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Article

Life Cycle Assessment of Embodied Carbon and Strategies for Decarbonization of a High-Rise Residential Building

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Abstract: The construction sector is responsible for the 40% of consumed resources, 40% of CO_2 emissions, and approximately 40% of construction and demolition waste. For the assessment of the building, there exists a standardized method, life cycle assessment (LCA), however, the process requires time, cost, and most importantly expertise. In this paper, a method is proposed and analyzed for the life cycle assessment of the building for the embodied carbon in the three stages, construction, operation, and demolition. Moreover, the result of the analysis is considered as the base result, and de-carbonization strategies identified through literature study for the three stages of construction, operation, and demolition are assessed with the same method to know how much each strategy will be effective in minimizing the embodied carbon. For the base case, a high-rise residential building in an urban region of India is analyzed, based on existing conditions through the building information modeling (BIM) method. The carbon emission of the selected building comes out to be 414 kg CO_2e/m^2/year, and assessing different decarbonization strategies, considering the first analysis as the baseline, it can be minimized to 135 kg CO_2e/m^2/year.

Keywords: construction; operation; demolition; decarbonization strategies; carbon potential; urban region of India; carbon emission

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1. Introduction

Worldwide, buildings and construction continue to be the world's largest carbon emitters, producing around 40% of all energy-related emissions. Of this 40%, 28% comes from carbon offset, which is associated with energy consumption in construction activities, such as heating, cooling, and electrical appliances. The remaining 12% comes from contained embodied carbon (EC), which is associated with energy (physical energy) and chemical processes during the extraction, production, transport, assembly, replacement, and construction of building materials or products [1–3]. Controlling and reducing greenhouse gas (GHG) emissions are a critical challenge in attaining a sustainable future. These gases encompass carbon dioxide (CO_2), methane, nitrous oxides, and chlorofluorocarbons, which are emitted at high rates in human activities, such as burning fossil fuels [4–6]. This effect causes global warming, a major contributor to climate change. Nevertheless, the successful reduction of OC has resulted in the EC' portion of whole-life building carbon allocation to increase attention is now being shifted to the construction and mitigation of EC impacts on buildings while there are ongoing efforts to reduce OC emissions [6,7]. The contributions of developed countries are thoroughly documented in the literature, whereas the contributions of developing economies are still under study.

India is one of the world's most rapidly developing countries. Its overall built-up area is continually expanding due to growth and development. The rapid development of the building construction industry is primarily due to rapid economic development, which is associated with urbanization; increased demand for housing for the rich and middle class; the growing demand for offices and commercial spaces from domestic and foreign companies; and a growing interest in the country as a tourist destination. Despite this fast expansion, there is a demand for energy-efficient buildings in India. However, as in other underdeveloped countries, the major focus is on reducing operational carbon (OC) as a way of achieving this, with EC issues being generally ignored [7,8].

The estimation of EC is one of the main ways to reduce carbon emissions. Estimation makes it possible to report actual emissions, compare alternatives, develop and extract low-carbon carbon solutions, and manage performance; without measurement, it can be difficult to inform policy and scope, and affect decision-making [8]. Compared to OC, measuring EC's buildings impacts is complex and challenging. Therefore, in many studies, the life cycle assessment (LCA) approach has been adopted to measure EC, as this allows for a comprehensive assessment of environmental impacts at different stages of the life cycle of a building [7]. BIM is now regarded as both a methodology and a technology, depending on the purpose for which it is employed. BIM, on the one hand, is the digital representation of a project (i.e., BIM model), which comprises parametric and data-rich elements [9]. The life cycle assessment (LCA) and life cycle costing (LCC) methodologies can greatly contribute to the sustainability of the built environment. To address these restrictions, subsequent research has focused on including environmental data (e.g., CO2 emissions) in the BIM model [4,10]. Still, adding information to objects is confined to building elements, making it impossible to conduct a thorough BIM-based LCA study [9].

The implications identified in the assessment of any life cycle assessment of the embodied carbon in building in different stages using any modeling software are the availability of the life cycle inventory of materials of a country; the conversion of electricity consumption from the kWh to the amount that any fossil fuel will release in producing electricity based on region; the accuracy of the model in different stages, such as architectural and structural; and the user-friendly nature of the whole process so it does not require any expertise. In this study, a user-friendly process involves the modeling of the built form on Revit, which is one of the most common pieces of software and is widely used by professionals around the world for BIM. For the LCA of that model one-click, LCA is used, which is a plugin of Revit, and is one of the advanced plugins available for the LCA, and many previous studies have been carried out and recommended it for the LCA study [11–16]. As it has different categories of inventories; public libraries, such as the ICE (Inventory of Carbon and Energy) 3.0; private libraries, which include libraries from ISO codes, and the advance library, which involves inventory that is directly uploaded by the vendor and cross-checked by the system, which allows the plugin for a more detailed assessment. Furthermore, after analyzing the envelope with the digital tools, a comparison of the results with the existing manual assessment to validate the study and the process is undertaken. In addition, after the validation of the analysis, decarbonization strategies, including material reuse and recycling strategies; low-carbon materials; material minimization and material reduction, construction optimization, material manufacturing and local sourcing, use of renewable source of electricity and incorporation of water efficient measures will be analyzed for the selected built form, based on a detailed literature study for each strategy. The case study selected will be used to test the adoption of this process and the demonstration of its benefits when compared to standard approaches [9].

There exist certain parameter uncertainties, which includes uncertainty due to methodological choices, model uncertainty, epistemological uncertainty, spatial variability, temporal variability, sources and objects variability and mistakes. To overcome these uncertainties in the life cycle assessment there are certain probabilistic approaches, which includes current measurement, life cycle measurement, tree representations and Monte Carlo simulations (MCS). Among the four, tree representation and MCS are generally used for the assessment of the embodied carbon of the future building stock and current measurement assumes that an existing building has an accurate embodied carbon value and does not change over the life cycle of the building; whereas life cycle measurement is the bridge between the current measurement and the assumption for the changes in the future. In this study, the life cycle measurement process is objectified over the life cycle of building and will provide readers an objective approach towards the LCA of any built form with the help of digital tools rather than any manual approach. The objective will be achieved by providing an overview of the LCA with the literature study and assumptions and uncertainties in the process. With the consideration of these factors, the application of the approach on an existing building and comparison of the assessment with the existing manual approaches will be undertaken. The study will also cover an objective approach rather than discussions towards the assessment of the decarbonization strategies and the effectiveness of each approach in minimizing the embodied carbon. The primary focus of the study is to represent a simple approach for the LCA of embodied carbon, which will eventually help in decarbonization of the buildings and achieving the target of net-zero carbon in construction industry.

2. Background and Methods

2.1. Estimating the Embodied Carbon of Construction Projects

The most developed and well-established assessment for analyzing environmental consequences connected with buildings is life cycle assessment (LCA). Life cycle assessment is a method of framework for measuring and evaluating the environmental impact of the entire product or life cycle of the service system from cradle to the grave [7]. It simplifies the estimating procedure, and as a result, it is widely utilized in the calculation of building energy and carbon emissions. LCA is divided into four steps by the International Organization for Standardization (ISO-14040, 2006): aim and scope definition, inventory analysis, impact assessment and interpretation. The important part of any assessment is defining the purpose of the system, which includes defining system boundaries and its functional units, which is considered critical in the first phase of any LCA application, regardless of the subject, as the LCA output are considered sensitive towards the model and to the assumptions adopted for the simulation. This reduces the risk of misinterpretation and/or misuse of LCA results.

Buildings are one-of-a-kind constructions that differ greatly from industrial methods. Because of the extended life cycle of buildings, the use of a variety of materials and processes, the unique character of each structure, the evolution of functions through time, maintenance and retrofitting, and other factors, LCA studies in the literature have been limited to certain aims and scopes. Similarly, most of the studies related to EC estimation in the existing literature have also been limited to the production stage or the cradle-to-gate system boundary; for many construction products, data on their impacts after they have left the factory gate are absent [7]. The construction of a life cycle inventory (LCI) is the second part of any LCA, and it covers the flows of resources (materials and energy inputs), as well as externalities (releases to air, land and water) associated with the product under consideration. Creating an LCI takes time and resources, and it needs specialist knowledge, as well as a large amount of primary material. To make EC effect estimation easier, inventories or databases have been created to offer EC coefficients for construction materials. The third step, life cycle impact assessment (LCIA), takes the data from LCI and examines the possible environmental implications, as well as the resources employed in the research. Several techniques have been widely documented, notwithstanding the lack of agreement on the best acceptable methodology for EC evaluation of buildings and construction [7]. Table 1 shows the complete process of the estimation of embodied carbon over all three stages, construction, operation and demolition. In the table, except for the first step of modeling, every step can be evaluated using the LCA plugin, which makes the process easy to follow.

Table 1. Steps of estimation of embodied carbon.

STEPS	GOAL	REQUIREMENT	OUTPUT
Modeling	To develop a model that has all the information in regard to the material and design.	Use of architectural and structural plans on software, such as Revit.	A well-informed BIM model of the building.
Estimate the quantity of material needed and total duration of use	To create an accurate bill of goods.	Estimate the productivity of equipment. Identify temporary material usage/work	Emission due to transportation of material and equipment to the site
			Emission due to operation of equipment
Estimate the cradle-to-grave embodied carbon	To identify the embodied carbon in the construction and demolition stage.	Manufacture LCA reports. Use of existing LCA Inventories, such as ICE 3.0.	Depreciation in EC of equipment
			Depreciation in EC of temp. material
Estimate consumption and renovation requirements	To create a consumption pattern of energy and water. To identify the life of equipment over the whole life of buildings.	Annual energy and water bills. Selected equipment details.	Emissions caused by energy and water consumption.
			Emission caused by renovation changes.
Estimate the embodied carbon	To identify embodied carbon in the operational stage.	Conversion of electricity and other consumption with the fossil used in producing it. Embodied carbon in the renovation.	Increase in EC of consumption
			Increase in EC of equipment
Estimate the embodied carbon of construction and demolition waste	To identify the carbon emissions incurred in the end-of-life (EOL)	Type of material used and the original design of building component. Availability of required local technologies for reuse and recycling and availability of local market for the product and local landfills for disposal of debris.	Carbon emissions incurred in the EOL phase of building's life cycle.

2.2. Methodological Approach for the BIM-Based LCA Analyses

The main goal of the approach is to develop a BIM–LCA integration process to gain information on material quantities and match the information with environmental data. The general approach for the goal is (1) the use of neutral file format for the open file-based exchange; (2) the creation of the visual interface to enhance the quality and documentation of BIM-based LCA. To combine these approaches and to achieve the goal in this study, a six-step strategy is used to determine the prerequisites for conducting a BIM-based LCA study. To begin, all models that will be analyzed (such as architectural and structural models) should be combined. Only by combining the models into a single model, the consequences of building solutions from various disciplines be compared holistically. Second, the information contained in the BIM model must be evaluated. If the model's information is exported, this process will be simple to do. Finally, the exported list must be verified for duplicates, i.e., solutions with the same names but different names. It is conceivable that the model comprises elements from the same family with the same name, or vice versa, i.e., the same components with different names. The third phase tackles these concerns, and it is recommended that the entire project be homogenized so that LCA tools can accurately read the bill of goods. Following the editing of the model, a new bill of quantities should be exported to ensure consistency. The project's fourth stage is to include environmental, economic and mechanical data and their relativeness in terms of project aspect, materials and future renovations. This list may then be filled with the necessary information for the analysis. Following that, the information in this list may be imported into the BIM model using this list (Figure 1). Finally, this information may be used to undertake a complete LCA study using the LCA plugin like in this case one-click LCA (fifth step).

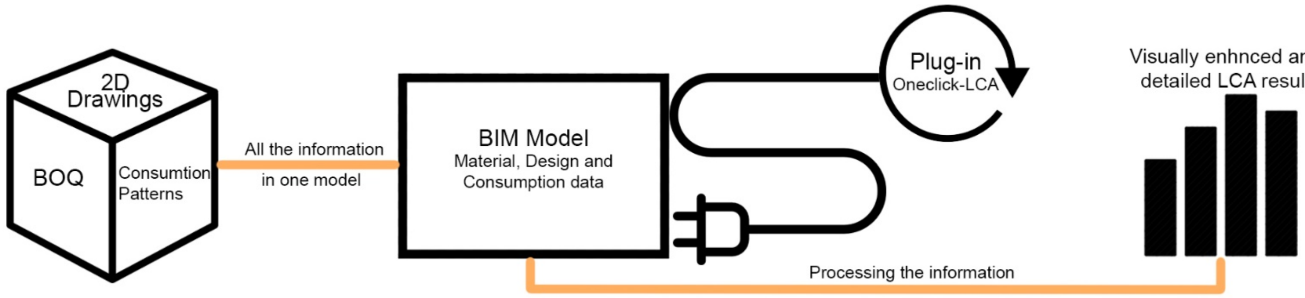

Figure 1. Workflow and process of estimation of embodied carbon.

2.3. Framework for Lifecycle Assessment

Following four phases, the BIM-based LCA process is carried out in line with ISO 21931-1:2010 (ISO, 2010), ISO 14040 and ISO 14044 (ISO, 2006a, 2006b): (i) the purpose and scope of the LCA; (ii) the lifecycle inventory analysis; (iii) the lifecycle impact assessment (LCIA); and (iv) the interpretation. A cradle-to-grave strategy is used, which incorporates aspects of the building's life cycle that have been highlighted in Figure 2 (material manufacturing, construction, usage and disposal). It also concentrates on the superstructure's structural and architectural aspects rather than mechanical, electrical or plumbing components, as they are not the main emphasis in decreasing embodied effects during the design stage. The exact performance characteristics of buildings or building components must be properly described for the sake of comparing LCA findings. As a result, to increase the accuracy and utility of the LCA findings, the functional equivalent technique was adopted in this work. The kind of building, related technical and functional criteria, gross floor area (GFA) and reference service life are all part of the functional equivalent method [5].

Compiling all input and output flows related to the declared purpose and scope of assessments is part of the lifecycle inventory process. If an adequate LCA outcome is to be reached, this phase is important to the future stage. All data necessary for the lifespan inventory analysis are incorporated into the BIM environment since the study's major purpose is to analyze the major elements responsible for the embodied carbon of the building and, through that same method, assess the decarbonization strategies for the minimization of embodied carbon. In addition, for the breakdown and classification of building elements/components, the proposed levels of evaluations are merged in this stage (Figure 2).

The results of the inventory analysis are utilized when associated with the dynamic modelling environment to calculate the building's energy and environmental consequences. It is simply calculated by multiplying the amounts of work by an appropriate impact factor, the energy usage and environmental implications at various lifespan phases may be predicted.

The results of the lifespan inventory analysis and lifecycle impact assessment are evaluated in a systematic way called lifecycle interpretation. At this point, the outcome is organized following the study's objectives and scope. The findings should be given in an easily understandable format, allowing for the integration of scenarios and variations in input data to improve the building's performance. Finally, decision-making is aided by findings, constraints, suggestions, and guidelines about the aim [18].

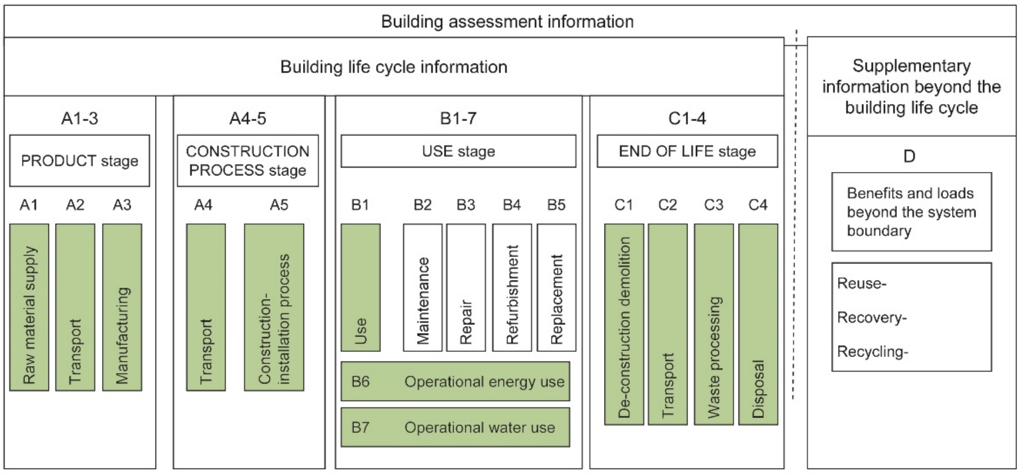

Figure 2. Life cycle phases according to BS EN 15978 [17], phases selected for the LCA assessment, have been highlighted by the author.

3. Description of the Selected Building

A complex high-rise residential building is analyzed to represent most of the high-rise residential buildings constructed in the urban areas of India. Detailed architectural, functional, and operational data are obtained from working drawings, and a Revit model is designed according to each element's specification. The details and characteristics of the studied building are presented in Table 2. Building reference service life is taken equal to 75 years in accordance with the EN 15978, as for the LCA building reference service life is required. The selected building has an average gross area of 1000 m^2 per story; 30 stories, excluding terrace and mumty; three types of dwelling units are identified. From the ground to the 21st story, there are two dwelling units per story with four bedrooms in each story, two common stairs and five common lifts; on the 22nd story there is a common hall and bar. The building configuration is from 23 to 28 stories, with two dwelling units per story, two bedrooms, one common stair and three common lifts. On the remaining two stories is one dwelling unit of a single-room apartment. BIM model and details of the imported and mapped material are available in the ESM.

Table 2. Description of the selected building.

Specification	Building
Number of Floor	30
Number of dwellings	56
Base Area (m^2)	1000
Roof Area (m^2)	635
Floor height (m)	3.2
Total height (m)	109
External walls	150 mm concrete block, 30 mm of plaster inside and outside.
Internal wall	100 mm concrete block, 24 mm of plaster inside and outside.
Roof	30 mm polyurethane and 150 mm concrete.
Windows	1.29 × 3.575 m PVC framed. 1.5 × 2.1 m PVC framed. 0.9 × 1.2 m wooden framed.
Door	2.45 × 2.4 m double sliding wood-framed. 1.27 × 2.4 m wood framed. 2.45 × 2.4 m steel door
Annual water consumption (Kl)	12,417
Annual energy consumption (kWh)	249,402

3.1. EC Impact Assessment

Using the findings of the LCI study, the EC effects of buildings were measured in this step. In this investigation, the EC estimate technique was established by RICS and used. Even though several software tools have been created to make the EC calculation procedure easier, the assessment in this study was done using the Revit and one-click LCA technique.

As a result, the billing of quantity (BOQ), which is a detailed itemized pricing document, and the environmental impact assessment (EIA) report, which is an elaborate process involving screening, preliminary assessment and scoping of the site, will be utilized to determine the main components and amounts used in each component. To ensure consistency throughout the estimation, the amounts of several units were converted to mass in kilograms (kg). These units included square meters (m^2), cubic meters (m^3), tonnes (*t*) and meters (m). The EC coefficient for each material referenced in ICE version 3.0 was multiplied by the material amounts. After that, the elemental EC was calculated by adding the EC values of all materials in each element. The EC of the building skeleton was calculated by multiplying the elemental EC values. The EC effect data were reported in $kgCO_2e$ and $kgCO_2e$ normalized per m^2 of gross floor area ($kgCO_2e/m^2$).

3.2. Construction Phase Analysis

Several quantitative methods to estimate the emissions of carbon during the construction phase have been developed by relying on actual site data [19,20]. In the construction phase, analysis is mainly dependent on the method of analysis that is used. Generally, the three methods that are used in the analysis are process analysis, input–output analysis and hybrid analysis. Process analysis is identified to be the most widely used approach, but due to the complexity of the requirements of goods, the approach has some disadvantages.

The input–output (I-O) analysis uses national average data for each sector of the economy and is considered more accurate by many researchers. The input–output analysis is usually used like a 'black box', having little or no understanding of the values being assumed for each process [21].

To eliminate downstream and horizontal truncation, I–O-based hybrid analysis combines process data and I–O data to process-based hybrid analysis [22]. The direct inputs of a specific product are calculated using process analysis, the use of process data increases the reliability of the analysis. A method proposed by Treloar [23] of hybrid analysis is used in several life cycle studies [24].

EE and CO_2 constitute the construction phase analysis. EE is defined as the total primary energy (MJ) required by the building materials during the manufacturing phase. Generally, it is the energy content of all the materials used in a building's new construction, renovation, technical installation and the incurrence of the energy [25].

Embodied energy can be divided into two main components [26], initial embodied energy: the energy embodied in a building's initial construction, and recurrent embodied energy: the energy required during the useful life of the building. In several previous studies, visualization-based methods have also been investigated as progressive monitoring and estimation of construction emissions [27–29].

In this study, EN-15798 [30] is used for the calculation of primary energy requirements and greenhouse gas emissions. The code includes EE, carbon and GHG (measured in kilograms of CO_2 equivalent, kg CO_2eq.) and when combined with the inventory of materials in the one-click LCA, offers value for many materials in the context of the region. The life cycle analysis is analyzed considering the recurrent embodied energy.

3.3. Operation Phase Analysis

Operational analysis is the energy and water required for the functioning of the buildings, energy includes energy for HVAC, lighting and energy for running appliances. The operation phase accounts for the largest portion of energy consumption in the life cycle of conventional residential houses [31]. In the minimization of the energy consumption, the selection of material for the fabric of the building plays a vital role [32] while water includes daily usage of water, water used during construction and usage of treated water.

In this study, the average energy consumption of an urban household is used to make the research ideal for any urban high-rise residential building. In India, the average energy consumption in a composite climate is 300 kWh [33], including cooling and heating load. For the selected building, energy consumption annually of the families will be 201,600 kWh. The energy consumption of basements, and water pumps and for the remaining two floors is 4780 kWh annually (calculated manually by defining the number of hours usage and appliances load). The energy consumption of the complete tower comes out to be 249,402 kWh. The CO_2 emission factor for the consumed electricity of the selected building is calculated by using the primary emission factor, obtained from the IEA 2019 [34].

For the water consumption, records from the EIA (environmental impact assessment) report calculated that the water consumption of the building is 34,020 L per day and an annual requirement of 12,417 m^3. According to the report, a moving bed biofilm reactor (MBBR) is installed at the selected site which has an efficiency of 98% [35], considering that all the other requirements of the site will be fulfilled using treated water. The average annual consumption of water is 12,417 m^3. During the construction phase, the water that is used is the treated water from the other completed site of the contractor, which is functioning, as mentioned in the report.

3.4. Demolition Phase Analysis

Demolition energy is the energy consumed at the end of the building service life to demolish it and transport the material to landfills or recycling plants [36]. Demolition energy is the sum of the energy consumed by the process of demolition and the required energy for the transportation of waste. The share of demolition energy was estimated at 0.2% of the total life cycle primary energy consumption of a building [37,38]. For the identification of total emissions released during the demolition stage, it is considered that the weight of the wastes, which is obtained during the dismantlement of the buildings, is converted to those to be transferred by trucks [39].

3.5. Assumptions and Uncertainties

Manual LCA of buildings contains many simplifications and assumptions related to the energy requirement of buildings in different phases, the estimated service life of the building and embodied energy associated with materials that will be used in the future. Through a BIM-based approach, these assumptions and uncertainties can be minimized (with proper architectural and structural plans) to a minimum and importing this building information into an online server of one-click LCA, which has an inventory of materials from around the world and the values are cross-checked and are differentiated based on region. The location of a building construction materials and system used, material manufacturing processes, and other factors will influence its total energy demand and variations [22]. Assumptions made during the simulation are as follows:

- The average occupancy of 4.5 people is assumed in a dwelling unit.
- It is assumed that the standard building construction method and materials are the same over the service life.
- Energy mix and intensities were considered constant over the next 75 years [40].
- The service life of the structural component is assumed to be the same as the building's service life.
- It was assumed that because of it being an urban area in the capital of a country, all final product manufacturing took place on-site or within a 30 km radius.
- In the operational phase, the prediction of the energy consumption is related to the change in price, regulation and environmental concern. Constant consumption of the same fuel is assumed.
- Building reference service life is taken equal to 75 years in accordance with the EN 15978; as for the LCA building reference, service life is required. In addition in the

demolition of the building, it is considered that it will include the usage of heavy machinery and the fuel utilized in those machines is diesel.

- Indoor environmental quality is considered constant over time and is not included in the simulation.

4. Results

In this study, the approach is to adopt the grey box model approach, so the modeled building is not only assessed based on data only but also on observation too. Based on analysis it is identified that carbon emission of the selected residential building in India is 414 kg $CO_2e/m^2/year$, which is 14,196 kg CO_2e/m^2 over the service life. The analyzed data are very close to the selected case studies, which have followed either process-based analysis or hybrid-based analysis of 448 kg $CO_2e/m^2/year$ and 368 kg $CO_2e/m^2/year$ [8,22].

Based on global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), the formation of ozone in the lower atmosphere (POCP) and primary energy of raw materials, different categories of the building have been assessed, as shown in Figure 3. In the analysis, it is identified that electricity shares 50%, concrete shares 13%, steel shares 18%, doors share 5%, water shares 7%, window shares 2% and other items share 5% of the total potential, including GWP, AP, ODP, POCP and primary energy of raw materials. The materials account for 37.5% or 11,631,188.20 kg CO_2e and energy accounts for 49.4% or 15,322,608 kg CO_2e; these are the two major contributors of CO_2 in the building LCA assessment, as shown in Figure 4. The remaining impact of 13.1% is divided between different stages, 2.2% water, 5.5% maintenance and replacement, 3.4% transportation, and 2% end of life. Based on elements, horizontal elements (floor, slabs, roofing deck, etc.) share 55.2% of the total carbon emissions and vertical structures (walls, façade, columns, load-bearing wall, etc.) share 40.9% of the total carbon emissions and the remaining amounts are split across the rest of the elements (window, doors, other structures), as shown in Figure 5.

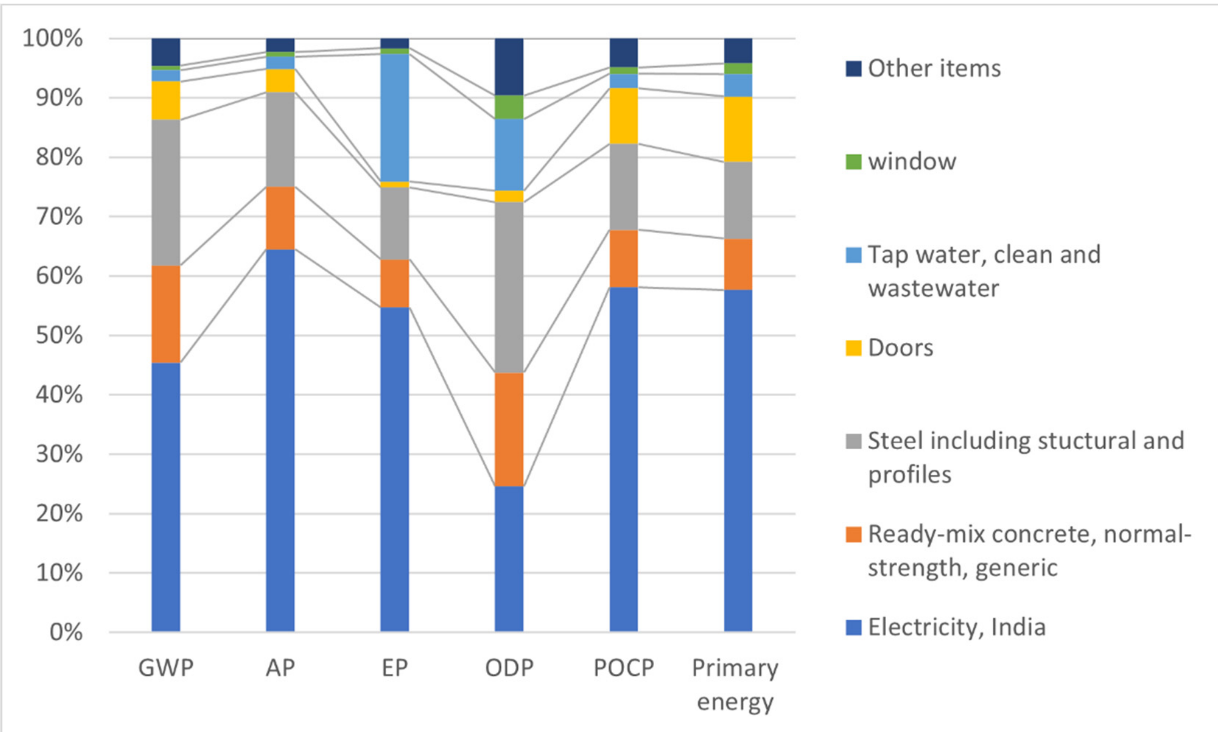

Figure 3. Life cycle impact by materials.

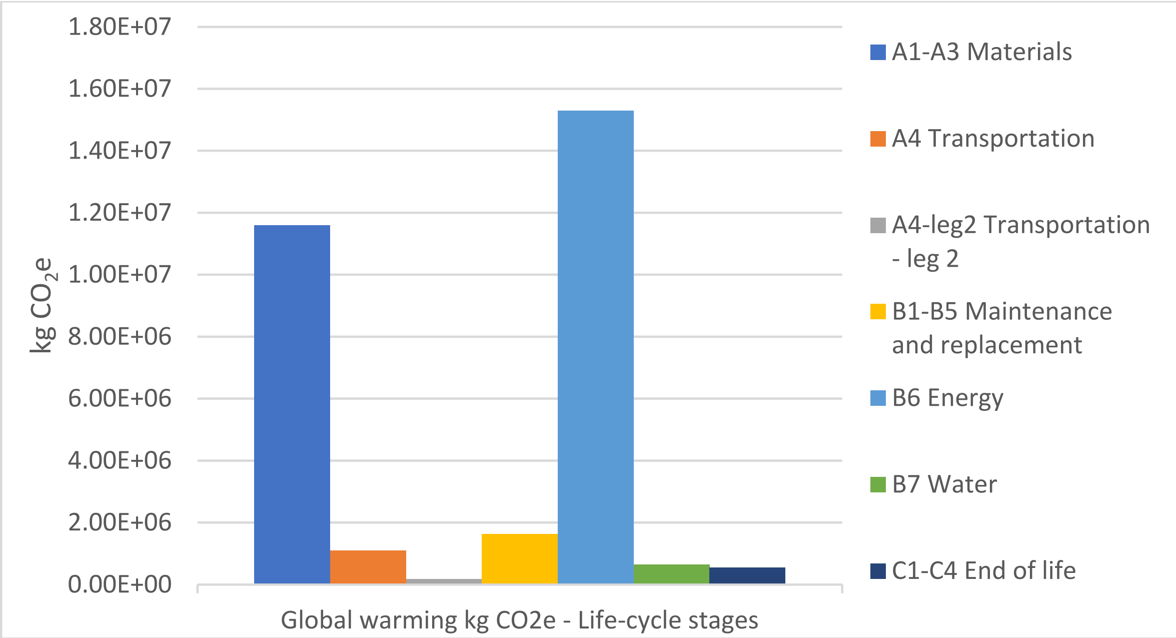

Figure 4. Embodied carbon based on life cycle stages.

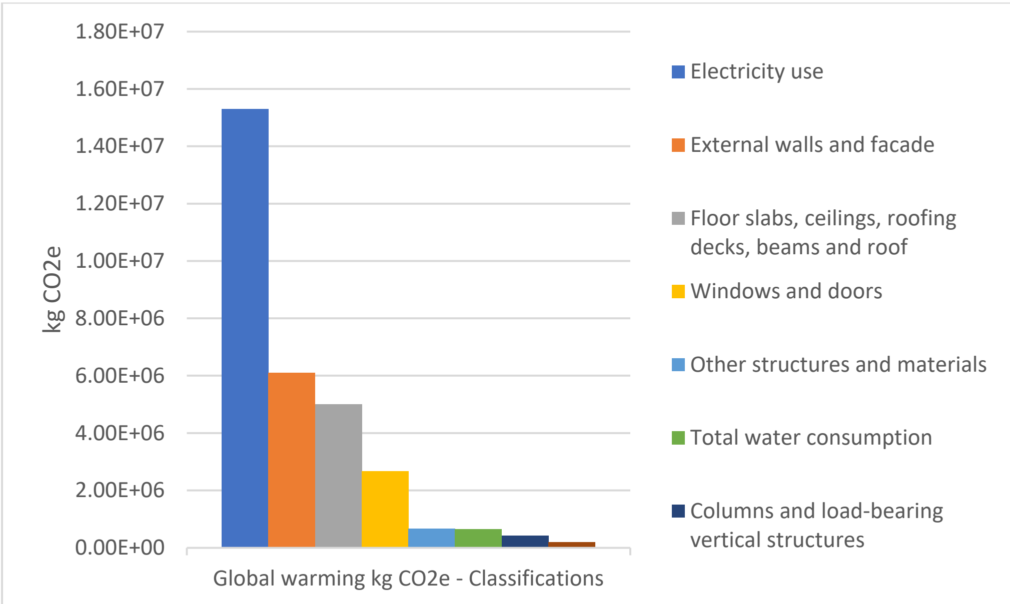

Figure 5. Embodied carbon based on element classification.

4.1. Decarbonization Strategies for Initial Embodied Carbon

Five categories to reduce the embodied carbon of buildings were identified in the study of Akbarnezhad and Xiao [41]; these categories are analyzed using BIM methods and the results will be compared with the baseline data to analyze the efficiency of each strategy. The strategies are (1) material reuse and recycling strategies; (2) low-carbon materials; (3) material minimization and material-reduction strategies; (4) construction optimization strategies; (5) material manufacturing and local sourcing. In this analysis, only alternatives for major contributors to the embodied carbon are assessed.

4.1.1. Material Reuse and Recycling Strategies

The recycling of concrete has been highlighted as an effective strategy to reduce carbon emissions and this also lowers the cost incurred in transporting and dumping debris and provides a sustainable source of mass [42–44]. The recycling strategy is considered one of the oldest sustainable strategies to deal with waste during demolition [44–51]. To analyze this methodology, BIM is identified as a useful tool to assess the effects of this strategy on the recycling parts. Material changes include 30–40% recycled binders in the cement of concrete, a change of 60% (ground granulated blast furnace slag) GGBS concrete composition and reinforcement in concrete [52].

Based on the analysis, with the help of materials reuse and recycling, the embodied carbon value of the materials lowers from 11,631,188 kg CO_2e to 8,424,435 kg CO_2e and, overall, the building's embodied carbon lowers from 414 kg CO_2e/m^2/year, 14,196 kg CO_2e/m^2 to 388 kg CO_2e/m^2/year, 11,517 kg CO_2e/m^2, as shown in Figure 6.

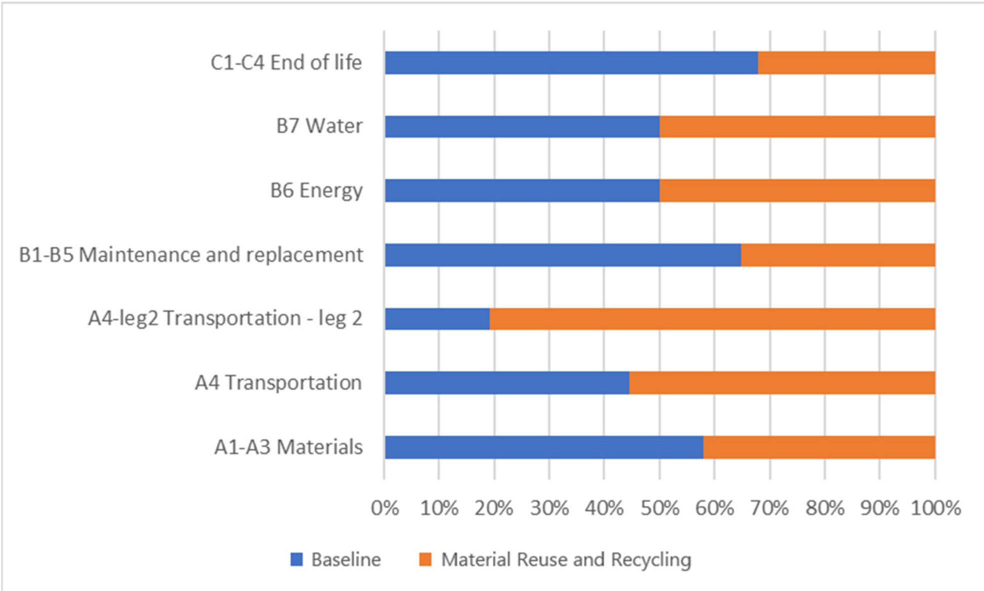

Figure 6. Comparison between baseline and material reuse and recycling on the different life cycles.

4.1.2. Low-Carbon Materials

The selection of materials plays a vital role in the embodied carbon material, as there is a limited number of alternative materials available for each element, it is vital to assess their performance against the technical requirement. The important effect of material selection has been studied in various previous case studies on the carbon footprint of structures [53–56]. Based on the case studies, alternate materials are analyzed for different elements to assess the effectiveness of low carbon material on the embodied carbon through BIM modeling. A material change includes increasing the recycling content in the concrete mixture to the point of safe stability.

Based on the analysis, low carbon-materials play a major role in the decarbonization of the embodied energy; with the help of low-carbon materials, the embodied carbon value of the materials lowers from 11,631,188 kg CO_2e to 5,798,178 CO_2e and also the maintenance and replacement value is decreased from 1,631,671 kg CO_2e to 883,205 kg CO_2e. Overall, the buildings embodied carbon lowers from 414 kg CO_2e/m^2/year, 14,196 kg CO_2e/m^2 to 333 kg CO_2e/m^2/year, 8084 kg CO_2e/m^2, as shown in Figure 7.

4.1.3. Material Minimization and Material Reduction

The quantity of material used in the buildings is directly proportional to the total embodied carbon of the structure. Therefore, material minimization can be a useful strategy in reducing the embodied carbon; it also optimizes the cost of the project; the structure must have an optimal design rather than design by maintaining the ability of the structure to meet all the technical performance requirements. This can also have a direct impact on the amount of waste produced during the different construction and deconstruction stages [57,58]. For this approach, the design must be focused on the decarbonization of embodied carbon from the concept stage because then it will be possible to have an optimal design. Another option in this strategy is stock modeling, through segmentation, characterization, quantification and validation of the designed model and identifying the use of energy at the stock level.

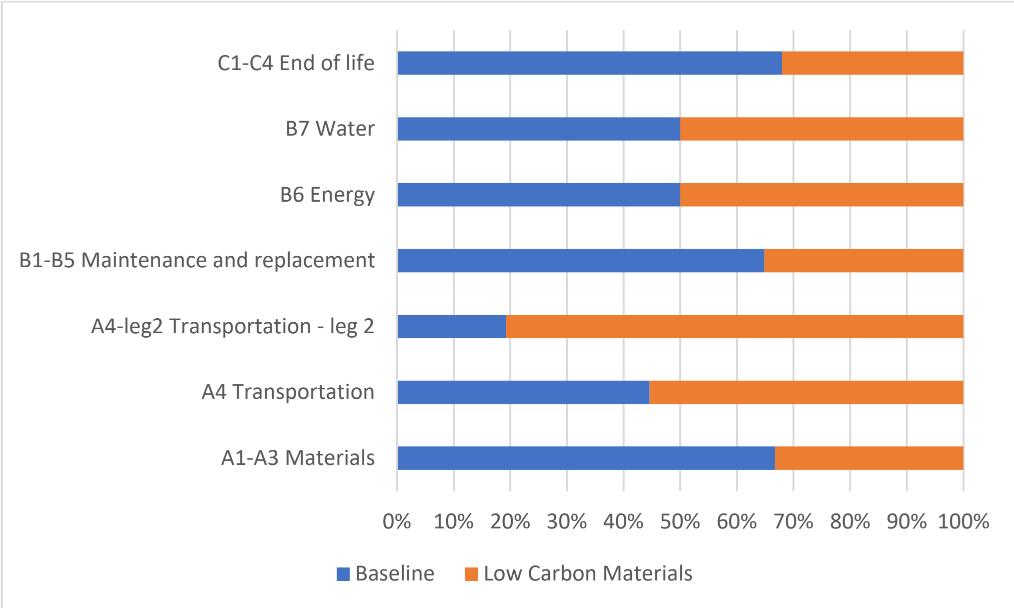

Figure 7. Comparison between baseline and low-carbon materials on the different life cycles.

4.1.4. Construction Optimization

The operation of construction equipment and the use of temporary construction material is identified as one the contributors to the embodied carbon associated with it. In the analysis, it is identified that emissions in the construction phase can be minimized through different approaches; reducing the idle time of equipment; optimizing the operation of equipment; minimizing the on-site transport, including both horizontal and vertical; and selecting optimal equipment for a construction operation, [59–64]. It will not be possible to assess the identified factors to be assessed through BIM, as the factors are mostly based on the performance of the machinery that is to be outsourced and has no relation to the building or construction. However, it is identified through literature studies that the most highlighted strategy is enhancing the operational efficiency of on-site equipment, which is considered the most feasible and effective [29,59,65,66].

4.1.5. Material Manufacturing and Local Sourcing

Local sourcing plays a major role in the decarbonization of embodied carbon; it can lower the impact of transportation, which is an important contributor to embodied carbon. Size of materials, the transportation distance and the mode of transport are identified as the main factor affecting transport emissions [67,68]. To assess the local sourcing strategy, the radius of the material sourcing is selected as 30 KM.

Based on the analysis, with the help of material production and local source, the embodied carbon value of the materials lowers from 11,631,188 kg CO_2e to 10,115,227 kg CO_2e, and overall the buildings embodied carbon lowers from 414 kg CO_2e/m^2/year, 14,196 kg CO_2e/m^2 to 396 kg CO_2e/m^2/year, 14,196 kg CO_2e/m^2. The changes in values are because of the easy availability of material and recyclable materials and less transportation fuel use (Figure 8).

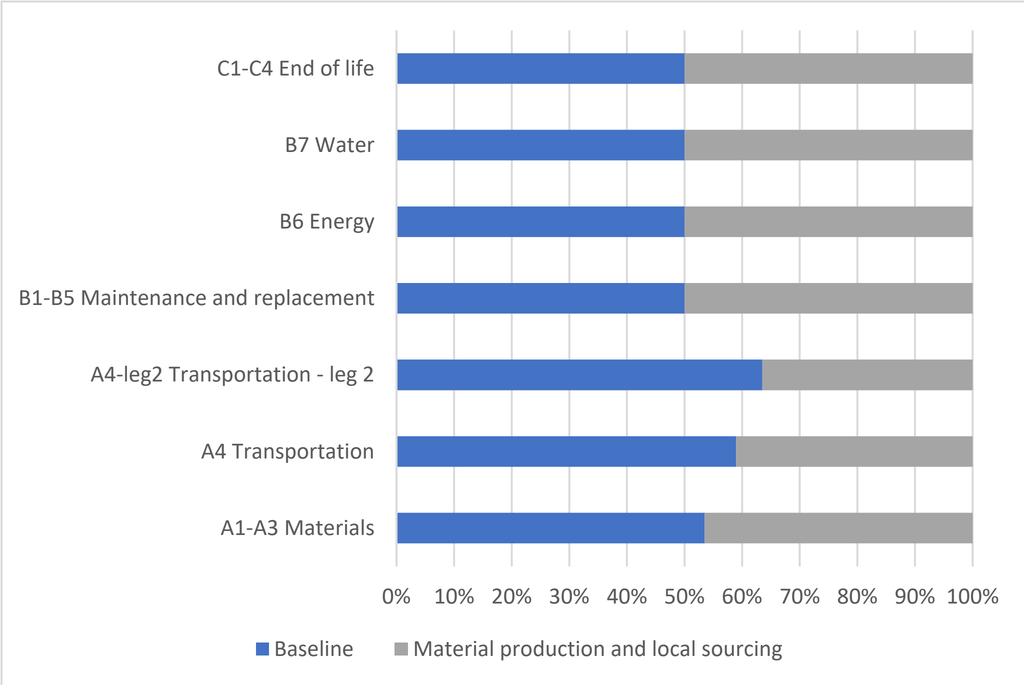

Figure 8. Comparison of baseline with the material production and local sourcing.

4.2. Decarbonisation Strategies for Recurrent Embodied Energy

Through literature studies, five strategies are identified to reduce the recurrent embodied carbon of buildings, these categories are analyzed using BIM methods, and the results will be compared with the baseline data to analyze the efficiency of each strategy. The strategies are (1) the use of the renewable source for electricity; (2) incorporation of water-efficient measures; (3) passive cooling and heating techniques to minimize the cooling and heating load. In this analysis, only two strategies are assessed using the BIM technique.

4.2.1. Use of Renewable Sources of Electricity

Renewable source of electricity plays a vital role in minimizing the energy consumption of the area. In this case, solar panels are selected as the renewable source of electricity. Solar panels are very common in India, and many government schemes minimize the cost of solar panels. Moreover, the government of India has introduced many schemes to promote the use of the solar panels in the built area; if the solar panel is used on the site then through these government schemes built-up area of the site can also be increased. The roof area of the selected building is 635 m^2, average annual solar radiation in Delhi (where the site is located) is 5.13 $kWh/m^2/day$ [69], which means 1872.45 $kWh/m^2/year$. The efficiency of selected PV panels is 18% [70] and an inverter of efficiency of 96% [71]. Based on the data, the PV panel generation can be calculated as:

$$\text{PV panel generation} = 635 \times 1872.45 \times 0.18 \times 0.96 = 205{,}460.2 \text{ kWh} \quad (1)$$

Generated energy through solar panels placed on roof will be 205,460.2 kWh for a year, and the required energy for a year 249,402 kWh, so if PV panel is installed properly according to sun direction and tilt angle based on that [70], only 43,941.8 kWh/year is required from the government providing body

In this analysis, carbon assessment and the life of solar panels are not considered. Based on the analysis, by using the renewable source of electricity, the carbon emission is lowered from 15,322,608 kg CO_2e to 3,339,380 kg CO_2e and overall from 414 kg $CO_2e/m^2/year$ to 254 kg $CO_2e/m^2/year$, as shown in Figure 9.

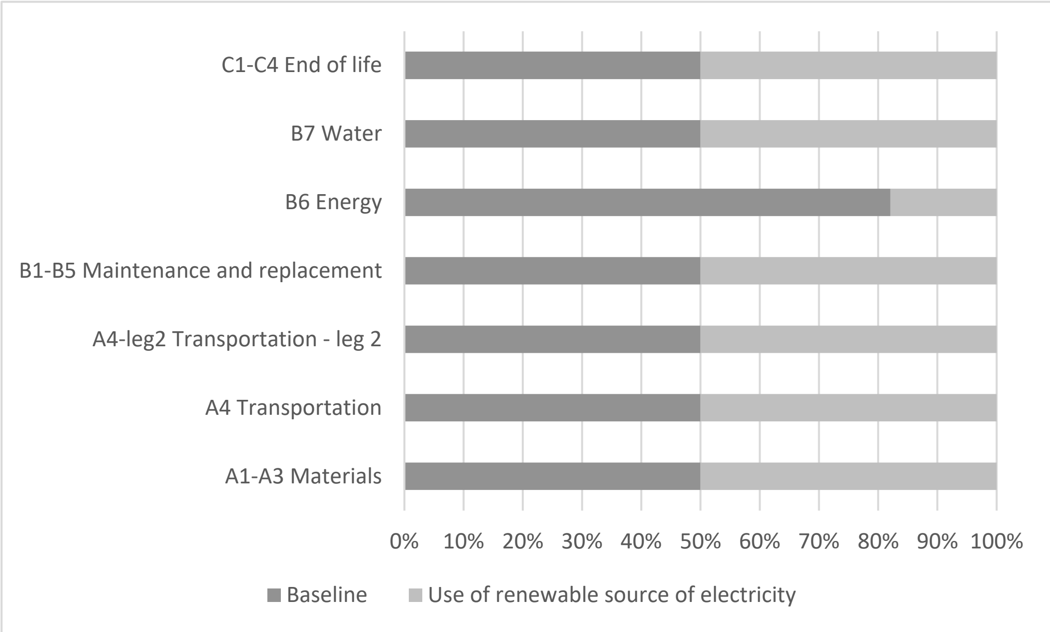

Figure 9. Comparison between baseline and use of the renewable source of electricity.

4.2.2. Incorporation of Water-Efficient Measures

In this analysis, only water-efficient measures that require minimum use of equipment, such as economic aerators, behavioral measures and installation of smart meters, are considered. In the study, it is identified that through economic aerators, an efficiency of 11.8%, behavioral measures with an efficiency of 15% and smart meters with an efficiency of 2% are found [72,73]. Therefore, the overall efficiency of 27% can be achieved in the water consumption, based on only these three parameters, from the base case the water consumption is 12,417 m^3, which will be minimized to 9064.41 m^3 (Figure 10).

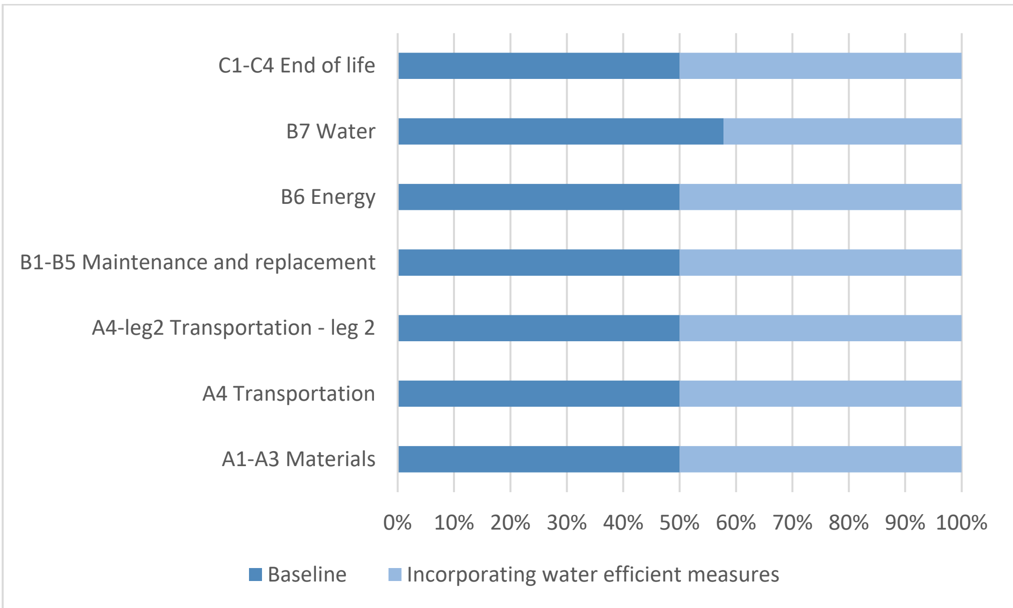

Figure 10. Comparison between baseline and incorporation of water saving measures.

In the analysis, it is identified that with global warming, kg CO_2 decreases from 64,4796 kg CO_2e to 470,701 kg CO_2e over the life of the building, and an overall difference from 414 kg $CO_2e/m^2/year$ to 412 kg $CO_2e/m^2/year$ is identified.

5. Analysis and Discussion

Following decades of regulatory scrutiny, modern architectural practices are adept at evaluating the operational implications of new buildings, particularly in terms of operational energy usage and carbon emissions. Although social shifts are pushing for the inclusion of environmental considerations in the early phases of the design process, design experience in the realm of embedded emissions is still limited. However, the current practices do not suggest that the all the implications and evaluation can be processed and resolved with a single method. The BIM is the method that is gaining popularity throughout the world, although complete potential of the BIM is still not utilized. As it has the ability to resolve many of the implications and evaluation at a single place. In the current practices, BIM model is only used as a data storage palace, where only users use the model for their requirement, for example using the model to extract the BOQ and analyzing LCC and LCA manually. However, through the facilitation of LCA-related data in the model, human error can be reduced, automation is supported and better use of the model across the life cycle of the building is supported.

The design process in building projects is described in both theoretical and empirical literature as a sequence of iterative decision processes throughout time, each of which takes the design to a higher degree of detail, reducing uncertainty. The design grows through time, from the early conceptual stages, when many variables are fluid and the design team explores numerous strategic and parametric alternatives, to the project completion, when all uncertainty is removed in the completed building. There is a need for simpler tools that can give better accuracy while employing few generalized parameters in the early design phase if environmental considerations are to be integrated more successfully in the early design process. In the general practice, for early design, the 3D view of the prototype is used for both the transparency of data and the visualization of the results, and many users follow the different plug-in workflow to assess the geometry of the prototype to achieve the same dynamic effects and test different design. As the plug-in approach is common in practice, it is easy to assess the different environmental and technical implications at different stages of the building design and also different evaluation requirement can be fulfilled, Although, for this to happen, there is requirement of neutral file formats, through which evaluation and implication can be assessed at a single platform.

The study suggests considering one of the approaches for life cycle assessment of a building through the common modelling approach (BIM) and combining it with the common plug-in approach to increase the automation process and minimize the error. In the study, the carbon emission of the selected building comes out to be 414 kg CO_2e/m^2/year, which is considered as the baseline study and different decarbonization strategies are assessed using the same approach to minimize the carbon emissions in construction, operational and demolition stages. Figure 11 shows the maximum reduction, which can be possible after incorporation of all the strategies that are analyzed altogether for every stage of life. The carbon emission of the building reduces from 414 kg CO_2e/m^2/year to 135 kg CO_2e/m^2/year, as the material reuse and recycling reduces carbon emissions, mostly in demolition stage; low carbon material reduces emissions in material stage; material manufacturing and local sourcing reduces emissions in the travel stage; use of renewable source of electricity reduces emission in the energy stage and incorporation of water efficient measures in the water stage. Based on the analysis and the comparison, it will be easier to provide renovation strategies for an existing building based on different strategies for different scenarios.

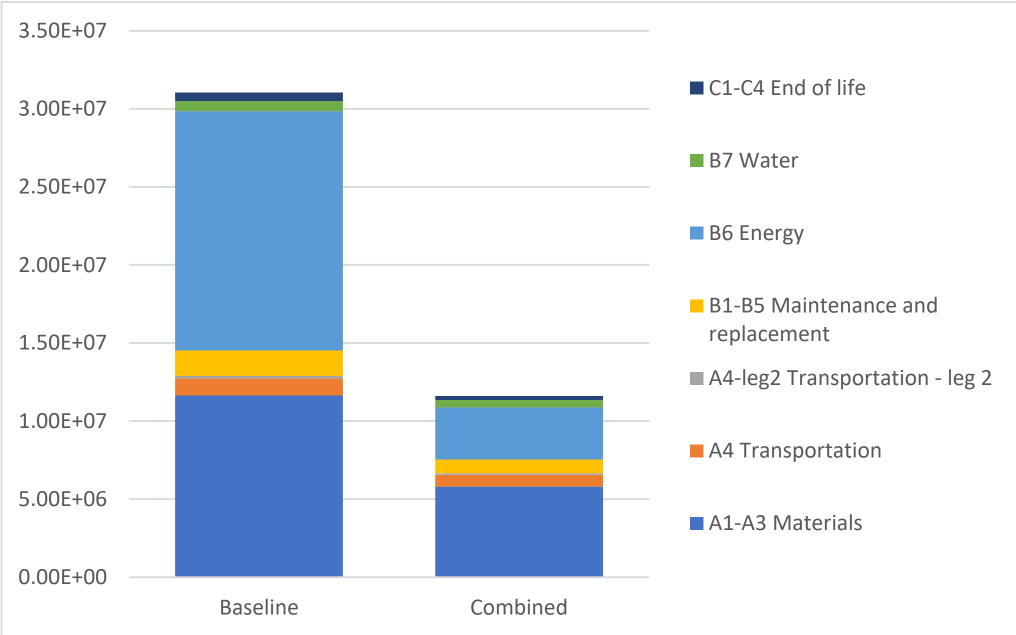

Figure 11. Comparison between baseline and incorporation of every decarbonization strategy.

6. Conclusions

The carbon footprint of the built environment is substantial and complex, and pathways for reducing its climate impact are understudied. The embodied emissions of buildings and the transport and energy systems as a result of their construction and maintenance must be reduced in line with stringent carbon budgets and climate mitigation goals. For any building, it is necessary to incorporate the decarbonization strategies from the conceptual stage of the building design, as the decarbonization strategies include proper material selection based on life and recyclability, and optimal design, as in the studies it is identified that the strategies that apply in the conceptual stage are more efficient in the decarbonization of the embodied carbon. In this paper, a complete process of life cycle assessment through BIM is identified, and the effectiveness of BIM in comparing and decarbonization of the carbon embodiment of the building and construction is analyzed. It is analyzed that utilities are the second major contributor to the embodied carbon other than materials, although based on the analysis, the embodied energy of utilities can also be minimized at the later stage of the design but minimizing the embodied energy of materials is a matter of concern.

The energy requirements and CO_2 emissions of materials and energy account for 37.5% and 49.4%, which are the two major contributors. Through proper decarbonization strategies the material emissions can be reduced by 27–35% and energy emissions can be reduced by 70–75%, the most important factor for these reductions is the stage of their application.

In comparison with the previous studies, which are generally on process analysis and hybrid analysis, they have an average EE intensity of 448 kg CO_2e/m^2/year, and 368 kg CO_2e/m^2/year. In contrast, the BIM-based studies involve more parameters than the two techniques and have accuracy in assessing the quantity of material and selection of material in different regions of the world through online inventory.

The analysis showed that embodied energy of the selected building is in the range of 414 kg CO_2e/m^2/year, which is fairly higher when compared to developed countries. This embodiment can be lowered down to 135 kg CO_2e/m^2/year, when the initial and recurrent decarbonization strategies are applied together.

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