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A novel life cycle assessment methodology for transitioning from nZEB to ZEB. Case-study

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ABSTRACT

This study analyzes the CO_2 equivalent emissions of a LEED-certified nearly Zero Energy Building (nZEB) using a simplified Life Cycle Assessment (LCA) methodology, aligned with EN 15978. Focusing on the building's energy performance across its life cycle, the study demonstrates that in 2022, 95 % of the energy used for heating came from renewable sources, which decreases to 86 % by 2050 due to milder winters. However, the need for cooling increases by 9 % over the same period due to hotter summers. By 2050 and 2080, if the EU transitions to renewable electricity, the operational Global Warming Potential (GWP) could approach zero. The study highlights that embodied emissions (69 %) outweigh operational emissions (31 %) in 2022, emphasizing the need to reduce embodied GWP through material reuse and recycling. Notably, concrete and aluminum were found to contribute the most to embodied emissions. The research also shows that nZEBs can exceed the EU's 2030 energy targets, with renewable energy contributing 67 % of the building's total consumption. As climate change favors nZEB performance, the operational emissions will trend towards zero, but embodied emissions will become increasingly significant. To achieve the EU's zero-emission goals, it is crucial to prioritize reducing embodied GWP in future nZEBs. This study underscores the importance of nZEBs in mitigating climate change impacts, offering a pathway toward sustainable construction and energy efficiency.

1. Introduction

Climate change is of paramount concern in today's world. Across the European Union, concerted efforts are underway to achieve carbon neutrality, aimed at tackling carbon emissions while fostering circularity. This ambitious endeavor underscores a collective commitment to transitioning towards sustainable practices, where carbon emissions are minimized and resources are utilized in a circular and regenerative manner, ultimately paving the way for a greener and more resilient future [1]. The transition to carbon neutrality necessitates a comprehensive approach that encompasses multiple facets of energy management and policy [2]. This entails a concerted effort to enhance energy efficiency, expand renewable energy sources, implement carbon trading mechanisms, and enact progressive energy policies. By addressing these areas, societies can effectively reduce carbon emissions and pave the way for a sus-

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tainable energy future. This integrated approach not only mitigates the impacts of climate change but also fosters innovation and resilience in the face of evolving energy challenges [3].

The excessive emission of GreenHouse Gases (GHGs) resulting from human activity directly contributes to global warming, thereby exacerbating climate change, as indicated by reports from the Intergovernmental Panel on Climate Change (IPCC). These underscore the urgent need for concerted global action to mitigate GHG emissions and address the underlying drivers of climate change, ensuring a sustainable future for generations to come [4].

Despite global efforts to decarbonize the energy sector, in 2021, electricity and heat generation accounted for nearly 44 % of global CO_2 emissions from fuel combustion. Coal-fired power plants were responsible for approximately 73 % of these emissions. Furthermore, fossil fuels continued to dominate the global energy supply, comprising approximately 80 % of the total energy supply (TES). Among fossil fuels, oil accounted for nearly 30 %, followed by coal (27 %) and natural gas (24 %). These statistics highlight the persistent reliance on fossil fuels and underscore the urgent need for accelerated transition to renewable energy sources and sustainable energy systems worldwide [5].

To mitigate the impacts associated with climate change, the recent United Nations Climate Change Conference 2023 (COP28) was held in Expo City, Dubai. During this conference, policies were agreed upon to limit the increase in global temperature. This event served as a crucial platform for international collaboration and collective action towards combating climate change and ensuring a sustainable future for all [6]. Currently, the average surface temperature of the Earth has risen to approximately 1.2 °C above preindustrial levels [7], resulting in heatwaves and other extreme weather events. This escalation highlights the urgent need for concerted efforts to address climate change and its long-term consequences on weather patterns and natural systems. The International Energy Agency (IEA) concluded that the pathway to limit global warming to 1.5 °C is extremely challenging but remains feasible. This assessment underscores the critical importance of immediate and ambitious actions at the national and international levels to curb greenhouse gas emissions and transition to low-carbon energy systems [8].

One of the action axes of COP28 is to accelerate the energy transition, increase electrification, and reduce the use of fossil fuels to mitigate the effects of climate change by reducing greenhouse gas emissions. The goal of tripling renewable capacity by 2030 is one of the major objectives of this climate summit [9]. Despite the great challenge and effort that decarbonizing this sector entails, some researchers are currently addressing this issue [10–12].

The European Commission has embraced a series of proposals to adjust EU climate policies, aiming to decrease net greenhouse gas emissions by at least 55 % by 2030 compared to 1990 levels [13]. This endeavor will entail enhancing overall energy efficiency and increasing the proportion of renewable energy sources [14].

The consumption of energy in buildings is experiencing a notable increase, primarily attributed to the heightened utilization of energy-consuming devices within these structures. Currently, energy demand in buildings accounts for a substantial portion, approximately 31 %, of the total global energy demand. Consequently, this sector is a significant contributor, responsible for around 23 % of carbon emissions worldwide. Given its substantial impact, the building sector emerges as a pivotal focus area, particularly in endeavors aimed at decarbonization efforts [15,16]. Remarkably, this sector alone is accountable for a staggering 36 % of all CO_2 emissions. Thus, addressing and mitigating the carbon footprint of buildings stands as a critical imperative in the broader context of sustainable development and climate action initiatives [17,18].

The new version of the EPBD, endorsed in March 2024, solidifies the groundwork for decarbonizing the building sector by 2050. New construction projects, up until the year 2030, are mandated to possess a certificate ensuring the high efficiency of the building, thereby qualifying as nZEB (nearly Zero Energy Building), with the operational GWP of the building being the pertinent metric to achieve a zero-emission building (ZEB). However, starting from 2030 onwards, the regulations become even more stringent. Buildings must achieve zero greenhouse gas emissions (ZEB), necessitating the calculation of GWP for the entire lifecycle of the building, with the role of energy efficiency and renewable energies being decisive [19]. Attia et al. [20] conducted a cross-sectional study to identify the barriers to the implementation of nZEB in 10 Eastern European countries and state that most of these countries are not prepared to comply with the EPBD guidelines.

This initiative can be approached by starting with a very low energy demand [21], applying the principles of sustainable architecture [22,23]. The building design should encourage passive measures, thereby maximizing energy efficiency. Crucially, this necessitates excellent thermal insulation and adequate ventilation. Moreover, the majority of the building's energy consumption should be sourced from renewable sources [11,24–27].

Researchers confirm that renewable energy generation, as well as the application of circular economy principles, contribute significantly to reducing a building's CO_2 equivalent emissions and dependence on fossil fuel consumption [28–31].

Barrutieta et al. [32] demonstrated that an nZEB building achieved a self-sufficiency level of 74.3 % in operational electrical energy. Its carbon footprint was reduced to 3.35 kg $CO_2/m^2 \cdot$year, representing a 92 % reduction compared to that of a standard office building in locations with similar climates.

In pursuit of climate neutrality by 2050 and in the fight against climate change, the EU sets ambitious targets to increase overall efficiency from 32.5 % to 36 % (and to 39 % for primary energy consumption) and to raise the share of renewable energy in final energy usage from 32 % to 40 %. The new directive will introduce additional energy efficiency indicators to decarbonize the construction sector, mandating a review of national renovation plans and introducing a new metric known as GWP for calculating lifecycle emissions for new construction buildings [33].

To assess the GHG impact, it is essential to understand the emissions generated by the building at each phase of the process, spanning the entire lifecycle. The UNE-EN 15978 standard delineates these lifecycle phases, as depicted in Methodology section (Fig. 6). Fig. 1 illustrates the carbon emissions percentage at each lifecycle phase of a ZEB building.

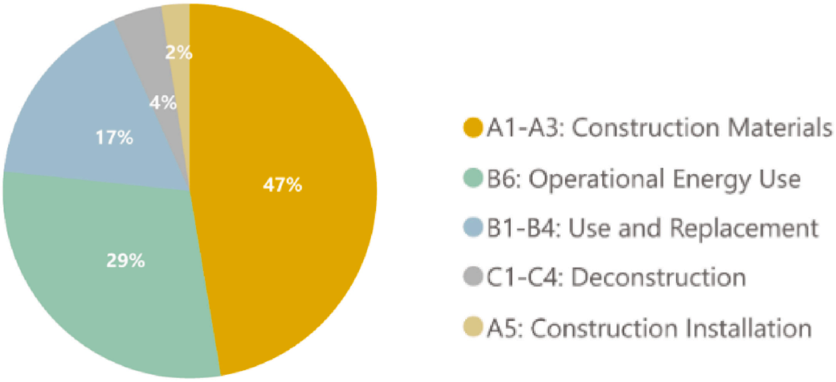

Fig. 1. Carbon Emission Percentages in each LifeCycle Phase for a ZEB [34].

The GWP serves as the ideal indicator for the development of this study. GWP quantifies CO_2 emissions both in the construction phase A1-A3 (referring to embedded CO_2) and in the use phase B1-B4 and B6 (operational CO_2).

The European objective of achieving climate neutrality by 2050 urges the development of a new decarbonization scenario for the building sector from a comprehensive perspective, considering both operational and embedded carbon. The latter is responsible for approximately half of the emissions associated with the building sector [35].

Fig. 2 shows how operational carbon emissions (during the use phase) decrease as the energy efficiency of the building increases. However, the percentage of embodied carbon remains notably high for a building with high energy efficiency. Therefore, the overall environmental impact of an nZEB is lower than that of a conventional building [35,36].

Maierhofer D et al. [37] conducted a life cycle analysis to calculate both embodied and operational GHG emissions. Considering the current mix of the Austrian energy grid, they concluded that embodied emissions account for 33 % of all LCA emissions. On the other hand, operational energy use accounts for approximately 67 % of all LCA emissions. This research clearly shows that passive building concepts alone are insufficient to achieve net carbon goals, highlighting the necessity of employing renewable energy sources.

Tumminia et al. [38] contribute to the transition towards low-carbon energy technologies with their work. They study a building equipped with a photovoltaic system without energy storage. The results show that using storage systems, in addition to reducing grid dependence, can enhance the environmental benefits of renewable energy sources, thereby decreasing the total GWP. Rodríguez L et al. [39] evaluate decarbonization strategies for design and construction through LCA analysis. The main findings emphasize the importance of using renewable energy sources in buildings to offset the impacts generated by other life cycle stages, such as raw material extraction and final material production.

C. Salaris et al. have been working to decarbonize the construction sector by implementing techniques that result in sustainable buildings, in order to ensure an integrated approach to reducing the global carbon footprint [40,41]. Although no progress has been found in the literature in recent years since the nZEB definition was framed, there are many proposals at a legislative level to mitigate the rising average surface temperature of the earth. Nevertheless, these restrictive measures are implemented by Member Stages in the EU. Applying BIM methodology involves a holistic approach to the creation and management of a 3D model and highlights the digital transition where the building sector is undergoing [42–45].

Many researchers focus on reducing operational emissions through the use of renewable energy sources; however, few emphasize the importance of embodied emissions. Hegarty et al. [46] analyze the LCA of a specific residential sector. They describe the forecasts

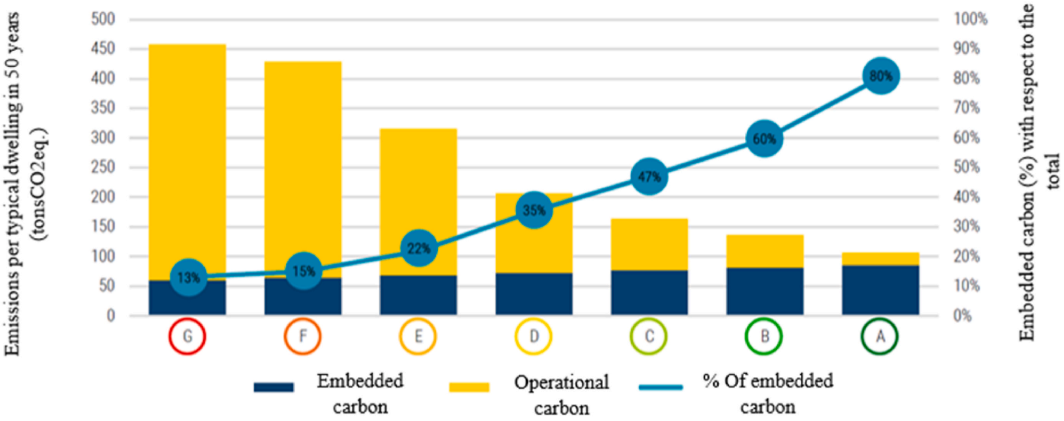

Fig. 2. Trend of embodied and operational carbon according to the energy rating of the Dwelling.

for operational emissions and the benefits that could be gained from the decarbonization of electricity. However, they assert that these benefits will be negated by the growth in embodied emissions associated with construction materials.

Cerezo-Narváez et al. [47] used a case study to analyze the energy, emissions, and economic impact on a townhouse located in various municipalities of Andalusia, Spain. In their research, they modified the building envelope, incorporating solar-thermal contributions to the domestic hot water supply and photovoltaic energy production to reduce electricity consumption. The results show a minimum energy savings of 69 %, a 65 % reduction in carbon emissions, and at least a 71 % reduction in energy bills (economic savings). The European objectives are exceeded by a wide margin.

Norouzi M et al. [48] evaluate the LCA of a low-energy house to address carbon footprint mitigation. Their goal is to investigate the potential reduction of GHGs in three different heating and ventilation options. The results show that using a compact heat pump leads to a 19 % reduction in the home's emissions. The authors emphasize the contribution of material efficiency strategies to reducing embodied carbon in future construction practices.

To assess the zero emissions of a university campus classroom building, a calculation tool is presented, analyzing the Life Cycle in the most representative phases, namely A1-A4 and B6, according to the previously mentioned regulations. Following the new guidelines of the EPBD 2024, the calculation of the proposed GWP indicator is established to determine the building's annual zero CO_2 equivalent emissions over its Life Cycle [49]. Likewise, an analysis of the impact of climate change on this type of building has been conducted, revealing that the cooling energy consumption increases while the heating energy consumption decreases.

1.1. *CASE STUDY: IndUVa nZEB*

This research examines the case of a nearly Zero Energy Building (nZEB) known as 'IndUVa,' situated in Valladolid, Spain, and affiliated to University of Valladolid (Spain) (Fig. 3).

The building has a total built area of 5846 m^2 spread across six floors and 34 classrooms accommodating up to 2500 students. The useable area of the building is 5540 m^2. It is structured into three longitudinal bands, with the two lateral ones (northeast and southwest facades) housing the classrooms (and ground floor facilities), while the central band corresponds to the circulation space. The building is occupied from 8 a.m. to 10 p.m. from Monday to Friday throughout the year, except for the months of July and August, summer holidays.

The Classroom Tower (IndUVa) has already been awarded the 5 GREEN LEAVES certification during the design phase, which represents the highest level of building sustainability certification in Spain. Additionally, it is striving for LEED PLATINUM certification on a global scale.

In the design of the IndUVa classroom building, cultural, technical, and social circumstances of the location have been considered, aiming to optimize its environmental performance and its conception as a high-energy-efficient building. Therefore, it has been conceived as a nearly zero-energy building with high internal thermal loads of variable and discontinuous patterns, which gives it a unique character. It employs a hybrid of passive and active technologies, renewable energy resources, demand management, and advanced passive solutions. A high-performance building envelope is strategically designed to reduce energy consumption. The heat transmission coefficients used in the building envelope are $U = 0.16\ W/m^2K$ for facades and $U = 0.15\ W/m^2K$ for green roofs. Additionally, high-insulation windows and low-emissivity, low-transmittance glass ($U = 1.10\ W/m^{2}{}^{\circ}C$) limit transmission losses, thereby reducing energy demand.

Due to its compact structure, the surface area exposed to the exterior is minimized, allowing for the reduction of losses and optimization of solar gains. Vertical sunshades are utilized to restrict solar gains and prevent glare.

This design achieves significant non-renewable primary energy savings with respect to the requirements of the Technical Building Code: 90 % in heating, 85 % in cooling and 75 % in lighting. In addition, the influence of the thermal inertia obtained in the facade

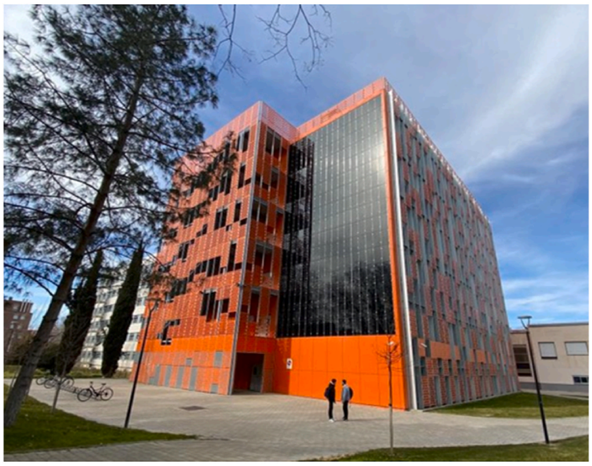

Fig. 3. IndUVa nZEB Building [50].

and the building structure (reinforced concrete) must be taken into account, especially on the roof, which has abundant vegetation covering more than 70 % of its surface.

The energy savings achieved are complemented by renewable energies (Fig. 4) and the integration of monitoring and optimized building management systems. Clean and sustainable energy sources meeting energy demand while reducing consumption and greenhouse gas emissions include:

Geothermal energy (Earth-to-Air Heat eXchangers, EAHX): This works as a support for the building's ventilation and air conditioning system, capitalizing on the stable temperatures of the shallow subsurface layer, which is warmer than ambient in winter and cooler in summer. The system consists of 28 buried pipes, 315 mm in diameter, and 2 m deep, providing an equivalent energy contribution of 29,654 kWh/year (17,136 kWh for cooling and 12,518 kWh for heating), thereby reducing the electricity required for indoor air conditioning.

Connection to the biomass urban heating network of the University of Valladolid, extending from the Miguel Delibes Campus (where the thermal plant is located) to the IndUVa building substation. This connection provides an equivalent energy contribution of 251,930 kWh/year.

Integration of photovoltaics on the southeast façade (Fig. 3): The sealing material of the ventilated façade is replaced with a photovoltaic glass cover. The system includes 272 panels installed vertically, producing 12,997 kWh annually. This achieves a reduction in the use of non-renewable primary energy by more than 10 %.

Regarding monitoring and control systems, advanced technologies and sensors have been installed. In every classroom, there is a CO_2 sensor and a temperature sensor to monitor ventilation demand. The SCADA (Supervisory Control and Data Acquisition) system automates the ventilation system along with the heat recovery units (EAHX) and the enthalpy rotary heat exchanger. This reduces energy consumption of the ventilation and cooling systems, supported by free cooling.

In terms of air conditioning installation, each classroom is equipped with a 4-pipe fan coil system that provides both heating and cooling.

The lighting system incorporates natural lighting with glass facades on the northeast and southwest sides for optimal light intake and protection against direct sunlight. Additionally, a Parans system captures natural light through fiber optics on the roof and transmits it indoors. Furthermore, high-efficiency LED technology is employed with DALI control equipment for energy-efficient lighting. Sensors ensure uniformity and energy savings.

Fig. 4 shows the building's renewable energy generation systems.

The building was designed with internal walls plastered and insulated with a thermal transmittance of 0.157 W/m^2 K and very high thermal inertia, thereby minimizing the impact of external temperature changes on the building. To minimize the environmental and life cycle impact of the building, it is constructed with materials certified for low carbon emissions.

Free cooling, heat recovery, and earth-to-air heat exchangers are strategies implemented in the building to enhance energy efficiency in ventilation. Fig. 4 depicts a simple schematic of all HVAC equipment and renewable energy systems in the IndUVa nZEB.

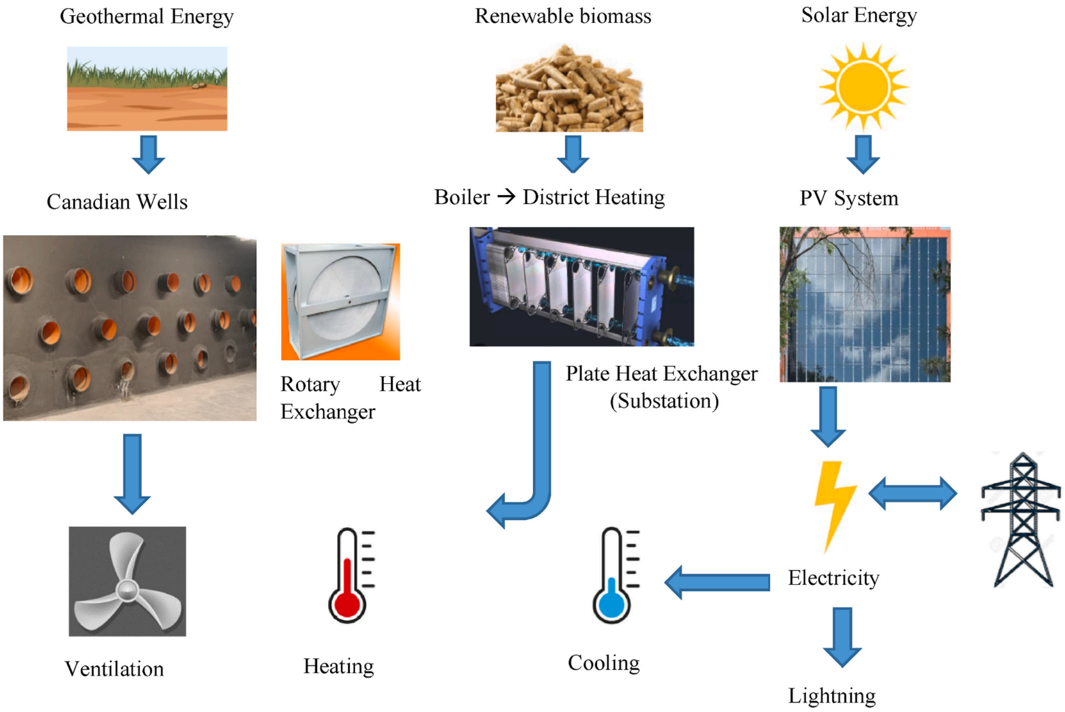

Fig. 4. Renewable Energy Generation Systems in the INDUVa nZEB.

2. Methodology

The building was validated. Subsequently, with the support of DesignBuilder software (Version 7), a calibrated simulation of the building's energy performance was obtained under different temporal scenarios (years 2050 and 2080). These results, available in Table 1 and Fig. 7, were used for studying the Energy Intensity (EI) indicator.

Furthermore, for the development of this study, the environmental indicator of operational and embodied Global Warming Potential (GWP) in the building's Life Cycle Assessment (LCA) was calculated. The methodology employed for calculating the total GWP of the building is outlined in Fig. 5 and further described in section 2.2. This indicator enables us to evaluate the building as a Zero Energy Building (ZEB) type.

The total Global Warming Potential (GWP) indicator of the building is calculated as the sum of the operational and embedded GWP. For the operational GWP, we conducted a calibrated dynamic simulation, using energy consumption data from a typical year and the emission conversion factor to obtain the kg CO_2 equivalent, the unit of measurement for this indicator. For the embedded GWP, an inventory of the materials used in the construction process was performed, and by relying on Environmental Product Declarations (EPDs), we calculated the kg CO_2 equivalent.

2.1. Energy Intensity (EI) Indicator

The energy efficiency indicators (IE final energy consumption), (IE_{pnr} non-renewable primary energy), (IE_{pr} renewable primary energy) and (IE_p total primary energy) represent the energy intensity of final and primary renewable and non-renewable consumption per useful m^2 of the building and per year.

Total primary energy represents the sum of non-renewable primary energy and renewable primary energy. Primary energy consumption is the key parameter for reporting the energy performance of EU buildings [51].

Table 1
Energy intensity indicators (kWh/m^2 year).

	EI Final Energy
2022	37.47
2050	31.67
2080	28.69

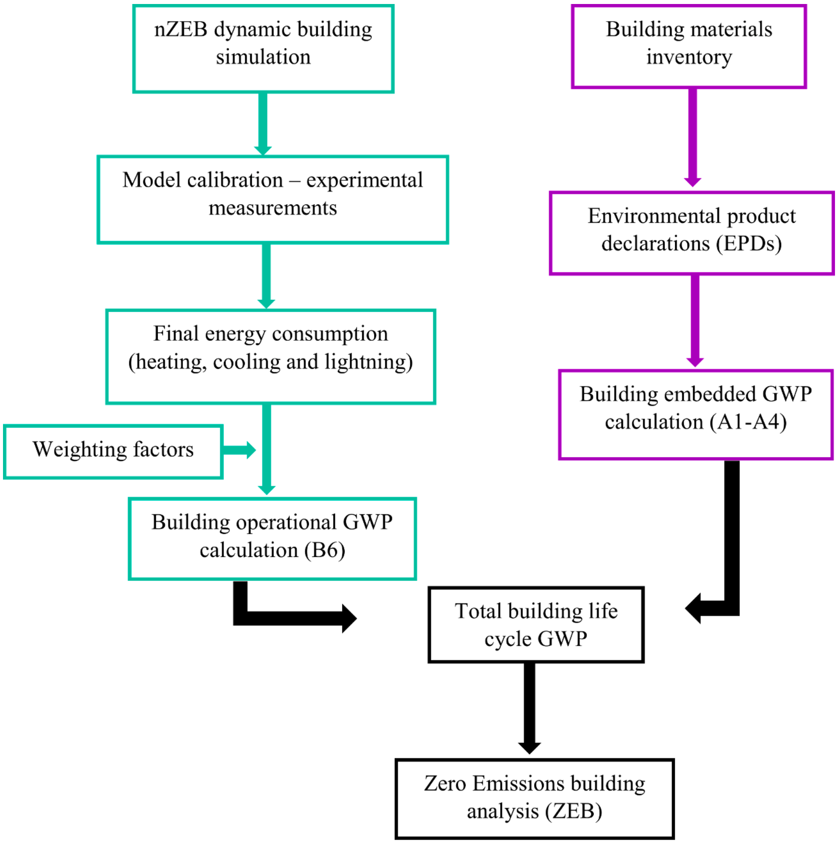

Fig. 5. Methodology used in the Calculation of Total GWP.

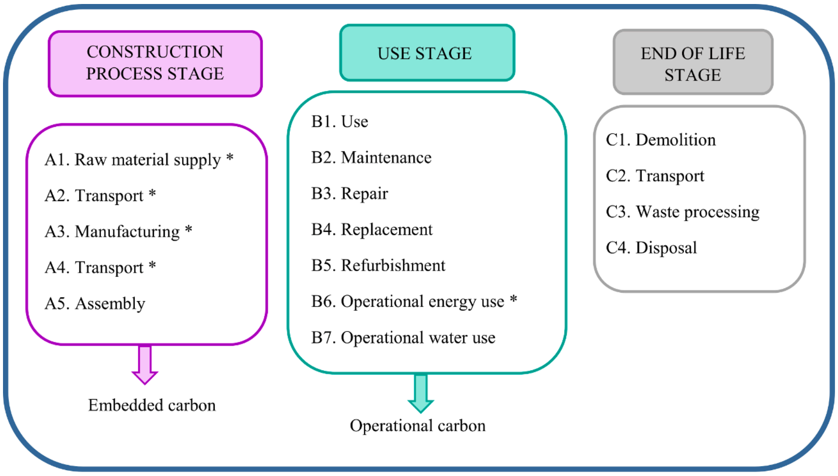

Fig. 6. Description of the LCA phases according to EN 15978.

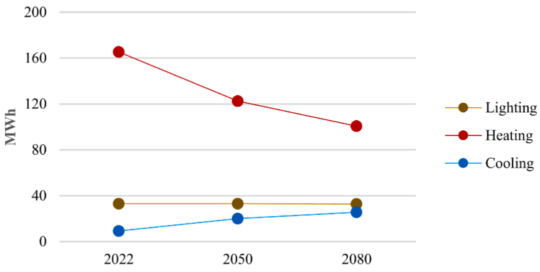

Fig. 7. Final Energy Consumption (MWh/year) at IndUVa nZEB.

2.2. *Global Warming Potential Indicator (GWP)*

The measurement of carbon throughout the building's life cycle is indicated by the Environmental Indicator known as Global Warming Potential (GWP). To assess the carbon footprint impact, the “cradle-to-grave” methodology, as defined in EN 15978 standard, is employed.

The stages considered by this standard are reflected in Fig. 6: (i) component manufacture (A1 + A2 + A3), where A1 is the supply of raw materials, A2 is the transport of raw materials and A3 is the manufacture of the product; (ii) building construction, which consists of the transport of materials to the factory (A4) and the on-site assembly of the building (A5); and (iii) operational energy use (B6).

Depending on the life cycle phase being analyzed, a distinction is made between embodied carbon and operational carbon. Fig. 6 outlines the life cycle phases according to this standard and illustrates the concepts related to embodied and operational carbon.

This study has been focused on the modules marked (*) (Fig. 6), as they account for over 80 % of carbon emissions, as indicated in the introduction (Fig. 1). Stages A1-A3+A4 quantify embodied carbon, while stage B6 refers to operational carbon.

2.2.1. *Operational GWP*

The GWP equivalent to operational CO_2 emissions (module B6 of the UNE-EN 15978 standard) quantifies the GHG emissions associated with the energy consumed during the building's use phase (operational) to maintain habitable conditions indoors, encompassing both heating and cooling systems as well as lighting.

In the results section, Table 1 presents the final energy consumption data of the nZEB building obtained through the DesignBuilder simulation program for the temporal scenarios of 2022, 2050, and 2080. Using the energy consumption data from a typical year (year 2022) and employing the emission conversion factor (according to Spanish regulations published by the ministry [52]), energy consumption was converted to $kgCO_2$ equivalent.

Table 5 displays the results of the environmental impact assessment of the building under climate change during the use phase. These emission results are presented as kilograms of CO_2 equivalents per square meter of useable interior surface area, which is the unit of measurement for GWP [53,54].

2.2.2. *Embedded GWP*

Embodied energy is measured as the amount of non-renewable energy per unit of material, component or building system [55].

The initial embodied carbon refers to the GHG emissions associated with the energy consumed in the production phases (stages A1-A3, according to the reference standard UNE-EN 15978), meaning the emissions occurring before the building is put into use, encompassing both the materials used and the construction processes. The transportation of materials, stage A4, is also considered.

The methodology used to calculate embodied CO_2 is based on the construction material inventory, considering Environmental Product Declarations (EPDs). EPDs are described by ISO 14025 standard.

As mentioned in the building description, construction materials are recycled with low carbon emissions. This directly affects the embodied CO_2 value and consequently the final value of the GWP indicator. The percentage in economic cost of recycled materials compared to the total materials used is 30 %.

3. Discussion and results

This research investigated how climate change and location affected the projected energy use of a real building until nearly the end of the century. The building was first validated through measured data (year 2022), and then DesignBuilder Software was used to obtain a calibrated simulation of the building's energy performance performance in different scenarios (years 2050 and 2080).

The available climate files for 2022 were used to analyze energy use in the building. This provided data for 2022 on heating (80 %), cooling (4 %), and lighting (16 %), as shown in Fig. 7. Additionally, calibrated simulation data for the future scenario under study are presented.

The annual heating energy consumption of the building decreases over time, as shown in Fig. 7. In 2050 scenario, it decreases by approximately 25 %, and by 39 % in the 2080 scenario, compared to the present. However, the annual cooling energy consumption increased by 100 % for the 2050 scenario and by 170 % for the 2080 scenario. On the other hand, lighting energy consumption remained almost constant in all temporal scenarios studied (Fig. 7).

Since lighting consumption remains nearly constant over the years, the percentage contribution of energy use will only be modified in heating and cooling consumption. Heating accounts for 95 % of the total final energy consumption of the building in 2022 and decreases to 86 % in 2050 scenario. However, the final cooling energy consumption of the building in the 2050 scenario will increase by 9 %. Analyzing 2080 scenario, the variation in final heating energy would be a decrease of 63 %, and cooling would represent an increase of 21 %.

Regarding the energy sources used in the building (Fig. 4), it is important to note that cooling consumption is electric (non-renewable), while heating consumption is supplied from biomass (renewable energy).

Heating consumption was reduced by 43,000 kWh in 2050 and 66,000 kWh in 2080 compared to 2022 values. Fig. 8 shows the trend of total monthly final energy consumption for heating over several years under the impact of climate change.

One of the direct consequences of climate change is the inevitable rise in temperature (Fig. 8). It is logical to expect that the demand for heating during the cold months of the year will decrease in each future scenario.

Fig. 9 shows the monthly variations in cooling energy consumption, with increases of 10,000 kWh and 16,000 kWh for the 2050 and 2080 scenarios, respectively, with respect to the 2022 scenario. During the months of July to August, IndUVa nZEB is closed (summer holidays).

When analyzing cooling consumption, the opposite effect occurs. Given that the impact of climate change will be even more critical during the summer months, the demand for cooling will be higher in each future scenario. This poses a challenge since cooling in INDUVa building is provided by non-renewable energy sources, which does not aid in decarbonization. However, it is reasonable to expect that by the 2050 and 2080 scenarios, the European Union will have adopted measures to ensure that a significant portion of electricity supply comes from renewable sources.

a) Energy Intensity (EI) Indicators.

Based on the energy consumption data and the useable floor area of the building, we can quantify the final energy indicator (Table 1).

It can be seen how this indicator decreases as global warming increases in each time scenario. The indicator is lower in the 2080 scenario, which means that greater decarbonization is obtained.

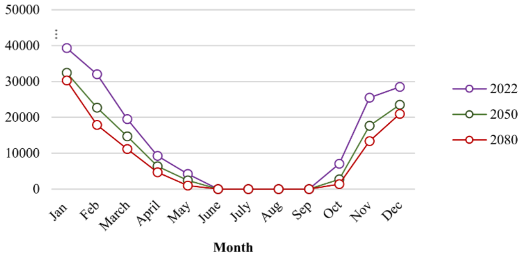

Fig. 8. Annual Heating Consumption in the three Scenarios under Study.

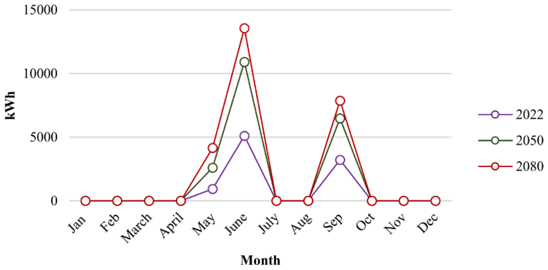

Fig. 9. Annual Cooling Consumption in the three Scenarios.

Table 2 shows the final energy consumptions broken down into heating, cooling, and lighting. Considering the conversion factors from final to primary energy for each energy source, the data for total primary energy consumption, renewable primary energy, and non-renewable primary energy for each category are obtained [56].

According to the useful surface of the building, Table 3 shows the data of the energy indicators associated to each consumption.

Comparing the results from Table 3 with the CTE DB HE 0 (Limitation of energy consumption, Spanish Standards [57]), it is evident that the building under study aligns closely with nearly Zero Energy Building (nZEB) standards.

b) GWP Indicator. (CO_2 operational + CO_2 embedded)

The lowest final energy consumption of the building, and consequently operational CO_2 emissions, occur for all three temporal scenarios during the months of April and December, coinciding with reduced energy usage due to holiday periods. Conversely, owing to high total cooling demands, peak energy consumption transpires during June and September (Fig. 10).

In 2022, the total operational CO_2 emissions amount to 66,635.33 kg CO_2. The unit of measure for the GWP indicator is kg of CO_2 equivalent per square meter of useable interior area for a reference study period of 50 years.

Throughout its lifespan, the building will have emitted 3,331,766.3 kg of CO_2. Therefore, considering the building's useable area, we can express the GWP value in the in-use phase (B6) in its units of measure. Hence, the CO_2 impact in the building's use phase amounts to 601.43 kg CO_2 eq./m^2.

Table 4 quantifies the operational GWP indicator value of the building in each temporal scenario. This table is based on the EU's objective to decarbonize the planet by increasing the use of renewable energies. It considers final consumptions (Table 1),

Table 2
Energy consumptions (kWh/year).

	Final Consumption	Total Primary Consumption	Renewable Primary Energy Consumption	Non-renewable Primary Energy Consumption
Heating	165,290	171,405.73	165,785.87	5619.86
Cooling	9270	21,951.36	3837.78	18,113.58
Lighting	33,020	78,191.36	13,670.28	64,521.08

Table 3
Energy intensity indicators (kWh/m^2 year).

	IE final	IE_p	IE_{pr}	IE_{pnr}
Heating	29.84	30.94	29.93	1.02
Cooling	1.67	3.96	0.69	3.26
Lighting	5.96	14.11	2.47	11.65
Total	37.47	49.01	33.09	15.93

Fig. 10. kg/month of Operational CO_2 by 2022.

Table 4
Evolution of the GWP indicator with climate change.

	2022	2050	2080
Operational GWP (kg CO_2 eq./m^2)	601.43	0.39[a]	0.33[a]

[a] 100 % Renewable Electricity.

Table 5
CO_2 emissions during construction and transportation (embedded CO_2).

Materials	GWP (kg CO_2 eq.) A1-A3	GWP (kg CO_2 eq.) A4
Stones and Soils	0 (100 % recycled)	1900.21
Steels	449,690.03	4385.1
Aluminum	1,716,983.05	15,128.60
Bronze and Zinc	13,451.76	365.43
Ceramics and Stoneware	51,828.3	501.81
Wood	68,288.39	1461.7
Plasterboard	0 (100 % recycled)	5393.67
Concrete	4,527,117.24	33,114.81
Mineral Wool	770.92	418.05
Extruded Polystyrene	1623.42	287.22
Glass	105,498.54	438.51
PVC	179,620.2	73.09
PV Panels	133,008	51.16
TOTAL	**7,247,879.85**	**63,519.35**

considering the CO_2 emission factor for densified biomass [56] and assuming that the CO_2 emission factor for conventional mainland electricity is zero in the years 2050 and 2080 (100 % Renewable Electricity)

Analyzing these results, it is evident how the operational GWP indicator (during the building's use phase) decreases drastically with climate change if, for the 2050 and 2080 scenarios, the measure of generating electricity renewably has been taken.

The inventory of construction materials used in the construction of the IndUVa nZEB is shown in Table 5. By relying on the EPD, it can be quantified the CO_2 emissions in the life cycle phases corresponding to embodied carbon, namely, phases A1-A3 + A4.

Therefore, the CO_2 impact in the construction phase (A1-A3) amounts to 1308.35 kg of CO_2 eq/m^2, which is the unit of measurement for GWP. The transportation phase of materials adds 11.47 kg of CO_2 eq/m^2 to this figure. The total embodied carbon impact (A1-A3+A4) constitutes a release into the atmosphere of 1319.82 kg of CO_2 eq/m^2.

The results indicate that the impact is much lower in operational carbon than in embodied carbon. This is shown in Fig. 11.

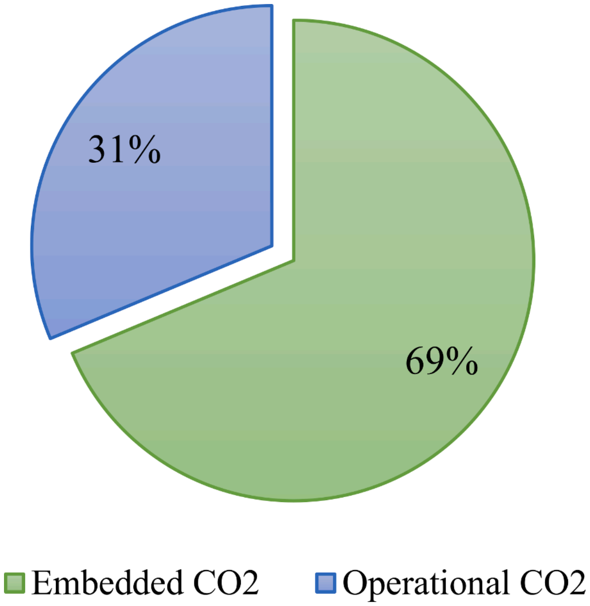

Fig. 11. Percentage of CO_2 Embedded and Operational in 2022 at IndUVa nZEB.

It is evident from analyzing the results that operational carbon emissions are significantly lower when dealing with a high-energy-efficient building. On the other hand, the percentage of embodied carbon is notably high for a building with these characteristics. These findings align with Fig. 2 in the introduction.

To further decrease lifecycle emissions, a greater contribution of energy generation in the building or increased use of materials with low emissions is required [58].

The results highlight the necessity of integrating life cycle thinking into building design and policy. The shift towards a circular economy in the construction sector, as advocated by the European Union's EPBD directive, will be crucial for achieving sustainable and resilient building stocks. This approach not only entails the recycling and reuse of construction materials but also optimizing building maintenance and end-of-life strategies to minimize overall environmental impacts. This comprehensive focus on reducing both operational and embodied GWP is essential to align with long-term climate goals and ensure the sustainability of future nZEBs.

4. Conclusions

This study presents an energy analysis of a university classroom nZEB. Constructing buildings with these features instead of conventional ones can reduce global energy consumption and carbon footprint since energy is generated within the building itself. The study analyzed shows how the total final energy consumption for heating (renewable) was 95 % in 2022 and is reduced to 86 % by 2050 owing to the reduced need for heating due to warmer winters. On the other side, the increased need for cooling from hotter summers increases the total final energy consumption for cooling (non-renewable) by 9 % from 2022 to 2050. According to the results, the building's renewable energy contribution is 67 %, surpassing what Europe is demanding by 2030. It is concluded that climate change favors nZEB buildings like IndUVa, as indicated by the final IE indicator, which decreases from the reference year 2022–2050 by 15.48 % and by 23.43 % by 2080.

CO_2 equivalent emissions was calculated using the Life Cycle Assessment (LCA) GWP indicator for in 2022, following the proposed methodology. Operational CO_2 equivalent emissions, represented by the operational GWP indicator, where current emission factors from the Spanish government must be considered, have a very small value over a 50-year timeframe. The results demonstrate that in an nZEB building, operational carbon emissions are much lower (601.43 kg CO_2 eq./m^2) than embodied emissions (1319.82 kg CO_2 eq./m^2). Specifically, we are talking about 31 % operational and 69 % embodied emissions. However, in most existing literature on traditional buildings, the value of operational GWP is significantly higher than embodied GWP.

Based on the results shown for this LEED-certified nZEB of embedded carbon emissions, the construction materials that contribute the most pollutant emissions to the atmosphere are concrete and aluminum, with values of 4,527,117.24 and 1,716,983.05 kg of CO_2 eq. respectively. Furthermore, when 100 % recycled materials are used, this contribution has a negligible value. According to the EU's energy transition and climate change, all electricity generation in Spain will be produced by renewable technologies by 2050 and 2080. In these cases, the operational GWP will be almost zero, meaning the impact of climate change on nZEB buildings for the operational GWP indicator will be practically Zero emissions, ZEB.

In these future scenarios, due to climate change, while the energy efficiency indicator for nZEB buildings will be very low, tending to zero, as well as the operational emissions of the building, it is then that it must be analyzed the embodied emissions of the building. Materials, transportation, maintenance, recycling, and reuse (LCA) will weigh more heavily on the total GWP indicators. Thus, the next objective set for the coming years will be to reduce the embodied GWP of the building in order to achieve zero-emission buildings, ZEB, as mandated by the new EU EPBD directive.

This groundbreaking study not only adheres to rigorous sustainability standards but also underscores the transformative potential of nZEBs in substantially curbing global energy consumption and carbon emissions. Through the implementation of the advanced methodology outlined in this research, we unlock the possibility of effectively mitigating the effects of climate change.

This study highlights the crucial need to address both operational and embodied emissions in the quest for zero-emission buildings (ZEBs). While operational emissions in nZEBs are expected to significantly decrease due to the increasing reliance on renewable energy by 2050, embodied emissions will become the dominant factor in the building's overall carbon footprint. Reducing embodied Global Warming Potential (GWP) requires a comprehensive approach that incorporates low-carbon materials, improved construction methods, and the reuse and recycling of high-impact materials like concrete and aluminum. To fully realize the carbon reduction potential of nZEBs, it is essential to adopt life cycle-based strategies that extend beyond operational efficiency and focus on minimizing embodied carbon. This calls for innovative material solutions, sustainable design practices, and strong policy support, aligning with the European Union's ambitious zero-emission goals. By advancing construction technologies and emphasizing material circularity, the building sector can play a pivotal role in mitigating climate change and advancing towards a decarbonized future.

CRediT authorship contribution statement

Amalia Palomar-Torres: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Javier M. Rey-Hernández:** Resources, Data curation. **Alberto Rey-Hernández:** Formal analysis, Data curation. **Francisco J. Rey-Martínez:** Validation, Supervision.

Declaration of competing interest

“The authors declare no conflict of interest."

Data availability

The data that has been used is confidential.

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