schematic view of the energy supply system model

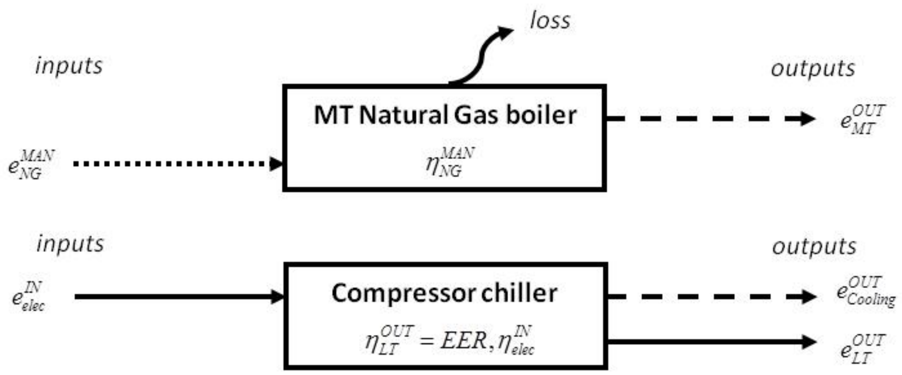

Fig. 2. Technology level energy balance examples

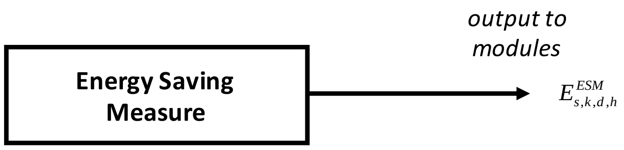

Fig. 3. Energy Saving Measure as virtual technology

Fig. 4. Views of the multi-family building located in Otxarkoaga (Spain)

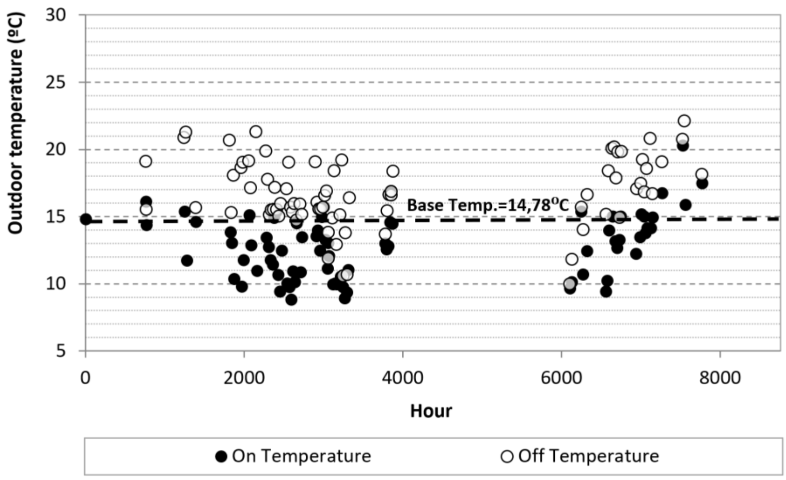

Fig. 5. Representation of the on-off temperatures and the corresponding base temperature for the reference case

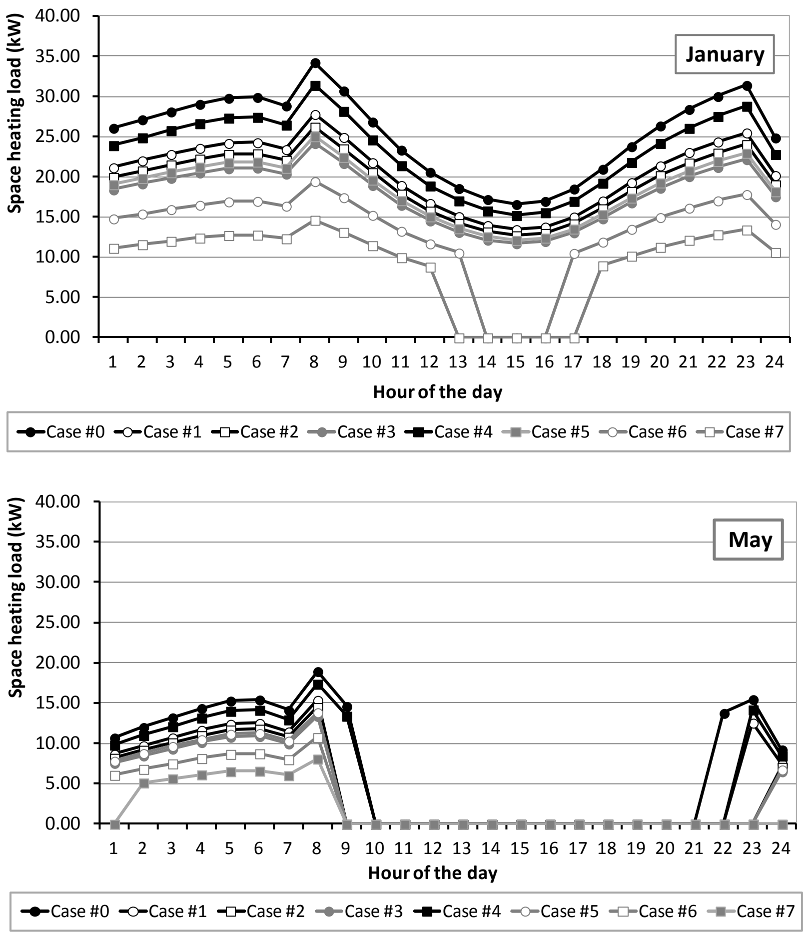

Fig. 6. Case dependency of the different ESMs for the January and May reference days

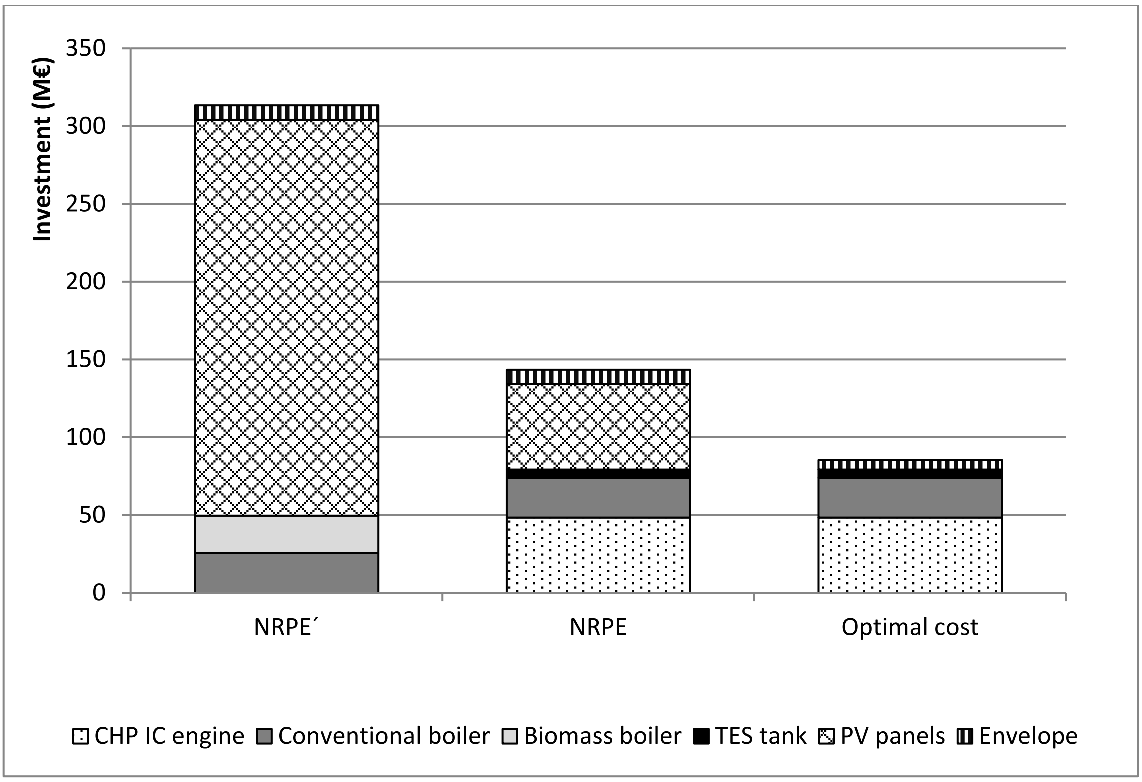

Fig. 7. Total investment for each of the cases disaggregated by components

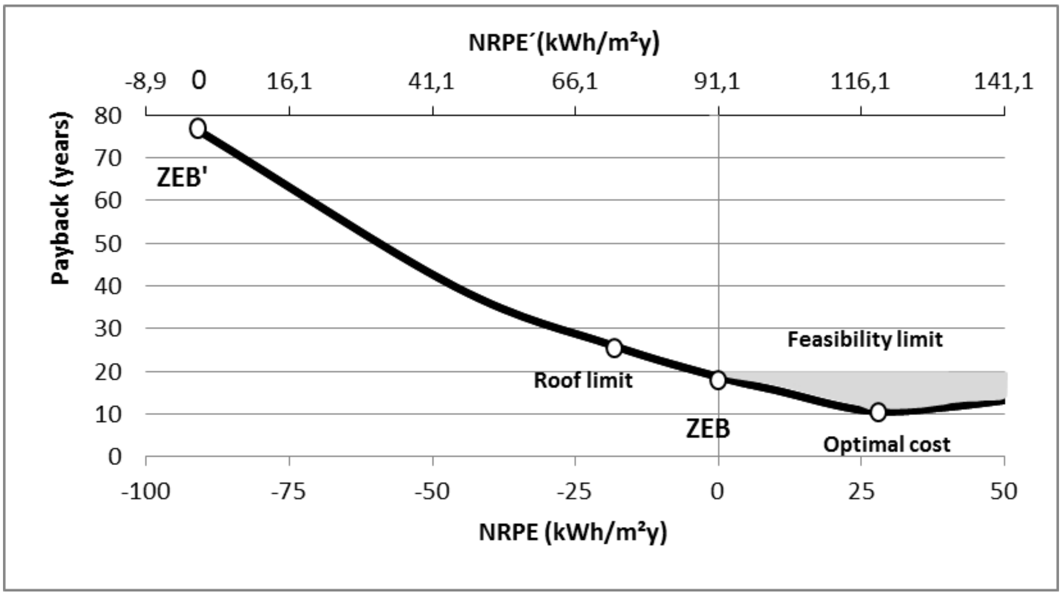

Fig. 8. Minimum annual cost for different NRPE consumption values

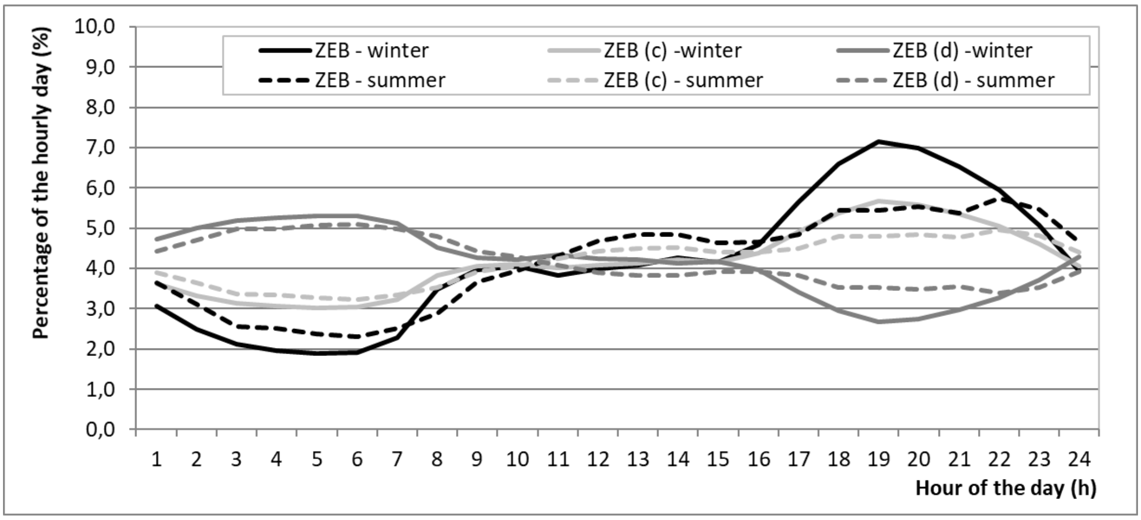

Fig. 9. Electricity load profiles considered for the sensitivity analysis (winter and summer)

Table1. a_k and b_k coefficients proposed by Erbs et al. [16]

Coefficicient	**1**	**2**	**3**	**4**
a_k	0.4632	0.0984	0.0168	0.0138
b_k	3.805	0.360	0.822	3.513

Table 2. Variable costs under consideration

Fuel	**Unitary cost (€/kWh)**
Natural gas - C_{NG}^{MAN}	0.054
Biomass (Pellet) - C_{BIO}^{MAN}	0.041
Electricity (purchase) - C_{ELE}^{BUY}	0.223
Heat (sale) - $C_{HT}^{SELL}, C_{MT}^{SELL}, C_{LT}^{SELL}$	0.000
Electricity (sale) - C_{ELE}^{SELL}	0.0496

Table 3. ESS technologies under consideration

Technology	Efficiency	Specific cost	Module
Compound parabolic collector	$\eta_0 = 64.5$ %; $k_1 = 0.858$; $k_2 0.005$	$c = 2{,}900.8\ n^{-0.211}$ (€/u)	HT
Organic Rankine CHP	$0.8517\ P_e{}^{0.0112}$ (thermal) $0.0675\ P_e{}^{0.0177}$ (electricity)	$c = 32{,}617\ P_e{}^{-0.503}$ (€/kWe)	HT
Thermal Energy Storage	-	$c = 63.353\ V^{0,646}$ (€/L)	HT, MT, LT
Evacuated tube collector	$\eta_0 = 79.6$ %; $k_1 = 1.282$; $k_2 = 0.008$	$c = 3{,}169.4\ n^{-0.176}$ (€/u)	MT
Internal Combustion Engine CHP	$0.7805\ P_e{}^{-0.039}$ (thermal) $0.2042\ P_e{}^{0.1367}$ (electricity)	$c = 12{,}480\ P_e{}^{-0.548}$ (€/kWe)	MT
Gas Turbine CHP	$0.7754\ P_e{}^{-0.131}$ (thermal) $0.1551\ P_e{}^{0,129}$ (electricity)	$c = 7{,}900.2\ P_e{}^{-0.397}$ (€/kWe)	MT
Biomass boiler	$0.9391\ P_t{}^{-0.006}$	$c = 1{,}584.4\ P_t{}^{-0.305}$ (€/kWth)	MT
Conventional natural gas boiler	$0.9833\ P_t{}^{-0.002}$	$c = 1{,}243.2\ P_t{}^{-0.415}$ (€/kWth)	MT
Flat plate collectors	$\eta_0 = 79.2$ %; $k_1 = 3.666$; $k_2 = 0.013$	$c = 2{,}574.7\ n^{-0.302}$ (€/u)	LT
Condensing natural gas boiler	$1.0492\ P_t{}^{0.0021}$	$c = 1{,}589.7\ P_t{}^{-0.475}$ (€/kWth)	LT
Air-to-water heat pump	$3.7035\ P_t{}^{-0.026}$	$c = 381.99\ P_t{}^{-0.144}$ (€/kWth)	LT
Amorphous photovoltaic modules	$\eta_0 = 7.83$ % ; γ =-0.19 %/ºC	$c = 553.48\ n^{-0.205}$ (€/u)	Electricity
Mono & Polycrystalline photovoltaic modules	$\eta_0 = 15.3$ % ; γ =-0.40 %/ºC	$c = 719.34\ n^{-0.042}$ (€/u)	Electricity

[1] The solar thermal collector efficiency is given by $\eta = \eta_0 - \frac{k_1 \cdot (T_m - T_{amb})}{G} - \frac{k_2 \cdot (T_m - T_{amb})^2}{G}$ [35]

[2] The photovoltaic collector efficiency is given by $\eta = \eta_0 \cdot \{1 + \gamma \cdot (T_C - T_{REF})\}$ [36]

Table 4. ESM solutions under consideration

	No window update		Window update	
***Reference building** (no insulation)*	**CASE 0**	**Total investment** **0 €**	**CASE 4**	**Total investment** **53,086 €**
	Current façade 2 cm insulation (U=0.74 W/m² K)	0 €	**Current façade** 2 cm insulation (U=0.74 W/m² K)	0 €
	Current roof No insulation	0 €	**Current roof** No insulation	0 €
	Current windows 4 / 6 / 4 (U=4.12 W/m² K)	0 €	**Window update** 6 / 12 / 6 (U=2.76 W/m² K)	53,086 €
BAU renovation *(typical insulation in renovations for northern Spain)*	**CASE 1**	**Total investment** **15,271 €**	**CASE 5**	**Total investment** **68,357 €**
	Façade update 6 cm insulation (U=0.43 W/m² K)	11,074 €	**Façade update** 6 cm insulation (U=0.43 W/m² K)	11,074 €
	Roof update 6 cm insulation (U=0.53 W/m² K)	4,197 €	**Roof update** 6 cm insulation (U=0.53 W/m² K)	4,197 €
	Current windows 4 / 6 / 4 (U=4.12 W/m² K)	0 €	**Window update** 6 / 12 / 6 (U=2.76 W/m² K)	53,086 €
Improved renovation *(with sensitive increase of insulation)*	**CASE 2**	**Total investment** **23,123 €**	**CASE 6**	**Total investment** **93,256 €**
	Façade update 8 cm insulation (U=0.36 W/m² K)	14,433 €	**Façade update** 8 cm insulation (U=0.36 W/m² K)	14,433 €
	Roof update 14 cm insulation (U=0.26 W/m² K)	8,690 €	**Roof update** 14 cm insulation (U=0.26 W/m² K)	8,690 €
	Current windows 4 / 6 / 4 (U=4.12 W/m² K)	0 €	**Window update** 3 /12/ 3 Low-emissivity (U=1.89 W/m² K)	70,133 €
High standard renovation *(with high increase in insulation)*	**CASE 3**	**Total investment** 37,766 €	**CASE 7**	**Total investment** 122,366 €
	Façade update 14 cm insulation (U=0.24 W/m² K)	25,610	**Façade update** 14 cm insulation (U=0.24 W/m² K)	25,610 €
	Roof update 20 cm insulation (U=0.19 W/m² K)	12,156	**Roof update** 20 cm insulation (U=0.19 W/m² K)	12,156 €
	Current windows 4 / 6 / 4 (U=4.12 W/m² K)	0 €	**Window update** 4 / 16 / 4 /16 / 4 (U=1.15 W/m² K)	84,600 €

Table 5. Yearly space heating demand reductions by ESMs

ESM case	**Space heating demand** $\left(\mathbf{L}^{\mathbf{d,h}}_{\mathbf{s_{CALEF}i}}\right)$ **(kWh/year)**	**Savings on space heating** $\left(\mathbf{L}^{\mathbf{d,h}}_{\mathbf{s\_CALEF}} - \mathbf{L}^{\mathbf{d,h}}_{\mathbf{s_{CALEF}i}}\right)$ **(kWh/year)**	**Savings on space heating** (%)	**Base temperature** (ºC)	**Heating peak load (kW)**
0	94,667	0	-	14.78	112
1	73,540	21,128	22.32%	14.11	87
2	68,254	26,413	27.90%	13.99	82
3	62,258	32,409	34.23%	13.80	78
4	85,681	8,987	9.49%	14.57	97
5	64,465	30,202	31.90%	13.86	71
6	47,436	47,231	49.89%	13.39	61
7	33,323	61,345	64.80%	12.78	51

Table 6. Configuration of the optimal ESS and ESM designs.

		Module	ZEB' (NRPE'=0)	ZEB (NRPE=0)	Optimal Cost
ESS technology	Compound parabolic collector	HT	-	-	-
	Organic Rankine CHP	HT	-	-	-
	HT Thermal Energy Storage	HT	-	-	-
	Evacuated tube collector	MT	-	-	-
	Internal Combustion Engine CHP	MT	-	20 kW_e	20 kW_e
	Gas Turbine CHP	MT	-	-	-
	Biomass boiler	MT	50 kW	-	-
	Conventional natural gas boiler	MT	175 kW [1]	175 kW [1]	175 kW
	MT Thermal Energy Storage	MT	-	1000 l	1000l
	Flat plate collectors	LT	-	-	-
	Condensing natural gas boiler	LT	-	-	-
	Air-to-water heat pump	LT	-	-	-
	LT Thermal Energy Storage	LT	-	-	-
	Mono & Polycrystalline photovoltaic modules	Electricity	390[2] (383%)[3]	84[2] (82,5%)[3]	-

		CASE 2	CASE 2	CASE 1
ESM	Wall insulation	8 cm (U=0.36 W/m² K)	8 cm (U=0.36 W/m² K)	6 cm (U=0.43 W/m² K)
	Roof insulation	14 cm (U=0.26 W/m² K)	14 cm (U=0.26 W/m² K)	6 cm (U=0.53 W/m² K)
	Window	4 / 6 / 4 [4] (U=4.12 W/m² K)	4 / 6 / 4 [4] (U=4.12 W/m2 K)	4 / 6 / 4 [4] (U=4.12 W/m² K)

[1] Only for covering peak periods, do not run under reference days
[2] Number of PV modules of 260Wp
[3] Percentage of occupation of available roof
[4] Windows are the building's original, no window upgrade is considered

Table 7. Operation results for the three analyzed cases

		ZEB' (NRPE'=0)	ZEB (NRPE=0)	Optimal Cost
NRPE	NRPE (kWh/m² y)	-91.1	0	26.1
	NRPE´ (kWh/m² y)	0	91.1	117.2
Thermal Energy	Thermal energy load (kWh/y)	134,829	134,829	140,115
	CHP IC engine (kWh/y)	0	137,823	161,536
	Conventional boiler (kWh/y)	0	14	2,705
	Biomass boiler (kWh/y)	134,829	0	0
	Stored energy (kWh/y)	0	50,417	50,388
	Heat release (kWh/y)	0	3,008	24,126
Electricity	Electricity load (kWh/y)	69,299	69,299	69,299
	Electricity generated (kWh/y)	74,156	77,138	71,690
	CHP IC engine (kWh/y)	0	61,166	71,690
	CHP PES (%)		25.43	19.52
	PV panels (kWh/y)	74,156	15,972	0
	Exported electricity (kWh/y)	43,812	26,342	21,182
	Self-consumed electricity (kWh/y)	30,344	50,796	50,508
	Imported electricity (kWh/y)	38,955	18,504	18,791

Table 8. Economic results for the three analyzed cases.

	ZEB’ (NRPE’=0)	ZEB (NRPE=0)	Cost Optimal
Investment (€)	313,466	143,444	85,448
Variable costs (€/y)	15,749	13,218	13,961
Annual cost (€/y)	31,422	20,390	18,233
Annual savings(€/y)	3,758	6,289	5,546
Payback (y)	76.6	18.7	10.8

Table 9. Configuration of the optimal ESS and ESM designs under fuel price variations.

		Module	ZEB (NRPE=0)	ZEB (a) (NRPE=0)	ZEB (b) (NRPE=0)
ESS technology	Compound parabolic collector	HT	-	-	-
	Organic Rankine CHP	HT	-	-	-
	HT Thermal Energy Storage	HT	-	-	-
	Evacuated tube collector	MT	-	-	-
	Internal Combustion Engine CHP	MT	20 kW_e	-	20 kW_e
	Gas Turbine CHP	MT	-	-	-
	Biomass boiler	MT	-	50 kW	-
	Conventional natural gas boiler	MT	175 kW	175 kW [1]	175 kW
	MT Thermal Energy Storage	MT	1000 l	-	1000l
	Flat plate collectors	LT	-	-	-
	Condensing natural gas boiler	LT	-	-	-
	Air-to-water heat pump	LT	-	-	-
	LT Thermal Energy Storage	LT	-	-	-
	Mono & Polycrystalline photovoltaic modules	Electricity	84[2] (82.5%)[3]	26[2] (25.5%)[3]	96[2] (94.3%)[3]

		CASE 2	CASE 2	CASE 1
ESM	Wall insulation	8 cm (U=0.36 W/m^2 K)	8 cm (U=0.36 W/m^2 K)	6 cm (U=0.43 W/m^2 K)
	Roof insulation	14 cm (U=0.26 W/m^2 K)	14 cm (U=0.26 W/m^2 K)	6 cm (U=0.53 W/m^2 K)
	Window	4 / 6 / 4 [4] (U=4.12 W/m^2 K)	4 / 6 / 4 [4] (U=4.12 W/m2 K)	4 / 6 / 4 [4] (U=4.12 W/m^2 K)

[1] Only for covering peak periods, do not run under reference days
[2] Number of PV modules of 260Wp
[3] Percentage of occupation of available roof
[4] Windows are the building's original, no window upgrade is considered

Table 10. Economic results for the three analyzed cases under fuel price variations.

	ZEB (NRPE=0)	ZEB (a) (NRPE=0)	ZEB (b) (NRPE=0)
Investment (€)	143,444	75,763	148,139
Variable costs (€/y)	13,218	16,111	12,317
Annual cost (€/y)	20,390	19,899	19,724
Annual savings(€/y)	6,289	3,396	7,190
Payback (y)	18.7	14.8	17.0

Table 11. Economic results for the three analyzed cases under electricity load profile variations.

	ZEB	ZEB (c)	ZEB (d)
Investment (€)	143,444	143,444	143,444
Variable costs (€/y)	13,218	13,099	12,942
Annual cost (€/y)	20,390	20,272	20,114
Annual savings(€/y)	6,289	6,407	6,565
Payback (y)	18.7	18.4	17.9