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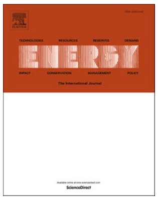

A general sizing methodology of grid-connected PV systems to meet the zero-energy goal in buildings

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ABSTRACT

This work expresses the most general definition of zero-energy building through a set of equations based on measured energy consumption and electricity generation predictions. This helps determining the optimal size of grid-connected photovoltaic systems for upgrading any highly efficient or conventional building into a zero-energy building. Opposed to previous works, which consider only electrical consumptions, this article includes consumption from fossil fuels and district heat and cooling networks. The study also covers environmental parameters and an economic study adaptable to any electricity market structure, contributing to deciding the best electricity tariff to hire.

The methodology was applied to passive and conventional single-family houses in Spain. Results showed that the performance of a grid-connected photovoltaic system depends critically on the energy sources imported by the building. In particular, the performance improves in buildings where the electricity represents most of the imported energy. The required minimum size of the photovoltaic system in the conventional house (14 kW_p) is far greater than in the passive house (9 kW_p). After the recent global increase in electricity prices, annual economic savings of 70.12 % and 49.71 %, and payback periods of 6 and 13 years for the passive and conventional houses, respectively, make the investment profitable.

1. Introduction

Nowadays, heating, air conditioning and domestic hot water (DHW) services in buildings account for 40 % of final energy consumption in the European Union. This implies 36 % of CO_2 emissions in the European Union [1] and, as a result, both the European and international communities have undertaken important efforts in legal matter to address this issue.

In Europe, several directives were developed towards the goals established in the Green Deal [2] and the European Climate Law [3], seeking to improve energy efficiency in buildings [4,5]. In them, nearly zero-energy buildings (nZEBs) are defined as *"buildings that have a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby"* [4]. More recently, the requirements were strengthened with Directive (EU) 2018/2001 [6], which proposes the development of an enabling framework to introduce renewable energy systems for self-supply, and encourages users of the building to generate, store, and sell their excess production of electricity.

However, the definition of nZEB is ambiguous: it does not quantitatively specify the maximum primary energy that the building can consume, how much of it must come from renewable sources, or the factors for the determination of the primary energy. The main reason for this limitation is that the definition of the nZEB results from European directives, and it is not based on exact instructions or regulations. The variability in the local conditions in different countries makes difficult to establish common baselines of primary energy consumption.

Parallelly, the Department of Energy (DOE) of the United States has been exploring the meaning of zero-energy building (ZEB) concept. Four definitions are cited in Ref. [7] which consider different metrics, depending on the zero-energy goal: net-zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions. The work reports large differences between those reference parameters and a lack of a clear, measurable, and common zero-energy definition. In 2015, the DOE developed a definition that meets these desired specifications. ZEBs consist of *"energy-efficient buildings where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable*

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Nomenclature

A_u	Useable area of the house (m^2)
C	Cost (€)
C_D	Cost of the electricity exported to the grid (€/kWh)
C_E	Cost of the electricity imported from the grid (€/kWh)
C_F	Cost of the fuel energy unit (€/kWh)
C_{HC}	Cost of the heat/cold energy unit (€/kWh)
C_P	Cost of the electrical power hired by the building (€/kW·day)
d	Day index (d = 1…365)
e	CO_2 emissions factor or final (end-use) energy (kg CO_2/kWh)
E	Energy (kWh)
E_{CO2}	CO_2 emissions (kg CO_2)
EcS	Annual economic saving (€/year)
EnS	Annual energy saving (kWh/year)
ET	Electricity tax (%)
EvS	Annual environmental saving (kg CO_2/year)
f	National average primary energy conversion factor from final (end-use) energy to primary energy (kWh_{PE}/kWh)
FC	Fixed cost (€)
h	Hour index (h = 1…8760)
I	Current output of a PV module (A)
I_{gl}	Global solar irradiation (W/m^2)
IC	Investment capital cost (€)
LHV	Low heating value (kWh/kg)
m	Month index (m = 1…12)
m^F	Mass of fuel (kg)
MER	Metering equipment rent (€/month)
N_p	Number of people living in the house
N_{PV}	Number of photovoltaic panels
P	Power (kW)
P_{inst}	Installed PV power (kW_p)
PE	Primary energy (kWh)
REcS	Relative economic saving (%)
REnS	Relative energy saving (%)
REvS	Relative environmental saving (%)
SPB	Simple payback period (years)
V	Voltage output of a PV module (V)
VAT	Value added tax (%)
VC	Variable cost (€)

Acronyms

CH	Conventional house
DHW	Domestic hot water
DOE	Department of Energy (of the United States of America)
E3	Energy, economic and environmental
HRV	Heat recovery ventilation
HVAC	Heating, ventilation, and air conditioning
nZEB	Nearly zero-energy building
PH	Passive house
PV	Photovoltaic
ZEB	Zero-energy building
ZEH	Zero-energy house

Greek symbols

ε_{drop}	PV panels yearly efficiency drop
η_{inv}	Inverter efficiency

Subscripts

cons	consumed
exp	exported
gen	generated by the array of panels (at the output of the array)
hir	hired
imp	imported
min	minimum
prod	produced by the PV system (at the output of the inverter)
reg	registered by the energy meter

Superscripts

B	biomass
E	electricity
F	type of fuel index (F=NG, G, B, etc.)
G	gas oil
HC	district heat and cooling
NG	natural gas
ref	reference case (without PV installation)
y	year of lifespan of the PV system index (y = 2 … 20)

exported energy” [8]. This means building must produce renewable energy for self-supply and surplus self-produced energy must outweigh the energy imports, on a primary energy basis. The definition addresses how energy consumption is measured and what energy uses and types to include in its determination.

Typical solutions to achieve energy-efficient buildings are reducing primary energy demand and producing energy from renewable sources. The first requires actions on the envelope that are not always possible, they are often difficult, and they are always costly. The latter focuses on adding technologies such as photovoltaic (PV) panels, solar thermal collectors, wind energy systems and air-source or ground-source heat pumps [9]. Under the actual energy framework, buildings tend to use PV systems for on-site energy generation, as this solution is cost-effective and easy to install in roofs and façades [10].

1.1. Literature review

The performance of existing ZEBs in scientific literature was assessed by few authors. Dong et al. [11] investigated the operational performance of a ZEB in Hangzou (China). The case three-storey office building achieved the ZEB conditions with good indoor environmental quality through PV panels installation. Feng et al. [12] reviewed 34 ZEB cases worldwide, focusing on hot and humid regions. Passive design strategies as daylighting, natural ventilation and efficient insulation materials for the building envelope showed a positive impact on the building’s energy efficiency. Authors also stated that effective operation management and engagement with occupants are relevant to ensure high energy performance. Shin et al. [13] analysed the energy performance of a zero-energy renovated office building in a hot and humid region. The studied building counted on several low-energy technologies including high-efficiency heating, ventilation, and air conditioning (HVAC) system, a high-performance building envelope, energy efficient lighting and a PV system. The annual performance was calculated based on in-site measurements coupled with regression analysis and calibrated building energy simulation models. The renovated ZEB saved 37–50 % of energy consumption. In all these cases, the condition for achieving the ZEB standard was based on the zero-energy source building.

Several studies assessed the feasibility of converting buildings into ZEB. Most of them rely on PV systems for renewable energy production. Zhou et al. [10] proposed a methodology to evaluate the zero-energy potential of buildings with PV systems at city level based on estimations of building energy consumption and solar energy availability. Junior et al. [14] analysed the technoeconomic feasibility of converting a university building in Brazil into a ZEB through retrofit measures and a PV system. Based on data of constructive characteristics, use and occupation, energy consumption and renewable energy generation, three scenarios of retrofit strategies were proposed: self-sufficient building, ZEB and energy-positive building. Ohene et al. [15] proposed retrofit guidelines that achieve net-zero energy targets for existing buildings in a tropical climate. They stated that passive design strategies combined with PV systems lead to reaching the ZEB standard. Fatemi et al. [16] presented a new configuration of heating and cooling systems to reach ZEB standard, suitable for hot and cold dry climates, based on direct evaporating cooling coupled with the ground, PV system and a heat pump. Rabani et al. [17] proposed an optimization method to find the best combination of measures minimizing energy use and achieving the nZEB target for an office building in Oslo. Measures included optimization of building envelope, building energy supply, fenestration, and shading device material. Subsequently, they studied integration of PV panels for achieving the ZEB level. Pirmohamadi et al. [18] developed an optimization algorithm to retrofit an existing office building envelope and replacing HVAC systems and appliances for more efficient alternatives, as well as incorporating a PV system and wind turbine energy generation. ZEB standard was possible combining energy retrofit measures and with twenty-four 2 kW wind turbines, three 9 kW wind turbines and 460 m^2 surface of PV system. Omar *et* al. [19] proposed a strategy to convert a conventional educational building in Egypt into a ZEB. They assessed the effectiveness of incorporating a grid-connected PV system under two scenarios: actual building in its current state and after replacing the lighting system for efficient LED lamps and the split units of air conditioners for solar-powered air conditioners. The PV system plus the energy retrofit measures combined was the best solution, in terms of costs and pollutant emissions. Alajmi et al. [20] proposed the transformation of a passive house in Portland (United States) into a ZEB, showing that PV panels was the most cost-effective alternative. They stated that an on-grid PV system without batteries was the most profitable choice. All these studies rely on the zero-energy site building definition, except for [17–19], which do employ the source definition.

Efforts were also made in integral design strategies for new ZEB buildings. Lin & Chen [21] proposed an integrated design approach of ZEBs based on simulations of plug loads, lighting and HVAC. They considered geometric effects, passive design strategies, active strategies (HVAC systems) and renewable energy strategies. Kim et al. [22] studied a ZEB design strategy based on an air source heat pump and a PV system, coupled with life cycle assessment. They applied the strategy to different climates in the U.S., finding that life cycle costs were lower in hot and mild climate zones than in cold zones. Cusenza et al. [23] also developed a design methodology based on life cycle analysis. Two configurations were studied for a building integrated PV system (with and without a battery storage system). If the source ZEB criterion is followed, the configuration without battery performs better from an environmental perspective. Almutairi et al. [24] analysed the feasibility of designing ZEBs in Muscat, Oman, considering thermal insulation and thermal inertia reduction, building facade, and spatial orientation or the building, as well as the required size of the PV installation. Authors proposed a ZEB design with a total area of 290 m^2 and a surface of 23 m^2 of PV panels.

Other authors studied the interaction between ZEBs and energy grids, assessing harmonic pollution or voltage flicker [25,26]. The use of PV powered thermoelectric cooling in ZEBs was also assessed. This is a solution with techno-economical potential to reduce energy consumption in buildings for heating, ventilation and air conditioning [27]. Finally, the energy flexibility study in ZEBs by Lu et al. [28] is highlighted. They demonstrated how ZEBs might store energy in the building's thermal mass to deal with adverse events without jeopardising the occupants' comfort.

1.2. *Aim of the work*

A detailed analysis of the literature highlights the existence of different definitions of ZEBs and a variety of papers presenting case studies on the operation of ZEBs, design strategies and the most appropriate technologies to achieve this status. Most of them only consider electricity consumption, renewable energy production through PV installations, and ZEB goal based on the net-zero site energy building definition. Besides, efforts focused on verifying if the balance between the building energy consumption and the PV generation is met, but rarely include economic or environmental studies. If they are included, quasi-constant reference prices for electricity are used, rather than modern electricity tariff structures, where prices vary hourly and are influenced by external factors (international conflicts or fluctuations derived from the growing implementation of renewable technologies in the global energy pool). As such, the aim of this work is, for any given building (highly efficient or conventional), any mix of energy supplies (electrical, fossil fuel, district heating), located anywhere and under any electricity market structure, to define a mathematical formulation that allows to determine the minimum size of a grid-connected PV system that fulfils the ZEB standard, based on the source definition. If any other action would be taken, the consumption of the building would be lower, and the size of the PV system could be reduced.

The main novelty is providing a full set of equations applicable to any building under any circumstances, based on a short definition, and that includes various types of energy, conversion factors and hourly data over a minimum period of one year. This work also includes an economic and environmental study, providing detailed information to decide the optimal size of the PV system. The interest of the studies that can be carried out using this methodology is shown through its application to two dwellings with different construction characteristics and energy consumption profiles: a single-family Passivhaus and a conventional single-family house in the northern Spanish region of Asturias. The optimal size of the PV installation required to meet the ZEB standard is analysed and the annual electricity bill is estimated based on real electricity prices. The effect of the recent rise in electricity prices from June 2021 is also studied, comparing the profitability of the PV installation in 2019 and 2022. According to ENTRANZE database, which provides in-depth information of buildings and related energy systems in EU-28, single-family houses represent 50 % of the European Union building stock [29]. Thus, as newly built houses meet efficiency standards similar to Passivhaus, and the majority of conventional houses have an energy consumption mix similar to that in the paper, these two case studies are highly illustrative of how PV installations lead to achieving restrictive energy efficiency standards in traditional and energy-efficient houses.

2. Methodology

The proposed methodology is based on experimentally registered renewable and non-renewable energy consumption in the houses and on a mathematical model to simulate the PV installation. In addition to electricity (E), this work considers typically consumed fossil fuels (F) and possible supply of heat and cold (HC) from district heat and cooling networks. These two last types of imported energy are clearly present in the definition of zero-energy building, but they were not considered in previous works. The flowchart of the methodology is shown in Fig. 1.

The first step is to identify the types of energy imported into the building without the PV installation and register them for at least one year. The consumed electricity should be registered hourly, $E^{E}_{cons}(h)$, while fuels or heat/cold consumption might be registered monthly, $E^{F}_{cons}(m)$, $E^{HC}_{cons}(m)$.

The second step is to select the components of the PV installation (mainly panels and inverter), and define an initial power, as reduced as allowed by local regulations. Then, the simulation of the solar system determines the hourly electricity production, $E^{E}_{prod}(h)$. Each hour, the difference between the electricity consumed in the house and the production is either imported, $E^{E}_{imp}(h)$, or exported, $E^{E}_{exp}(h)$, through the site boundary.

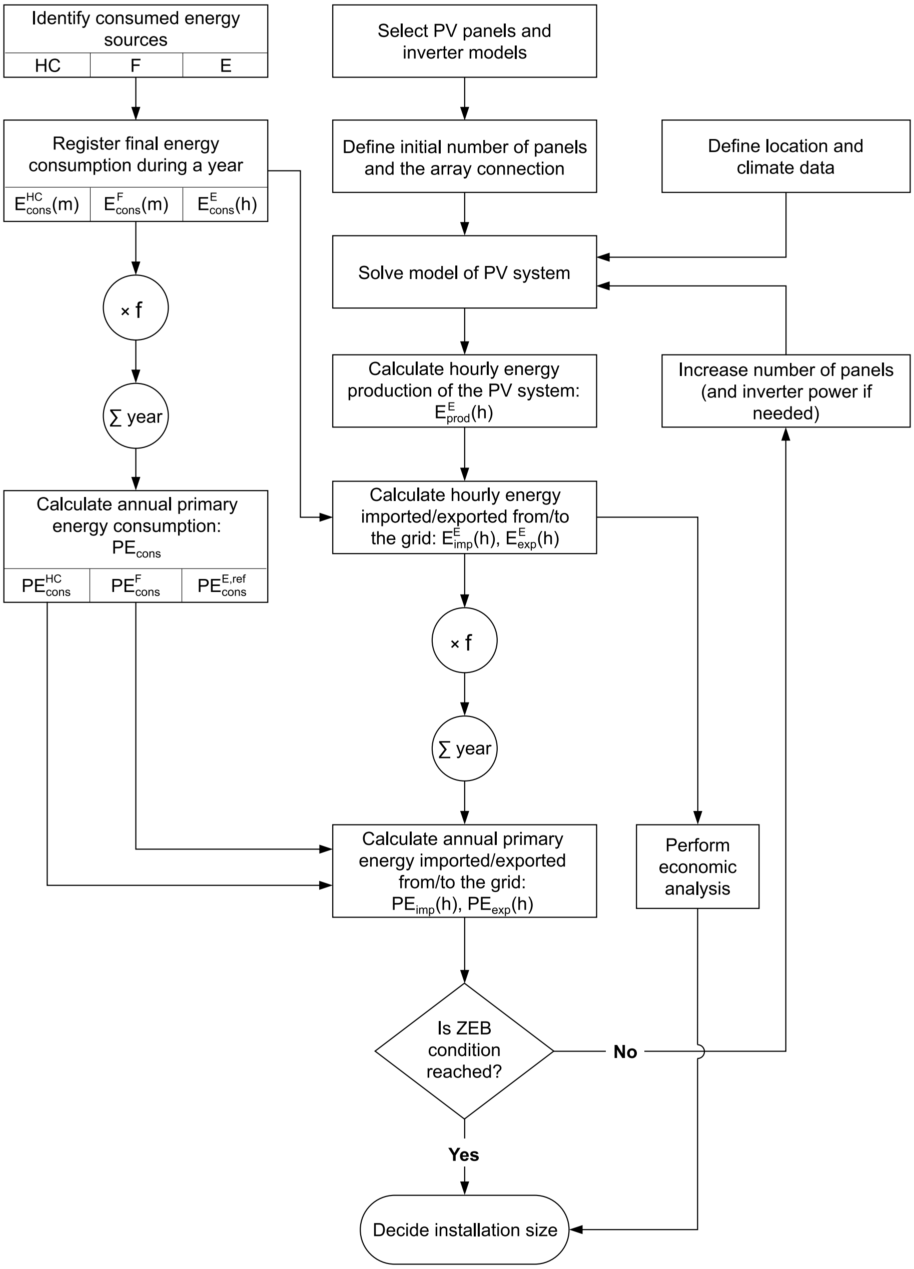

Fig. 1. Flowchart of the work methodology.

The third step is to apply national average primary energy conversion factors, *f*, to transform the different types of end-use energy into primary energy, $PE^{E,ref}_{cons}$, PE^{F}_{cons}, PE^{HC}_{cons}. As a result, the annual primary energy imported, PE_{imp}, and exported, PE_{exp}, through the site boundary are obtained and the condition of ZEB is checked.

The size of the PV installation is gradually increased until the ZEB goal is accomplished. Finally, an economic analysis is performed based on the best size of PV installation to achieve the maximum economic savings and the most profitable return on investment.

Although the construction characteristics, the energy systems of the studied building and the local climate are key aspects to reach the ZEB goal, the proposed sizing methodology is general and not limited to the case study of this paper. At present, most electrical companies worldwide offer hourly data of electricity imports and exports, and any software that provides the estimation of the energy production of a PV system can be used, so the work is easily reproducible.

3. System description and analysis

The definition of ZEB is based on the energy transfer through the site boundary. For a single building, the site boundary is typically the property boundary. The system analysed in this work is compared to a reference case of the building without the PV system. The energy transfers are defined for both situations in this section.

3.1. Reference system and energy consumption

The reference system is a general building that consumes energy from different sources, renewable and non-renewable. According to the DOE definition of ZEBs, they are.

a) electricity (E),
b) fuels (F), where the most common are: natural gas (NG), gas oil (G) and biomass (B),

c) heat/cold energy (HC) supply.

The site boundary defined for the reference system only includes the building and the energy transfers through it are represented in Fig. 2.

Energy imports from the different sources are registered by the utility meters. The most common situation involves hourly-registered electricity consumption, $E_{reg}^{E,ref}(h)$, and monthly-registered data for fuels, $E_{reg}^{F,ref}(m)$, and for heat/cold, $E_{reg}^{HC,ref}(m)$. Fuel mass consumption is generally registered monthly, $m^F(m)$, and its corresponding end use energy is calculated by multiplying it by its lower heating value, LHV^F, see Eq. (2). These data are summed throughout a year and multiplied by the corresponding conversion factors, f^E, f^F and f^{HC}, to obtain the annual primary energy imports of each type of energy source, $PE_{imp}^{E,ref}$, $PE_{imp}^{F,ref}$ and $PE_{imp}^{HC,ref}$:

$$PE_{imp}^{E,ref} = \sum_h E_{reg}^{E,ref}(h) \cdot f^E \tag{1}$$

$$PE_{imp}^{F,ref} = \sum_F \sum_m E_{reg}^{F,ref}(m)\, f^F, \text{ where } E_{reg}^{F,ref}(m) = m^F(m) \cdot LHV^F \tag{2}$$

$$PE_{imp}^{HC,ref} = \sum_m E_{reg}^{HC,ref}(m) \cdot f^{HC} \tag{3}$$

The total primary energy imported by the reference building, PE_{imp}^{ref}, is the sum of the primary energy import of each energy source:

$$PE_{imp}^{ref} = PE_{imp}^{E,ref} + PE_{imp}^{F,ref} + PE_{imp}^{HC,ref} \tag{4}$$

As the reference system does not include on-site generation, the building must import all the energy needed to satisfy the energy loads. The primary energy consumption, PE_{cons}, equals the primary energy import:

$$PE_{cons} = PE_{imp}^{ref} \tag{5}$$

The primary energy consumption of electricity, fuels, and district heat and cooling, PE_{cons}^{E}, PE_{cons}^{F} and PE_{cons}^{HC} respectively, must equal the corresponding primary energy import:

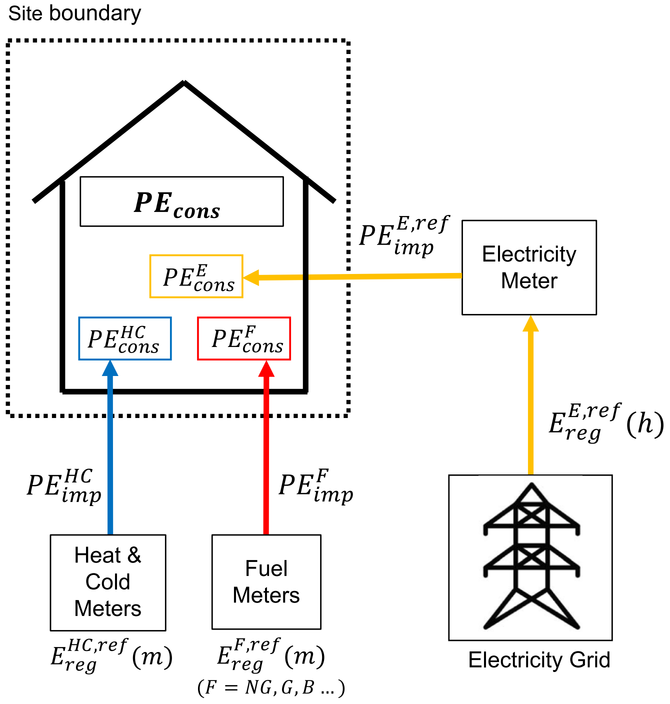

Fig. 2. Site boundary and energy balance in the reference system.

$$PE_{cons}^{E} = PE_{imp}^{E,ref} \tag{6}$$

$$PE_{cons}^{F} = PE_{imp}^{F,ref} \tag{7}$$

$$PE_{cons}^{HC} = PE_{imp}^{HC,ref} \tag{8}$$

Thus, the total primary energy consumption of the reference building is also expressed as the sum of the primary energy consumption associated with all energy sources:

$$PE_{cons} = PE_{cons}^{E} + PE_{cons}^{F} + PE_{cons}^{HC} \tag{9}$$

Summarizing, the data registered by the energy meters throughout a year are used to calculate the annual primary energy consumption of the reference building.

3.2. Studied system

To upgrade the building to a ZEB, on-site PV generation is added to the reference system, with a grid-connected solar system that includes an array of photovoltaic panels and a DC/AC inverter (Fig. 3). This solution is the most interesting technology and regime of use for domestic and services buildings under the current energy framework.

As the upgrade of the reference system to the ZEB status does not change the energy needs of the building, it consumes the same energy as the reference building. This means that PE_{cons}^{E}, PE_{cons}^{F} and PE_{cons}^{HC} do not vary. Besides, the fuel and the heat/cold consumptions and imports are not influenced by the presence of the PV system. Thus, imported fuel primary energy, PE_{imp}^{F}, and district heat and cooling PE_{imp}^{HC} are unaffected:

$$PE_{imp}^{F} = PE_{imp}^{F,ref} \tag{10}$$

$$PE_{imp}^{HC} = PE_{imp}^{HC,ref} \tag{11}$$

Regarding the electricity, the consumption is satisfied both by the PV system and the grid imports. Besides, the surplus energy is exported to the grid. The hourly electricity balance at the on-site node is:

$$E_{prod}^{E}(h) + E_{imp}^{E}(h) = E_{cons}^{E}(h) + E_{exp}^{E}(h) \tag{12}$$

In each hour, it must be determined whether the building imports or exports electricity, as electricity imports and exports cannot happen simultaneously. Also, $E_{cons}^{E}(h)$ is the same in the reference and the study cases, as the energy demand remains unaffected by the installation of the PV system.

3.3. PV system and energy production

TRNSYS software [30] is used to calculate the PV electricity production. TRNSYS has been widely used in the literature for PV system performance simulations, and its accuracy has been successfully contrasted with other well-known simulation packages [31]. TRNSYS provides an intuitive simulation environment with an open modular structure. A TRNSYS project is typically setup by connecting components (referred to as Types), described by a mathematical model in the simulation engine [32].

The model of the PV system in this work consists of.

1) PV array of panels modelled by Type 94,
2) inverter modelled by Type 48, and
3) meteorological data for the studied location, introduced by Type 15, which reads a file where hourly solar radiation, ambient temperature, and pressure from Meteonorm database [33] are specified.

Type 94 uses equations derived from an empirical equivalent circuit model to predict the current-voltage characteristics of a single PV

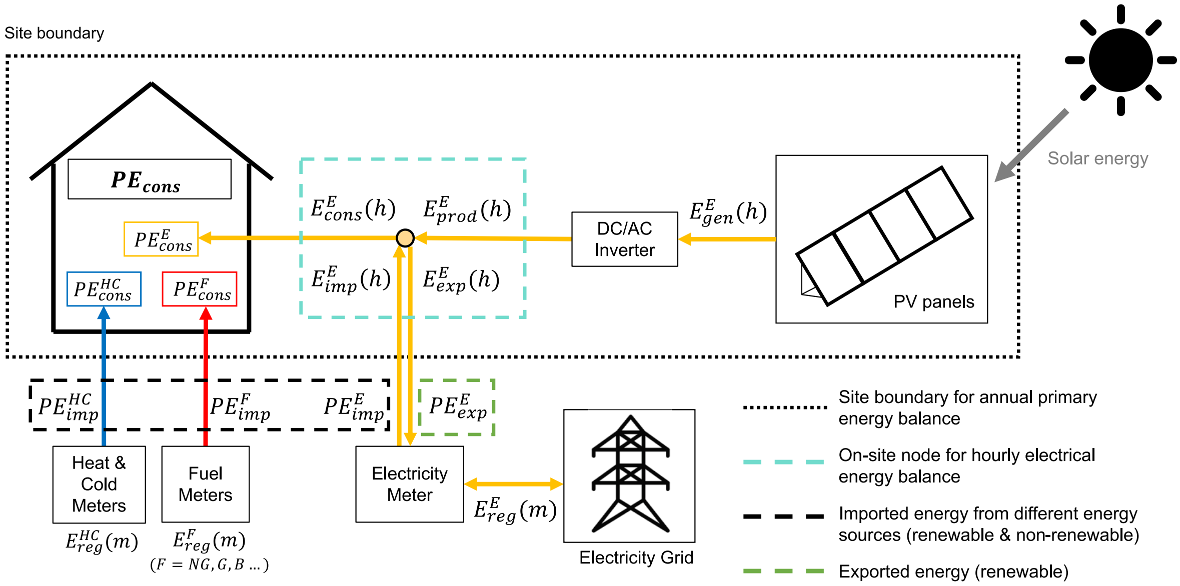

Fig. 3. Site boundary and energy balance in the studied system.

module. The results for a single module are extrapolated to predict the performance of a multi-module array. For crystalline modules (single-crystal or polycrystalline), the "four-parameter" equivalent circuit described in Ref. [34] is employed. As the current-voltage characteristics of the module are dependent on the solar radiation and the ambient temperature, the PV power generation varies instantaneously. The energy generated by the PV array, $E^E_{gen}(h)$, is obtained from Eq. (13), where N_{PV} is the number of panels, $V(h)$ is the voltage output and $I(h)$ is the current output.

$$E^E_{gen}(h) = N_{PV} \cdot V(h) \cdot I(h) \tag{13}$$

The inverter is provided of a maximum power tracker system that forces the module to operate at the maximum power point corresponding to the instant solar radiation and ambient temperature. Thus, the power output of the module is optimized instantaneously. The inverter also adapts the resulting power from the PV array so that its voltage is equal to that required by the load. Power losses associated with the tracking process and the DC-AC conversion are given by the inverter efficiency, η_{inv}, so the energy produced by the PV system is obtained from equation:

$$E^E_{prod}(h) = \eta_{inv} \cdot E^E_{gen}(h) \tag{14}$$

Finally, the primary energy associated with the electricity production of the PV system, PE^E_{prod}, is calculated by multiplying it by the corresponding conversion factor:

$$PE^E_{prod} = \sum_h E^E_{prod}(h) \cdot f^E \tag{15}$$

3.4. Energy transfers through the ZEB site boundary and ZEB condition

Each hour, the PV electricity production, $E^E_{prod}(h)$, is compared to the corresponding electrical consumption, $E^E_{cons}(h)$. If the electrical consumption is greater than the output from the PV system, all the production is self-consumed, and the additional required energy is imported from the grid. Thus, the electricity export in that hour is zero. Contrarily, if the PV electricity output exceeds the electricity consumption, the production is used to satisfy the electrical load in that hour, and the surplus energy is exported to the grid. Thus, electricity imports in that hour are zero. These two situations are reflected in the following equations:

$$E^E_{imp}(h) = \begin{cases} E^E_{cons}(h) - E^E_{prod}(h) & \text{if } E^E_{cons}(h) > E^E_{prod}(h) \\ 0 & \text{if } E^E_{cons}(h) \leq E^E_{prod}(h) \end{cases} \tag{16}$$

$$E^E_{exp}(h) = \begin{cases} E^E_{prod}(h) - E^E_{cons}(h) & \text{if } E^E_{cons}(h) < E^E_{prod}(h) \\ 0 & \text{if } E^E_{cons}(h) \geq E^E_{prod}(h) \end{cases} \tag{17}$$

The primary energy associated with the electricity imports is:

$$PE^E_{imp} = \sum_h E^E_{imp}(h) \cdot f^E \tag{18}$$

The total primary energy imported by the building is:

$$PE_{imp} = PE^E_{imp} + PE^F_{imp} + PE^{HC}_{imp} \tag{19}$$

And electricity is the only type of exported energy:

$$PE_{exp} = PE^E_{exp} = \sum_h E^E_{exp}(h) \cdot f^E \tag{20}$$

The energy transfer through the site boundary allows to express the condition that the building must fulfil to achieve the ZEB status:

$$PE_{exp} \geq PE_{imp} \tag{21}$$

3.5. Energy, environmental and economic (E3) performance indexes

Yearly energy savings, *EnS*, and relative energy savings of the building with the PV system with respect to the reference situation, *REnS*, are expressed in terms of primary energy:

$$EnS = PE_{imp} - PE^{ref}_{imp} \tag{22}$$

$$REnS = 1 - \frac{PE_{imp}}{PE^{ref}_{imp}} \tag{23}$$

Yearly environmental savings, *EvS*, and relative environmental savings of the building with the PV system with respect to the reference situation, *REvS*, are expressed in terms of CO$_2$ emissions, E_{CO2}:

$$EvS = E_{CO2} - E^{ref}_{CO2} \tag{24}$$

$$REvS = 1 - \frac{E_{CO2}}{E^{ref}_{CO2}} \tag{25}$$

$$E_{CO2} = E^{E}_{CO2} + E^{F}_{CO2} + E^{HC}_{CO2} \tag{26}$$

$$E^{E}_{CO2} = \sum_{h} E^{E}_{reg}(h)\cdot e^{E} \tag{27}$$

$$E^{F}_{CO2} = \sum_{F}\sum_{m} E^{F,ref}_{reg}(m)\cdot e^{F} \tag{28}$$

$$E^{HC}_{CO2} = \sum_{m} E^{HC,ref}_{reg}(m)\cdot e^{HC} \tag{29}$$

where e^E, e^F and e^{HC} are the CO_2 emission factors per final energy consumption unit of electricity, fuels and district heat and cooling, respectively.

Yearly economic savings, *EcS*, and relative economic savings of the building with the PV system with respect to the reference situation, *REcS*, are expressed in terms of annual costs, *C*:

$$EcS = C - C^{ref} \tag{30}$$

$$REcS = 1 - \frac{C}{C^{ref}} \tag{31}$$

The annual costs include the cost of the electricity, C^E, different fuels, C^F, and heat/cold supplies, C^{HC}:

$$C = C^{E} + C^{F} + C^{HC} \tag{32}$$

The annual cost of electricity depends on the specific tariff structure of the country. The case of Spain will be analysed in the subsequent section. Annual costs of fuels and heat/cold supplies are calculated as:

$$C^{F} = C^{F,ref} = \sum_{F}\sum_{m} C_{F}\cdot E^{F}_{imp}(m) \tag{33}$$

$$C^{HC} = C^{HC,ref} = \sum_{m} C_{HC}\cdot E^{HC}_{imp}(m) \tag{34}$$

where C_F and C_{HC} are the unitary monthly costs of fuel and district heat and cooling energy.

Finally, the simple payback index, *SPB*, which represents the period required to recover the capital cost of the investment, *IC*, is used to evaluate the feasibility of the PV system:

$$SPB = \frac{IC}{\overline{EcS}} \tag{35}$$

The economic savings are averaged over a horizon of 20 years, considering the annual drop of the efficiency of the PV panels (ε_{drop}) that reduces the energy generated as follows [35]:

$$E^{y}_{gen} = (1 - \varepsilon_{drop})\cdot E^{y-1}_{gen} \tag{36}$$

where the superscript y refers to the current year in analysis and $y - 1$ to the precedent.

4. Case study scenarios

The characteristics and energy supplies of the passive house (PH) and the conventional house (CH) selected for the application of the sizing methodology are explained under this section. As the study is based on the Spanish electricity market, this section also describes the structure of the electricity tariff. In addition, the characteristics of the TRNSYS components are included here, as well as the data and factors used in the conversion of the different end-use energy types into primary energy and CO_2 emissions.

4.1. Characteristics and energy systems of the studied houses

Both CH and PH are single-family houses located in Gijón, a coastal city in northern Spain. The weather is oceanic, with moderate temperatures (around 9.5 °C in winter and 19.5 °C in summer), abundant rainfall during the cold season and intermittent winds.

The CH is inhabited by a retired old couple, whereas the PH is home of a family of five: a working medium-aged couple, two teenagers, and an old person. The main construction characteristics of the houses differ significantly, as the Spanish building regulations have evolved along the last 15 years, implementing the increasing requirements of European Directives. The CH was built in 2010 under an early version of the Spanish Technical Building Code [36] with performance and efficiency requirements far from nZEB, and the PH was built and certified under the Passive House Standard [37] in 2018. The houses are also different in shape, floor distribution and useable area. The CH consists of a single floor dwelling with useable area of 168 m^2, and the PH accounts for useable area of 232 m^2 divided in three floors.

Table 1 summarizes the different types of energy consumed in each house, indicating loads and energy systems, and the frequency of energy consumption registering. The main differences are the systems that cover the thermal energy demand of DHW, and HVAC. They are based on conventional non-renewable sources in the case of the CH and on high-efficiency equipment in the PH. As the energy demand of the CH is much higher than in the PH, the size of the thermal energy systems is also greater. The DHW and heating system of the CH consists of a gas oil boiler of 32.6 kW rated at 89 % efficiency. The CH has no ventilation installation. The DHW and heating system of the PH is mainly based on a 4.7 kW aerothermal air-water reversible heat pump (Vaillant aroTHERM VWL 55/2 A), rated at nominal coefficient of performance of 4. The installation is provided with 300 l tank for DHW, and 40 l inertia tank for the different heating systems. A 2.5–8 kW pellet stove (Rika Roco Multiair), rated at 90.4 % efficiency, helps the heating system during especially cold winter days. The PH ventilation system consists of a Zehnder Comfoair Q350 unit rated at 92 % efficiency, equipped with a post-heating water battery for additional heating under cold outdoor conditions.

Table 1
Energy consuming systems in the studied houses.

Type of house	Type of energy	Consumption register	House loads	Energy systems
Conventional	Electricity	Hourly	Lighting Appliances	Plugs
	Fuels: gas oil	Monthly	Heating DHW	Boiler
	Heat/Cold	–	–	–
Passive	Electricity	Hourly	Lighting Appliances	Plugs
			Heating DHW	Heat pump
			Ventilation	HRV unit
	Fuels: biomass pellets	Monthly	Heating	Stove
	Heat/Cold	–	–	–

4.2. Characteristics of the PV system components

The TRNSYS model of the PV system requires the definition of parameters for the PV panels and the inverter that are normally defined in the technical specifications of the manufacturers. The main parameters of the panel used in the model are summarized in Table 2. Regarding the inverter, the family Sunny Boy, with a wide range of DC input and AC output specifications, was selected to adapt the PV array to the load. An average efficiency of 97 % was considered for all of them [38].

As the inverters are provided with two trackers of the maximum power point, the system must contain an even number of panels, arranged in two lines in parallel of $N_{PV}/2$ panels in series. Each line is connected to a tracker of the maximum power point and, in the application of the sizing methodology, the power of the PV system is

Table 2
Technical specifications of the monocrystalline 150-cell module Vertex TSM-DE18M [39].

Electrical data (Standard conditions[a])	**Value**
Peak power (P_{MAX})	500 W_p
Short-circuit current (I_{SC})	12.28 A
Open-circuit voltage (V_{OC})	51.7 V
Maximum power current (I_{MPP})	11.69 A
Maximum power voltage	42.8 V
Efficiency	20.7 %
Annual efficiency drop	0.5 %
Temperature ratings	**Value**
Temperature coefficient of P_{MAX}	−0.34 %/°C
Temperature coefficient of I_{SC}	−0.25 %/°C
Temperature coefficient of V_{OC}	0.04 %/°C
Other parameters	**Value**
Nominal cell operating temperature (NOCT)	43 °C
Ambient temperature at NOCT	20 °C
Irradiance at NOCT	800 W/m^2
Dimensions	2187 mm × 1102 mm × 35 mm

[a] Irradiance 1000 W/m^2, cell temperature 25 °C, air mass 1.5 a.m.

increased in steps of 1 kW_p.

The investment capital cost of the PV system includes the PV panels, inverter, structures, additional electrical material, and labour costs. To obtain the most realistic data for the analysis, an effort was made to get up-to-date pricing from manufacturers of solar components and installers. The breakdown of the PV system costs is shown in Fig. 4 for the wide range of installed power analysed in the study. These prices are similar to the average price of PV systems in Germany (1392.1 €/kW), the country with the largest installed PV capacity in Europe, according to Kraschewski et al. [40].

4.3. Electricity costs and tariff scenario

In Spain, the electricity cost for a user who produces electricity for self-supply is the result of the combination of a fixed cost (FC^E), a variable cost (VC^E), the metering equipment rent (MER), and electricity tax (ET), plus value added tax (VAT). The annual electricity cost is expressed as:

$$C^E = \left[\left(FC^E + VC^E\right)\cdot(1 + ET) + MER\right]\cdot(1 + VAT) \tag{37}$$

The fixed cost depends on the power hired by the customer, P^E_{hir}, and the daily cost of installed power $C_P(d)$:

$$FC^E = FC^{E,ref} = \sum_d C_P(d)\cdot P^E_{hir} \tag{38}$$

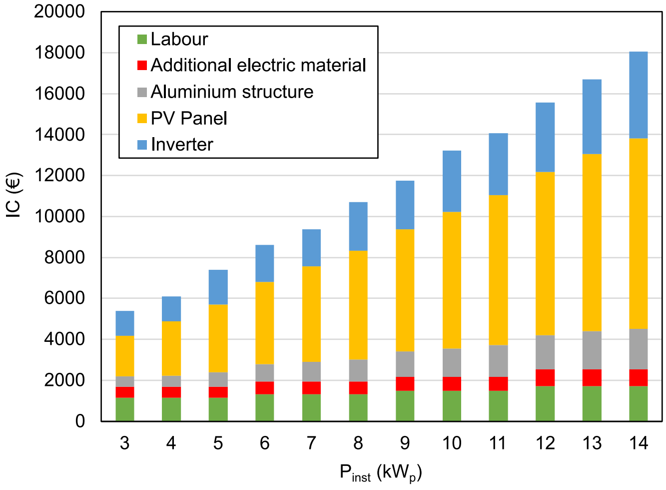

Fig. 4. Breakdown of the PV system investment costs.

The variable cost depends on the energy imported and exported from/to the grid, hourly cost of consumed electricity $C_E(h)$ and, for the case with PV system, on surplus energy hourly discount $C_D(h)$. Variable cost can never be negative over a month, according to the latest regulation [41].

$$VC^E = \begin{cases} \sum_h \left[C_E(h)\cdot E^E_{imp}(h) - C_D(h)\cdot E^E_{exp}(h)\right] & if\, C_E(h)\cdot E^E_{imp}(h) > C_D(h)\cdot E^E_{exp}(h) \\ 0 & if\, C_E(h)\cdot E^E_{imp}(h) \leq C_D(h)\cdot E^E_{exp}(h) \end{cases} \tag{39}$$

$$VC^{E,ref} = \sum_h C_E(h)\cdot E^E_{imp}(h) \tag{40}$$

Additionally, the Spanish electricity tariff structure was reformed in June 2021 [42]. This reform has had a significant impact on electricity prices. To assess the effect of this change on the economic viability of the PV system, the economic study compares the period when experimental data were registered in the two houses (year 20,219), and an equivalent period after the reform (year 2022).

The prices of hourly consumed electricity, hired power and surplus energy discount are fixed by the government and are updated daily. They are available in the Spanish Electricity Grid official website [43]. Fig. 5 shows the hourly price of consumed electricity and the hourly surplus discount for 2019 and 2022 periods. The increment of the imported electricity price in 2022 is observed, reaching in March values ten times higher than those of 2019.

Other necessary data to perform the economic analysis are: the metering equipment rent is 0.815 €/month, the electricity tax is 5.11269632 % and VAT is 21 %. These additional costs have been obtained from the electricity bills of the houses.

4.4. Energy and environmental data and factors

The Low Heating Values (LHV) of the fuels consumed in the houses are 11.944 kWh/kg of gas oil and 4.582 kWh/kg of biomass pellets [44].

The primary energy conversion factors, f ,and the CO_2 emission factors, e, are stipulated by the government over the Spanish territory [45]. The values of the primary energy conversion factors for the different types of energy consumed in the houses are set to 1.182 kWh_{PE}/kWh of gas oil, 2.403 kWh_{PE}/kWh of electricity and 1.113 kWh_{PE}/kWh of biomass pellets. The values of the CO_2 emission factors for the different types of energy consumed in the houses are equal to 0.252 $kgCO_2$/kWh of gas oil, 0.357 $kgCO_2$/kWh of electricity and 0.018 $kgCO_2$/kWh of biomass pellets.

5. Results and discussion

As this study refers to houses, in this section the nomenclature ZEH is used instead of ZEB. Firstly, the experimental data recorded by the energy meters of the two houses are analysed. Then, the minimum size of the PV system that converts each house into a ZEB, $P_{inst,min}$, is determined. In addition, the following parameters obtained for these PV sizes are analysed: PV electricity production during typical summer and winter days, energy balance at the on-site node, and E3 savings. Finally, the simple payback period and the influence of the electricity tariff on the annual energy bill are studied over a wide range of the PV system power.

5.1. Analysis of the energy consumption profiles

Fig. 6 shows the energy imports, expressed in terms of primary energy, that the owners of the houses registered during two consecutive

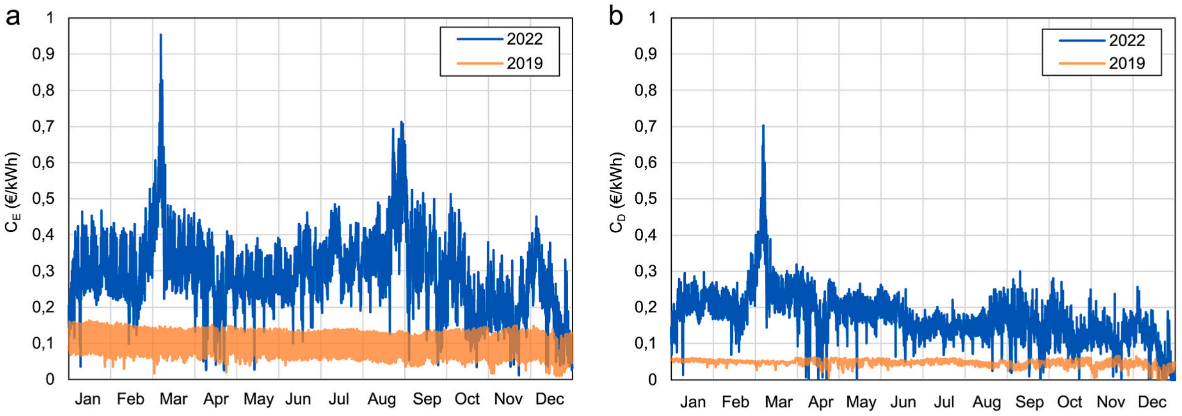

Fig. 5. (a) Consumed electricity costs in the regulated market and (b) surplus energy discounts in the regulated market.

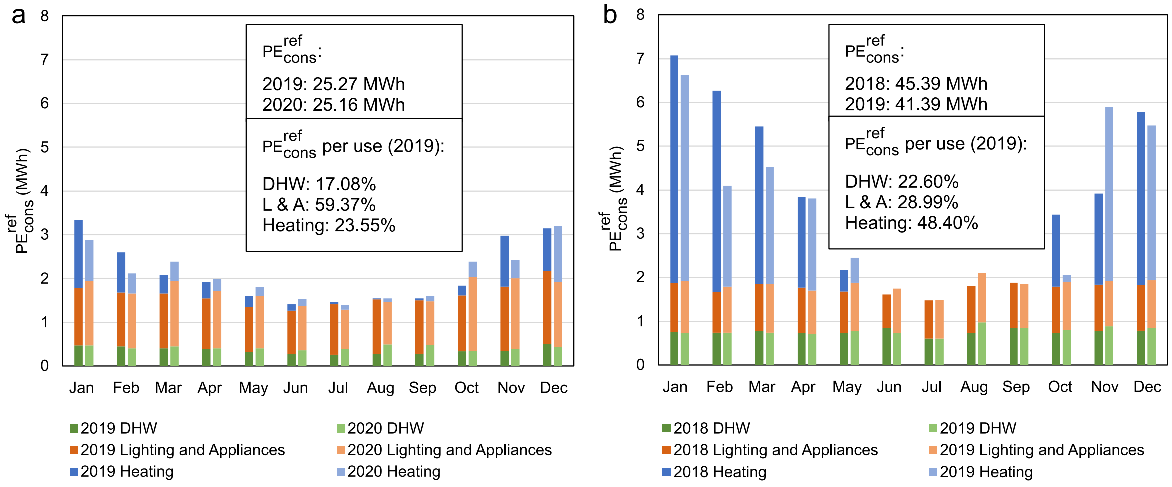

Fig. 6. Primary energy consumption in two consecutive years by end use: (a) PH and (b) CH.

years. As 2019 is a common period in both houses, it has been selected for the application of the proposed methodology. The figure allows to verify that the monthly and annual consumptions are practically constant in the registration periods. Thus, 2019 is considered representative of the monthly energy consumption any year. According to section 3.1, these data represent the primary energy consumption of the houses for the reference situation.

Consumption energy rates and profiles are completely different in the two houses. Due to the more efficient equipment and design, annual energy consumption in the PH is almost half that of the CH, even if its useable area and number of inhabitants is greater.

Besides, monthly consumption is more regular during the year in the PH, with maximum values around 3 MWh and minimum values of 1.6 MWh. The CH shows a larger variation, ranging from 7 MWh in winter to 1.6 MWh in summer. DHW and lighting & appliances consumptions are constant throughout the year in both houses, while heating consumption largely fluctuates. This is more relevant in the conventional house, where fossil fuels used for heating represent the major consumption.

Finally, Table 3 compares the annual primary energy consumption in both houses, including the ratios with the useable area, A_u,and the number of inhabitants, N_P. The CH consumes twice as much primary energy per useable area as the conventional house, and five times primary energy per person.

Table 3
Annual primary energy comparison considering the useable area and the number of inhabitants.

Type of house	A_u (m^2)	N_p (persons)	PE^{ref}_{cons} (MWh)	PE^{ref}_{cons}/A_u (kWh/m^2)	PE^{ref}_{cons}/N_p (MWh/ person)
Passive	232	5	25.27	108.94	5.02
Conventional	168	2	41.39	246.40	20.70

5.2. *Energy production and size of the PV system for achieving a ZEH*

The minimum PV system power required to achieve the ZEH status is determined in Fig. 7, where the evolution of the annual primary energy flows in each house is represented for increasing sizes of the PV system. The PH requires 8.2 kW$_p$ to fulfil the ZEH goal, while the CH needs 13.5 kW$_p$. As the panels selected for this study are rated 0.5 kW$_p$ and must be added in groups of two, the minimum power to install is 9 kW$_p$ in the PH and 14 kW$_p$ in the CH, including 18 and 28 panels respectively.

This substantial difference between the two dwellings is due to the consumption profiles and types of energy. In the PH, the design strategies provide a low energy demand, met with high efficiency appliances. Because most of the consumed energy is electricity, the on-site energy production is directly consumed, leading to a greater reduction of primary energy consumption. Since less exported energy is needed to fulfil the ZEH standard, a smaller PV installation is required. In the CH, however, energy consumption is much higher and electricity consumption is less significant in the balance. This implies that, even if the hourly PV electricity generation can fulfil the electricity demand easily, a huge PV installed power is still necessary to export enough renewable

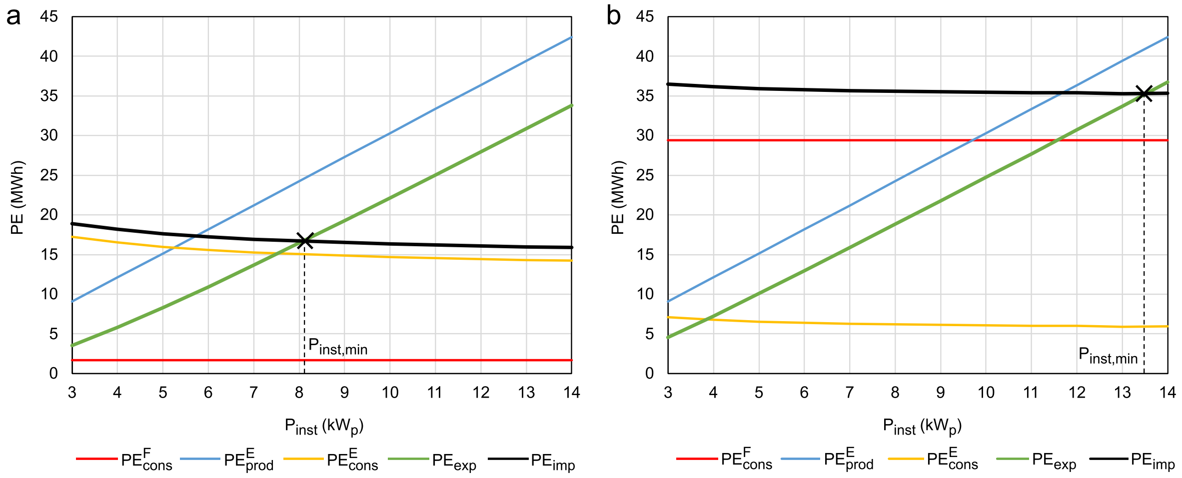

Fig. 7. Annual primary energy balances as a function of installed PV power: (a) passive house and (b) conventional house.

energy to the grid that compensates the imported primary energy.

The Spanish Technical Building Code [36] stablishes the criterion of nZEB according to the definition of energy efficiency indicators in ISO 52000–1:2017 [46]. This norm stablishes that exported energy is the sum of surplus renewable energy and the self-supplied renewable energy used for services different from HVAC, DHW production and lighting. As such, exported energy under this scheme is greater than the actual exported energy (according to the DOE criterion). Given that imported energy is the same for both criteria, the ISO definition followed in Spain will lead to a lower $P_{inst,min}$. In consequence, if the ZEB criterion is fulfilled, the Spanish Building Code will be fulfilled too.

The performance of the PV system for the required size in each house to fulfil the ZEB condition is assessed in Figs. 8 and 9, where global solar irradiation, I_{gl}, is also included for reference. The electricity flows in the on-site node are shown for a week in summer and winter. The PH exports far less power to the grid than the CH. Also, the PH shows similar consumption and exportation patterns, whereas the CH exports to the grid much more power in summer than in winter. This is summed up in Fig. 10: up to nearly 90 % of the produced power by the PV system is exported to the grid in the CH, whereas this stands around 70 % in the passive house. Electricity consumption in the CH comes in almost equal parts from the grid and from the PV system, while in the PH the majority is imported from the grid.

5.3. E3 savings of the ZEH

The energy, economic and environmental (E3) savings obtained for the minimum size of the PV system that converts each house into a ZEH are summarized in Table 4. In the reference cases, the primary energy consumption of the CH is 16 MWh higher than that of the PH. Due to the fuel consumption, CO_2 emissions of the CH are more than double those of the PH. This also implies higher energy costs in the CH. The energy costs and economic savings before and after the electricity tariff reform are also included. A significant increase after the reform is observed.

The E3 savings show that the PV system is more efficient in the PH, where relative economic savings in 2022 reach 70.12 %. This is because the PH self-consumption is greater than in the CH. Besides, conversion and emissions factors for electricity are higher than for fossil fuels in Spain [45]. All of this explains that, even with a PV system of 14 kW_p in the CH and 9 kW_p in the PH, the latter still yields a better performance in terms of energy consumption and CO_2 emissions.

5.4. Economic analysis

The economic analysis is based on the comparison of three parameters and covering the range from 3 kW_p to 14 kW_p of installed PV power.

1) Annual energy cost,

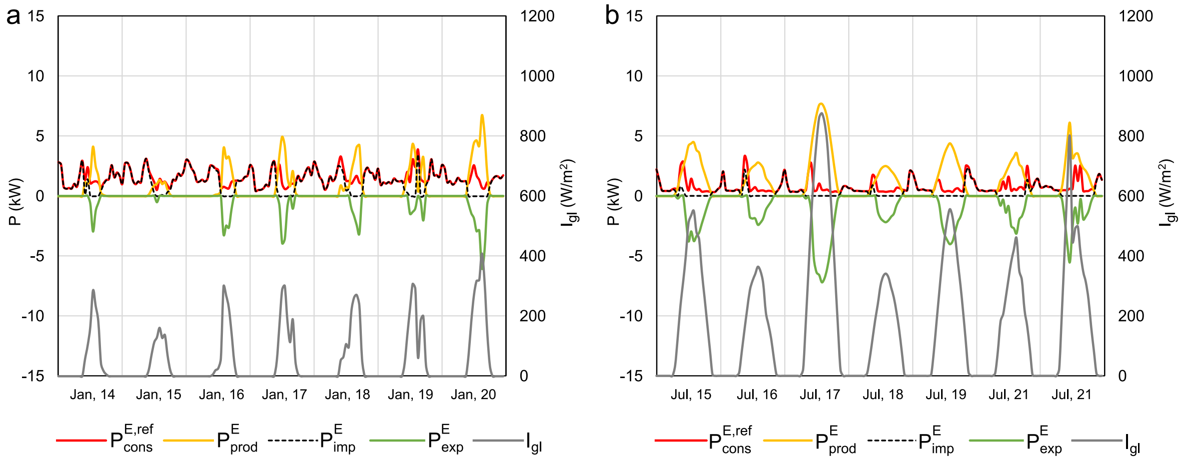

Fig. 8. Power distribution of the 9 kW_p PV installation in the PH: (a) in winter and (b) in summer.

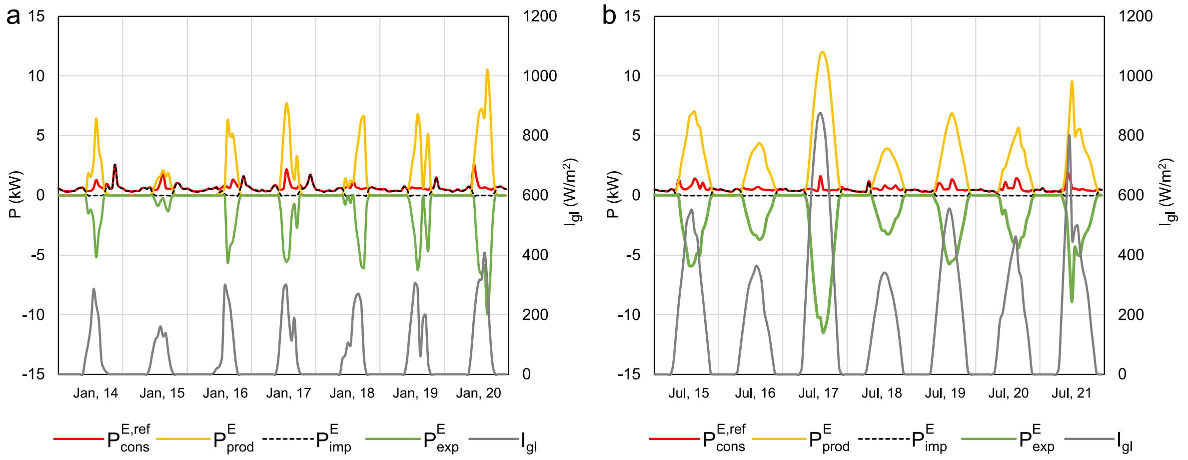

Fig. 9. Power distribution of the 14 kW_p PV installation in the CH: (a) in winter and (b) in summer.

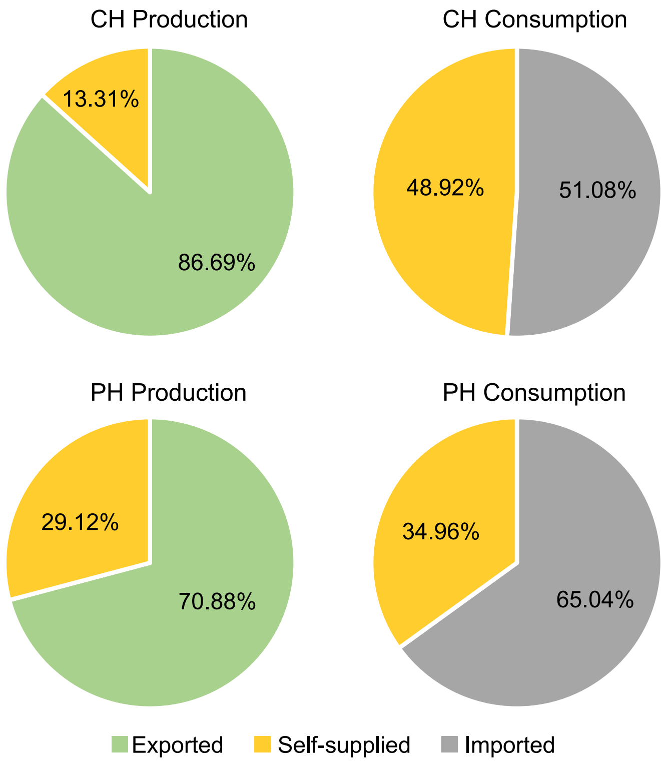

Fig. 10. Annual power balance on the on-site node for CH and PH with minimum installed power that fulfils ZEH condition.

Table 4
Imported primary energy, CO_2 emissions and total energy costs for the reference case and relative savings with PV installation (9 kW_p for PH and 14 kW_p for CH).

		CH	PH
PE_{imp}^{ref} (kWh)		41394.30	25271.68
E_{CO2}^{ref} (t CO_2)		8.05	3.54
C^{ref} (€)	2019	2762.67	1503.70
	2022	3839.44	3733.15
REnS (%)		14.63	37.12
REvS (%)		11.18	36.84
REcS (%)	2019	22.18	53.89
	2022	47.91	70.12

2) Annual economic savings respect to the reference situation without the PV system, and
3) Payback of the investment on the PV system.

For each, the impact of the electricity price increment since June 2021 is also quantified.

The annual energy costs, represented in Fig. 11 (a), are sensibly greater in the CH than in the PH. This is mainly because the electricity consumption of the CH is far lower than that of the PH. Therefore, it is less affected by the rise in the electricity price. The increase in the energy price is especially relevant in the PH for low installed PV power. However, as the self-consumption is higher in the PH, greater PV installations reduce drastically annual energy costs.

Regarding the annual savings respect to the reference case without the PV system, represented in Fig. 11 (b), the behaviour is the opposite. In the PH, any increase in the size of the PV system leads to continuously improving economic savings (which range approximately from 4 % to 8 % per kW_p). In the CH, the increase rate of the total savings is slower, and it becomes imperceptible for PV sizes greater than 9 kW_p. This is because the variable term of the electricity bill tends to zero as electricity exports discount is greater than electricity consumption cost, and the bill is entirely due to the fixed cost, plus taxes. This does not happen in the PH, as it mainly consumes electricity, and it is unlikely that the variable cost is cancelled.

Finally, Fig. 11 (c) shows the variation of the payback period of the PV system investment. The payback period is always shorter in the PH, as the PV system leads to larger discounts in the energy bill. The optimal (or minimum) payback period is achieved for sizes in the range from 4 to 7 kW_p. With the new electricity prices, payback periods shorten drastically, with respect to the equivalent cases in 2019. Both in the PH and CH, the payback period is reduced by more than the half. The payback of the PV installation with $P_{inst,min}$ for the prices of 2022 is 6 years in the PH, and 13 years in the CH.

6. Conclusions

This study proposes a general methodology for sizing a grid-connected PV installation to transform a building into a ZEB. Based on the definition of the net zero source energy building, this work developed a comprehensive set of equations to calculate the minimum size of the PV system. The equations are applicable to any type of building and consider any type of imported energy: electricity, fuels, and district heat and cooling. The methodology was applied to two different dwellings: a conventional house and a certified passive house, both in northern Spain, whose real electricity and fuel consumptions were registered for two years. PV electricity production was calculated with TRNSYS

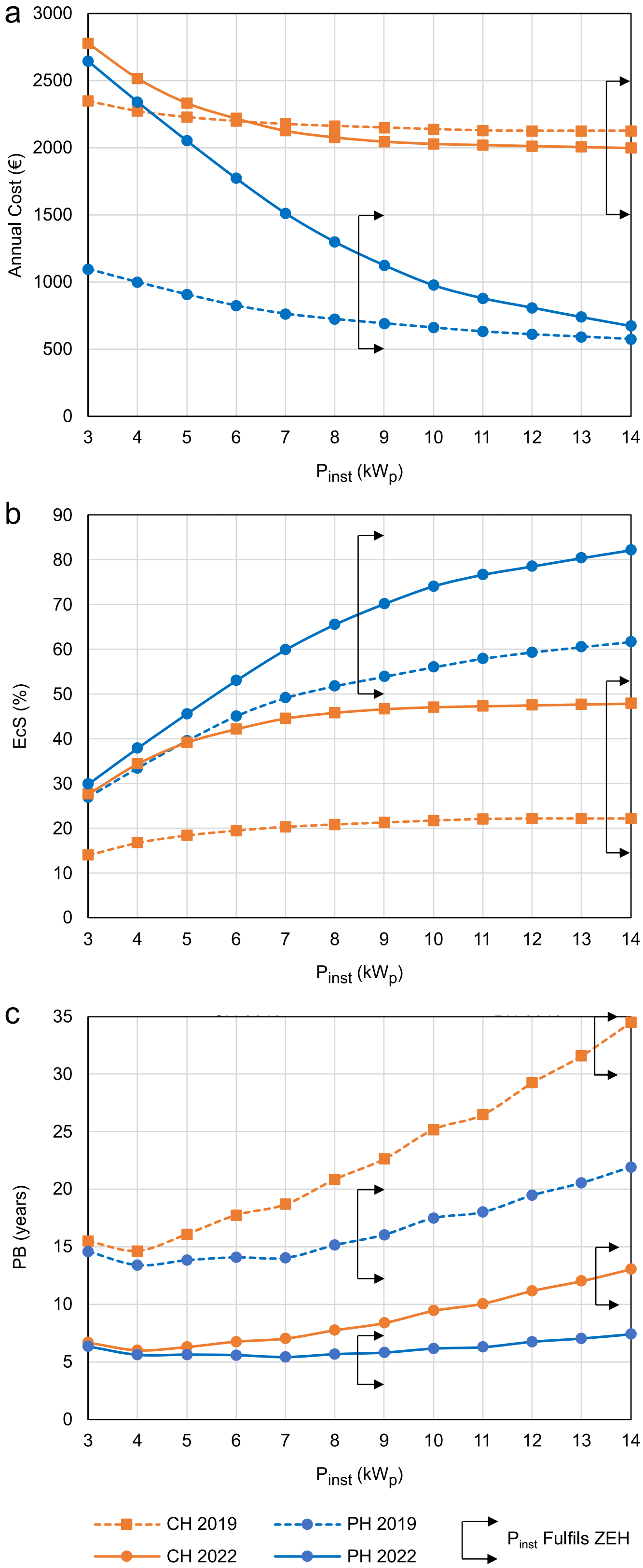

Fig. 11. Economic performance of the PV installation in the CH and PH in 2019 and 2022: (a) annual cost of the installation, (b) economic savings in electricity bills, and (c) payback period of the installation.

software. The following conclusions were drawn.

1. The application of the methodology revealed that the minimum installed PV power to meet the ZEB standard in highly electrified buildings is lower. The ZEB condition is reached either reducing energy imports or increasing renewable energy exports. In highly electrified buildings, the installation of a PV system fulfils both requisites simultaneously. Buildings that rely on less efficient energy systems need to export more renewable energy to compensate for their higher primary energy consumption, needing a greater PV installation.
2. Economic savings thanks to the PV installation are greater in buildings with high baseline electricity consumption than in buildings that rely mainly on fossil fuels. This was demonstrated in the economic analysis, which revealed that PV system that reached the ZEB goal in the passive house reduced the annual costs of energy by 70 %, while in the conventional house they were reduced by 50 %.
3. The present methodology demonstrates that a PV system allows less energy efficient buildings, with high fossil fuel consumption, to reach the ZEB standard without refurbishment of complex modifications. Although they require a greater PV installation, it might be the only viable alternative in cases where other reforms cannot be implemented.
4. The current context of electricity prices increased the profitability of PV installations. The methodology reflects this and highlights the benefits from upgrading buildings into the ZEB standards with the installation of PV systems. The evaluation of the E3 savings using data from modern metering equipment and electricity tariffs showed that payback periods were halved from 2019 to 2021.

The developed methodology allows to compare the energy costs and the profitability of grid-connected PV installations of any desired installed power. The electricity generated by the PV system is obtained by simulation, and any software package can be used, as long as it provides hourly values with a scientifically demonstrated accuracy. As a result, the present methodology is a powerful tool for users and policymakers to find the most profitable PV installation that leads to meeting the ZEB definition, regardless of the energy import pattern of the building, and the electricity tariff context. If real energy consumptions are replaced by estimated values from model simulations of the building, the methodology is also a powerful tool in the design stage of buildings with integrated grid-connected PV systems.

CRediT authorship contribution statement

Ines Suarez-Ramon: Writing – original draft, Supervision, Software, Methodology, Conceptualization. **Matias Alvarez-Rodriguez:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology. **Carlos Ruiz-Manso:** Writing – review & editing, Investigation. **Fernando Perez-Dominguez:** Software. **Pablo Gonzalez-Vega:** Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matias Alvarez-Rodriguez reports financial support was provided by Spain Ministry of Universities.

Data availability

Data will be made available on request.

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