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Original article

Innovative exergy indicators for analyzing an nZEB building to promote new areas of improvement

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ABSTRACT

This study evaluates the energy and exergy performance of buildings towards achieving nearly Zero Energy Building (nZEB) standards by introducing three exergy-based indicators alongside conventional energy metrics. Focused on the LEED Platinum-certified LUCIA building at Valladolid University (Spain), the analysis examines energy and exergy transformations throughout the building's lifecycle, emphasizing resource consumption, generation systems, and environmental equilibrium across seasons. The study reveals a Non-Renewable Primary Energy Ratio of 67 kWh/m^2, closely mirrored by an exergy ratio of 67.2 kWh/m^2 due to the high-quality factor of fuel resources. Conversely, the Renewable Primary Energy Ratio stands at 121 kWh/m^2, with a corresponding exergy ratio of 88.36 kWh/m^2, reflecting the significant contribution of geothermal energy while highlighting areas for demand side optimization. For the same reason, the Renewable Energy Ratio is 0.66 and the Exergy Ratio is 0.56. Despite meeting nZEB criteria, exergy indicators underscore untapped energy-saving potential by aligning resource qualities with demand characteristics. Identifying system weaknesses informs future improvement strategies, potentially enhancing LEED scores. The study advocates for incorporating exergy-based indicators alongside traditional energy metrics in European regulations to accurately assess building performance and define low-ex buildings. Overall, the exergy analysis reveals equipment-specific losses and underscores the qualitative match between energy demand and supply.

Introduction

Buildings are responsible for more than one third of the total energy consumed in the European Union (EU) and for almost 30 % of greenhouse gas emissions. These data are supported by numerous studies based on measured consumption, as well as models based on real data [1,2]. In order to change this situation, the EU and many other countries have proposed regulations to reduce primary energy consumption in buildings. The directives and policies over the last 50 years of the EU, related to the promotion of energy efficiency in buildings, have been analyzed by Economidou et al [3]. For its part, as a guide for action, the European Performance of Buildings Directive (EPBD 2010/21/EU [4]) required new public buildings to be nearly zero energy buildings (nZEB) by 2018 [5]; also, all new buildings were required to undergo regular energy inspection by 2020. Achieving these targets have been involved a large use of on-site renewable energy combined with energy saving measures [6]. Recently, with the new EPBD (2024/1275/EU [7]), the goal has become more ambitious and overall strengthened, focusing its efforts on achieving a highly energy-efficient and decarbonized building stock by 2050. Thus creating a stable environment for investment decisions, and enabling consumers and businesses to make better informed decisions in saving energy and money. As it is well known, an nZEB has a very low energy consumption and covers its energy needs mainly

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Nomenclature

Abbreviations

ABS	Absorption System
AHU	Air Handling Unit
A_{net}	Useful area [m^2].
BIPV	Building Integrated PhotoVoltaic
CHP	Combined Heat Power
CCHP	Combined Cooling, Heating and Power
CH	Chiller
CMV	Controlled mechanical ventilation
CTE	Spanish Building Code
CTE-DB-HE	Basic Document on Energy Saving of the Technical Building Code
$c_{p,i}$	Specific heat capacity of the mass flow i.
D	Exergy destruction [kWh]
DHW	Domestic Hot Water
E	Power consumption [kWh]
EAHX	Earth Air Heat Exchanger
$E_{del,i}$	On-site energy supplied
EPBD	Energy Performance Building Directive
$E_{P,i}$	Primary energy
$E_{del,i}$	Energy produced on site or in the surrounding area
$\mathrm{E}_{\mathrm{exp,i}}$	Exported energy
$E_{ren,i}$	On-site renewable energy consumed
$\mathrm{E}_{\mathrm{EPus,i}}$	Energy used by the technical systems of the building services
$EP_{p,ren}$	Renewable energy consumption (kWh/m^2·y)
$ExP_{p,ren}$	Renewable exergy consumption (kWh/m^2·y)
$EP_{p,nren}$	Non-renewable energy consumption (kWh/m^2·y)
$ExP_{p,nren}$	Non-renewable exergy consumption (kWh/m^2·y)
Ex_{F_i}	Fuel flows
Ex_{m_i}	Heat transfer fluid flows
Ex_{sun}	Solar radiation flows
Ex_{W_i}	Electricity flows
Ex_1, Ex_2	Specific air exergy in inlet and outlet dampers [kJ/kg], being $Ex_1 = 0$.
$\Delta Ex_{ground}^{winter}$	Variation of soil exergy [kWh]
$f_{p,i}$·	Conversion factors
$f_{P,tot,i}$	Total primary energy factor
$f_{P,ren,i}$	Primary renewable energy factor
$f_{P,nren,i}$	Non-renewable primary energy factor
$fx_{P,nren,i}$	Non-renewable primary exergy factor for the supplied energy vector i [-]
$fx_{P,exp,i}$	Non-renewable primary exergy factor of supplied energy compensated by exported energy for energy vector i [-]
F_{car}	Carnot factor corresponding to the quality factor of a heat flow
h_1, h_2	Specific enthalpy of air in the inlet and outlet dampers respectively [kWh/kg]
IAQ	Indoor Air Quality
ICE	Internal Combustion Engines
LEED	Leadership in Energy and Environmental Design
$\dot{m}_a$	Ventilation air flow that is pre-heated and goes into the building [kg]
m_i	Mass flow of the flow i.
MS	Member State (European Un on)
nZEB	nearly Zero Energy Building
Q_C	Heat removed [kWh]
RER_P	Renewable Energy Ratio
$RExR_P$	Renewable Exergy Ratio
T_0	Reference Environment Temperature
T_i	Temperature of the flow i.
T_{sun}	Temperature of the sun, (5777 K)
USGBC	US Green Building Council
$\Delta U_{ground}^{summer}$	Internal energy variation of the soil in summer [kWh]
$\Delta U_{ground}^{winter}$	Internal energy variation of the soil in winter [kWh]
ψ_{sun}	Petela factor that weights the quality of solar radiation.
φ	Exergy efficiency
φ_c	Overall exergy efficiency

through renewable energy sources. They are built following very high energy efficiency standards and use advanced thermal insulation, ventilation, and heating and cooling technologies [8–10].

In this context, in January 2018, Member States (MS) confirmed and updated the political agreement on the EPBD 2018 by making their proposals [5]. Likewise, the Commission indicated that Member States had 20 months to transpose it into their regulations and urged them to establish a long-term strategy to support the renovation of their national building stock [11]. As a result, Member States (MS) agreed to develop renovation strategies to achieve a decarbonized building stock by 2050, reducing EU greenhouse gas emissions by 80–95 % compared to 1990. Among the different building certifications as voluntary standards, one can find the internationally recognized LEED (Leadership in Energy and Environmental Design) [12], introduced by the US Green Building Council (USGBC). It establishes standards for designing and constructing environmentally sustainable buildings. LEED certification is based on achieving a series of points obtained by meeting specific sustainability objectives and the maximum score is called the “Platinum” certification level.

Regarding the Spanish regulations, they have been developed in parallel to the EPBD updates. Thus, in 2013 the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) was created, which is the transposition of the first EPBD 2010 into Spanish legislation [4]. Lopez-Ochoa et al. [13] reviewed the transpositions of this regulation over the last 15 years and analyzed the most novel aspects and changes introduced in the Spanish Building Standards (CTE-DB-HE) [14]. The latest update of CTE-DB-HE-2022, preserves the nZEB definition established in the previous CTE-DB-HE-2019, but also reduces, the non-renewable primary energy consumption by 46 % according the climate zones and the total primary energy consumption by 13 % with respect to CTE-DB-HE-2013 [14]. In addition, buildings built after 2019 must use biomass boilers or incorporate solar photovoltaic systems and/or heat recovery systems to become nZEBs.

One option to improve the energy efficiency of buildings is based on cogeneration to reduce the need for energy from external sources, thus reducing the carbon footprint [15–17]. Gandiglio et al. [18] studied the introduction of micro-CHP in the European framework focused on the building sector. The main advantage of micro-CHP, according to Sibilio et al. [19], is to achieve higher primary energy efficiency, above 80 %, compared to the separate production of heat and electricity. By 2050, electricity from cogeneration is expected to account for 26 % of the total electricity generation in the EU. So, if electricity is cogenerated from renewable energy sources, the results are more satisfactory, as demonstrated by examples of green cogeneration in both non-residential [20] and residential buildings [21].

In addition, the current climate change is forcing us to react to the scarcity of non-renewable fossil resources and to propose cleaner and more effective alternatives [22,23]. Combined Cooling, Heating and Power (CCHP), also known as trigeneration, is a promising alternative due to its positive economic, energy and environmental performance

[24]. However, both the energy demand and the operating strategy, particularly thermal energy storage, must be carefully studied and optimized for proper operation, as done in many previous studies [25–27].

Consequently, in order to save energy in buildings, it is not surprising that other innovations are being proposed, both in the building façade and in the thermal air-conditioning systems [28]. Desideri et al. [29], among others researchers, served as a roadmap to promote energy efficiency actions in buildings. Accordingly, bioclimatic building design, optimal insulation, passive ventilation and other strategies and technologies can significantly reduce energy demand. The main goal is to build zero-energy buildings or even positive buildings that, apart from not consuming energy, generate energy from renewable sources [30–33]. The thermodynamic property of exergy defines the maximum work that can be obtained from an energy flow until it reaches equilibrium with the environment [33]. Depending on the nature of the energy flow, it can be converted entirely into work (electricity, for example, is 100 % exergy) or only partially, as is heat. Thus, when considering "energy quality" (exergy), the level of adaptation of energy flows along the production chain (from primary energy to demand) are measured. Thus, low quality energy sources (such as waste heat) can be used to satisfy low quality demands (such as air conditioning); rather than high quality energy sources (such as fossil fuels). Thus, on the one hand, by using the quality variable one can quantify the minimum energy consumption necessary to satisfy the demand, and it can promote energy efficiency and renewable sources [34]. On the other hand, the most inefficient thermodynamic processes can be quantified by means of what is known as exergy destruction. Therefore, the objective is to reduce the exergy destruction of each energy transformation as much as possible by adapting the natures of the energy flows involved in the process. Although most researchers and engineers use this term, exergy destruction is sometimes referred to as "exergy consumption", and it can be separated into two parts: one refers to the consumption necessary for the system to operate properly and the other to unnecessary and avoidable consumption that, ideally, should be reduced completely.

Based on this premise, it is clear that the building sector has a great potential for improvement, energy transformations in thermal installations significantly reduce the exergy of the flows, since they use high quality energy sources to satisfy demands that require low quality energy, such as heating or DHW. Nevertheless, although the potential of exergy analysis in buildings is recognized, there is little work on this application due to its complexity and the fact that the results can be difficult to interpret. In addition, exergy analysis highlights the low exergy performances of conventional systems, which can be a problem for some professionals. However, working with the exergy variable makes it possible to develop strategies to reduce fossil fuel consumption, increase the use of renewable energies and use them more efficiently. In this way, the quality of the energy supplied can be adapted to the quality of the energy demanded.

Among the literature review of exergy application in buildings, there are some researchers over the last two decades. In this regard, the work of Shukuya [34] should be highlighted. In addition, Sala-Lizarraga et al. [35] carried out a deep analysis from an exergy point of view concerning the thermoeconomics of buildings, both façade and facilities, being applied for design, optimization and maintenance purposes. In this way, the weak points of the application of the Second Law of Thermodynamics in dynamic building systems were overcome, and the necessary guidelines to achieve a low-ex building were described. Picallo-Perez et al. [36] studied the polygeneration system of an office building in different Spanish climatic locations under the energy and exergy perspective, showing the weaknesses of an analysis based exclusively on energy balances. Likewise, this analysis was implemented by Picallo-Perez et al. [37] applying it to any HVAC system, such as a ventilation system with heat recovery. This study showed that, although the energy efficiency of the ventilation system is 89 %, the exergy efficiency is 4 %. As a result, exergy studies provide extra and relevant information when analyzing energy systems.

Evola et al. [38] reviewed the methods commonly used in exergy analysis and highlighted discrepancies and open methodological issues in this type of analysis. Among other issues to be discussed, for instance, the exergy method is used to integrate renewable energy in buildings. This was discussed by Zhou et al. [39], who proposed a general approach for assessing the efficiency of renewable energy in buildings. After all, to calculate the exergy, the dead state or Reference Environment (RE) must be chosen, since it is the state from which no useful work can be extracted. This RE should be chosen with caution as, contrary to the energy balances, it is not compensated in the exergy balance and its values influence the results. For the case of buildings, Annex 49 of Schmidt et al. [40], recommended using the air surrounding the building as RE [41].

As said above, the exergy analysis of energy transformations is a valuable tool for assessing the sustainability of buildings, especially considering the scope of their architectural and engineering solutions and the dependence of energy needs on local environmental conditions. In this work, an nZEB LUCIA building is analyzed during a year using the exergy methodology, comparing it to the conventional energy analysis. In this way, it is possible to analyze and verify the energy and exergy efficiency in different periods, in order to propose new saving interventions. To do this, new exergy indicators are defined for the building, which serve as a reference to compare the current requirements of European regulations and with other public nZEBs intended for educational and/or research purposes.

It should be highlighted that the concept of nZEB implies that the building produces as much energy as it consumes, but does not automatically mean that it is also a net-zero carbon building. The reason lies in the second law of thermodynamics, which accounts for the real losses and, therefore, the impacts of each process. According to this law, real processes (even highly efficient ones) always have a certain exergy destruction that reduces the availability of the energy to perform useful work, which means that this destruction must be offset in the built environment, possibly using some fossil fuels and therefore causing CO_2 emissions. Regarding this issue, Kilkis et al. [42] concluded that near-unavoidable CO_2 emissions can no longer be ignored when developing new sustainable decarbonization strategies, as analyses based not only on the first law but also on the second law will help to comply with the Paris Agreement by considering emissions liabilities. Due to this, although a building may be self-sufficient in terms of energy, it does not necessarily eliminate its carbon footprint. Therefore, the destruction of exergy in a net-zero energy building has broader implications in the global energy context and cannot be ignored when considering sustainability and carbon emissions.

The manuscript is structured as follows: after the introduction, Section 2 sets out the methodology, describing the general energy-chain of a building, indicating the expressions of the exergy flows and defining the new indexes. Section 3 describes the case study of the nZEB building, located in Valladolid with its technology and control. In Section 4, the energy demand of the building is compared with the exergy demand and the balances in the different equipment are presented; the indicators are also calculated and compared with the corresponding conventional indicators. Finally, section 6 discusses the results obtained and draws the main conclusions.

Methodology

The methodology used along this study, based on exergy analysis, is very useful when designing and analyzing different systems operating in buildings. Exergy analysis offers several key advantages that make it a valuable tool in assessing energy systems. To begin with, it considers not only the quantity but also the quality of the energy flow by signaling the level of adequacy of the transformations through exergy destruction, which allows a more accurate assessment of the system performance. From this information, energy sources can be adjusted to meet the demands for instance, by using, waste heat and increasing the efficiency of the system; even more now that renewable energy sources are becoming increasingly important.

Knowing where the most energy is destroyed allows one to identify opportunities for improvement and optimization, since exergy efficiency provides information on the proximity of the system to the ideal reversible process. Thus, exergy efficiency is based on energy quality, i.e. on a common basis that allows energy flows of different natures to be compared; a very valuable information especially in building systems that work close to the ambient conditions. This means that the heat supplied by various sources, such as a fuel boiler or solar gain through a window, can be evaluated on an equal basis. For all these reasons, exergy analysis plays a crucial role in guiding the design and implementation of energy-efficient solutions. Accordingly, the equations and methodology for the energy and exergy analysis of a building are summarized in this section.

Energy & exergy chains in a building

Under a global perspective, the energy system of a building can be analyzed considering all the stages of the energy chain, from primary energy to final consumption and energy export, until the energy flows achieve equilibrium with the environment, as shown in Fig. 1:

The annual primary energy/exergy consumption, measured in MWh/year, provides an overview of the primary energy resources utilized to meet the corresponding demands of the main systems. This consumption reflects the quantity of energy/exergy required to cover the various energy/exergy needs within the system. By analyzing the annual primary energy consumption, it becomes possible to assess the efficiency and adequacy of the energy resources utilized, helping to identify potential areas for improvement and optimization.

Another important factor to consider is the annual on-site energy/exergy generation, distribution, and storage chain, also measured in MWh/year, which reflects the energy flows from the generation equipment to the terminal elements within the system. It encompasses the generation of energy on-site, as well as its distribution and storage for subsequent use. By analyzing this chain, one can gain insights into the efficiency of the energy usage within the system, identify opportunities for optimizing energy flows and enhance the overall system performance. Thus, the flows are transformed in each process, reducing their capacity to produce useful work (i.e. destroying exergy) up to the final on-site demand and generation till equilibrium.

Furthermore, in addition to the technical availability and economic viability of energy systems, the related environmental impacts must also be considered. In the current energy framework, this impact is a decisive factor when evaluating and comparing different sources and technologies, as it is important to discriminate the environmental costs from resource extraction, production, transport and use of each energy source. This global analysis is the only way to compare the various technologies and fuels with each other, considering all the stages of the energy chain up to the equilibrium.

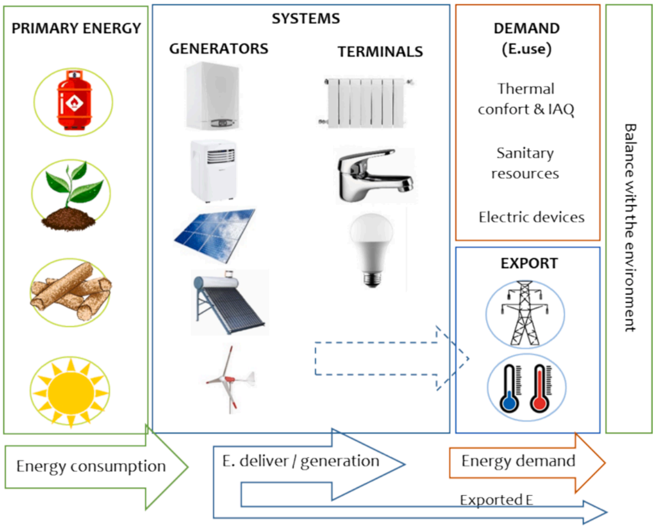

Fig. 1. Primary energy consumption, generation and demand till the equilibrium with the environment.

Equations to calculate exergy

The exergy of each flow is calculated according to its nature:

- Solar radiation flows (Ex_{sun}) that power renewable technologies such as PV panels or solar collectors. We calculate the exergy of solar radiation using the following equation described by Petela [43]:

$$Ex_{sun} = E_{sun}\cdot\psi_{sun} = E_{sun}\cdot\left[1-\frac{4}{3}\frac{T_0}{T_{\mathrm{Sun}}}+\frac{1}{3}\left(\frac{T_0}{T_{\mathrm{Sun}}}\right)^4\right] \tag{1}$$

- Fuel flows (Ex_{F_i}) that power the combustion generation systems, which can be fossil, biomass, etc.

$$Ex_{F_i} = E_{F_i}\cdot QF_{fuel} \tag{2}$$

- Heat transfer fluid flows (Ex_{m_i}) that usually refers to water flow rates, in the distribution circuit for heating, cooling and DHW demands.

$$Ex_{m_i} = m_i\cdot c_{p,i}\left[(T_i - T_0) - T_0\cdot\ln\left(\frac{T_i}{T_0}\right)\right] \tag{3}$$

- Heat flows (Ex_{Q_i}) such as heating and cooling demands.

$$Ex_{Q_i} = E_{Q_i}\cdot F_{car.} = E_{Q_i}\cdot\left(1-\frac{T_0}{T_i}\right) \tag{4}$$

- Electricity flows (Ex_{W_i}), such as the electrical demands of the building and the electrical consumption of the heating and cooling facilities.

$$Ex_{W_i} = E_{W_i} \tag{5}$$

Where:

- E_i: represents solar irradiation (E_{sun}), the calorific value of fuel (E_{F_i}), the heat (E_{Q_i}) or the electricity (E_{W_i}).
- T_0 : refers to the temperature of the Reference Environment (RE).
- T_{i}: is the temperature of the flow i.
- T_{sun}: is the equivalent temperature of the sun, around 5777 K.
- ψ_{sun}: is the Petela factor that weights the quality of solar radiation.
- m_i: is the mass flow of the flow i.
- $c_{p,i}$: The specific heat capacity of the mass flow i.
- $F_{car.}$: Carnot factor corresponding to the quality factor of a heat flow.

At this point, it is important to emphasize the influence of the Reference Environment (RE), linked to T_0; since, generally, the outside air temperature sufficiently far from the building is used. However, this T_0 is especially relevant in the exergy analysis, as it can be higher, equal to or lower than the working temperatures of the equipment, changing the direction of the flow with respect to the energy and continiuosly modifying its value. Therefore, the exergy values can vary whether they are analyzed in winter or summer, at night or during the day.

Definition of new exergy indicators for nZEB

The equations for calculating six indicators to characterize nZEB buildings are shown in this section: three of them are based on energy balances, according to the methodology proposed by the EU, adopted in Spain by the ISO 50000–1 Standard [44]. Similarly, we define three indicators based on exergy balances. These six indicators are: Non-renewable energy/exergy consumption ($EP_{p,nren}$ and $ExP_{p,nren}$) [kWh/m^2·y]; Renewable Primary Energy/Exergy Consumption ($EP_{p,ren}$ and $ExP_{p,ren}$) [kWh/m^2·y]; Renewable Energy/Exergy Ratio (RER_P and $RExR_P$) [-]. Accordingly, Fig. 2, modified from ISO 52000-1, shows the stages of the energy chain from start to end-use for an energy vector i, comprising the following stages: (1) primary energy $E_{P,i}$, (2) on-site energy supplied $\mathrm{E_{del,i}}$, (3) on-site renewable energy consumed $\mathrm{E_{ren,i}}$, (4) energy produced on site or in the surrounding area $\mathrm{E_{del,i}}$, (5) exported energy $\mathrm{E_{exp,i}}$ and (6) energy used by the technical systems of the building services $\mathrm{E_{EPus,i}}$; the energy chain ends when the flow is in equilibrium with the environment at $\mathrm{T_0}$. In order to convert from primary energy to supplied energy, the corresponding conversion factors $f_{p,i}$ must be known.

These conversion factors from primary energy to energy supplied and energy exported depend on the energy vector as follows:. (1) the total primary energy factor $f_{P,tot,i}$, (2) the primary renewable energy factor $f_{P,ren,i}$ and (3) the non-renewable primary energy factor $f_{P,nren,i}$. Fig. 3 shows an example of how these factors are calculated for the electricity vector, consumed in a heat pump (HP) and the gas vector, consumed in a boiler (Bo).

According to the specific example of Fig. 3, on the one hand, $\mathrm{E_{del,elec}}$=1 kWh (④$|_{\mathrm{HP}}$) of electricity is supplied in situ to a heat pump with a COP=2, of which, 0.25 kWh (②$|_{\mathrm{HP}}$) comes from renewable resources and 2.5 kWh (③$|_{\mathrm{HP}}$) from gas extraction, i.e., a total of 2.75 kWh (①$|_{\mathrm{HP}}$). On the other hand, $\mathrm{E_{del,gas}}$=1 kWh (④$|_{\mathrm{BO}}$) gas is also supplied in situ to a boiler of $\eta = 0.9$, of which, 1.1 kWh are consumed (①$|_{\mathrm{BO}}$ = ③$|_{\mathrm{BO}}$) in gas extraction. Thus, the conversion factors can be calculated as follows:

$$\mathrm{f_{P,tot,i}} = \frac{\textcircled{1}}{\textcircled{4}} \quad ; \quad \mathrm{f_{P,ren,i}} = \frac{\textcircled{2}}{\textcircled{4}} \quad ; \quad \mathrm{f_{P,nren,i}} = \frac{\textcircled{3}}{\textcircled{4}} \tag{6}$$

In our case study, located in Spain, the values to be used in the year 2023 for some energy vectors are shown in Table 1 coming from the energy mix at that time [14].

Non-renewable primary energy indicator

The Non-Renewable Primary Energy Indicator, $EP_{P,nren}$, is calculated from the energy supplied and exported (on-site generation of electricity, district heating and cooling, fuels) considering Primary Energy Factors [45,46] which are defined at the National level.

$$E_{P,nren} = \sum\nolimits_i \left(E_{del,i}\hat{A}\cdot f_{P,nren,i}\right) - \sum\nolimits_i \left(E_{exp,i}\hat{A}\cdot f_{P,exp,i}\right) \tag{7}$$

$$EP_{P,nren} = \frac{E_{P,nren}}{A_{net}} \tag{8}$$

Where:

- $E_{P,nren}$: Non-renewable primary energy [kWh/y]
- $E_{del,i}$: Power supplied on-site or nearby [kWh/y] by energy vector i during the year.
- $E_{P,exp,i}$: Energy exported on-site or nearby [kWh/y] by energy vector i during the year.
- $f_{nren,i}$: Non-renewable primary energy factor for supplied energy vector i [-].
- $f_{P,exp,i}$: Non-renewable primary energy factor of exported energy for energy vector i. It is equal to the default factor of the energy supplied, if not otherwise defined at the national level [-].
- A_{net}: Useful area [m^2].
- $EP_{P,nren}$: Non-Renewable Primary Energy Indicator [kWh/m^2·y].

In Spain to consider a building as nZEB, $EP_{p,nren}$ must be less than a limit value ($\mathrm{C_{ep,nren}}$), which depends on the climatic zone of the building location. The latest update of the CTE 2019 defines the nZEB by imposing thresholds for non-renewable primary energy $\mathrm{C_{ep,nren}}$ and total primary energy $\mathrm{C_{ep,tot}}$, or non-residential buildings and other uses, based on those defined in the Commission Recommendation (EU) 2016/1318 of July 2016 [6].

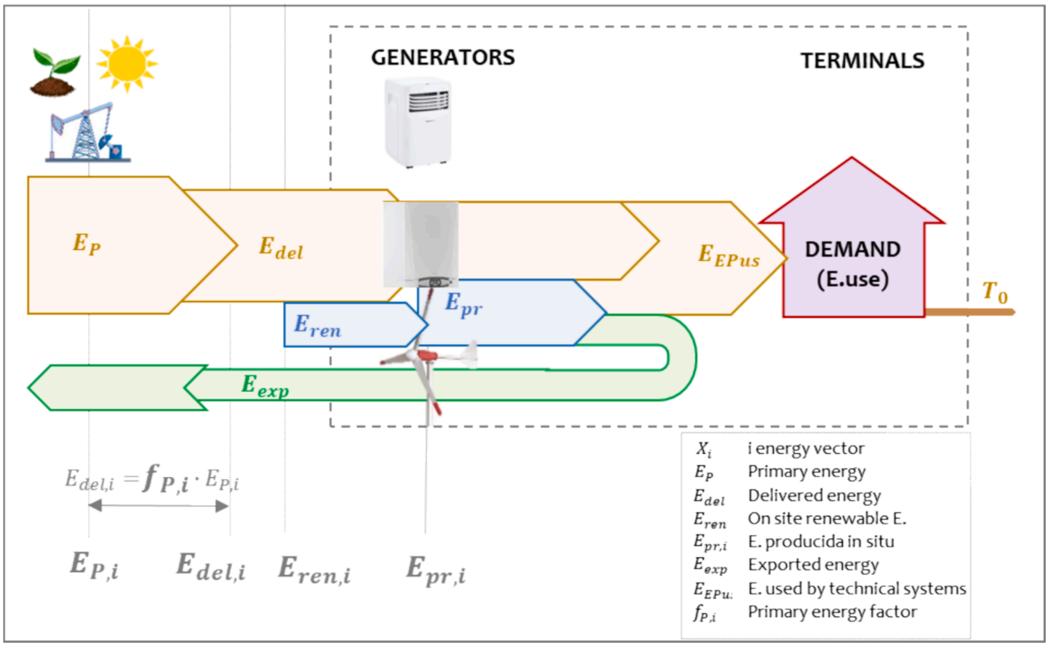

Fig. 2. Energy chain from the energy (modified from ISO 52000-1).

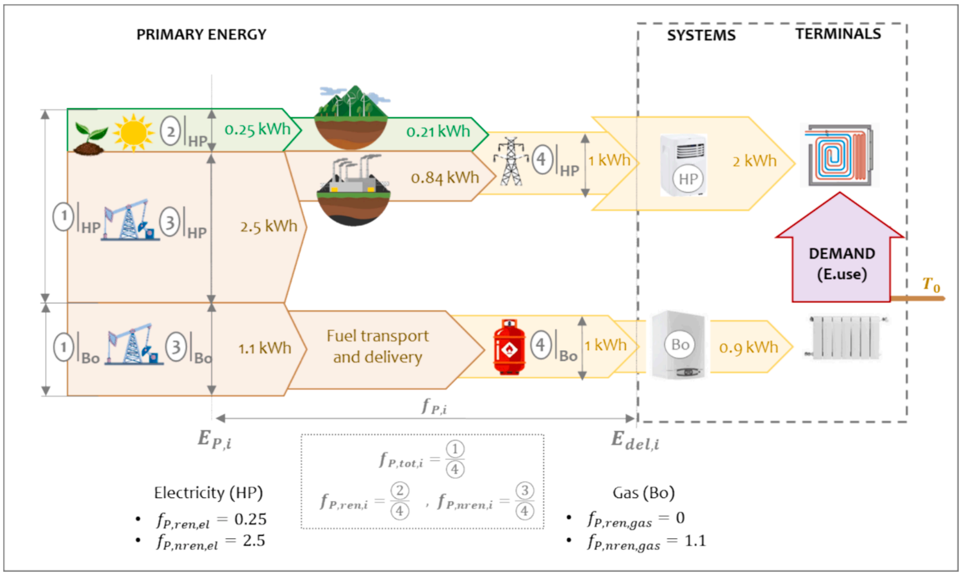

Fig. 3. Obtaining primary energy factors of electricity and gas (modified from ISO Standard 52000-1).

Table 1
Primary energy conversion factors as defined in the Spanish building standards.

Energy	Source	Use	$f_{p,ren}$	$f_{p,nren}$
Electricity	**Grid**	**Input**	**0.414**	**1.954**
Electricity	**On-site**	**Input**	**1**	**0**
Biomass	**On-site**	**Input**	**1**	**0**

Non-renewable primary exergy indicator

This non-renewable primary energy index is defined as follows:

$$Ex_{P,nren} = \sum_i \left(Ex_{del,i}\hat{A}\cdot fx_{P,nren,i}\right) - \sum_i \left(Ex_{exp,i}\hat{A}\cdot fx_{P,exp,i}\right) \tag{9}$$

$$ExP_{P,nren} = \frac{Ex_{P,nren}}{A_{net}} \tag{10}$$

Where:

- $Ex_{P,nren}$: Non-renewable primary exergy [kWh/y]
- $Ex_{del,i}$: Exergy supplied on site or nearby [kWh/y] by energy vector i.
- $Ex_{exp,i}$: Exergy exported in situ or nearby [kWh/y] by energy vector i.
- $fx_{P,nren,i}$ Non-renewable primary exergy factor for the supplied energy vector i [-].
- $fx_{P,exp,i}$: Non-renewable primary exergy factor of supplied energy compensated by exported energy for energy vector i [-].
- $ExP_{P,nren}$: Primary exergy indicator [kWh/m^2·y].

The primary exergy factors for Spain in 2023 are shown in Table 2, where the non-renewable part of the grid electricity is considered to come from fossil fuels, using the formula of eq.(2). Nevertheless, as shown in Fig. 3, the result of the factor depends on the proportions of the renewable and non-renewable mix which vary throughout the year.

Table 2
Primary exergy conversion factors obtained.

Exergy	Source	Use	$fx_{p,ren}$	$fx_{p,nren}$
Electricity	Grid	Input	0.414	2.032
Electricity	On-site	Input	1	0
Biomass	On-site	Input	1.05	0

Renewable primary energy indicator.

$$EP_{P,ren} = \frac{E_{P,ren}}{A_{net}} = \frac{E_P - E_{P,nren}}{A_{net}} \tag{11}$$

Where:

- E_P: Total primary energy [kWh/y]

Renewable primary exergy indicator

Similarly, $ExP_{P,ren}$ is defined as:

$$ExP_{P,ren} = \frac{Ex_{P,ren}}{A_{net}} = \frac{Ex_P - Ex_{P,nren}}{A_{net}} \tag{12}$$

Where:

- Ex_P: Total primary exergy [kWh/y]

Renewable energy ratio

The Renewable Energy Ratio (RER$_p$) describes the normalized proportion of renewable energy used, considering all sources. It relates total building energy consumption and total primary energy, netting out exported and supplied energy:

$$RER_P = \frac{E_{p,ren}}{E_{P,tot}} = \frac{\sum_i E_{ren,i} + \sum_i \left[E_{del,i}\hat{A}\cdot\left(f_{P,tot,i} - f_{P,nren,i}\right)\right]}{\sum_i E_{ren,i} + \sum_i \left(E_{del,i}\hat{A}\cdot f_{P,tot,i}\right) - \sum_i \left(E_{exp,i}\hat{A}\cdot f_{exp,tot,i}\right)} \tag{13}$$

Where:

- RER_P: Renewable Energy Ratio based on total primary energy.
- $E_{ren,i}$: Renewable energy produced on-site or nearby for energy vector i [kWh/y].
- $f_{P,tot,i}$: Total primary energy factor for supplied energy vector i [-].
- $f_{exp,tot,i}$: Total primary energy factor of supplied energy offset by exported energy for energy vector i [-].

Renewable exergy ratio

The total primary exergy (RExR$_p$) shows the relationship between the renewable primary exergy and the total primary exergy used by the building:

$$RExR_P = \frac{\sum_i Ex_{ren,i} + \sum_i \left[Ex_{del,i}\hat{A}\cdot\left(fx_{del,tot,i} - fx_{del,nren,i} \right) \right]}{\sum_i Ex_{ren,i} + \sum_i \left(Ex_{del,i}\hat{A}\cdot fx_{del,tot,i} \right) - \sum_i \left(Ex_{exp,i}\hat{A}\cdot fx_{exp,tot,i} \right)} \tag{14}$$

The interest of defining these exergy indicators is based on considering that all the energies involved are now weighted by their quality factor, i.e., by their capacity to do useful work. This is why the information contained in these indexes is more precise than conventional indexes, since a building's operation is more efficient when the less natural resources are consumed and the exergy method measures the amount of useful resources. Considering this, it is interesting to highlight the reflections expressed by Sala-Lizarraga et al. [35] where the sustainable building is defined as: a building that (1) adapts energy sources to the needs of each use, (2) increases the efficiency of energy use (reduces irreversibilities), (3) takes advantage of local energy sources, and (4) takes advantage of solar and other renewable energies. Thus, the exergy approach aims to minimize resources and their extraction and to minimize environmental degradation.

As it is well known, when calculating the Primary Energy of an energy vector, the energy required in each process (extraction from the sink, transport, manufacture, etc.) up to the final objective should be analyzed. Thus, raw materials from the earth's crust are linked to a zero energy value before extraction. In the same way as with energy, resources can be aggregated in terms of exergy considering the quality factor according to their nature. Thus, a distinction is made between the exergy of energy resources (oil, natural gas, coal, solar radiation, wind, etc.), which specifies the capacity to perform useful work up to equilibrium with the environment; and the exergy of non-energy resources (such as raw materials, iron, aluminum), which indicates the difference in concentration between the extracted raw materials and the geosphere. Therefore, the greater the difference between the concentration of a substance in the reference medium and in the deposit from which the raw material is extracted, the greater the exergy. Thus, by means of exergy, the depletion of energy resources and raw materials can be analyzed from the same perspective.

Taking all this into account, the "cumulative exergy" measures the quality of the transformations throughout in the entire energy chain and can be used in an analogous way to the Primary Energy; even increasing the limits up to "solar radiation" in order to give values to green energies. This type of analysis is proposed in such methodologies as Ecological Cumulative Exergy Consumption or Extended Exergy Analysis. However, calculating the "solar radiation" of each flow implies increasing the imprecision of the analysis.

Case study

This paper analyzes the "LUCIA" building of the University of Valladolid, Spain [47]. It has a total area of 7,500 m^2 and is certified as a Nearly Zero Energy Building (nZEB). The architectural description of the building as well as the thermal characteristics of the façade can be found in Ref. [48].

The building is monitored by using the ModBus protocol [49], with more than 97 analyzers, where the main demands of (1) lighting, (2) DHW, (3) cooling, (4) heating and (5) ventilation are controlled by pulse counters. In addition, when there is a surplus of (6) electricity generation, it is exported to the grid.

Fig. 4 shows the flow diagram of the building's energy processes, from primary energy to demand within the building, until the flows are balanced with the environment.

Accordingly, the generation systems of the building under study are (Fig. 4):

- Electric generation, which is composed of ventilated facade PV panels (BIPV), tri-generation Combined Central Heat Power (CCHP) and the grid to which it is connected.
- Heating generation, which consists of a biomass boiler (Boiler) and the heat production part in the internal combustion engines (ICE) of the CCHP, which is also fed with biomass gas.
- Cooling generation, consisting of a CHiller (CH) and the ABSorption System (ABS) of the CCHP, fed from the electrical generation equipment and/or grid and heat generated.

The thermal demands for heating, cooling and ventilation are supplied from an Air Handling Unit (AHU) connected to the previous generation circuits with a constant flow rate of 15,000 m^3/h.

- This unit stands out for having an energy recovery system composed of a geothermal heat recovery unit (EAHX), 16 m deep. The AHU takes advantage of this acclimatized air from the EAHX or by-passes it to implement free-cooling and heat recovery from the extracted air. This system is fully described by Rey-Hernández et al. [50].

Thus, the renewable resources obtained on-site in the building are:

- Solar radiation, which is converted into electricity by PV panels.
- Non-densified biomass (wood chips) that feeds the boiler and is partly gasified in order to feed the ICE for cogeneration.
- Outdoor air conditioning by geothermal energy in EAHX.

And the non-renewable resources are included in the energy mix of the grid.

Table 3 lists the main equipment characteristics.

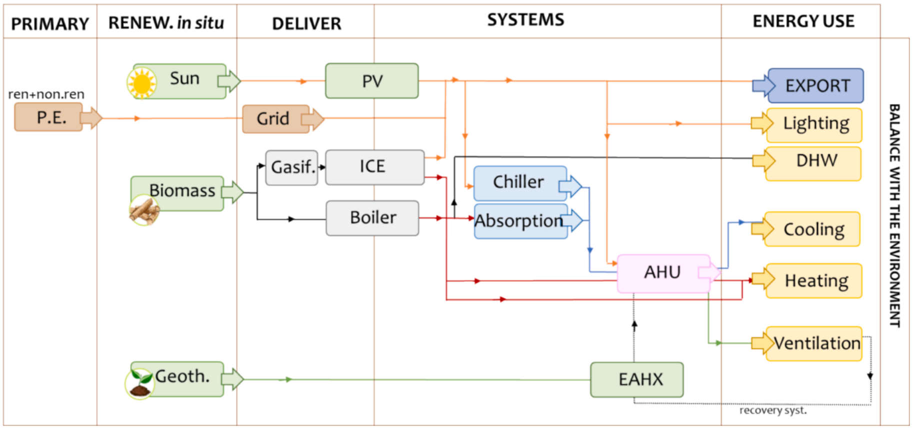

Fig. 4. Flow diagram of the nZEB energy systems.

Table 3
Nominal characteristics of the main energy systems.

System	Nominal Power [kW]	Energy Efficiency
PV system	15.12 kWp	12 %
EAHX	112,740 kWh/year	61 %
ICE System	90 kWt/u112 kWe/u	$\eta_t = 35\%$ $\eta_e = 44\%$
Boiler	329 kW	88 %
Chiller	232.7 kW	EEE=3.3
Absorption	176 kW	EEE=0.7

Exergy analysis of the most significant generation systems

As said above, high exergy performances mean using energy properly, in a more rational way, and vice versa. Therefore, the difference between energy and exergy performances of LUCIA's generation systems must be highlighted [35], which are EAHX, a chiller and a cogeneration engines.

Exergy analysis of an EAHX

In the winter season, the energy balance at EAHX is:

$$\Delta U_{ground}^{winter} = m_a(h_2 - h_1) \tag{15}$$

Where:

- h_1, h_2: Specific enthalpy of air in the inlet and outlet dampers respectively [kWh/kg]
- $\dot{m}_a$: Ventilation air flow that is pre-heated and goes into the building [kg]
- $\Delta U_{ground}^{winter}$: Internal energy variation of the soil [kWh]

The useful effect of EAHX in winter, in terms of energy, is the increase in air enthalpy, so in terms of exergy, one can conclude the following:

$$\Delta Ex_{ground}^{winter} = m_a(Ex_2 - Ex_1) + D \tag{16}$$

Where:

- Ex_1, Ex_2: specific air exergy in inlet and outlet dampers [kJ/kg], where $Ex_1 = 0$.
- $\Delta Ex_{ground}^{winter}$: variation of soil exergy [kWh]
- D: exergy destruction [kWh]

In summer, the air is pre-cooled by EAHX, so the energy balance is:

$$\Delta U_{ground}^{summer} = m_a(h_1 - h_2) \tag{17}$$

However, this decrease in enthalpy implies an increase in air exergy, so the exergy balance results in:

$$\Delta Ex_{ground}^{summer} = m_a(Ex_2 - Ex_1) + D \tag{18}$$

the useful effect of EAHX, being the increase of air exergy, also m_aÂ·Ex_2.

The economic (or environmental) return of EAHX is calculated by comparing the cost of heating and cooling, which is variable at different times of the year, along with its investment cost (or environmental impact during the construction of its components and placement).

Energy and exergy efficiency of the chiller

The EEE for an electrically driven chiller is defined as:

$$EEE = \frac{Q_C}{E} \tag{19}$$

Where:

- Q_C: heat removed [kWh]
- E: power consumption [kWh]

The exergy efficiency φ of the chiller is calculated as follows:

$$\varphi = \frac{Ex_{Q_C}}{Ex_E} = \frac{\left(1 - \frac{T_0}{T_c}\right)Q_C}{E} = \left(1 - \frac{T_0}{T_c}\right)EEE \tag{20}$$

Where:

- T_C and T_0: cold source and RE temperatures, between which the chiller works [K].

It is shown that the exergy performance φ, unlike EEE, is always less than 1, since from an exergy balance $E = \left(1 - \frac{T_0}{T_c}\right)Q_C + D$.

Energy and exergy efficiency of ICE cogeneration system

The overall efficiency of a cogeneration engine η_{cog} can be defined as:

$$\eta_{cog} = (E + Q_H)/F \tag{21}$$

Where:

- E: Electricity generated [kWh]
- Q_H: Cogenerated heat energy [kWh]
- F: Fuel consumption [kWh]

The overall exergy efficiency φ_c is defined as:

$$\varphi_{cog} = \frac{E + Ex_{Q_H}}{Ex_{F_i}} \tag{22}$$

Where:

- E: Exergy from cogenerated electricity [kWh]
- Ex_{Q_H}: Exergy from cogenerated thermal energy [kWh]
- Ex_{F_i}: Exergy of the fuel consumed [kWh]

This performance measures the thermodynamic quality of the cogeneration, so it will be closer to 1 the better the system is; and the unity if it is ideal (i.e. without irreversibilities). However, the energy performances η_{cog} do not provide this information and can even lead to wrong interpretations. Indeed, it is possible to find a facility in which the thermal production efficiency is high and the overall plant efficiency is, consequently, very high. However, as the thermal energy produced is of low quality (e.g. heating water at 50 °C), the system will have high irreversibilities, with a low energy performance and, finally, it will be a system of low thermodynamic quality.

Results

The annual energy/exergy demand of a building refers to the amount of energy/exergy required throughout the year to ensure good IAQ levels through properly controlled mechanical ventilation (CMV). Hence, the exergy demand refers to the exergy content of the energy demand, this being the minimum useful work required to satisfy the energy demand. Thus, if the energy supplied to satisfy the demand has a higher quality than necessary, exergy is destroyed. For instance, this happens when trying to maintain the air at a temperature of 21 °C with a heating system at 80 °C. Therefore, in an ideal situation, the minimum exergy demand for comfort must be supplied. Accordingly, the exergy demand is calculated from the energy demand, either by the simplified or the detailed method, following the methodology developed by ECBCS Annex 49.

Monthly energy and exergy balance

A complete monitoring of building flows and consumptions makes it possible to evaluate the performance of the nZEB building and to assess the losses and efficiencies of each energy system. In addition, the energy and exergy analysis allows enhancing actions to be defined and to evaluate whether to apply the same strategies to other buildings. The thermodynamic data were obtained from the calibrated model based on the data recorded by the SCADA monitoring system and entered into the DesignBuilder V6 software [51], with an error of less than 3 %. The exergy fluxes of each energy vector were calculated by applying equations (1–5) with one-hour time interval. For space reasons, Fig. 5 shows only the accumulated monthly results which are plotted following the structure of (a) primary consumption, (b) supply and (c) demand.

(a) Energy [kWh/month] and exergy [kWh/month] consumption of resources (solar radiation, biomass, geothermal resource, and primary energy for grid production) are shown in Fig. 7, where it is verified that:
   - o The energy scale is very similar to the exergy scale given the quality factors of each resource.
   - o Almost half of the total resources over the year are obtained from local biomass (48 % energy and 51 % exergy as the quality factor is$QF_{fuel} = 1.03$), where part is gasified to feed ICE.
   - o Summer season requires the most primary resources, almost all of which are obtained from the grid. Thus, 33 % of total resources (35 % of exergy resources) are consumed between the months of May and September.
   - o The solar resource remains practically constant throughout the year and corresponds to 14 % of the total (due to the factor $\psi_{sun} \simeq 1$).
   - o Although there is a geothermal contribution of 5 % in summer, this resource has little impact on the exergy supply, since it is very close to the environmental conditions.

(b) The energy [kWh/month] and exergy [kWh/month] supplied to power the HVAC system is shown in Fig. 6, including the electrical input (obtained from the grid, from the PV electric production and the ICE) as well as the thermal input (from the ICEs and the B) powering the rest of the HVAC systems.
   - o The total electric energy generation (which supplies the main equipment and lighting demands) corresponds to 62 % compared to 38 % of thermal energy produced by the Chiller and the absorption system (supplying AHU and DHW demands). However, in terms of exergy, due to the low energy quality of the heat flux, 88 % of the total exergy generated corresponds to the electrical flux, and the rest to the thermal.
   - o ICE engines generate 66 % of the total energy consumed by the systems and 53 % of the total energy generated on-site.
   - o Only summer season consume electricity from the grid; but PV generation (4 % energy and 6 % exergy) is almost constant all year.

(c) Energy demand [kWh/month] and exergy demand [kWh/month] to maintain indoor comfort conditions (heating, cooling, lighting, etc.), air quality (ventilation) and DHW are shown in Fig. 7, as well as electricity exported to the grid.
   - o The energy scale is significantly larger than the exergy scale. Likewise, at the energy level, the thermal demand, which includes heating, cooling, ventilation and DHW, represents 63 % of the total, while in exergy terms it represents only 22 %, the rest being the export and electricity demand.
   - o This fact indicates that, if the generation and demand of thermal resources were adequately matched, the exergy requirement (related to primary consumption) could be significantly reduced by using energy sources in a more optimal way. That is, by using low-quality energy sources to cover low-quality demands. Specifically, through the contribution of the geothermal resource that allows the recovery of a large part of the consumption to acclimatize the building.

Annual energy and exergy balance

The annual balance helps to take a global view of the incoming and outgoing vectors of the system. Thus, according to the EPBD recast, to calculate the supply and export nearby, the energy and exergy fluxes of the facilities contractually linked to the building must be added to or subtracted from the on-site supplied and exported energy flows, as shown in Fig. 8.

Thus, the yearly accumulated results are shown in Fig. 9:

- The total amount of energy supplied on-site is 140.82 kWh/m^2·y and the total amount of exergy supplied is 105.19 kWh/m^2·y.
   - o This difference in values is due to the quality factors of the resources. The solar radiation or biomass quality factor is close to unity; but, the one of EAHX is low due to the proximity to the RE. Therefore, although quantitatively it is an energy flow to be

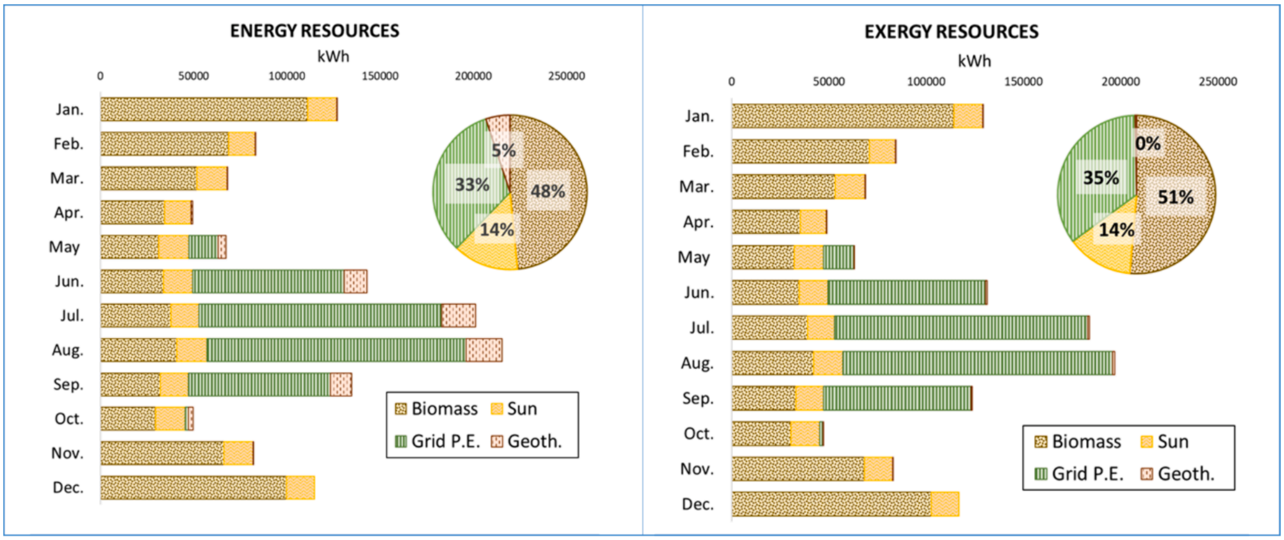

Fig. 5. Energy consumption [kWh/month] and Exergy consumption [kWh/month] of energy resources.

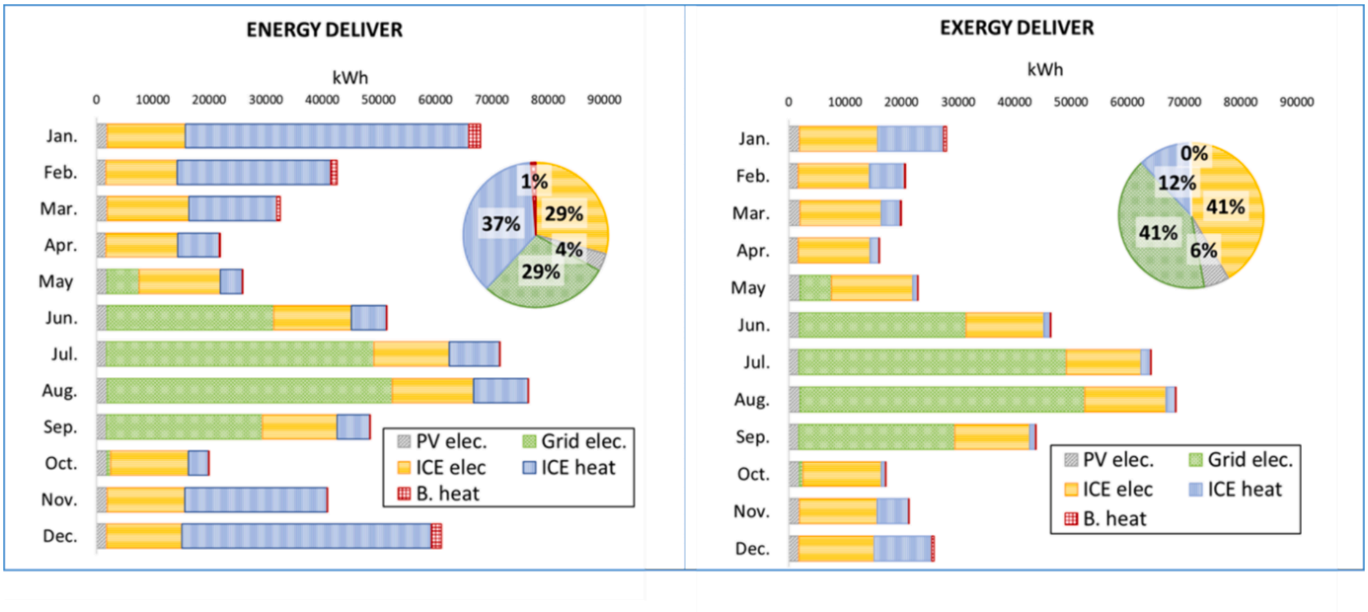

Fig. 6. Energy [kWh/month] and Exergy [kWh/month] supplied to power HVAC equipment.

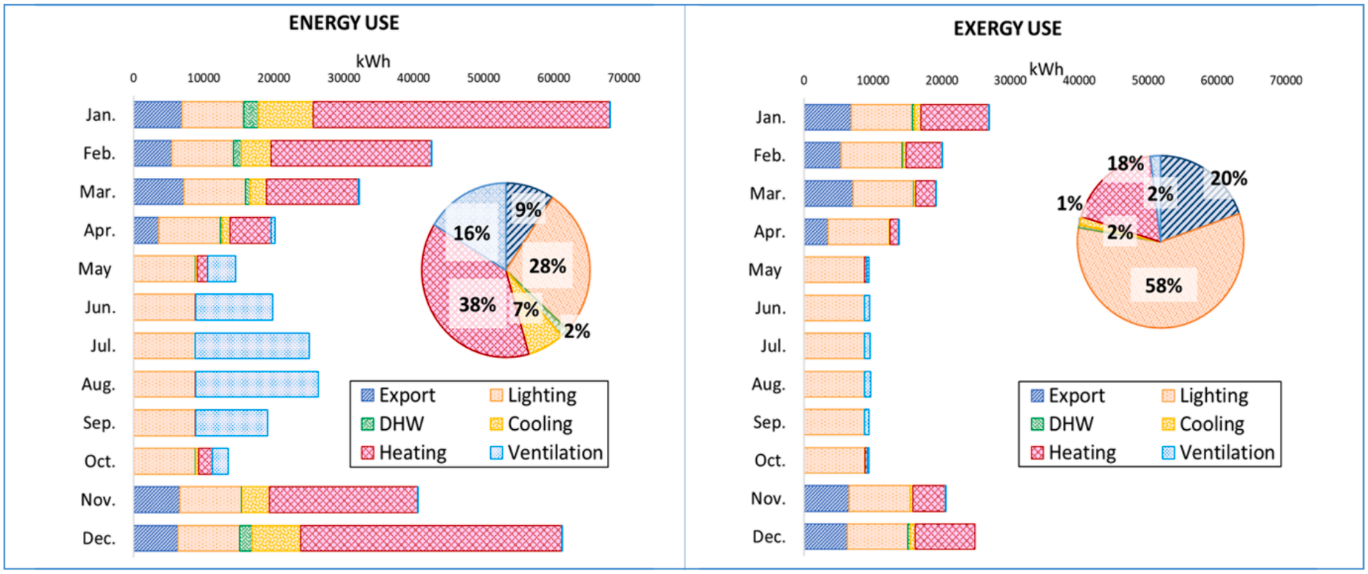

Fig. 7. Energy Demand [kWh/month] and Exergy Demand [kWh/month].

considered (40 kWh/m^2·y), its value in exergy is very small (1.2 kWh/m^2·y).

- The conclusions on energy and exergy demands are similar to the monthly basis.

Energy and exergy indicators

Based on the results, the previously defined indicators are calculated.

Non-renewable primary energy & exergy indicators

The first indicator, $E_{p,nren}$ kWh/m^2·y (Eq. (8)), corresponds to the supply of non-renewable energy to cover heating, cooling, DHW, lighting and ventilation demands, as well as exported energy.

$$EP_{p,nren} = 67.2\frac{kWh}{m^2y} \tag{23}$$

In the city of Valladolid, with a continental climate, the maximum national thresholds for this indicator $EP_{P,nren}^{max}$ are 85 kWh/m^2·y to 100 kWh/m^2·y of total primary energy consumption for commercial and office buildings. Therefore, it is fulfilled that: $EP_{p,nren} < EP_{P,nren}^{max}$.

Regarding the Non-Renewable Primary Exergy indicator (Eq. (10)) the results are very similar, since only the imported grid electricity is taken as a non-renewable vector, with an exergy factor slightly higher than the energy one, as shown in Table 2.

$$EPx_{P,nren} = 69.9\frac{kWh}{m^2y} \tag{24}$$

To decrease this value, the grid supply should be reduced, for instance by including more on-site PV production or making the energy mix more renewable. To supply the electric demands (lighting or other equipment), energy of the same quality (work) or higher quality (fossil fuels) is needed.

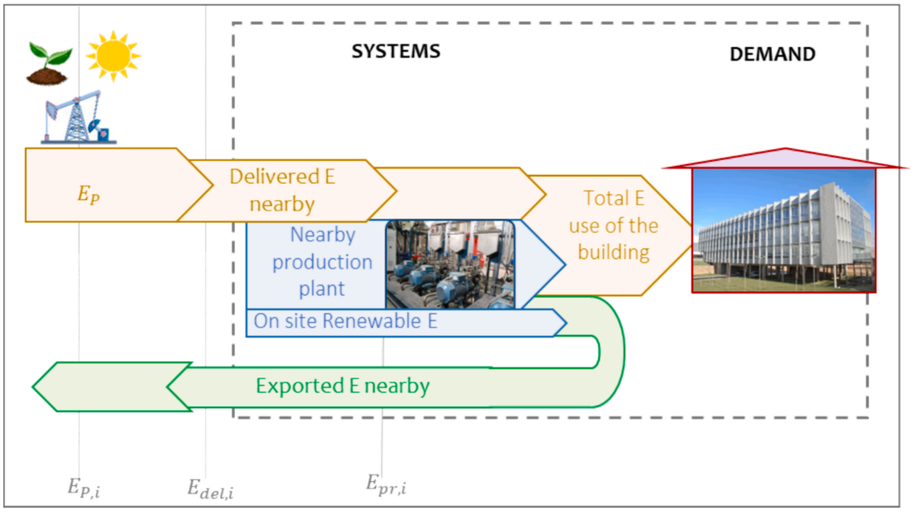

Fig. 8. Energy flows in the LUCIA nZEB.

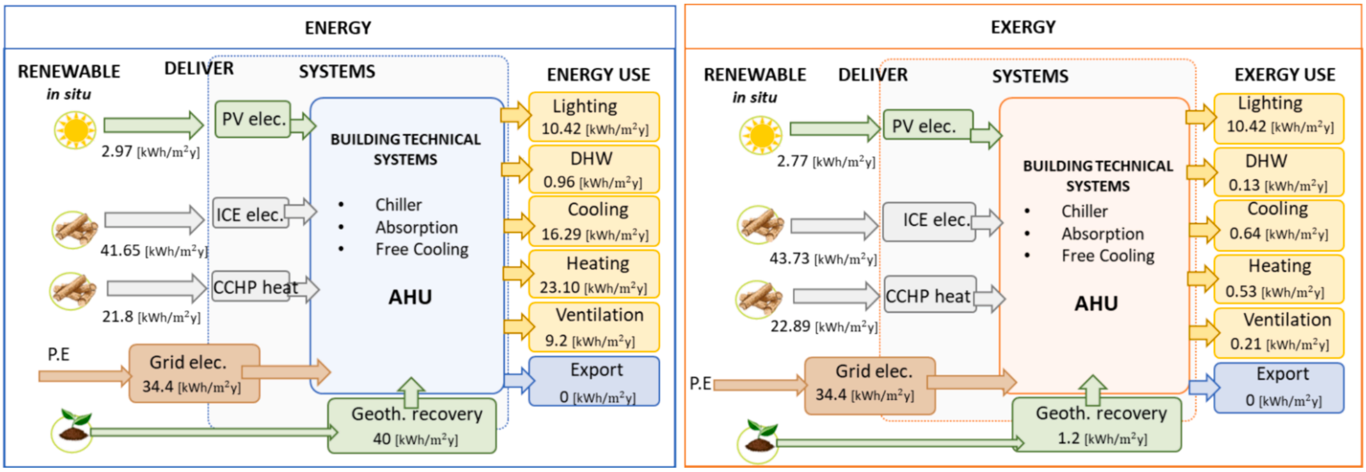

Fig. 9. Energy and Exergy Balance at LUCIA nZEB. (a) Energy Balance. (b) Exergy Balance.

Renewable primary energy & exergy indicators

The second indicator defines the renewable primary energy value of the LUCIA building, (Eq. (11)). The total primary energy (EP_p) is calculated as the heat from biomass consumption multiplied by its primary energy factor and the heat recovered by the EAHX, added to the multiplication of the primary energy factor for electricity and the difference between the final electricity consumption and the solar photovoltaic production; achieving a value of $EP_P = 188.2\,\frac{kWh}{m^2y}$:

$$EP_{p,ren} = 121\frac{kWh}{m^2y} \tag{25}$$

The EU proposes that the renewable contribution of primary energy must be higher than $EP^{min}_{p,ren} = 45$ kWh/m^{2}y, so it is fulfilled that: $EP^{min}_{p,ren} < EP_{p,ren}$. In Spain, according to the characteristics of the building and its location LUCIA building complies with the Spanish CTE HE0 standard. Detailed system boundaries for calculating supplied and exported energy is extended from the EN15603 assessment boundary. As indicated in the EPBD recast, the positive influence of renewable energy produced on-site reduces the amount of required supplied energy and can be exported when the building's demand is exceeded [52].

Regarding the Primary Renewable Exergy indicator (Eq. (12)):

$$ExP_{p,ren} = 86.83\frac{kWh}{m^2y} \tag{26}$$

This indicator decreases compared to the energy indicator for the reasons explained above: the exergy of renewable geothermal heat recovered decreases significantly, although the biomass factor increases from 1 to 1.03.

Renewable energy & exergy ratio indicators

The Renewable Energy Ratio (Eq. (13)) determines the contribution rate of renewable energies in the LUCIA nZEB, and it is obtained by using f_i factors of Table 1.

$$RER_P = 0.66 \tag{27}$$

Spain requires that the renewable energy contribution for nZEB buildings be greater than 60 %, therefore, the third indicator shows that LUCIA building qualifies as an nZEB. And, according to Eq. (14):

$$RExR_P = 0.56 \tag{28}$$

The ratio of renewable energy decreases compared to the energy ratio by the same reason as $ExP_{p,ren}$ indicator.

The advantage of characterizing the performance of the building by these exergy-based indexes is the fact of considering the different thermodynamic quality of all the energies involved, which is the novelty of the work, in contrast to the corresponding energy indexes. In energy indexes, quality factors are not applied and consequently, the kWh of electricity is compared to a kWh of thermal energy, which is of lower quality. Thus, the primary exergy requirement is greater than the energy, and the renewable exergy ratio decreases.

Conclusions

This work analyses the energy and exergy performance of the nZEB university building in Valladolid (Spain) called LUCIA, with a LEED Platinum certification The innovation lies in including exergy indicators in the nZEB analysis, in addition to the current energy indicators (such as renewable and non-renewable primary energy); a fact that, to the author's knowledge, had not been done before.

After all, the irreversibilities and exergy destructions, calculated through the second law of thermodynamics, allows for more precise analysis of the effectivity of the processes considering not only the quantities of energy involved but also the qualities. Another aspect to take into account is that analyses based on the second law can assign responsibility for emissions to the specific process that generates them. In this way, CO^2 emissions that were previously identified as quasi-inevitable can be taken into account when developing sustainable decarbonization strategies; and thus use energy sources adapted to the quality of demand. This will make it possible to achieve not only zero-energy buildings, but also net-zero carbon building.

Thus, comparing the energy of the consumed resources with the exergy results of LUCIA, the exergy of the raw materials do not vary significantly (1,215 MWh/y) since the quality factors of biomass and solar radiation are close to unity, although the geothermal exergy contribution has low quality factor. On the other hand, the exergy demand decreased by 22 % compared to the energy demand, with a value of 146 MWh/y. This is because the energy flows are close to ambient conditions and are finally destroyed once they achieve the equilibrium with the environment. Considering all this, it has been demonstrated that the low exergy geothermal waste heat utilization system is very suitable for supplying the thermal demands of heating, cooling, ventilation and DHW because it adapts to the energy quality.

Regarding the indicators, on the one hand, the Non-Renewable Primary Energy indicator ($EP_{P,nren} = 67$ kWh/m^{2}y), was lower than the indicator required by Spanish Standards for high internal load building type such as LUCIA, (80 kWh/m^2·y). The Exergy indicator was very similar due to the exclusive non-renewable use of electricity from the grid ($ExP_{P,nren} = 69.9$ kWh/m^2·y). Nevertheless, it is clear that these indicators will vary as the proportion of the mix of incoming resources varies; therefore, the best option is related to the minimum grid consumption and maximum consumption of renewable systems such as PV and EAHX. On the other hand, the Renewable Primary Energy Indicator is$EP_{p,ren} = 121$ kWh/m^{2}y while the exergy values showed that the capacity to do useful work was lower ($ExP_{p,ren} = 88.36$ kWh/m^{2}y) because primary energy related to the geothermal contribution was considered. Furthermore, the Renewable Energy Ratio showed that the building is above the standard (RERp = 0.66) although it was slightly overestimated with respect to its capacity, since $RExR_P = 0.56$.

Considering the proposed exergy indices, comparative limits should be established to analyze whether the building can be determined as low-exe Building, as is done with energy to determine the nZEB. This is due to its ability to adapt generation-quality to demand. In addition, the responsibility for CO_2 emissions caused by the exergy destructions must be highlighted since there is a direct dependence on external energy sources to make up the destruction, which often involves the use of fossil fuels with their corresponding carbon emissions. This responsibility involves recognizing that the destruction of exergy through a building's systems increases carbon emissions elsewhere in the energy system. It is therefore crucial to incorporate this consideration into the sustainability assessments of net-zero energy buildings in order to ensure a comprehensive approach to reducing their overall carbon footprint. Therefore, because of this research, exergy is considered to be a useful indicator for analyzing low-carbon systems (such as waste heat recovery) and this work is the first step in being able to propose technological or control improvements in high standard buildings so as to be able to reach even a positive production building.

For all these reasons, this work aims to extend the application of ISO 52000-1 and the nZEB concept and to include exergy indicators for a more in-depth study. It also advocates for incorporating exergy-based indicators alongside traditional energy metrics in European regulations to accurately assess building performance and define low-ex buildings.

CRediT authorship contribution statement

Javier M. Rey-Hernández: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Francisco J. Rey-Martínez:** Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **Jose M. Sala-Lizarraga:** Validation, Supervision, Data curation, Conceptualization. **Ana Picallo-Perez:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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