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A Parametric Integrated Design Approach for Life Cycle Zero-Carbon Buildings

Ehsan Kamel [1], Francesco Pittau [2,*], Laura Mora Dal Verme [1,3], Piergiorgio Scatigna [1,3] and Giuliana Iannaccone [2]

[1] Department of Energy Management, New York Institute of Technology, Old Westbury, NY 11568, USA; ehsan.kamel@nyit.edu (E.K.); lauramora.dalverme@mail.polimi.it (L.M.D.V.); piergiorgio.scatigna@mail.polimi.it (P.S.)
[2] Department of Architecture Built Environment and Construction Engineering (ABC), Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy; giuliana.iannaccone@polimi.it
[3] School of Architecture Urban Planning and Construction Engineering, Politecnico di Milano, Via Ampere 2, 20133 Milan, Italy
* Correspondence: francesco.pittau@polimi.it; Tel.: +39-02-2399-6011

Abstract: Implementing net-zero carbon design is a crucial step towards decarbonizing the built environment during the entire life cycle of a building, encompassing both embodied and operational carbon. This paper presents a novel computational approach to designing life cycle zero-carbon buildings (LC-ZCBs), utilizing parametric integrated modeling through the versatile Grasshopper platform. A residential building located at the New York Institute of Technology, optimized to fulfill the LC-ZCB target, serves as a case study for this comprehensive study. Four main influencing design parameters are defined, and three hundred design combinations are evaluated through the assessment of operational carbon (OC) and embodied carbon (EC). By incorporating biobased materials in the design options (BIO) as a replacement for conventional insulation (OPT), the influence of biogenic carbon is addressed by utilizing the GWPbio dynamic method. While both OPT and BIO registered similar OC, with values ranging below 0.7 kg CO_2eq/m^2a, the EC is largely different, with negative values ranging between −0.64 and −0.54 kg CO_2eq/m^2a only for BIO alternatives, while the OPT ones achieved positive values (2.25–2.45 kg CO_2eq/m^2a). Finally, to account for potential climate changes, future climate data, and 2099 weather conditions are considered during the scenario assessments. The results show that OC tends to slightly decrease due to the increasing productivity of PV panels. Thus, the life cycle emissions for all OPT alternatives decrease, moving from 2.4–3.0 kg CO_2eq/m^2a to 2.2–2.4, but none of them achieve the LC-ZCB target, while BIO alternatives are able to achieve the target with negative values between −0.15 and −0.60 kg CO_2eq/m^2a. There is potential for achieving LC-ZCBs when fast-growing biobased materials are largely used as construction materials, fostering a more environmentally responsible future for the construction industry.

Keywords: parametric building design; zero-carbon building; biobased materials; biogenic carbon; climate change

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1. Introduction

Climate change is one of the most significant challenges of our time, and the construction sector, which accounts directly and indirectly for about 40% of global energy- and process-related emissions, is a primary focus for policymakers to achieve the expected decarbonization targets of national economies by 2050. Data show that in 2021, direct and indirect emissions from the operation of buildings increased by 2% compared to 2019 values and by about 5% compared to 2020. In detail, as shown in Figure 1, around 8% of global energy and process-related CO_2 emissions are associated with the use of fossil fuels for building heating, another 19% to the use of electricity for building usage, and a further 6% to the production of materials used by the construction industry and onsite installation [1].

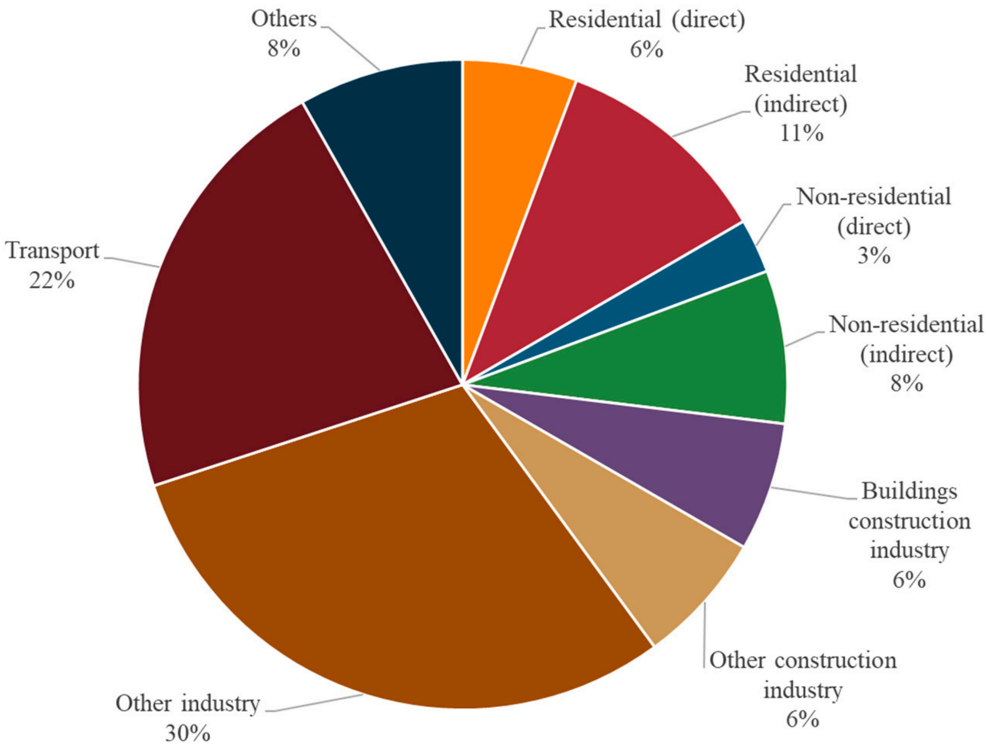

Figure 1. Global energy and process emissions from buildings, including embodied emissions from new construction. Re-elaborated data from IEA, 2022 [1].

In Europe, as in the United States, due to its potential to implement cost-effective energy-saving solutions, the construction sector is at the forefront of national action programs aimed at reducing CO_2 emissions. Indeed, already since 2010, the EU's Energy Performance of Buildings Directive (EPBD) mandated that all new buildings become "nearly zero-energy buildings" (nZEB) by the end of 2020. Similarly, the U.S. Department of Energy (DOE) aims to achieve "marketable zero-energy homes in 2020 and commercial zero-energy buildings in 2025" [2]. These standards primarily address the reduction in the operational energy demand of the building stock—maximizing thermal comfort and daylight access while producing renewable energy—and only partially the problem of reducing the overall impact of the construction sector concerning climate change [3].

Indeed, these standards are based on the assumption that the operational energy of a building, and the emissions associated with it, is usually greater than the embodied energy, which includes energy consumption, and the related emissions, throughout its entire life cycle, not just during the use phase. The more the energy consumption of a building is reduced through an improved building envelope design and more efficient systems, the more the energy demand to produce building materials and components increases; consequently, the contribution of embodied energy to the overall life cycle emissions becomes even more significant [4]. In the case of buildings, moreover, it becomes particularly important to consider not only the emissions, embodied and operational, associated with energy, but also the indirect carbon emissions that are often underestimated [5].

In this context, the concept of nZEB has evolved to a life cycle zero-carbon building concept (LC-ZCB), which considers the entire life cycle of the building. While it is true that carbon emissions include those associated with energy use, they are nevertheless influenced by the type of fuel mix and, for the embedded part, by the chemical processes of materials that emit and sequester carbon [6]. Neglecting embodied carbon could unfairly penalize the use of biobased building materials, such as wood, which can potentially remove CO_2 from the atmosphere by storing biogenic CO_2 during their growth and contribute significantly to the decarbonization efforts in response to climate change challenges [7]. Previous studies have highlighted the contribution of storing in buildings the atmospheric CO_2 removed by biobased materials when used as an alternative to conventional structural and insulation materials [8]. The following section explores the background research on the evolving concept of life cycle zero-carbon buildings (LC-ZCBs) and emphasizes the significance of considering both embodied and operational carbon emissions in the construction sector.

1.1. Background to Research

To achieve the zero-carbon goal, this study argues for the importance of considering both embodied carbon (EC) and operational carbon (OC) in evaluating building emissions and suggests using parametric design and life cycle assessment (LCA) as practical tools for designers to orient preliminary design choices considering the storage potential of biogenic CO_2 in different building materials.

LCA is the methodology commonly used to evaluate the environmental impact of buildings. However, many LCA studies overlook the effects of biogenic CO_2 when it comes to biobased materials. Typically, these studies assume that emissions and sequestration of biogenic CO_2 balance out during biomass growth. However, since these events occur at different times, dynamic approaches have been introduced to account for their temporal effects [9–11]. Dynamic LCA (DLCA) approaches can assess the impact of timing, such as how long CO_2 stays in the atmosphere. For instance, DLCA applied to wooden products shows that carbon neutrality is achieved after about half of the rotation period [12]. Considering the urgent need to take action against climate change, adopting a dynamic approach for carbon flows can aid decision-making in the construction sector, both for new and existing buildings, by promoting the use of biobased materials as an effective means of carbon storage in the built environment and encouraging uptake in the land [13]. Incorporating environmental assessment methods during the early stages of the design process can have the most significant impact, as costs [14], operational energy demand, and environmental effects can be optimized and minimized at this stage [15].

The background research in this field shows that the literature is focused on the following four major areas:

1. Achieving zero-carbon buildings
2. Life cycle assessment (LCA) and environmental impact
3. Energy poverty and social housing
4. Strategies for sustainable building practices

1.1.1. Achieving Zero-Carbon Buildings

One of the comprehensive studies is the International Energy Agency (IEA) [16] report focused on achieving zero-carbon-ready buildings by 2030 to align with decarbonization goals, emphasizing the need for extensive renovation of existing building stock, integration of clean energy technologies, and supportive policy frameworks. Challenges include high upfront costs, limited resources, and resistance from the construction industry. Strategies include implementing mandatory codes, deploying renewable energy solutions, and promoting energy efficiency. The report also highlights innovation themes such as flexible energy systems, renewable integration, and behavioral changes to accelerate progress as summarized in Table 1.

In another study, Santamouris [17] addresses critical issues in Europe's built environment: energy consumption, poverty, and climate change, advocating a "zero-concept world" to minimize global impact. It analyzes sectors, identifies problems, and proposes a roadmap with future targets and technological, economic, and social forces, transforming challenges into opportunities. The construction sector significantly affects energy use, pollution, and housing deficits. Efforts include deep retrofitting and reducing energy needs. The paper highlights the interconnectedness of these issues, advocating comprehensive solutions and policies addressing energy consumption, climate change, and poverty for a sustainable built environment. It urges proactive strategies to tackle challenges and foster opportunities in Europe.

Table 1. Summary of the International Energy Agency (IEA) report on achieving zero-carbon-ready buildings.

IEA Report's Sections	Key Points
Renovation of Near 20% of Existing Building Stock to Zero-Carbon-Ready by 2030 is Ambitious but Necessary	The urgency of renovating existing buildings, challenges in retrofitting, and the need for political will and supportive policies
All Countries Targeted for Zero-Carbon-Ready Codes for New Buildings by 2030	Importance of zero-carbon-ready codes, slow progress in retrofitting, and adoption of performance-based building energy codes
Installation of About 600 Million Heat Pumps Covering 20% of Building Heating Needs Required by 2030	Significance of heat pumps in reducing emissions, challenges in upfront costs and awareness, and focus on innovation for cost-effective solutions
Approximately 100 Million Households Rely on Rooftop Solar PV by 2030	Role of rooftop solar PV in reducing emissions, challenges in upfront costs and grid integration, and emphasis on innovation for residential PV deployment
Solar PV and Wind Supply About 40% of Building Electricity Use by 2030	Projection for renewable energy in building electricity, challenges in upfront costs and system reliability, and focus on innovation for integration and control
350 Million Building Units Connected to District Energy Networks by 2030 Provide About 20% of Space Heating Needs	Importance of district energy networks in heating, challenges in high initial costs and regulatory frameworks, and focus on innovation for system optimization and awareness
Solar Thermal Technologies Deployed in Around 400 Million Dwellings by 2030	Deployment goals for solar thermal technologies, challenges in policies and certification standards, and emphasis on innovation for performance improvement and affordability
Targeting 100% LED Lighting Sales by 2025	Importance of LED lighting in zero-carbon buildings, challenges in upfront costs and quality assurance, and focus on innovation for efficiency and circularity
Residential Behavior Changes Lead to a Reduction in Heating and Cooling Energy Use by 2030	Impact of behavior changes on energy use reduction, challenges in predicting outcomes and integrating technologies, and focus on policy interventions and innovation for occupant comfort
By 2030 EVs Represent More Than 60% of Vehicles Sold Globally and Require an Adequate Surge in Chargers Installed in Buildings	Significance of EV adoption and charging infrastructure, challenges in upfront costs and grid connections, and focus on innovation for energy management and interoperability
Technology and Innovation Pathways for Zero-Carbon-Ready Buildings by 2030: TCP Strategic Vision on IEA Net Zero by 2050 Building Milestones	Strategic vision for achieving net-zero buildings, targets for codes, renovation, heat pumps, solar PV, wind, district energy, solar thermal, LED lighting, behavior changes, and EV chargers, and emphasis on policy recommendations and innovation themes
Conclusions	Urgency of achieving zero-carbon buildings, the importance of clean energy technologies and supportive policies, challenges in upfront costs and regulatory frameworks, and focus on systemic flexibility and international collaboration

Similar results are obtained in studies in different climate zones. Stephan and Stephan [18] investigated achieving zero life cycle primary energy and greenhouse gas emissions in Mediterranean apartment buildings, considering associated costs. Their analysis includes the building's embodied energy, operational energy use, and emissions. Measures for energy reduction and installing photovoltaic panels are explored. Results show feasibility in Mediterranean climates, with subsidies needed in some countries like Lebanon. The study underlines the potential for net-zero buildings in various contexts, providing valuable insights into feasibility and costs.

1.1.2. Life Cycle Assessment (LCA) and Environmental Impact

Life cycle assessment (LCA) is crucial for understanding environmental impact and guiding sustainable building practices, as reported in studies on carbon retrofits and building decarbonization. Desvallées [19] explores challenges and strategies in achieving carbon retrofits in southern European social housing, focusing on energy efficiency and poverty. It compares approaches in Porto and Barcelona with broader social housing contexts, finding a priority on envelope retrofits over renewable energy due to cost concerns. However, this overlooks energy poverty's multidimensionality. The paper shows social housing's role in energy efficiency and inclusion, noting opportunities for low-carbon transitions. It highlights the "prebound effect", where residents consume less energy than projected due to outdated housing and poverty, challenging standardized efficiency models. Overall, it emphasizes addressing energy poverty and conducting life cycle assessments for improved housing sector sustainability.

Norouzi et al. [20] assess the environmental impact of building decarbonization in Northern Ireland, focusing on the energy performance and life cycle assessment (LCA) of four single-family houses. Standardizing ISO norms for LCA, the study highlights operational energy as the main contributor to environmental impact, stressing the importance of enhancing energy efficiency. Proposed strategies include building-integrated photovoltaics/thermal systems and passive heating techniques to improve building performance. Emphasizing low-energy standards and electrical heat pumps, the paper discusses the significance of considering future electricity mix scenarios for emission reduction. It emphasizes the need for sustainable construction practices, addressing energy poverty and achieving zero-carbon buildings to reduce energy consumption and greenhouse gas emissions.

Decorte et al. [21] examine buildings' environmental impact, focusing on embodied emissions from material production and operational energy use. They stress the growing importance of considering material impacts alongside energy efficiency in building codes and advocating for comprehensive life cycle assessments (LCAs). Simplifications in LCAs, due to resource constraints, can lead to incomplete results, particularly in assessing heating and ventilation systems. The study finds that simplified approaches may underestimate impacts by up to 12%. It underscores the need for further research to develop guidelines for accurate assessments, highlighting the significant contribution of operational energy and materials to overall impact.

Costa et al. [22] conducted a review focusing on renewable and sustainable energy, particularly life cycle assessment (LCA) in analyzing building technologies. They stress the significance of LCA in evaluating environmental performance, including impacts on climate change and human toxicity. The review encompasses topics such as photovoltaic panels, renewable energy production, and energy payback time. It advocates for zero-carbon buildings, addressing energy poverty, and promoting sustainable communities. Additionally, the paper highlights the rising importance of battery energy storage systems (BESS) for electric vehicle deployment and smart grids.

1.1.3. Energy Poverty and Social Housing

Exploring carbon reduction targets reveals the intricate interplay between economic growth, innovation, and urbanization in mitigating energy poverty and addressing environmental concerns. Tiwari et al. [23] examine the impact of carbon reduction targets on energy poverty in China, using data from 30 cities (2004–2017). Successful provinces show reduced carbon intensity and progress toward net-zero emissions. Economic growth and patents aid in alleviating energy poverty, but total energy use and urbanization exacerbate it. Their study stresses green technology innovation for renewable energy management and sustainable development. Balancing economic growth and urbanization is crucial to prevent energy poverty and environmental decline.

Huang et al. [24] review building life cycle carbon emissions (LCCE), analyzing 826 global cases. They organize findings into five modules: production, construction, use, end-of-life, and benefits. They discuss the relation of LCCE to life cycle assessment

(LCA) and energy assessment (LCEA/LCCEA). Their study identifies six carbon reduction strategies, including data reduction and emission factor lowering. It highlights gaps in LCCE studies, such as research goals and calculation methods, offering suggestions for improvement. Overall, the paper comprehensively examines building LCCE, providing insights into their implications and suggesting avenues for future development.

1.1.4. Strategies for Sustainable Building Practices

Sustainable building practices involve integrating energy efficiency and renewables while considering the entire life cycle of structures to minimize environmental burdens and achieve net-zero carbon emissions. Asdrubali and Grazieschi [25] focus on applying life cycle analysis (LCA) in the construction sector, particularly concerning energy-efficient buildings. It highlights the goal of achieving nearly zero-energy buildings (NZEBs) by 2020 in Europe, emphasizing energy efficiency and renewable energy integration. However, improving energy efficiency and implementing new energy systems may shift environmental burdens to other phases of the building's life cycle. By comparing ideal and real case studies, the research assesses the environmental effectiveness of different building typologies and energy retrofit interventions. Enhanced energy efficiency reduces non-renewable primary energy demand, cumulative energy demand (CED), and global warming potential (GWP). Yet, due to impacts shifting to embodied components, the achievable reduction in non-renewable energy and emissions in the life cycle is lower. The transition to renewables has a limited impact on life cycle CED reduction.

Shen et al. [26] explore achieving net-zero-carbon buildings, emphasizing consideration of all stages in the building life cycle, including demolition, recycling, and material reuse. Their study targets the reduction in both embodied and operational carbon emissions, especially in residential buildings. Through a novel conceptual framework based on key decision variables, they highlight the importance of comprehensive approaches. Utilizing an open international standard and ontology-based representation via digital twins, their framework aims to facilitate data integration for informed decision-making. While contributing to net-zero goals, the study shows the need to address limitations and promote sustainable building practices across the building life cycle.

The reviewed literature provides insights into the challenges and strategies for achieving zero-carbon buildings, addressing energy poverty, and promoting sustainable building practices through comprehensive approaches and innovative solutions as summarized in Table 2.

Table 2. Challenges, strategies, and innovations for achieving zero-carbon buildings.

Topic	**Key Points**
Achieving Zero-Carbon Buildings	Emphasis on renovating existing buildings, implementing zero-carbon-ready codes, and deploying renewables.
Life Cycle Assessment (LCA)	Challenges in achieving carbon retrofits, the importance of considering the entire building life cycle, and evaluating environmental impacts through LCA.
Energy Poverty and Social Housing	Impact of carbon-cutting targets on energy poverty approaches to achieving carbon retrofits in social housing and exploring implications of building life cycle carbon emissions.
Strategies for Sustainable Building Practices	Importance of considering all stages of the building life cycle, application of LCA in assessing environmental impact, and exploring strategies for sustainable energy systems.

1.2. Objectives and Research Questions

Based on these premises, the objectives of this paper are identified as follows: (1) to develop a simplified decision-making tool for the preliminary assessment of parameters influencing carbon neutrality of buildings; (2) to implement a methodological framework to integrate biogenic carbon evaluation and consider the potential of carbon capture and storage from biobased building materials; and, in consideration of the global decarbonization target by 2050, (3) to understand how future weather scenarios impact the emission balance between EC and OC towards long-term carbon neutrality. The following research questions are proposed to address these objectives: (1) What are the key parameters that significantly impact the carbon neutrality of buildings, and how can they be integrated into a decision-making tool for preliminary assessment? (2) How can biogenic materials be effectively integrated into building design and construction to reduce carbon emissions, and what is the environmental impact of their use compared to conventional materials? (3) What are the potential future impacts of climate change on building design and construction, and how can designers and stakeholders adapt to mitigate these impacts and improve the overall carbon neutrality of buildings?

1.3. Structure of the Paper

To address the objectives, this paper has been prepared under the following sections starting with a Methodology that outlines the approach used to achieve the study's objectives. Following that, the Results and Discussion Section (Sections 3 and 4) presents the findings of a parametric study, including the optimization process for achieving zero-carbon emissions in buildings. Additionally, this section discusses the performance of the building designs under future climate scenarios and evaluates the strengths and limitations of the study. The Conclusions Section (Section 5) summarizes the key findings of the research, highlighting the development of a parametric tool for designing life cycle zero-carbon buildings (LC-ZCBs) and emphasizing the importance of sustainable alternatives, such as biobased insulation materials, in achieving carbon neutrality. Lastly, future research directions are proposed to further advance sustainable construction practices and address the challenges of climate resilience in building design. The utilization of biobased materials, prototype building properties, and some equations are also discussed and listed in Appendices A–C.

2. Methodology

The following steps are proposed to achieve the study's objectives:

- selection of a typical building and its modeling using Grasshopper for Rhino using the main parameters that influence its total emissions (geometry, envelope material characteristics, plant type, etc., as later specified);
- use of a custom code, Bombyx, and Honeybee plugins to integrate OC and EC into the model;
- conversion of operational energy to operational carbon in consideration of the energy mix of the reference country (in this case, the United States);
- identification of alternative configurations, and related parameters, for optimizing the base case, both for operational carbon reduction (transparent/opaque envelope ratio, thickness of insulation material, and photovoltaic surface area) and embodied carbon reduction (replacement of insulation material with biogenic materials);
- comparison of the results obtained for the different alternatives in terms of kg CO_2 eq/m^2/year;
- validation of the results against future climate scenarios up to the end of the century.

The tool Bombyx—a design-integrated parametric tool for real-time life cycle assessment (LCA) developed at ETH in Zurich [27–29]—is used to calculate the embodied emissions. It allows a simplified LCA, based on a Rhino/Grasshopper model, and permits different levels of detail (LODs)—a term used in building information modelling to describe the precision of a model. Since all the materials have been identified for this case study, a high LOD has been used. The parametric LCA (pLCA) method, compared with conventional methods in Figure 2, allows for modifications of the main building parameters and generates a real-time impact assessment calculated on the updated configuration of the model [28].

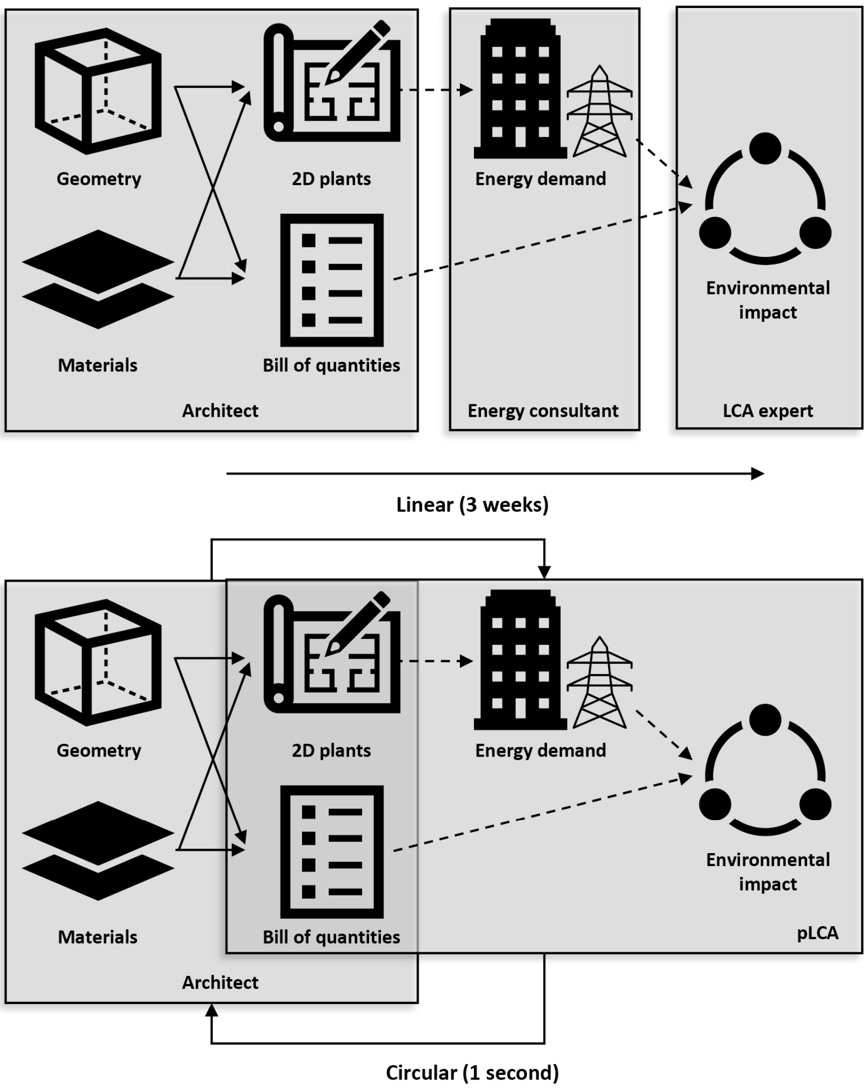

Figure 2. Process of LCA in architectural practice today (**top**) and parametric LCA (**bottom**).

Since the Bombyx tool does not contemplate biogenic CO_2, effectively implying the impossibility of achieving climate neutrality with renewable energy production alone, a Grasshopper-specific code was developed based on the biogenic global warming potential (GWPbio) index method considering a time horizon of 100 years. This method is based on dynamic life cycle analysis that assumes the biomass turnover period and storage period as variable functions. The goal is set to obtain a total net GWP of 0 kg CO_2eq/m^2 through an estimated sum of OC and EC. To consider carbon emissions, emissions associated with energy were converted to carbon emissions in consideration of the mix of energy sources in the United States. The summary of the adopted methodology is presented in Figure 3.

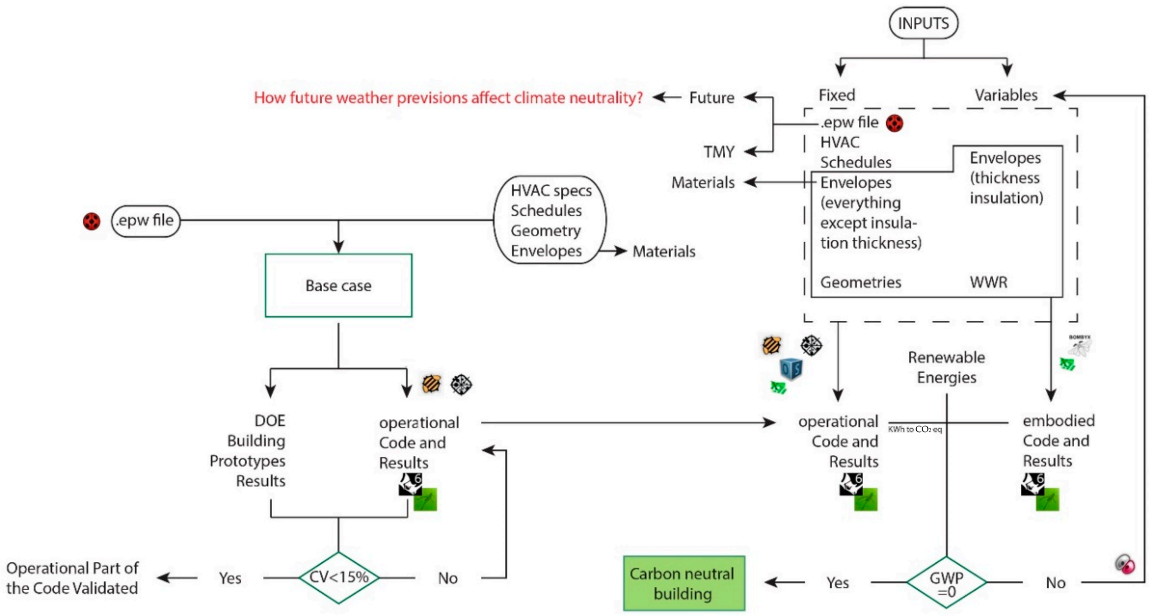

Figure 3. Adopted methodology flowchart.

2.1. Case Study: Single-Family Detached House

The case study is a residential single-family house with 2 floors adopted from the Department of Energy (DOE) prototype building built in the 1980s (Figure 4). Its characteristics are based on the International Energy Conservation Code (IECC) [30], with a slab-on-ground foundation and a heat pump as the heating and cooling system, with specifications reported in Appendix C (Tables A1 and A2). The climate zone chosen for the simulation is 4A, the representative city is New York City, and the weather data (.epw file) come from John F. Kennedy International Airport. The number of occupants considered is 3. With an internal surface of 220 m^2 (≈2368 sq ft), the building includes a pitched roof and eight windows with a window/wall ratio (WWR) reported in Table 3. The building also has a non-heated attic of 110 m^2 (≈1184 sq ft). As shown in Figure 4, the building envelope consists of two types of walls (i.e., the Exterior_Wall and Gable_End), a basement floor (i.e., Basement_floor), a roof (Roof), and two interior floors (Int_Floor and Attic_Floor).

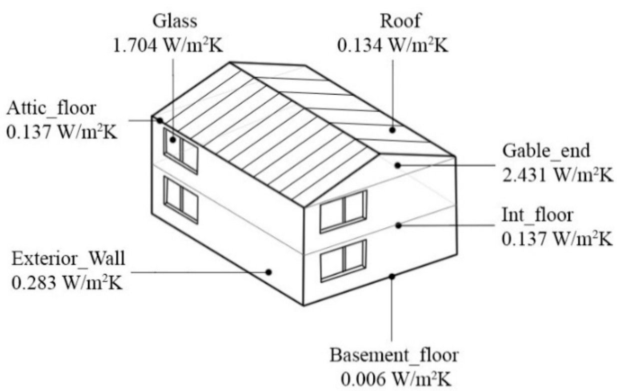

Figure 4. Model of the considered building.

Table 3. Window–wall ratio (WWR).

	Total	North	East	South	West
Gross WWR (%)	15.00	13.12	15.28	13.12	15.28

The overall R-values of the envelope components, their construction layers' physical and thermal properties, the heating and cooling system properties, and other equipment are reported in Appendix C (Tables A3 and A4). The glass used in the model has a U-value of 1.704 W/m^2K, a solar heat gain coefficient (SHGC) of 0.334, and a visible transmittance (VT) of 0.880. The window–wall ratio is also reported in Table 1. The weather data comprise the John F. Kennedy International Airport EnergyPlus weather (EPW) file representing the 4-A climate zone (i.e., mixed–humid) in New York City. The temperature in this climate zone is defined by CDD 10 °C ≤ 2500 AND HDD 18 °C ≤ 3000, where CDD and HDD are cooling and heating degree days, respectively. EnergyPlus™ version 9.0. was used to simulate the prototype building's energy use.

2.2. Integrating Operational and Embodied Carbon Emissions

The life cycle carbon footprint assessment (LC-CFA) consists of two phases: (i) operational carbon (OC) and (ii) embodied carbon (EC). The Honeybee tool is used to calculate the OC, while the EC consists of two parts: fossil carbon (FC) and biogenic carbon (BC). The first one is calculated by multiplying the mass of each material (M_j) with the material's specific emission factor (EF_j) (Equation (1)), while the second one is evaluated by multiplying the total mass of CO_2 stored in a specific biobased product (CC_j) with the specific GWPbio index according to the (i) type of biomass and (ii) storage period (see Appendix A) (Equation (2)). First, the areas of the different building elements (A_i) must be calculated to determine the mass of the involved materials. Then, it is multiplied by the thickness (t_j) and density of the specific material. The density data are obtained from the KBOB database together with the specific EF. For some materials, such as windows, the KBOB database provides the EF per surface area of the element. In this case, the element area A_i can directly be multiplied by the EF_j.

Additionally, the number of replacements (R_j) is considered for each material used. To calculate it, the reference study period (RSP) has been divided by the reference service life (RSL) of the building component (Equation (3)). As Bombyx is based on Swiss standards, the RSL is defined in SIA 2032 [31], and the RSP for residential buildings is assumed equal to 60 years. The RSP of 60 years is maintained because it is typical in the U.S. and is a reasonable value for this type of calculation.

$$FC = \sum_j (M_j \times EF_j \times (1 + R_j)) \quad (1)$$

$$BC = \sum_j (CC_j \times GWP_{bio,j}) \quad (2)$$

$$R_j = (RSP/RSL_j) - 1 \quad (3)$$

2.3. Code and Model Validation

The next step is determining the operational energy calculation using Honeybee and Ironbug components and validating the Grasshopper model. Once the system is set, it is validated and compared to the results from the residential single-family model from the DOE building prototypes. The inputs are as follows: schedules, geometry, heating, ventilation, and air conditioning (HVAC) efficiency, envelopes, materials, and the New York City J. F. Kennedy weather file, downloaded from the Ladybug Tool EPW map website. Honeybee and GhExcel are used for the geometrical and material properties, respectively. The workflow creates zones based on plan dimensions, height, roof type, and window–wall ratio. The inputs follow ASHRAE 90.1-2010 with equipment, lighting, occupancy, temperature setpoints, and zone load schedules. Ironbug determines HVAC inputs from the .ifc file. The "Honeybee Export To Openstudio" plug-in executes the simulation, producing 19,230.6 kWh for the "Midrise Apartment" schedules. The model is validated against the prototype building using ASHRAE Guideline 14-2014 and the "coefficient of variation of the root-mean-square error" (CV RMSE), with a limit of 15% [32]. The Grasshopper model produces the CV RMSE, as shown in Figure 5, confirming the model's validity.

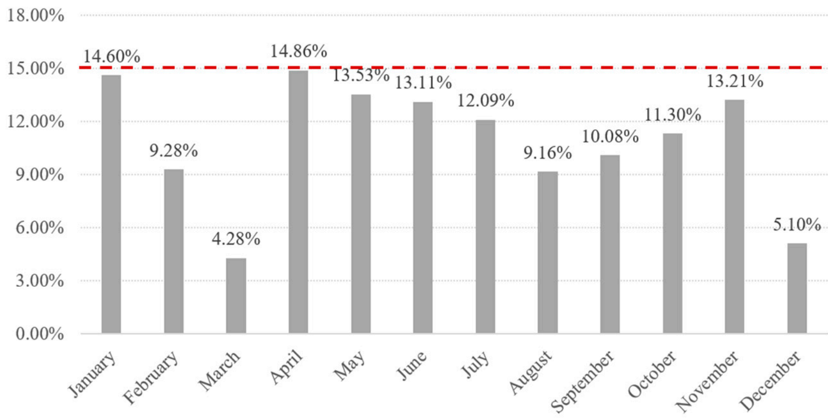

Figure 5. Monthly CV RMSE error compared to 15% (the dashed line).

2.4. Optimization of the Base Case Building and Carbon Neutrality Considering the U.S. Energy Mix

Using the Grasshopper code, an optimization process is applied to the existing model to introduce new materials and a photovoltaic (PV) system to achieve the nZEB standard. The building's global warming potential (GWP) is used to evaluate the success of the optimization, with a target of reaching 0 kg CO_2eq/m^2 per year. The GWP is calculated as the sum of operational and embodied energy. To calculate the operational energy, the electricity consumption is first converted from "kWh/m^2" to "kg CO_2eq/m^2" using the average U.S. electricity source emissions of 0.429 [30] for the reference building in New York City. The embodied energy is calculated using the Bombyx plug-in's bottom-up approach, which considers material properties, thicknesses, reference service life, component surface areas, and window details. The energy conversion is assumed to be steady, but this value may change in the future as the energy source mix changes.

The construction material properties were sourced from the KBOB Swiss database, but the present study used Environmental Product Declarations (EPDs) from local producers due to imprecise material information in the DOE. The EPDs provide material properties like density, embodied energy, renewable energy, non-renewable energy, greenhouse gas emissions, thermal conductivity, and others.

This study evaluates two variations to optimize the base case scenario: BASE_OPT and BASE_BIO. BASE_OPT improves energy efficiency by adding sufficient PV-covered surfaces, while BASE_BIO incorporates more biobased materials (i.e., hemp shives) than the base case, reducing embodied GWP values to achieve the nZEB condition. Life cycle impact assessment (LCIA) databases and validated standards do not currently include carbon storage and end-of-life considerations for biobased products due to methodological limitations. This creates a challenge for accurately assessing the environmental impact of wood and other biobased materials, as their ability to store carbon and delay greenhouse gas emissions temporarily is not fully captured [11]. To address this issue, this study utilizes the GWPbio index method, developed by Guest et al. [10], which considers a 100-year time horizon and incorporates dynamic life cycle analysis with variables such as rotation period and storage period explained in Appendix A and shown in Figure A1. The results showed that using fast-growing materials like straw, hemp, and flax as thermal insulation in buildings can be a negative carbon technology, as the carbon embedded in the biobased product is fully regenerated within one year of crop growth [8].

Ladybug is used to analyze PV panel-covered surfaces like walls and roofs, and utilizing the Galapagos plugin, potential values for various parameters can be inputted to identify the optimal solution for achieving zero-carbon emissions. Figure 6 summarizes the parametric inputs used in this study. The range of glazed surfaces is defined based on their orientation, with the north-facing surface having greater extremes, as it is not exposed to direct solar radiation. Following the ASHRAE code, the minimum and maximum values for the window–wall ratio (WWR) are set to 10% and 40%, respectively [30]. To achieve the zero-energy building target, renewable energy sources, such as PV panels, were added to the roof of the DOE prototype building. The insulation thickness of the base case is 14 cm and is increased to 16 and 18 cm, but ultimately, a thickness of 20 cm is chosen due to its minimal difference in results compared to the 16 cm thickness.

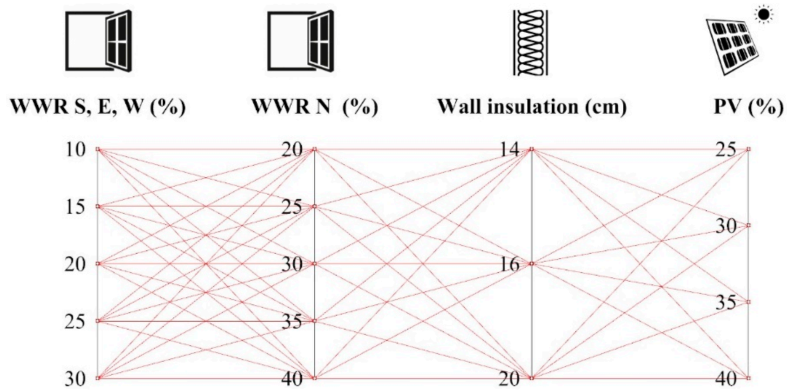

Figure 6. Parameter values used for Grasshopper generative simulation scenarios.

2.5. Evaluation of the Best Solutions for a Future Climate Scenario

To assess the validity of the best solutions obtained, it is essential to evaluate their performance under future climate conditions. To achieve this, the developed and calibrated models are subjected to simulation using the current typical meteorological year (TMY) tailored for the year 2099. These weather files are generated through the utilization of the WeatherShift Tool [33], which takes into account climate change projections and incorporates them into the current TMY files. By employing TMY as a study parameter in the Honeybee and Grasshopper platforms, the identification of the optimal solutions can be investigated as well as how they perform in the face of potential climate variations expected in the distant future. This analysis is crucial as buildings and their energy systems are long-term investments, and their design should account for changing climatic conditions to ensure their sustainability and efficiency over time. Additionally, it allows us to make informed decisions about the suitability and reliability of these solutions in mitigating environmental impacts and addressing climate change challenges in the years to come.

3. Results

3.1. Parametric Study Results

After setting up the code and its variables, the Galapagos plug-in simulates 300 possible solutions. The results show the base case and solutions with minimal energy consumption for both optimization scenarios. Achieving a negative GWP through the addition of renewable sources in Bombyx is not feasible without considering biogenic GWP. To satisfy the nZEB requirements, it is necessary to cover a percentage of the south wall surface with PV panels, ranging from 30% (13.35 m^2) to 40% (21.37 m^2). The primary objective is to achieve climate neutrality, prompting the use of hemp shives as biogenic insulation. Adopting biobased materials facilitated the achievement of the LC-ZCB condition. Additionally, the approach led to solutions requiring fewer PV panels and larger windows, demonstrating the advantages of designing with biogenic materials. All the solutions in Table 4 are nZEB.

Table 4. Comparison of building design options.

# Option	WWR—South (%)	WWR—North (%)	Exterior_Wall Insulation Thickness (cm)	PV Surface on the Roof (%)	PV Surface on the South Wall (%)
Base Case	15	15	14	0	0
1 OPT	20	10	20	100	40
2 OPT	25	10	20	100	40
3 OPT	20	10	16	100	40
4 OPT	20	10	20	100	35
5 OPT	30	10	20	100	40
6 OPT	20	10	14	100	40
7 OPT	20	15	20	100	40
8 OPT	25	10	16	100	40
9 OPT	25	10	20	100	35
1 BIO	25	15	20	100	35
2 BIO	30	10	16	100	35
3 BIO	20	15	16	100	35
4 BIO	30	10	20	100	30
5 BIO	20	15	20	100	30
6 BIO	35	15	20	100	40

The choice between the two should be based not solely on energy and environmental analysis but also on cost, feasibility, and building appearance, which should be the subject of further research. As demonstrated in Figure 7, biobased materials significantly reduce the embodied equivalent carbon (i.e., green points), and using PV panels leads to lower operational equivalent carbon (i.e., red points).

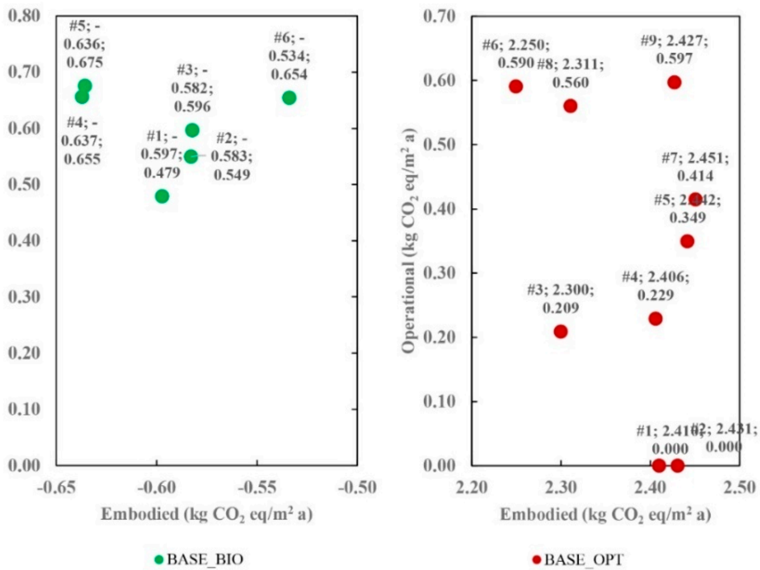

Figure 7. Operational carbon (OC) and embodied carbon (EC) of the six combinations minimize the overall emission profile for the biobased solutions (on the left) and the nine combinations for the conventional base solutions.

3.2. Climate Neutrality for the 21st Century

Using fTMY for three future periods (i.e., 2026–2045, 2056–2075, and 2080–2099), the changes in the base case and optimal solutions throughout the 21st century are assessed, as depicted in Figure 8. The observed rise in temperature and global irradiance results in increased power output from PV panels, enabling the total energy demand to be met in the future. As a result, the nZEB BASE_BIO cases (with negative GWP values) are expected to achieve the LC-ZCB condition in future scenarios. Although the tool effectively addresses the primary objectives, some areas still require further attention and future research. For instance, it is imperative to incorporate the emissions resulting from the life cycle of the structure, HVAC, or PV panels. Adding shading systems and doors could also improve the model's accuracy. Because of the unavailability of the exact location of the building, the model has not accounted for transport emissions.

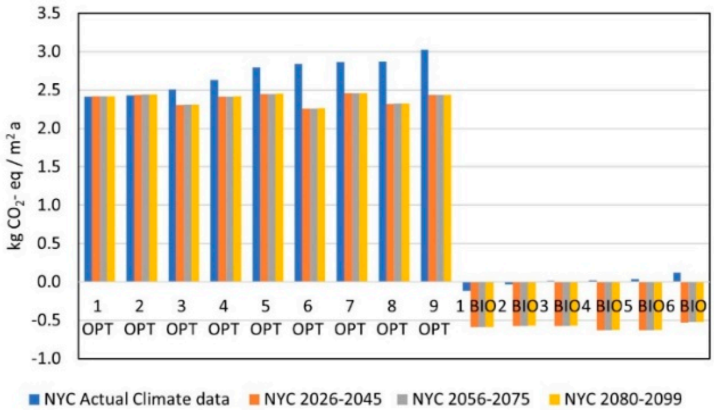

Figure 8. Annual GWP through the century.

The first nine combinations that minimize whole life cycle carbon emissions to achieve a net-zero target are analyzed from the 200 generated within the parametric integrated platform. All combinations have a glazing exposition ranging between 15 and 35% on the south facade and between 10 and 15% on the north facade and an insulation thickness ranging between 14 and 20 cm. Partial coverage of the south facade is required for all combinations, ranging between 35 and 40%. As shown in Figure 8, none of the OPT combinations achieve absolute zero due to the carbon intensity of the construction materials. However, all BIO combinations achieve nearly LC carbon goals due to low emissions for biobased insulation manufacturing and fast carbon CO_2 uptake during hemp regeneration of the crop. The evaluation of future climate scenarios shows that the overall carbon emission of the building is reduced for every combination except for OPT 1 and OPT 2, where high glazing exposition, conventional insulation EC, and PV panels increase energy demand and consequential OC for cooling. However, future climate scenarios only consider energy need estimation, ignoring the negative consequences of increased risk of extreme events and building vulnerability.

4. Discussion

4.1. Interpretation of Results and Recommendations

This section elaborates the implications of the parametric study results and their significance for achieving climate neutrality in the 21st century. The findings highlight the feasibility of reaching LC-ZCB conditions through a combination of renewable energy sources and biobased materials like hemp shives. While biobased materials notably reduce embodied carbon emissions, the incorporation of PV panels contributes to lower operational carbon emissions. However, the decision-making process for choosing between conventional and biobased solutions should also consider cost and feasibility factors, necessitating further exploration. Adopting biobased materials facilitates the achievement of the LC-ZCB condition. Additionally, the approach leads to solutions requiring fewer PV panels and larger windows, demonstrating the advantages of designing with biogenic materials. As demonstrated in Figure 7, biobased materials significantly reduce the embodied equivalent carbon (i.e., green points), and using PV panels leads to lower operational equivalent carbon (i.e., red points).

Moreover, the study emphasizes the importance of considering future climate scenarios, as increasing temperatures and global irradiance may affect energy demand and building performance over time. Future research should prioritize incorporating life cycle emissions, enhancing model accuracy by integrating shading systems and doors and addressing transport emissions. Despite challenges, the study highlights the potential of integrating biobased materials and renewable energy sources in building design to mitigate carbon emissions and advance towards climate neutrality. The evaluation of future climate scenarios shows that the overall carbon emission of the building is reduced for most of the combinations.

In comparing the results of this study with existing literature, several key insights emerge. Both emphasize the imperative of achieving zero-carbon buildings, albeit through differing approaches. The importance of considering both embodied and operational carbon emissions is highlighted by both this study and existing literature. In addressing energy poverty, the existing literature examines the impact of carbon reduction targets and building life cycle carbon emissions. This study's findings complemented these insights by recommending strategies such as the substantial use of biobased insulation materials for carbon storage and the integration of renewable energy sources. Lastly, in discussing strategies for sustainable building practices, both this study's outcomes and existing literature emphasize the importance of considering all stages of the building life cycle and applying LCA to assess environmental impact. While previous research provides frameworks and conceptual models, this study offers practical tools and methodologies for designers to evaluate building emissions comprehensively.

4.2. A Methodological Framework for Biogenic Carbon Accounting

Arguments about the effectiveness of mitigating the climate through storing carbon in biobased construction and using cities as "carbon sinks" are today strongly debated as a standard method for biogenic carbon accounting is not universally accepted by the scientific community. One of the points under debate is the inclusion of effects over long timespans in LCA. Time-independent LCA in general considers all effects as if they would happen today. Time-dependent or dynamic LCA includes the moment of emissions in the calculation of an LCA. The two methods come to different conclusions when assessing climate disturbance from carbon dioxide over the life cycle of a building. While standard LCA is not able to measure the effect on climate change from storing carbon and uptake during the regeneration of the biomass in the land due to the independency of the method from the time, time-dependent LCA can capture the influence of GHG emissions and carbon sequestration through a dynamic approach. Thus, the integration of dynamic methods for carbon accounting into the ordinary design practice is a fundamental step in order to include the environmental benefits from implementing biobased solutions for construction. The novel methodological framework proposed in this work allows designers to assess the influence of implementing biobased solutions, fast-growing insulation in this case, for achieving the life cycle zero-carbon building target.

4.3. Strength and Limitations

This study does not consider HVAC's properties in the parametric study and instead focuses on the building envelope embodied energy and its impact on operational energy. A critical factor in this study is the future climate data, and RCP 4.5 is assumed as the representative scenario of future climate. The outcomes could be different under a different climate change scenario. The present case study does not consider transportation due to the unavailability of data concerning the type and quantity of means of transport used.

5. Conclusions

This paper presents a research effort that culminates in the development of a parametric tool for designing life cycle zero-carbon buildings (LC-ZCBs) with minimized operational carbon (OC) and embodied carbon (EC) throughout their lifecycle. By defining and implementing critical parameters, such as geometry, construction technology, envelope thermal resistance, and on-site renewable energy production, into the Grasshopper platform, the tool provides a versatile and effective means of achieving carbon neutrality in buildings. The validation of this tool using a prototype residential building demonstrates its accuracy, with the CV-RMSE staying consistently below the 15% limit.

This study undertakes a comparative analysis of two distinct building envelope options: the conventional timber frame and insulation (OPT) versus the biobased hemp shives and fiber insulation (BIO). To reach the nZEB condition, a total coverage of the roof with PV panels and 30–40% of the south façade as well is requested for all alternatives. While the two categories of alternatives (OPT and BIO) register similar values achieved for operational carbon, with carbon emissions ranging below 0.7 kg CO_2eq/m^{2}a, the embodied carbon is largely different, with negative values ranging between −0.64 and −0.54 kg CO_2eq/m^{2}a only for BIO alternatives, while the OPT ones achieved positive values (2.25–2.45 kg CO_2eq/m^{2}a) due to the absence of the negative contribution of carbon sequestration and fast uptake. In a life cycle scenario, considering the evolution of global warming according to future climate change scenarios, the operational carbon tends to slightly decrease due to the increasing productivity of the PV panels. Thus, the life cycle emissions for all OPT alternatives move from 2.4–3.0 kg CO_2eq/m^{2}a to 2.2–2.4, while all BIO alternatives achieve LC-ZCB targets with negative values between −0.15 and −0.60 kg CO_2eq/m^{2}a.

The results show the limitations of conventional materials, as none of the conventional combinations could achieve absolute zero-carbon emissions, primarily due to the carbon-intensive nature of these construction materials. However, in stark contrast, the implementation of biobased insulation materials in all BIO combinations leads to the realization of an LC carbon goal, signifying the efficacy of sustainable alternatives in promoting carbon-neutral construction.

Nevertheless, the research acknowledges the influence of future climate scenarios on building performance. While the study offers valuable insights into the potential impact of climate projections on energy needs, it also highlights the need to consider additional factors such as increased risks of extreme events and the building's vulnerability to such conditions. A more comprehensive approach to climate resilience should be pursued in future investigations to create buildings that not only minimize carbon emissions but also withstand and adapt to changing climate patterns.

In conclusion, the development of a parametric design tool for LC-ZCBs marks a significant advancement in the construction industry's journey toward sustainability. By optimizing both operational and embodied carbon, the tool sets a new standard for environmentally conscious building design. The positive results achieved through the implementation of biobased insulation materials emphasize their potential in driving the transformation towards net-zero carbon buildings. As the field of sustainable construction continues to evolve, future research should explore the integration of other eco-friendly materials and innovative design strategies to further advance the construction sector's contributions to global decarbonization goals. Further investigations should clarify the relationship between the carbon removal by the regeneration of the biomass and the biogenic emissions that occur at the end of life of the building when biobased materials are disassembled and treated as waste. This is a fundamental step that provides important knowledge to decision makers for the selection of the proper novel eco-friendly material during building design. Moreover, a continuous investigation of the influence of other factors that contribute to sustainable development and carbon savings, e.g., sufficiency principles and consistency of energy sources, should be included in future works to identify best practice to reduce the carbon intensity of buildings during their service life. By embracing such advancements and promoting interdisciplinary collaboration, a greener and more sustainable future can be collectively achieved.

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Nomenclatures

BC	Biogenic Carbon
CC	CO_2 Storage in Biobased Product
CDD	Cooling Degree Days
DOE	U.S. Department of Energy
DLCA	Dynamic LCA
EC	Embodied Carbon
EF	Emission Factor
EPD	Environmental Product Declaration
EPBD	Energy Performance of Buildings Directive
EPW	EnergyPlus Weather
FC	Fossil Carbon
GWP	Global Warming Potential
GWPbio	Biogenic Global Warming Potential
HDD	Heating Degree Days
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LC-CFA	Life Cycle Carbon Footprint Assessment
LC-ZCB	Life Cycle Zero-Carbon Building
LOD	Levels of Detail
nZEB	Nearly Zero-Energy Building
OC	Operational Carbon
pLCA	Parametric LCA
PV	Photovoltaic
RSL	Reference Service Life
RSP	Reference Study Period
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year
VT	Visible Transmittance
WWR	Window–Wall Ration
ZEB	Zero-Energy Building

Appendix A

Biobased materials can help decrease GHG emissions by capturing and storing CO_2. More precisely, the biomass is stored in the anthroposphere as a harvested product (e.g., solid wood), while the carbon sequestration happens in the biomass that is regrowing through photosynthesis, reducing atmospheric carbon dioxide [34]. To take into account this biogenic CO_2 deposit in the anthroposphere, the method [35] illustrated in Figure A1 is used, which includes a GWPbio index to consider the benefits of biogenic carbon over a 100-year time horizon. This method incorporates the interface between biomass growth and global carbon cycle emissions. As can be seen, the rotation and retention periods vary from 0 to 100 years, while the time horizon is set at 100 years. Furthermore, the GWPbio index decreases with the increase in the storage period and with smaller rotation periods. Hence, to absorb the same amount of carbon that is stored in biogenic products, fast-growing plants need a shorter time than slow-growing ones, resulting in a more beneficial effect on GWP.

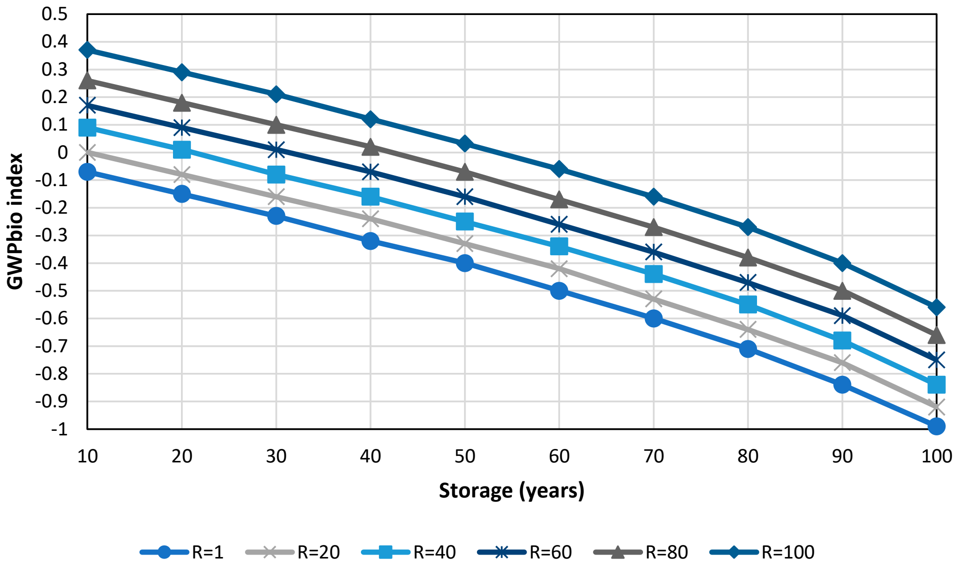

Figure A1. The biogenic global warming potential (GWPbio) factor values for six rotation periods (R) as a function of the storage period (S), calculated for the 100-year time horizon (TH). Re-elaborated data from Guest et al. [10].

The CO_2 storage of the new biobased compounds (CC) can be determined according to the following Equation (A1), as defined by CEN/TC175, "Wood and wood-based products—Calculation of sequestration of atmospheric carbon dioxide" [36]:

$$CC = \rho_0 \times C \times BC \times 3.67 \text{ [kg } CO_2/\text{kg]} \quad \text{(A1)}$$

where

- ρ_0 is the dry density of the material;
- C is the percentage of carbon content;
- BC is the percentage biomass content of the finished compound;
- 3.67 is the molar weight ratio between CO_2 and C.

Subsequently, by multiplying the carbon storage with the GWPbio index defined above, the absorbed carbon is obtained by the following Equation (A2):

$$GWP_{bio} = CC \times GWP_{bio} \text{ index} \quad \text{(A2)}$$

Finally, the Net-GWP of construction materials is assumed as the sum of the GWP at 100 years, calculated according to the IPCC 2013 method, and the related biogenic GWP, also referred to as the carbon footprint, as obtained by Equation (A3):

$$\text{Net-GWP} = \text{GWP}_{\text{fossil}} + \text{GWP}_{\text{bio}} \tag{A3}$$

where

- Net-GWP: carbon footprint;
- $\text{GWP}_{\text{fossil}}$: CO_2 emissions;
- GWP_{bio}: CO_2 absorption.

Appendix B

Non-biobased materials have no carbon deposition or absorption, so their net values are always positive. On the contrary, every biobased material has a storage potential and also depends on carbon emissions for its production or transport; their net values can be positive, however, much lower than conventional ones, or even negative.

The last factor to be determined is the dry density of the material ρ_0, as defined by CEN/TC175, "Wood and wood-based products—Calculation of sequestration of atmospheric carbon dioxide" [36].

For a water content of $\leq$25%, Equation (A4) is assumed as follows:

$$\rho_0 = \rho_{\omega \leq 25} \times (100 + 0.45 \times \omega)/(100 + \omega)\ [\text{kg} \times \text{m}^{-3}] \tag{A4}$$

In contrast, a water content > 25% is expressed by Equation (A5) as follows:

$$\rho_0 = \rho_{\omega > 25} \times 111.25/(100 + \omega)\ [\text{kg} \times \text{m}^{-3}] \tag{A5}$$

where

- ρ is the density [$\text{kg} \times \text{m}^{-3}$];
- ω is the water content in percentage.

Appendix C

The building is equipped with an electric boiler for domestic hot water (DHW). The heating and cooling system (Table A1) is located in the attic, using the same circuit for both systems. Other equipment includes fans (Table A2) and pumps for domestic water. Table A3 reports the miscellaneous equipment's nominal capacity. The overall R-values of the envelope components and their construction layers' physical and thermal properties are reported in Table A4.

Table A1. Heating pump coil specifications.

	Capacity at Peaks (W)	Nominal Efficiency
Main Heating Coil	5547.18	3.69
Cooling Coil	5232.20	4.07
Supp Heating Coil	6737.66	1.00

Table A2. Fan specifications.

	Pressure (Pa)	Air Flow (m^3/s)	Input (W)	Efficiency
Exhaust air fan	227	0.03	82.6	0.6
Fresh air fan	400	0.27	146.8	0.5

Table A3. Electric miscellaneous equipment nominal capacity.

	Nominal Capacity (W)
Washing Machine	28.47
Dishwasher	65.70
Electric Burner	248.10
Electric Dryer	213.06
Refrigerator	91.05
Television	130.00

Table A4. Total R-value of building envelope components and their construction layers' physical and thermal properties.

	Layer Name	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (J/kg·K)	Thermal Resistance (m^2·K/W)
Exterior_Wall	Syn_stucco	0.003	0.087	2775.0	878.64	0.0352
	Sheating_consol_layer	0.031	0.035	20.1	1465.42	0.8807
	OSB_7/16in	0.011	0.116	544.6	1213.36	0.0956
	Wall_consol_layer	0.140	0.057	120.8	1036.26	2.4438
	Drywall_1/2in	0.013	0.160	800.9	1087.84	0.0793
		0.198	0.455		5681.51	3.535
Gable_end	Cement_stucco	0.019	0.721	2775.0	878.64	0.0264
	Bldg_paper_felt					0.011
	OSB_5/8in	0.016	0.116	544.6	1213.36	0.1365
	Air_4_in_vert					0.158
	Drywall_1/2in	0.013	0.160	800.9	1087.84	0.0793
		0.013	0.160		1087.84	0.411
Basement_ Floor	Carpet_n_pad	0.025	0.060	32.0	836.80	0.0015
	Plywood_3/4in	0.019	0.115	544.7	674.54	0.0022
	Floor_consol_layer	0.000	12.990	55.1	916.93	0.0000
	R_high					177.0000
	Soil_12in	0.305	1.731	1842.3	232.60	0.1761
		0.350	14.896		2660.87	177.180
Roof	Asphalt_shingle	0.006	0.082	1121.3	1255.20	0.0774
	OSB_1/2in	0.013	0.116	544.6	1213.36	0.1092
	Ceil_consol_layer	0.444	0.062	41.9	776.25	7.2015
	Drywall_1/2in	0.013	0.160	800.9	1087.84	0.0793
		0.476	0.420		4332.651	7.468
Int_Floor	Plywood_3/4in	0.019	0.115	544.7	674.54	0.1650
	Carpet_n_pad	0.025	0.060	32.0	836.80	0.4224
	Ceil_consol_layer	0.444	0.062	41.9	776.25	7.2015
	Drywall_1/2in	0.013	0.160	800.9	1087.84	0.0793
		0.457	0.222		1864.09	7.281
Attic_floor	Plywood_3/4in	0.019	0.115	544.7	674.54	0.1650
	Carpet_n_pad	0.025	0.060	32.0	836.80	0.4224
	Ceil_consol_layer	0.444	0.062	41.9	776.25	7.2015
	Drywall_1/2in	0.013	0.160	800.9	1087.84	0.0793
		0.457	0.222		1864.09	7.281

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