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LCA of the NZEB El Salvador building, a model to estimate the carbon footprint in a tropical country

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ABSTRACT

Life cycle assessment (LCA) in buildings is an objective process that evaluates the environmental burdens generated by their entire life cycle. In this way, it works as feedback to the building design and construction process, highlighting better choices of materials and construction systems, when evaluating decarbonization strategies. This article summarizes the findings from the implementation of an LCA in a net zero energy building (NZEB) located in El Salvador, Central America, on the campus of the Central American University. The assessment determined the carbon and energy impacts generated by the building, with an emphasis on its construction systems, throughout the life cycle. Two LCA methodologies were applied. The first one was a simulation by means of the SimaPro 9 software faculty version and the Ecoinvent database, under the cradle-to-grave approach. The second one was a calculation aided by an interactive table created by Bath University, United Kingdom, which is based upon the Carbon and Energy Inventory (ICE) utilized for calculating buildings' built-in impacts under the cradle-to-gate approach.

The main results highlight the importance of using renewable energy as a building's energy source, to avoid and compensate for impacts generated by other stages of the life cycle, for instance, the stage of raw materials extraction and final materials production, which generate the most significant impacts, from both the energy and carbon equivalent perspectives. Therefore, materials selection becomes crucial for reducing or avoiding impacts within a building's structure throughout its useful life. Also, applying circular economy principles through the reuse and recycling of materials is fundamental to minimizing the life cycle impact of a building in this context.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) recently urged immediate and accelerated actions to mitigate global emissions (Lee et al., 2023). Those actions include implementing efficient buildings, fuel switching, construction material substitution and onsite renewables. Sustainable and Net Zero Energy Buildings (NZEB) are an alternative for the decarbonization of the building sector. The topic of life cycle assessment (LCA) of sustainable buildings in tropical climates has been explored in the literature. For instance, in one study, the life cycle assessment (LCA) of a passive house in the sub-tropical climatic zone indicated that the envelope (floors and wall systems) contributed considerably to the environmental performance of the energy efficiency without burdening substantially its total embodied energy (Kylili et al., 2017). Another study on LCA of university buildings in a tropical climate, suggests including material reusing, recycling, and use of low-carbon building materials, to reduce the share of building embodied energy (Chang et al., 2019). In the same way, another study on the ranking of materials using eco-efficiency for tropical climatic conditions, integrated the life cycle thinking approach with eco-efficiency analysis, to compare and evaluate the materials, and persuade building developers, to select the most desirable for their projects, considering costs and environmental impacts of the material life cycle (Gurupatham et al., 2021). However, despite some progress, the environmental impact of these buildings throughout their life cycle is poorly understood, particularly in tropical building contexts, given the incipient use of standards that regulate energy consumption and materials in a building.

If the overall impact of materials is unknown, decarbonization goals may be negatively impacted, even if the building generates energy on site. In other words, if the environmental impacts of extracting raw

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materials are more severe than the benefits of net zero energy operation, the overall result is not optimal. This article determined the embodied energy and embodied carbon of an NZEB pilot project in El Salvador, Central America, at latitude 13°41′56″N, whose climate is Tropical Savannah type (Peel et al., 2007), identifying that certain materials which contribute to energy efficiency can cause the most significant life cycle impacts in terms of embodied carbon.

This project is consistent with the Sustainable Development Goals (SDG), promoted by the United Nations for the period 2015–2030, which consider global warming, innovation, and sustainable consumption. Moreover, among the 17 objectives, Goal 7 stands out: “Affordable and clean energy” whose target for 2030 requires: “Ensure access to affordable, secure, sustainable and modern energy for all”, “Double the global rate of improvement in energy efficiency” (Nations, n.d.). Under this global context, and as a contribution to the aforementioned SDGs, the research project “Net Zero Energy Buildings in El Salvador”, was implemented as a pilot project for the development of high-performing sustainable buildings in the tropics.

A net zero energy building, NZEB, by definition, produces, through renewable sources, all the energy required for its operation within the constructive building’s footprint (Marszal et al., 2011) (Sartori and Hestnes, 2007) (Pless and Torcellini, 2010). This is a concept widely researched internationally, but modestly explored in the Central American region. There are still many questions related to the viability of this concept in tropical latitudes, regarding design, construction, and energy use patterns. For an NZEB-type building to take advantage of self-produced energy throughout its life cycle, it must have been designed with energy efficiency concepts. This implies making use of passive design strategies (architectural elements and construction systems with thermal characteristics that avoid excessive solar gains, elements that enhance the use of natural lighting and ventilation, among others), as well as active strategies (control and high efficiency of mechanical, lighting, ventilation and air conditioning systems, achieving the best performance with the lowest energy consumption).

The research project that provided the foundation for the present work included the design, construction, and monitoring of a 100 m^2 laboratory with an energy performance that exceeds ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) 90.1–2013 Standard (Energy Standard for Buildings Except Low-Rise Residential Buildings) requirements by 42% (Martínez et al., 2020) (L. Martínez et al., 2018). The study was conducted in three phases, as shown in Fig. 1.

- Phase I, Generation of initial model: In which are considered, the owner project requirements (OPR), the site study, which is then fed back by the basis of design (BOD) and design regulations.
- Phase II, Iterative optimization process: It begins with the process of energy simulation, lighting simulation and air flow. In this case fourteen iterations were made to reach an optimized load model that finally gave way to the calculation of renewable energy potential (ASHRAE, 2013).
- Phase III, Generation of technical and legal documents: Development of construction plans, technical specifications, programming of works, budget and construction permits which open the way to the building construction that later, during the operational stage of the building, allowed to make energy measurements in order to control and study energy consumption and generation.

The data collected during the three phases are the foundation for a global life cycle assessment over NZEB El Salvador, under the standard of ISO 14044 which establishes that the analysis of the life cycle of a building, requires the evaluation of each one of the building’s life stages, from the extraction of raw materials, the production and distribution of energy, to the use, reuse and final disposal of a product (Standardization, 2006). LCA is a tool intended for comparison options, rather than absolute evaluation, helping decision makers in a design process to

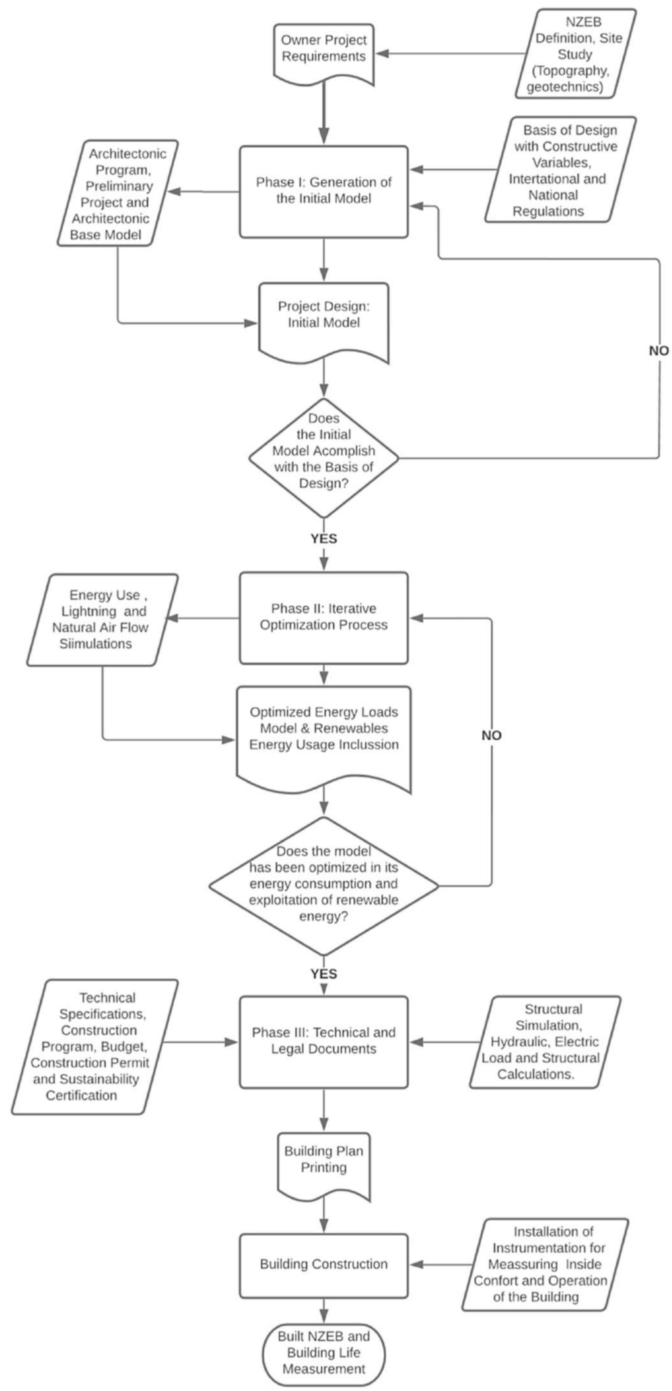

Fig. 1. NZEB building design methodology with ASHRAE standards (L. A. Martínez et al., 2023).

evaluate the main environmental impacts when comparing between alternativeconstruction systems and materials. (Curran, 2008), especially when referring to high performance materials, which is the case of materials that make up the structure and the envelope, which are an essential part of a building. The structure affects the building safety and integrity, in the case of the envelope, it affects energy efficiency, and in the case of buildings whose façade is made up of structural walls, a comprehensive analysis is required, in order to optimise materials that comply with structural and energy standards, as is the case of NZEB El Salvador.

The aim of this work is to implement the methodology of life cycle assessment (LCA), in a net zero energy building (NZEB) located in El

Salvador, in order to determine the environmental impacts characterized by two metrics: Embodied Energy and Embodied Carbon (CO2 equivalent), considered relevant in the construction industry, (Hammond and Jones, 2008), These metrics aim to measure the energy and carbon inputs throughout the life cycle and understand how each stage contributes to the overall impact.

NZEB design focuses on ensuring that the operational stage is free of emissions. However, other stages in the life cycle can cause emissions, and the research question is how to minimize the overall life cycle impact of a building, including embodied carbon and embodied energy? The LCA methodology can help answer that question by evaluating the effectiveness of two strategies implemented in NZEB El Salvador: 1) embodied impacts evaluation of a design carried out under the principles of industrialized prefabrication and 2) evaluation of the potential impacts avoided in the end-of-life scenarios, that is, to evaluate the design strategies for disassembly (Dodd et al., 2017).

According to the LCA methodology there are four phases: Objective and scope, inventory analysis, impact analysis and interpretation. The objective and scope is to characterize the environmental impacts in the different stages of the life cycle of the NZEB El Salvador building to verify if there is balance in the life cycle equation (1) (Chau et al., 2015) with the vision of circularity and reversibility equation (2) (Rodríguez et al., 2023). Equation (1) shows the carbon cycle at all stages of a building under the "cradle to grave" approach. However, to verify the investigative question, the new concept of circularity called "new life" is introduced. Equation (2) synthesizes extraction and manufacturing as manufacturing and contemplates in the operation the energy consumption, maintenance and remodeling scenarios, as well as the potential for energy generation that is the case of NZEB buildings.

$$CO_{2total} = CO_2extraction + CO_2manufacture + CO_2building + CO_2operation + CO_2demolition + CO_2recycling + CO_2disposal \quad \text{(Eq. 1)}$$

$$CO_2 = CO_2fabrication + CO_2building + CO_2operation + CO_2new\ life \quad \text{(Eq. 2)}$$

According to the ISO 14041 standard, the inventory analysis requires the collection and quantification of inputs and outputs of the building, NZEB El Salvador was broken down into each material considered in the construction systems organized according to two types of carbon inventory databases, an open database and a closed one. Finally, life cycle interpretation should be a systematic technique for identifying, quantifying impacts assessment. This phase requires a set of conclusions and recommendations for the design team (Muralikrishna and Manickam, 2017).

The different types of analysis are a simplified form of LCA, with a specific focus according to the research objective. In the case of NZEB El Salvador, two variants of these approaches have been developed: the Life Cycle Energy Assessment (LCEA) and the Life Cycle Carbon Emissions Assessment, LCCO2A).

The life cycle of a building is summarized of four stages: manufacturing, construction, operational stage, and final disposal. The manufacturing stage begins with the extraction of raw materials, which can be of recycled origin, transporting these to production centers, followed by the construction materials manufacture. The construction stage covers from the materials distribution to the site and the assembly process of the entire building. The operational stage is the period from the completion of construction to the end of its life. At this stage, the necessary maintenance during the useful life is considered (Basbagill et al., 2013). The final disposal stage begins at the end of the building's useful life, considering final disposal scenarios, where after the disassembly or controlled demolition of the building, there is an option to reuse, recycle or deposit the remaining waste in landfills (Jusselme et al., 2020) (Fig. 2).

2. Bases for the life-cycle assessment of NZEB El Salvador building

2.1. Construction systems of the NZEB El Salvador's building

Despite being only one hundred square meters of construction, the complexity of the NZEB El Salvador's building has been considered and divided into construction systems (Table 1) to facilitate the analysis, based on the sets of elements that make up a unit of a constructive objective, whether structural, enclosure, or as thermal insulation. These are sixteen construction systems, namely: Foundations, first-level walls, mezzanine, staircase, second-level walls, trusses, roof structure, roof, hydraulic installations, electrical installations, mechanical installations, floor finishes, wall finishes, doors, windows, sanitary appliances and accessories, and Photovoltaic panels.

2.2. Considerations for the operational stage

Within the operational stage, two aspects have been taken into account: Both maintenance, treatment of exposed wood and retouching of paint walls, as well as annual energy consumption and generation. These aspects have been calculated for a period of the building's useful life, 50

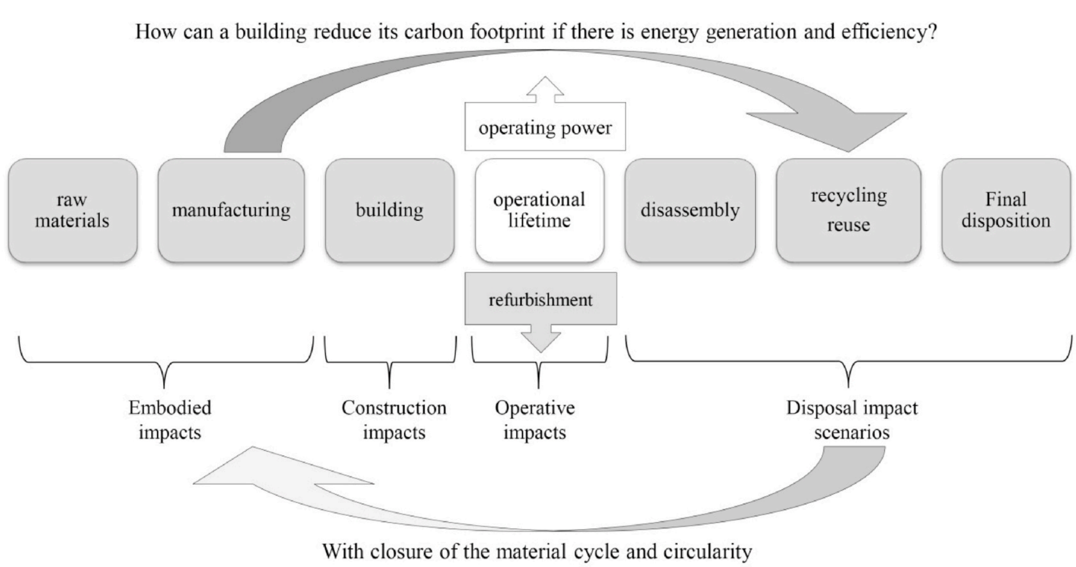

Fig. 2. Stages of the life cycle methodology. Own elaboration based on data from (Chau et al., 2015).

Table 1
Construction systems and groups of construction systems.

Groups of construction systems (for simulation methodology)		Construction systems (for calculation methodology)	
FON	Foundations	FON	Foundations
FLW	First level walls	FLW	First level walls
MEZ-S	Mezzanine and staircase	MEZ	Mezzanine
		STR	Staircase
SLW	Second level walls	SLW	Second level walls
R-ST-T	Roof structure, roof and trusses	TRU	Trusses
		R-STR	Roof structure
		R	Roof
H–I	Hydraulic installations	H–I	Hydraulic installations
		SAA	Sanitary appliances and Aaccessories
E-I	Electrical installations	E–I	Electrical installations
M-I	Mechanical installations	M-I	Mechanical installations
F–W–F	Floor and wall finishes	F–F	Floor finishes
		W–F	Wall finishes
D-W	Doors and windows	D	Doors
		W	Windows
FOTV	Photovoltaic panels		

years as stipulated by the European Union Level(s) framework (Dodd et al., 2017).

Within the maintenance, it is planned to be carried out every four years, and treatments against xylophages intended for exposed wood, low volatile organic compounds (VOC), as well as sealant and waterproofing, dye and varnish. Moreover the paint retouching of interior and exterior walls is considered too.

For the consumption and energy generation of the building, measurement data are taken from March to December 2019. The data for January and February 2019 are averaged between the data for March, April and May, since this period was for calibration of instruments. Likewise, it is assumed that the energy consumed in the building throughout the year is mostly generated by solar panels. Such generation is significantly greater than the energy consumed by the building from the local power grid. The net residual positive energy is injected into the grid of the Central American University, which, as a result, sustains a decrease in the use of energy from the external supply network (Chichique et al., 2021).

A fundamental part of carrying out the analysis of the NZEB El Salvador's life cyclis the energy measurements, since it is possible to know the actual consumption of the building and the amount of energy it generates. In addition, it allows greater precision when obtaining the life cycle analysis results (Asdrubali et al., 2013), since it is not using hypothetical simulation data, but rather, from building data in one year of use.

The annual energy consumption of the NZEB building, according to the measurements made in 2019, is 4556,37 kWh while the annual energy generation is 12626,85 kWh. If the building's useful life of 50 years is assumed, the total energy consumed would be 227818,67 kW h and the generated energy would be 631342,50 kW h, which is almost 3 times the energy consumed (Funes et al., 2020) (Fig. 3).

2.3. Final disposal scenarios

At the end of the useful life, alternatives are proposed for handling and treating the components. These alternatives will depend on the context, technical and environmental conditions, and the characteristics and specifications of the elements to be treated. Among the management and final disposal alternatives can be mentioned: The deposition in a landfill of the residual components, the reuse of elements while maintaining their constructive value without being underused, elements of treated wood converted into firewood or formwork wood, or the recycling of objects through some process that involves a transformation that invests extra energy and melting of metal components for transformation into new elements, these alternatives are effective after a process of controlled building disassembly.

Considering these aspects, the possibility of recycling or reusing the building's materials was analyzed, based on studies (Asam, 2007) (Huuhka, s., Naber, N., Asam, C., Caldenby, 2019), (Instituto de Tecnología de la Construcción e Cataluña (ITeC), 2022) (Hillebrandt, 2019) (Dodd et al., 2017). The result yielded the total building percentage that could be recycled (47%), reused (23%) or disposed of with final destination being a landfill (30%)

For analysis purposes, two possible scenarios are proposed:

- Scenario 1: A disassembly process is carried out, in which the integrity of its parts or the separation of its materials is not a priority, since all the building's waste resulting from this process is transferred to the landfill to accomplish the necessary processes for its disposal.
- Scenario 2: The possibility of the building undergoing a disassembly process is considered with the vision of recovering the materials and constructive elements. Also, it considers that the process of recycling and/or waste reuse can be optimized. This is possible, thanks to the constructive prefabrication technologies used in the building.

For example; if the assembly is screwed, bolted, welded, or monolithically set, if the union of materials becomes a fusion, adhesive, or if they are kept separate, in short, it is evaluated with percentages, the loss of integrity when disassembled in a controlled manner based on cases and reference literature. The evaluation was carried out for the materials grouped into families, which make up the construction systems and have been grouped into nine families of materials (Fig. 4).

By introducing into the system scenarios other than final disposal in landfill, there is a reduction in impacts in the case of recycling and an increase in environmental credits for benefits beyond the limits of the system in the case of reuse.

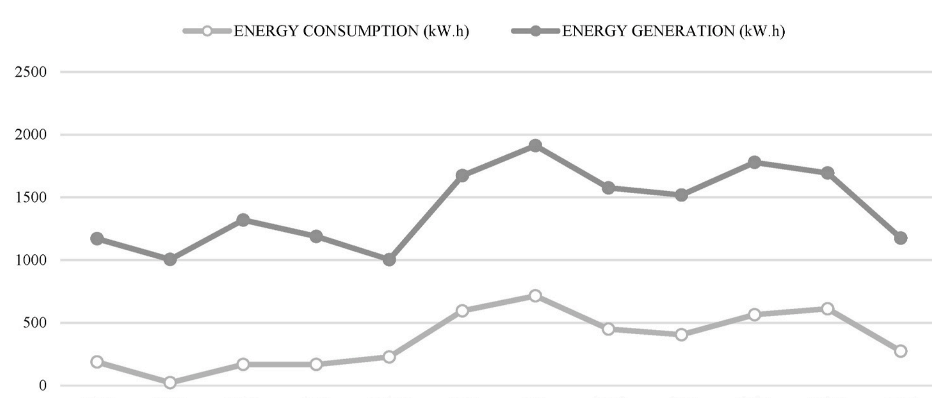

Fig. 3. Graph of energy consumption and generation in one year (kW.h). Own elaboration with data from (Funes et al., 2020) (Hernández et al., 2019).

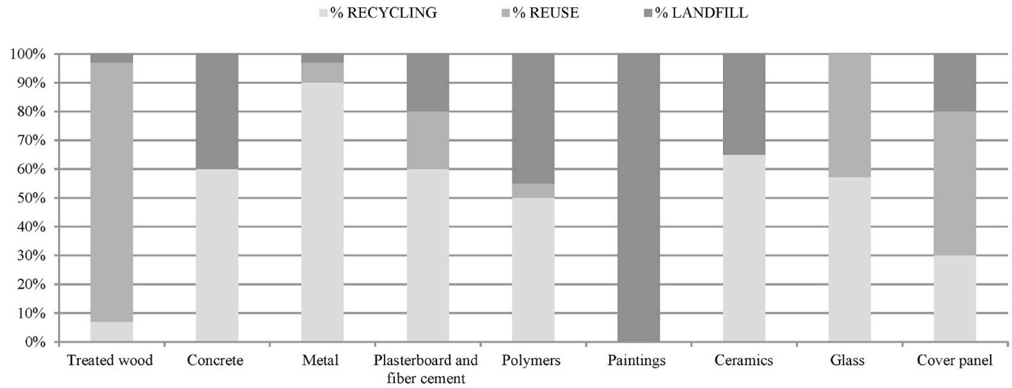

Fig. 4. Types of final disposal by material. Own elaboration.

3. Application of LCA methodology in NZEB El Salvador

The application of the methodology called Life Cycle Assessment in this research, is carried out in two parts. The first one is called calculation methodology with the ICE database, which has a cradle-to-gate approach. It focuses on the materials used for the building construction and the incorporated impact provoked by their use. The second part is named simulation methodology. It has a cradle-to-grave approach, which changes the focus and shifts it towards identifying, the life cycle stages generating more impact. Both methodologies analyze, with a particular emphasis, the building's impact on the carbon footprint and energy.

It is worth noting that the calculation methodology has a more limited scope than the simulation methodology, however, the calculation work was carried out using an open database. The trends of the results were similar to the ones obtained using the simulation methodology, which uses a closed database. This result suggests that open data can be a reliable alternative for conducting LCA analyses (Fig. 5).

3.1. Calculation methodology for LCA

The objective of the LCA when applying the calculation method is to determine the energy and carbon equivalent impacts generated by the construction materials and process, including material waste and their transport to the site. This calculation was done using programmed spreadsheets, resulting in the impacts distributed by materials and construction systems.

The scope of the LCA, by using the calculation methodology, is based on the cradle-to-gate vision, going from raw materials, extraction, and materials manufacturing to the construction and work completion.

The elements taken into consideration within the inventory analysis are those entries that allow analyzing the life cycle. Among them, namely the dimensions, quantities, densities and materials masses, the database, are obtained from the Carbon and Energy Inventory (ICE) of Bath University, United Kingdom (Circular Ecology, 2019) (Hammond and Jones, 2008) including the distances between the construction site and material suppliers.

The NZEB El Salvador building contemplates different construction systems, which have Wood as a base construction technology, and is comparable with other construction technologies. Therefore, functional units have been considered to compare these construction systems (Table 1). The budget base and part of the contractual documents were considered to calculate these impacts. The calculation tool is organized by construction systems that in turn, are broken down into elements and construction materials that make them up. In it are the dimensions, lengths, areas, and volume that, together with the density, the mass of the materials is calculated and multiplied by the ICE factor. In this way the impact of both energy and carbon is found. In the next part of the

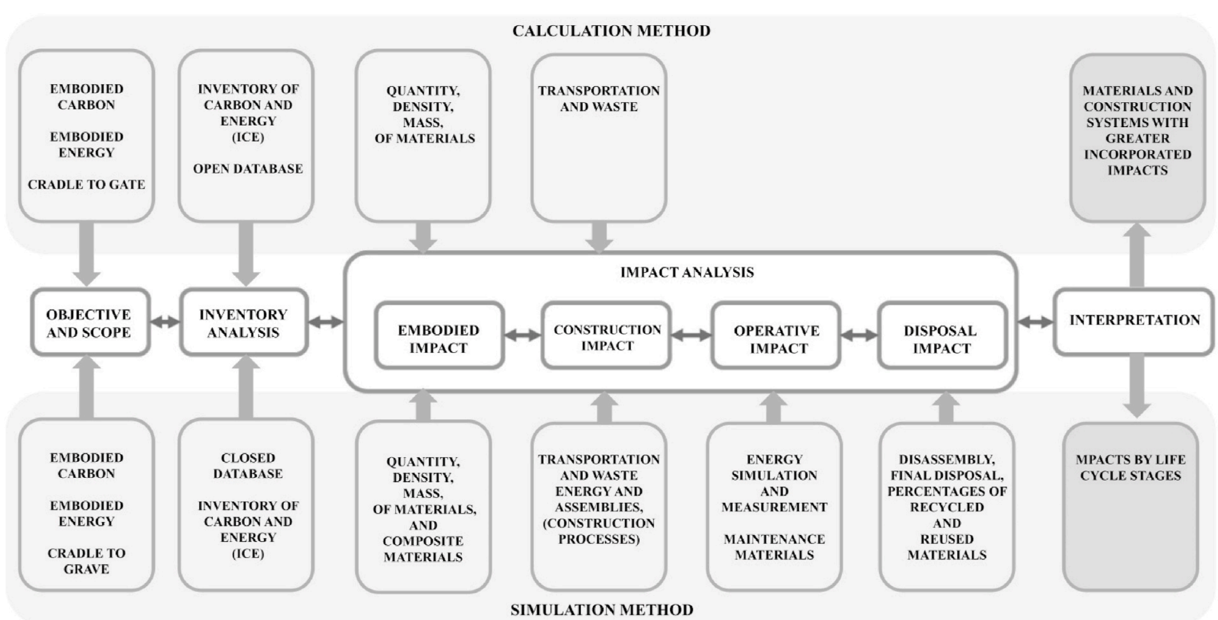

Fig. 5. Methodology chart. Own elaboration.

calculation tool, they are classified by materials, to know the total impacts by materials of each construction system.

3.2. Simulation methodology for LCA

The objective of the LCA by simulation method is to know the energy and carbon equivalent impacts generated throughout the life cycle of the building, going from the extraction of raw materials, manufacturing and construction to the operational stage and final disposal. For the simulation of the life cycle a specialized software SimaPro faculty version, was used, taking into account the energy used both in the construction and in the operational stage, the transports and the different materials that make up the construction systems, in addition to the possible scenarios of final disposal. The purpose of doing so is to know the stage that generates the greatest impact during the building's life cycle assuming 50 years of useful life, where maintenance and energy consumption of this stage will be considered.

The scope of the LCA by simulation methodology is based on the cradle-to-grave vision (McDonough and Michael, 2002), taking into account the impacts from the raw materials extraction, materials manufacturing, construction, operational stage and final disposal, however, two scenarios were simulated for the final disposal. The "grave" can be considered a "cradle" in scenario 2 only, since recycling and reuse are included (Zabalza Bribián, Aranda Usón and Scarpellini, 2009).

The basis of this methodology are the local energy matrix, the construction process and systems technical sheets, due they systematize and summarize all the information necessary to generate the simulation. Energy measurements, disassembly and final disposal scenarios were also required. In addition, within the software, the Ecoinvent 3 database was selected. For the inventory analysis, the mass breakdown of the materials was considered, both simple and composite was considered, to facilitate entry into the simulation software.

The functional unit for the building is complex, if one considers that the building is composed of multiple combinations of materials and construction systems with different characteristics, which must be considered when comparing them with each other. Also, the weight is a parameter of comparative analysis, however, if the benefits and contributions to the efficiency and building's safety are not considered, the interpretation of environmental impact data is incomplete. For example, the construction systems that contribute to energy efficiency, and reduce energy consumption throughout the useful life, or the construction systems on which structural safety depends may be the heaviest or most robust, but the building's integrity depends on them.

Therefore, in the life cycle analysis of the NZEB El Salvador building, the surface ($m^{2)}$ of construction contemplated by the building has been considered as a functional unit. In this case, the area of the NZEB El Salvador building is 100 m^2 and the environmental impacts that will be considered are the following: The global warming potential, in units of kg CO_2e (kilograms of carbon dioxide equivalent) and the consumption of energy resources, with the characterization factor in amount of energy consumed with the MJ units (Megajoules). According to the study of the impacts characterization, these two indicators are the most significant and verifiable (Crawley and Aho, 1999).

To perform the simulation of the NZEB El Salvador building's life cycle, the academic version of the SimaPro software was used. This software specializes in modeling life cycles for products. Also, it uses life cycle assessment to measure their environmental impact and, through analysis, determines are the materials or stages of the life cycle that most increase the environmental impact (Chang et al., 2019) (Asdrubali et al., 2013). It is useful for modeling environmental impacts such as CO_2e and primary energy. The methodology is based on inputs and outputs, with inputs, materials and energy required to transform of materials and outputs are the impacts.

4. Results of the life-cycle assessment in NZEB El Salvador building

4.1. LCA results with calculation methodology

The results are classified in two ways. First, by materials and groups of materials, allowing to know which group of materials generates the greatest impact on both energy and carbon footprint. Second, by construction systems, to identify which system and component impact the most on the building (Table 2).

Of the embodied impacts of construction materials, it should be noted that the extraction of raw materials and the production of polyurethane, aluminum, wood, wood treatments and structural steel, represent more than 70% of the building's energy impact (Fig. 6). However, when comparing the mass percentages these materials represent within the building, it is notorious to observe that; polyurethane (1,86% of the total mass), aluminum (1,13% of the total mass), wood treatments (1,31% of the total mass) and structural steel (3,60% of the total mass) make up less than 8% of the building total mass the and have a ratio equal to 76,18 GJ per ton, which is 10,2 times greater than the impact per ton of wood, that makes up more than 20% of the total mass and has a ratio, impact on mass, of 7,48 GJ per ton.

As for the impact of carbon, the extraction of raw materials and the wood production, aluminum, structural steel, polyurethane, and reinforced concrete, represent more than 70% of this (Fig. 7), however, when making the comparison between the mass of these materials inside the building, it is shown that structural steel (3,60% of the total mass), polyurethane (1,86% of the total mass) and aluminum (1,13% of the total mass), make up less than 7% of the total mass and have an impact ratio per ton of 4,14 tons of CO_2e. This is 30 times greater than reinforced concrete, which represents more than 55% of the total mass and has an impact of 0,14 tons of CO_2e per ton of mass. In the case of wood, which has a mass of more than 20% of the total building and an impact equal to 0,59 tons of CO_2e per ton of mass, resulting four times greater than the impact per ton of concrete.

When performing a comparative analysis of the energy and carbon equivalent impact by the mass of the materials included in the building, it is observed that the impact is not directly proportional to the mass of the material, where materials such as reinforced concrete, with a mass equivalent to more than 55% of the total mass, only generates 4,90% of the energy impact and 11,69% of the equivalent carbon impact. These

Table 2
Materials and group of materials.

Group of materials		Materials	
RC	Reinforced concrete	RC	Reinforced concrete
W	Wood	W	Wood
M	Metals	STS	Structural steel
		SS	Stainless steel
		C	Copper
		AL	Aluminum
GL	Glass	GL	Glass
POL	Polymers	HDPE	High density polyethylene
		NY	Nylon
		PC	Polycarbonate
		PVC	Polyvinyl chloride
		PU	Polyurethane
		V	Vinyl
TR-PN	Treatments and paints	TR	Treatments
		PN	Paints
CER	Ceramics	CER	Ceramics
DRY-FC	Drywall and fiber cement board	DRY	Drywall
		FC	Fiber cement

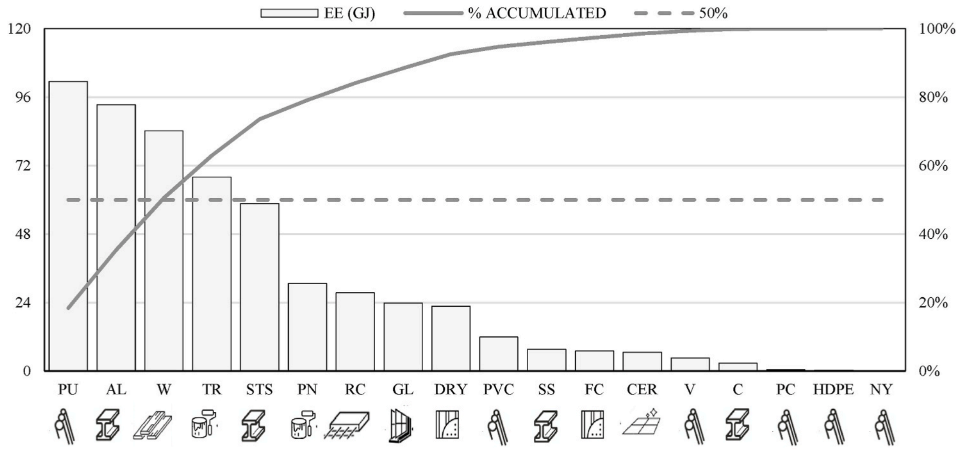

Fig. 6. Pareto graph of energy impacts by materials (GJ). Own elaboration.

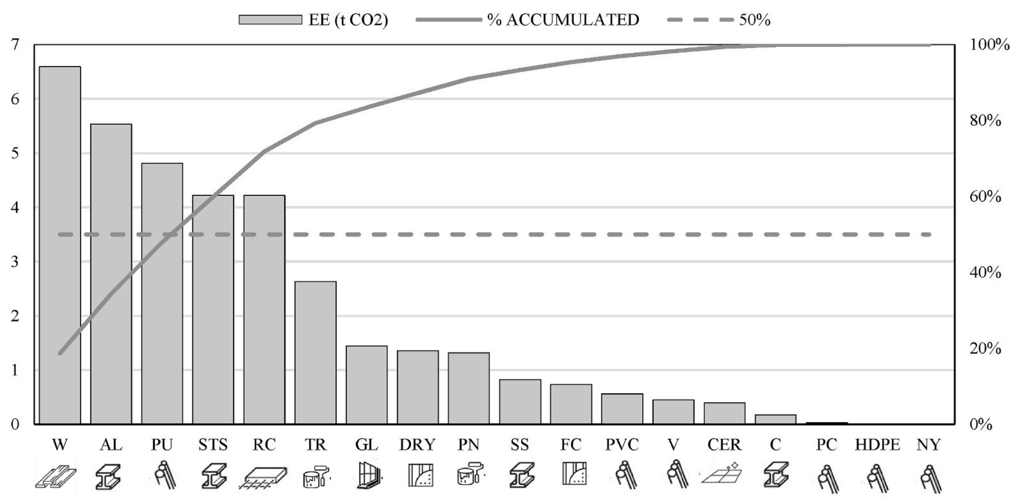

Fig. 7. Pareto graph of carbon impacts by materials (tCO_2e). Own elaboration.

results show that a material with significant weight does not generate most of the impacts, while materials such as polyurethane represent 1,86% of the total mass generate 18,12% of the energy impact and 13,33% of the equivalent carbon. This is a percentage of impact up to nine times greater than the percentage of the mass. In the same way there are materials whose impact is proportional to their mass, such as ceramics, plasterboard and fiber cement.

On the other hand, making a comparative analysis between the ICE factor (Carbon and Energy Inventory) and the impact of the materials used in the building, it is possible to observe that the relationship between these two elements, like the relationship between mass and impact, is not directly proportional, since materials such as nylon that

Table 3
Results according to Functional Units for LCA with calculation methodology.

Construction systems		amount	Functional Unit		EE (GJ)	EC (tCO_2e)	EE/UF (MJ/UF)	EC/UF ($kgCO_2e$/UF)
FON	Foundations	12,1	m^3	Foundations volume	28,0	4,3	2323,2	353,7
FLW	First level walls	103,4	m^2	Walls surface in level one	69,9	4,0	676,4	38,8
MEZ	Mezzanine	33,9	m^2	Mezzanine surface	53,0	3,7	1563,7	108,7
STR	Staircase	4,4	m^2	Staircase surface	3,1	0,2	706,9	41,2
SLW	Second level walls	87,8	m^2	Walls surface in level two	56,2	3,1	640,9	35,7
TRU	Trusses	18,4	m^2	Trusses surface	29,5	1,8	1603,5	97,4
R-STR	Roof structure	233,2	m	Primary roof structure length	74,0	4,4	317,4	18,7
R	Roof	105,4	m^2	Roof deck surface	71,9	3,8	682,0	35,7
H-I	Hydraulic installations	78,2	m	Hydraulic pipe length	4,7	0,2	59,6	2,9
E-I	Electrical installations	266,4	m	Electrical pipe length	11,2	0,6	42,0	2,3
M-I	Mechanical installations	5,4	t	Refrigeration tons	8,6	0,9	1597,8	158,7
F-F	Floor finishes	31,7	m^2	Floor surface coating	4,6	0,5	145,8	14,2
W-F	Wall finishes	395,7	m^2	Finishing surface on walls	15,8	0,8	39,9	1,9
D	Doors	39,1	m^2	Door surface	56,2	3,4	1557,1	93,4
W	Windows	26,1	m^2	Windows surface	61,5	3,7	2358,9	140,8
SAA	Sanitary appliances and accessories	2,0	u	Sanitary unit	3,1	0,2	1523,8	91,1
				Total	551,3	35,3		

has the second largest ICE factor among all the materials used only represents 0,01% impact. Both energy and carbon equivalent, and materials such as wood that has the third of the smallest ICE factors among the materials used, generate an impact is equal to 15,04% of the energy impact and 18,27% of the equivalent carbon impact.

Considering the functional units of the calculation methodology for construction systems, the incorporated impacts results are established according to Table 3.

Figs. 8 and 10 show the Pareto graph with the values of significant impacts. However Figs. 9 and 11 are double axis and show on the vertical axis the percentage of mass of material contained in the building's construction. The other vertical axis, shows the impacts in Gigajoules or in tons of CO_2e. The most significant difference between the impacts, both in energy and carbon equivalent and mass, is noticeable in the following construction systems: First-level walls, roof structure, electrical installations, doors and windows, which proportionally to their low weight, their impact is much greater. On the other hand, there are the stands, hydraulic installations and mechanical installations, whose impacts and weights are proportional to each other. In the case of foundations, in energy impacts, the mass is greater than its impact, however, they are aligned in the equivalent carbon impacts.

Therefore, it is demonstrated that the envelope (facade, floor and roof) is the system that contains the highest equivalent carbon, compared to the rest of the construction systems. The reason is that the façade is also a high-performance structural wall that must be sufficiently rigid to resist both gravity loads and lateral thrusts. This is why there is a greater density of material per wall area. On the other hand, the foundations respond to the requirement of transmitting the loads of the building to the ground and supplying the lack of bearing capacity of the latter, and when the ground has a low bearing capacity, the mass of the foundation increases, however in this case, since the building is made of wood, it weighs at least two times less than if it were made of concrete, thereby reducing the carbon footprint of the foundation.

4.2. *LCA results with simulation methodology*

In the simulation process, in addition to consulting the carbon inventory database, the means of energy and transport have been selected to obtain the final impacts. Unlike the calculation process with open data, in which work is done with carbon equivalent and primary energy factors, the simulator takes into account more data that generates higher impact results. Likewise, the simulation process allows calculating the impacts of all life cycle stages.

In the simulation methodology it is possible to determine the environmental benefits that result from the reduction of environmental loads due to the potential impacts avoided (Ram et al., 2020), especially in two stages of the LCA: Operation and final disposal. In the operational stage that corresponds to the useful life of the building, the environmental benefits stem from the avoided energy consumption from the grid due to PV energy generation. On the other hand, environmental benefits in the final disposal stage are obtained by projecting scenarios at the end of the life cycle. In this case, two scenarios have been considered. Scenario one consists of landfill without environmental benefit. In the second scenario, the building constructive components that, at the end of the life cycle, retain their integrity when disassembled and can be reused, or at least are recycled, will become new raw materials for subsequent uses. The environmental benefits are assumed as negative values that decrease the total impact in the life cycle.

4.2.1. *Embodied impacts by construction system*

Within the stage of embodied impacts, which consists of raw materials extraction phase and materials manufacturing, the results are presented by groups of construction systems. The photovoltaic panel system is also considered, unlike the calculation methodology (Table 4). In the simulation methodology, it is notorious that the impact of the roof accounts for more than 90% of the building's, total impact, both energy and carbon equivalent. This is because the predominant material in the building is wood from the structural wall system, and the values of the Ecoinvent inventory consider the benefits beyond the system, overcoming the values of the ICE database considered in the calculation methodology. This indicates that the less generalized, the carbon and energy inventory data, the more accurate the analysis will be (Figs. 12 and 13).

4.2.2. *Carbon equivalent and energy impacts by construction stage*

The breakdown of those elements that have been taken into account in the construction stage and their impacts is presented below. At this stage, three aspects were considered, the materials transportation to the site, the energy used during construction, and the material waste generated during this process. The results are shown in Table 5 and Figs. 14 and 15.

It is notorious that the impacts from construction are much lower than the embodied impacts. This is because the inputs are energy and waste of materials, however, the design has been developed for both prefabrication and deconstruction, and this avoids waste since each piece of material used in each has been calculated by construction system.

4.2.3. *Carbon equivalent and energy impacts by operational stage*

In the operational stage, two aspects were taken into account, maintenance and energy consumption and energy generation during the operational stage equal to 50 years of useful life. In Figs. 16 and 17, the vertical axis establishes the impact in tons of carbon dioxide equivalent, while the horizontal axis identifies maintenance, energy consumption

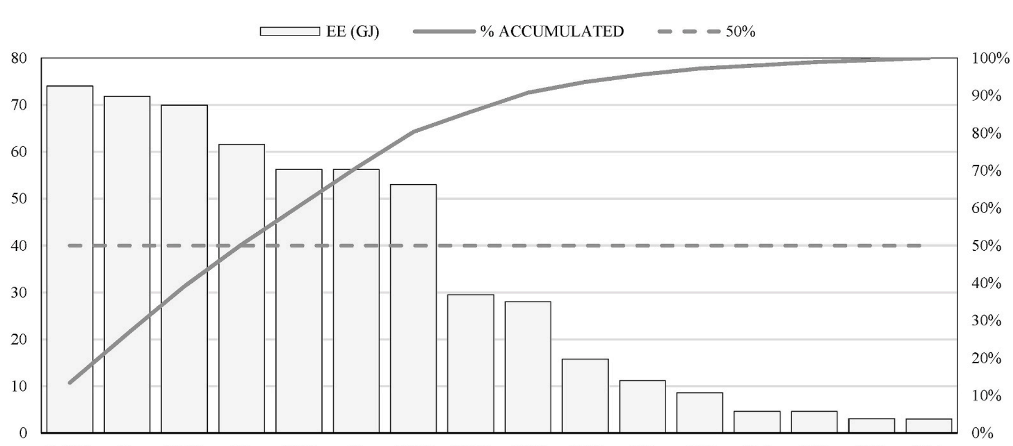

Fig. 8. Pareto graph of energy impacts by construction systems (GJ). Own elaboration.

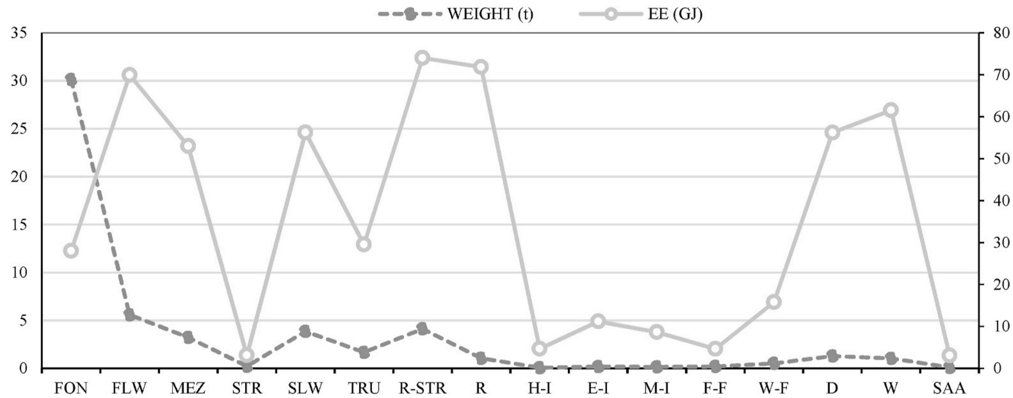

Fig. 9. Graph of energy impacts by construction systems (GJ) related to mass (t). Own elaboration.

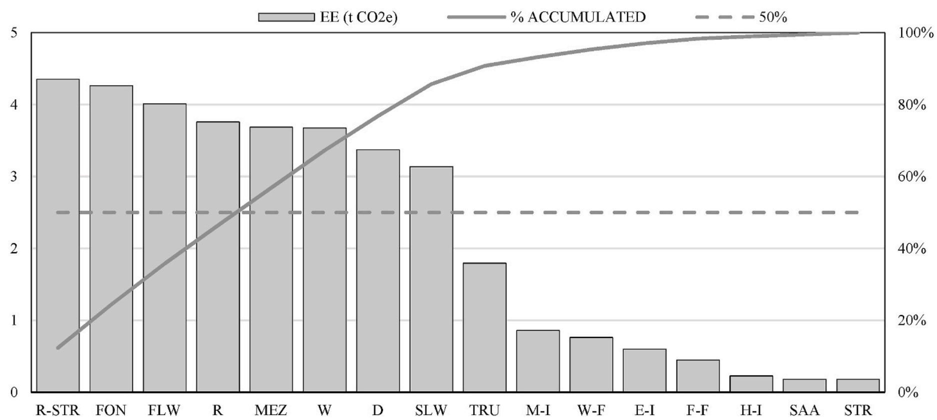

Fig. 10. Pareto graph of equivalent carbon impacts by construction systems (t CO_2e). Own elaboration.

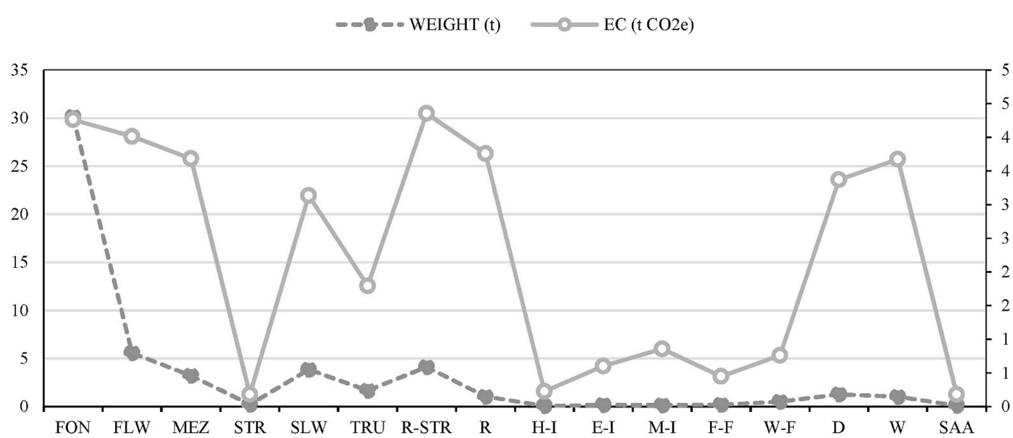

Fig. 11. Graph of carbon equivalent impacts by construction systems (t CO_2e) related to mass (t). Own elaboration.

and power generation. Energy generation produces environmental credits since this generated energy is discounted from the energy consumed in the building and the residual is injected into the Central American University network. This mechanism prevents energy consumption from the network reducing non-renewable energy consumption, which generates a greater, more significant environmental impact than the one obtained from renewable sources, produced by the NZEB El Salvador building. Refering to carbon equivalent, the most significant impact is generated by maintenance, the breakdown is the treatments for wood, and wall painting, both interior and exterior (Table 6).

4.2.4. Life cycle impacts, final disposal scenarios 1 and 2

Two final disposal scenarios were established. The first one, with 100% of waste directed to landfill, the second one, has to do with a situation on which 30% is directed to landfill, 47% to recycling and 23% to reuse. It is worth mentioning that for the scenario 2, the elements disassembly, the materials characteristics and their function within the construction systems were considered.

The most significant impact is generated by scenario 1, with 100% of the waste landfilled, while scenario 2, which has recycling and reuse, is negative. This means there are environmental credits or avoided impacts from this stage, as benefits surpass the system's limits (Table 7).

Emphasizing the energy impacts of the life cycle stages, and

Table 4
Embodied impacts by construction system.

code	Construction system	EE (GJ)	% Impact	code	Construction system	EC (tCO_2e)	% Impact
R-ST-T	Roof structure, roof and trusses	630,0	28,2%	R-ST-T	Roof structure, roof and trusses	13,7	24,3%
FLW	First level walls	544,0	24,3%	FLW	First level walls	8,0	14,2%
SLW	Second level walls	354,0	15,8%	D-W	Doors and windows	7,5	13,3%
MEZ-S	Mezzanine and staircase	244,0	10,9%	FOTV	Photovoltaic panels	7,5	13,2%
D-W	Doors and windows	208,0	9,3%	FON	Foundations	5,8	10,3%
FOTV	Photovoltaic panels	128,0	5,7%	SLW	Second level walls	5,4	9,6%
FON	Foundations	50,3	2,3%	MEZ-S	Mezzanine and staircase	4,3	7,6%
F–W–F	Floor and wall finishes	42,0	1,9%	F–W–F	Floor and wall finishes	2,2	3,8%
E-I	Electrical installations	23,2	1,0%	E-I	Electrical installations	1,3	2,3%
H–I	Hydraulic installations	9,0	0,4%	H–I	Hydraulic installations	0,6	1,0%
M-I	Mechanical installations	4,2	0,2%	M-I	Mechanical installations	0,2	0,4%
	Total	2236,7	100%		Total	56,4	100%

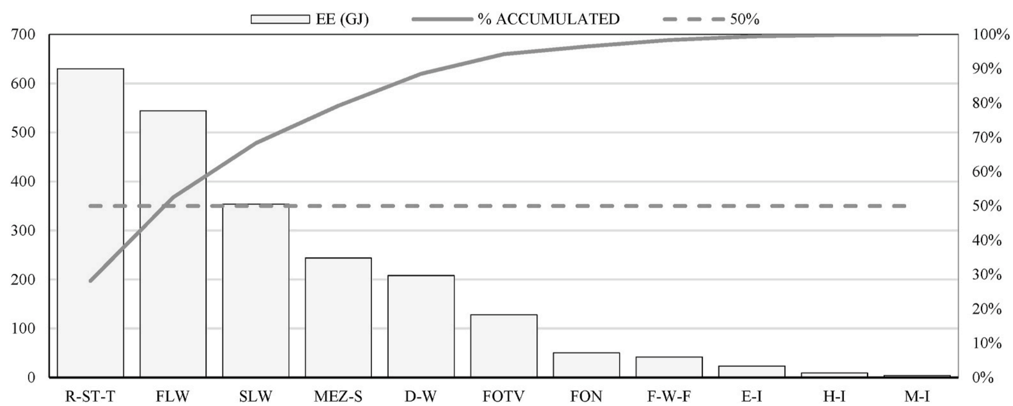

Fig. 12. Energetic embodied impacts by construction system (GJ). Own elaboration.

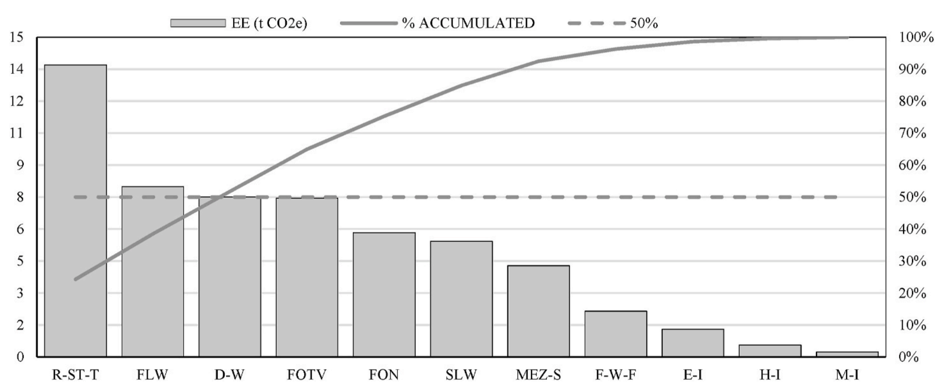

Fig. 13. Carbon equivalent embodied impacts by construction system (t CO_2e). Own elaboration.

Table 5
Carbon equivalent and energy impacts by construction stage.

Sub-stage	Impact (GJ)	Impact (t CO2e)
Transportation 1	0,5	0,03
Transportation 2	19,4	1,1
Diesel machine	3,8	0,3
Energy Mix	11,0	0,3
Construction waste	196,0	7,7
Total	230,7	9,3

considering both final disposal scenarios, can be seen that the trends remain the same as in the equivalent carbon impact, where the embodied impacts of the materials mostly generate the impactand the operational stage generates credits that allow reducing the total impact. Again the scenarios difference is observed in the final disposition, where in this aspect the scenario of final disposal 1 increases the impact generated by the previous stages by just over 4%. While the scenario of final disposal 2 contributes reducing 145% of the impact generated in the previous stages. Therefore, this second scenario compensates for all the impact generated in the previous stages thanks to the deconstructive characteristics with wood (Figs. 18 and 20).

While in the equivalent carbon impacts of the life cycle stages, considering both scenarios of final disposal, the stage generating the most significant impact is the one related to the extraction and manufacture of construction materials. It is also noteworthy the operational stage that generates benefits beyond the system and allows to reduce the total building impact. The difference between both scenarios lies in the final disposal, where depending on the destination of the waste, the impact that this stage can generate, translates into an increase of more than 125% of the impact generated in the previous stages (incorporated impacts, by construction and operational stage) or benefits beyond the

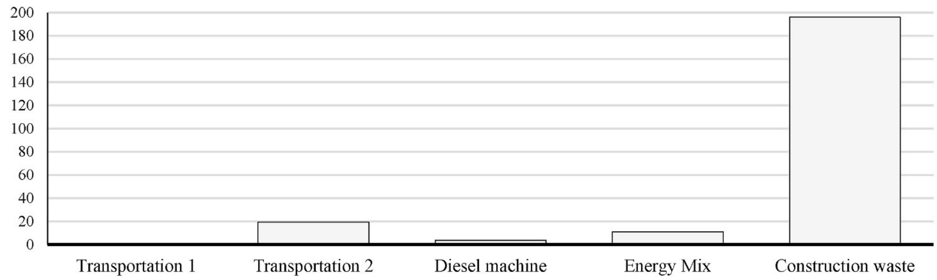

Fig. 14. Energy impacts by construction stage (GJ). Own elaboration.

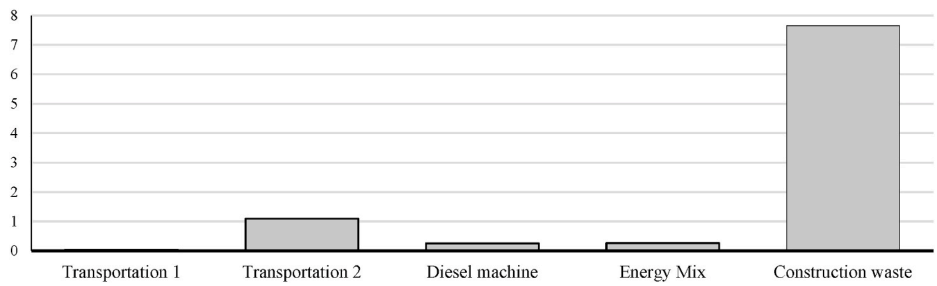

Fig. 15. Carbon equivalent impacts by construction stage (t CO_2e). Own elaboration.

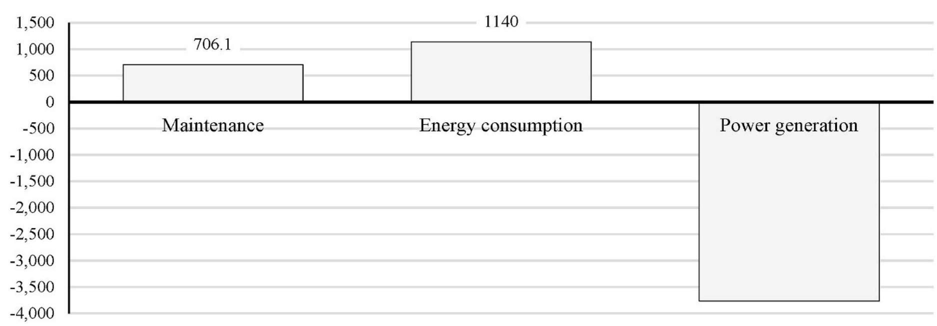

Fig. 16. Energy impacts of the operational stage (GJ). Own elaboration.

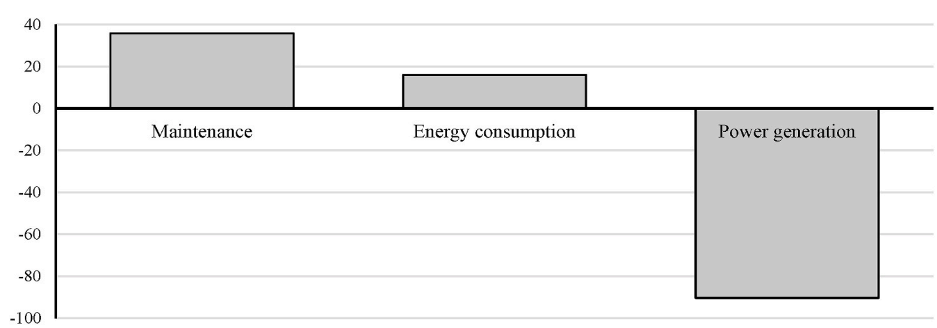

Fig. 17. Carbon equivalent impacts of the operational stage (t CO2e). Own elaboration.

Table 6
Carbon equivalent and energy impacts by operational stage.

Sub-stage	Impact (GJ)	Impact (t CO2e)
Maintenance	706,1	35,8
Energy consumption	1140,0	16,0
Power generation	−3770,0	−90,3
Total	−1923,9	−38,5

system limits, that allowing to reduce little more than 4% of the previous stages impacts (Figs. 19 and 21).

5. Results discussion

LCA shows that polyurethane generates the greatest energy impact, despite having a mass equivalent of only 1.86% of the total mass. This material is used as thermal insulation throughout the building envelope and is necessary for energy efficiency. Such high impact is caused by having one of the five largest energy impact factors. However, this

Table 7
Life cycle impacts, final disposal scenarios 1 and 2.

Life cycle stage	Impact (GJ) Scenario 1	Impact (GJ) Scenario 2	Impact (t CO_2e) Scenario 1	Impact (t CO_2e) Scenario 2
Embodied stage	2236,7	2236,7	56,4	56,4
Construction stage	230,67	230,7	9,3	9,3
Operational stage	−1923,9	−1923,9	−38,5	−38,5
Final disposition stage	20,8	−741,0	32,9	−1,1
Total	564,3	−197,5	60,1	26,1

material can reduce more than 50% of the impact generated using air conditioning systems during the useful life period of 50 years. Having established that both polyurethane and aluminum generate a significant impact, alternatives with less environmental impact that can fulfill the same functions within a building must be evaluated.

It is worth mentioning that wood, used as the main material for the building's structure, represents the highest equivalent carbon impact, with 11,24% of the building total mass, and an equivalent carbon impact factor (ICE) that is among the three lowest of the materials and in this case the impact avoided by carbon dioxide sequestration has not been considered. The impact clearly grows because it is one of the main materials and is present in almost the entire building, since it is a load-bearing structure and main component of the envelope (façade). On the other hand, in addition to contributing to the greatest impact of equivalent carbon, wood as a material, must be treated and maintained in the

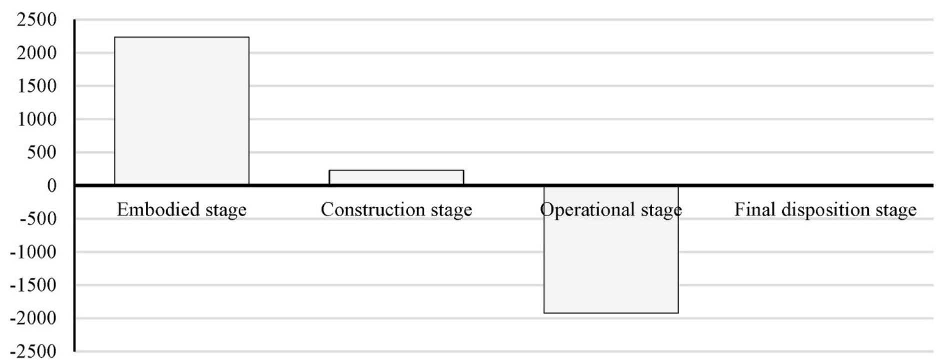

Fig. 18. Life Cycle Energy Impacts Graph, Final Disposal Scenario 1 (GJ). Own elaboration.

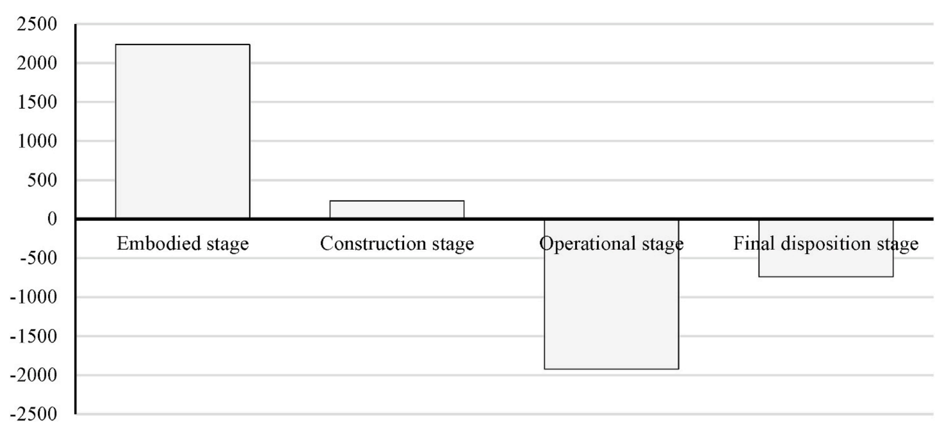

Fig. 19. Life Cycle Energy Impacts Graph, Final Disposal Scenario 2 (GJ). Own elaboration.

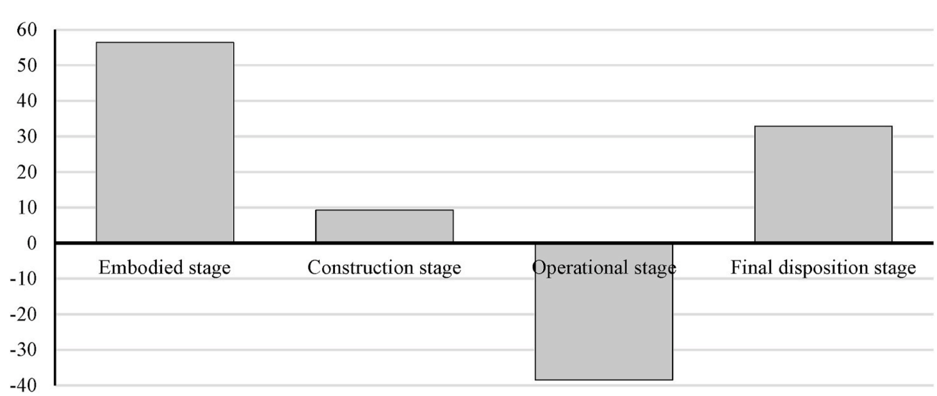

Fig. 20. Life Cycle Equivalent Carbon Impacts Graph, Final Disposal Scenario 1 (tCO_2e). Own elaboration.

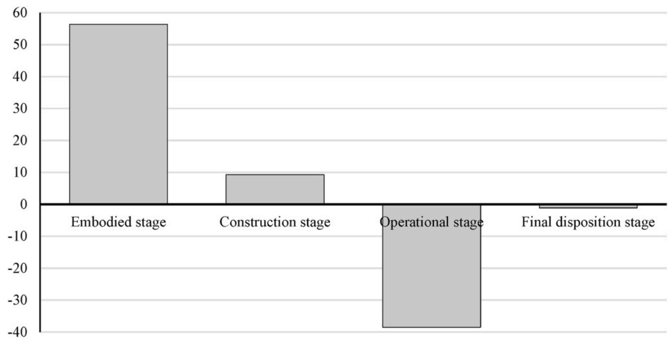

Fig. 21. Life Cycle Equivalent Carbon Impacts Graph, Final Disposal Scenario 2 (tCO_2e). Own elaboration.

construction process and throughout the useful life of the building. In this aspect, its impact becomes four times greater in carbon equivalent and almost seven times greater in energy impact.

It should be noted that, based on the relationship between the environmental impact versus the materials mass, and the impact versus the ICE factor of the material, both the mass and the factor alone are not an indicator of the possible impact a material may cause. The real impact of each material used can be determined only when the factor and mass of the materials present in the design are conjugated. In addition, only by breaking down the impact of the building in each construction system will it be possible to contrast the impact it generates against the impact of another building with different construction technologies. That is why selecting of the functional unit according to construction systems is more appropriate than for the building as a whole.

On the other hand, the use of the material within the building or its function within a construction system, can justify the impact it generates in the building, being the case of some materials and specialized components such as photovoltaic panels that represent one of the greatest impacts on carbon. However, energy generation helps offset the full impact of the building life cycle, as benefits beyond the system.

In the dismantling of a building, there are procedures that can increase the costs and times of disassembly compared to traditional demolition; however, this procedure facilitates the separation of residual materials and increases the possibilities of their reuse and/or recycling, reducing the impact that the final disposal can have (Rodrírguez et al., 2020).

When making a comparison between the results of embodied impacts for both methodologies, two relevant points stand out: The difference in absolute values and the trend of the results. Concerning the difference in absolute values, the calculation method yields a total of 551.3 GJ and 35.3 tCO_2e. In the case of the values of the simulation method it yields a total of 2236.7 GJ and 56.4 tCO_2e, having registered significant differences in the case of embodied energy, since the simulation method is 4 times greater than the calculation method. In the case of embodied carbon, the difference is up to 1.5 times greater than the result of the simulation method.

The difference in absolute values is understandable. After all, the simulation process requires more input data from the database and energy. However, the trend in the data is remarkable, since, in both methodologies, the highest significant values above 50% correspond to the envelope (facade and roof). This evidence shows that different methodologies, using different databases, determine which elements of the building contain more embodied carbon, regardless of the absolute values. And therefore, it validates the use of open data in the application of LCA in project decision-making processes.

As a result of the simulation method, the embodied impacts of carbon equivalent of the building are 56,41 tons of CO_2e equivalent. To relativize the result, it can be said that this impact is comparable with the one generated by production of 2148 cement bags 42,5 kg each, taking into account that the data from the production of one ton of cement reports an impact of 0,60 tons of CO_2e equivalent (AB, 1998). In the case of the life cycle of the NZEB El Salvador building, from the extraction of raw materials to the final disposal, taking as reference the most unfavorable scenario, it results in 60,11 tons of CO_2e equivalent. This impact is comparable to the impact caused by three round trips through the Panamerican highway (4800 km) from Valparaíso, Chile to Fairbanks, Alaska. Considering the functional unit, which for the simulation methodology is the surface in m2 of building's construction (see Fig. 22), both energy and carbon results are indicated in Table 8.

Table 9 shows the comparison of the equivalent carbon footprint per square meter of construction between the NZEB El Salvador building and four other buildings, highlighting that the difference in results, besides of being due to the materials and construction systems of the different buildings, are also affected by the location and energy characteristics. As a source of operational energy consumption or the energy impact of consumption of air conditioning equipment, the typical house (Malmqvist et al., 2011), incorporates elements such as heating, hot water, and cooling systems and electricity consumption for daily use. On the other hand, the multifamily building, by the same authors, in addition to having the same characteristics as the typical house, has floor heating throughout the construction area.

The school building in Northern Ireland (Paya-Marin et al., 2013) has heating provided by a natural gas boiler, in addition to the electrical energy of daily use. Regarding the ECO building, by the same authors, its ventilation, heating and air conditioning system is based on an air source heat pump, which produces enough heat for heating spaces and hot water. The space heating system is based on radiators. The ventilation system uses the concept of decentralized mechanical ventilation with heat recovery in wintertime and natural ventilation in the summertime. The entire system is controlled by CO_2e sensors, which generate less carbon impacts compared to the school building built. Everything mentioned above establishes the clear difference between the energy characteristics of these buildings compared to the NZEB El Salvador building.

6. Conclusions

The conclusions are based on the results found in both methodologies, calculation and simulation, which diverge in magnitude but not in trends. Significant differences were observed in the case of embodied energy, since the simulation method yields a result 4 times greater than the calculation method. And in the case of embodied carbon, the difference is up to 1.5 times greater than the result of the simulation method. The explanation for this is the fact that the simulation process requires more input data from the database and energy. However, the application of open data in LCA is an option to support decision-making in design processes when evaluating decarbonization strategies.

Results demonstrate that energy efficiency, renewable energy generation, prefabrication, and the application of circular economy principles contribute to reducing the carbon footprint of a building and reducing dependence on the consumption of non-renewable resources. Likewise, the LCA analysis of NZEB El Salvador could be used as a baseline for sustainable buildings in the region.

The net-positive energy performance provided benefits or credits that compensated impacts generated in other life cycle stages. This impact compensation was crucial for achieving a low overall carbon and energy footprint. However, some materials that are beneficial to energy efficiency are impactful in terms of CO_2e emissions, which highlight the importance of assessing the life cycle impact of design decisions and prioritizing the use of lower carbon material alternatives.

Additionally, waste and waste materials are most impactful during the construction stage. Construction strategies that include modular elements and designs could reduce waste and facilitate final disposal scenarios (reuse, recycling) consistent with circular economy principles. In the future, with more LCA data, benchmarking building designs with the appropriate functional units should become standard practice and

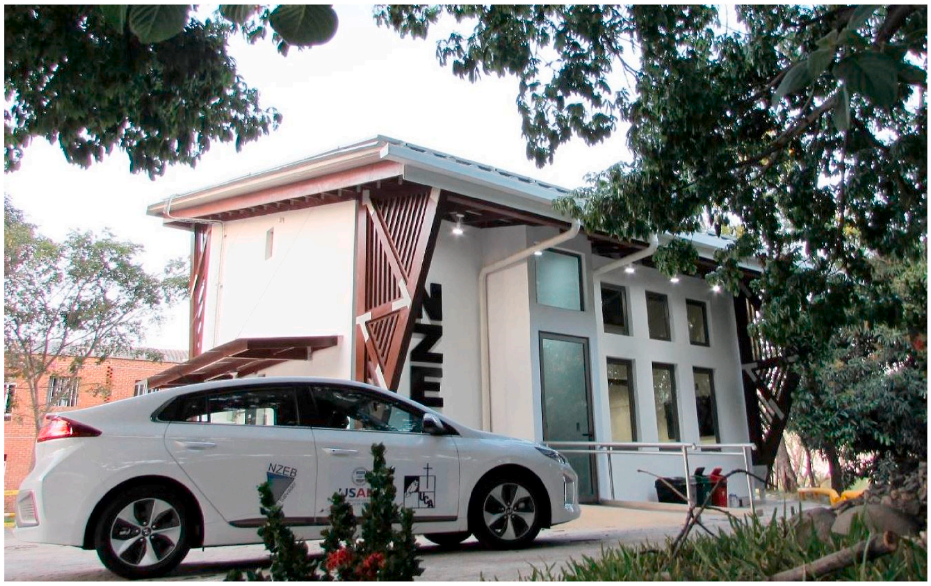

Fig. 22. Laboratory with electric vehicle. NZEB El Salvador project.

Table 8
Results according to functional units for LCA with simulation methodology.

Results	Functional Unit	Impacts (kgCO_2e/ m^2)	Impacts (MJ/ m^2)
Final disposal scenario 1	m^2 construction area	601,1	5642,7
Final disposal scenario 2	m^2 construction area	260,8	−1975,3

Table 9
Carbon impact comparisons between NZEB El Salvador and other buildings.

Building	Source	Carbon impact	Scope
Multifamily building 2900 m^2, without location	Malmqvist et al. (2011)	870 kg CO_2e per m^2	Includes embodied impacts and operating energy
Typical house 120 m^2, without location		376 kg CO_2e per m^2	
School building, 120 m^2 in Northern Ireland	Paya-Marin et al. (2013)	4373 kg CO_2e per m^2	Includes embodied impacts and operating energy
ECO building, 120 m^2, unbuilt		2680 kg CO_2e per m^2	
NZEB El Salvador building final disposal scenario 1, 100 m^2		601 kg CO_2e per m^2	Includes embodied impacts, and, construction, operation (energy and maintenance) and final disposal 1 impacts.
NZEB El Salvador building final disposal scenario 2, 100 m^2		261 kg CO_2e per m^2	Includes embodied impacts, and, construction, operation (energy and maintenance) and final disposal 2 impacts.

inform design professionals on what can be achieved toward carbon neutral building life cycles.

CRediT authorship contribution statement

Lizeth Rodríguez: Supervision, Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Luis Martínez:** Conceptualization, Investigation, Methodology, Formal analysis, Writing – review & editing, Validation, Visualization. **Ronald Panameño:** Methodology, Resources, Formal analysis, Software, Data curation. **Oriol París:** Conceptualization, Investigation, Methodology, Data curation, Writing – review & editing. **Adrián Muros:** Conceptualization, Investigation, Methodology. **Raquel Rodríguez:** Data curation, Resources, Software, Formal analysis, Visualization. **Rafael Javier:** Data curation, Resources, Software, Formal analysis, Visualization. **Carlos González:** Data curation, Resources, Software, Formal analysis, Visualization.

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

No data was used for the research described in the article.

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