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Evaluation of Embodied Energy for Building Construction under Urban Renewal Schemes in Core City Area - A Case of Rasta Peth, Pune

Anushka Rudrabhate
Dr. B. N. College of Architecture, Pune, India
(Corresponding Author: es2109.anushkar@bnca.ac.in)

Prajakta Dalal Kulkarni
Dr. B. N. College of Architecture, Pune, India

Highlights

- Urban Building Energy Modelling (UBEM) is used to study embodied energy in urban redevelopment scenarios.
- In comparison with existing and conventional 2030 scenarios, the low-carbon 2030 scenario had lower embodied energy (EE) and Embodied carbon (EC).
- Choosing low-carbon materials and optimizing massing layouts play a crucial role in reducing total embodied carbon in the building stock.

Abstract

Building construction accounted for more than 40% of global energy consumption and 30% of greenhouse gas emissions. It is essential to understand embodied carbon in buildings at the neighbourhood level, as after construction, it will be locked there for several years. This study aims to analyze the embodied energy (EE) of the neighbourhood for redevelopment scenarios using (UBEM). The study area chosen was Rasta Peth, Pune. The primary sources of embodied energy were discovered by analyzing existing dense neighbourhoods. Massing cases for redevelopment scenarios were created according to UDCPR guidelines. A comparative analysis of EE between the redeveloped 2030 scenarios was conducted. The research results show that the low carbon 2030 scenario has 27.9% lower EE than the conventional scenario. The findings emphasized the importance of embodied energy in sustainability strategies for urban planners and policymakers. This research contributed valuable insights for reducing embodied energy in urban areas.

Keywords: Embodied energy, Neighbourhood, Redevelopment, Urban Building Energy Modelling (UBEM)

Introduction

The built environment significantly consumes energy resources and has a lasting environmental impact. Rather than embodied energy, operational energy is the primary energy consumer throughout a building's lifespan. Embodied energy refers to the energy used in extracting, producing, and transporting construction materials. Embodied carbon emissions constitute about 10% of global CO_2 emissions [1]. The whole life cycle energy of a building encompasses both operational and embodied energy. Measured in CO_2, global warming potential reflects the associated embodied emissions. Embodied carbon emissions are primarily released during the construction, renovation, and deconstruction phases, making them challenging to monitor and control [2]. Urban centers have the potential to both contribute to and mitigate climate change [3]. Over 100 cities have committed to achieving net-zero carbon emissions by 2050, and India is targeting carbon neutrality by 2070. To ensure carbon emissions from the global building stock stay below 300 $GtCO_2$ by 2050 [4].

The embodied energy of a building includes the energy consumed during the extraction, manufacturing, transportation, and assembly of construction materials. Through building renovation or new construction, urban renewal initiatives seek to revitalize urban areas. However, these activities have an impact on the environment because they use resources and energy. This study aims to evaluate the embodied energy related to building construction in urban renewal initiatives within core cities. This research helps promote sustainable building methods in the context of urban revitalization by looking at the environmental effects of urban renewal. The research objectives are to study the embodied energy of materials in the redeveloped scenario by constructing a new material inventory, to examine trends in building materials for redevelopment, and to predict future embodied emissions, to design multiple building massing layouts for the redevelopment scenario, calculate their embodied emissions, and to propose strategies to minimize embodied energy. With an emphasis on urban renewal initiatives, the research is intended to provide insightful contributions to understanding and reducing embodied energy in building construction.

Embodied energy refers to the energy that is required to produce, transport, and construct building materials and systems [5]. The built environment accounts for a significant proportion of global energy consumption, and the embodied energy of buildings - that is, the energy used in their construction, operation, and disposal - is an essential factor to consider in achieving sustainable development [6]. The energy usage of a building can primarily be categorized into operational and embodied energy; depending on the composition of a building, embodied energy can range up to 60% of the total energy spent, as there is a need to consider Embodied energy emissions [7]. However, embodied energy has received significantly less consideration than operational energy, both in practice and within academia [8].

About 36% of final energy use and 39% of energy-related carbon dioxide emissions are attributed to the building sector [9][10]. In recent years, researchers have developed methods to assess and reduce embodied energy in building materials, such as using the Universal Building Energy Model (UBEM) and Rhino + UMI software. Urban building energy modelling (UBEM) is a physics-based bottom-up method for simulating the thermal performance of multiple buildings that has been created to act as the analytical foundation for the above-described decision-making procedures [11].

There is a need for accurate and up-to-date data on building stocks, particularly in light of climate change and the increasing importance of sustainable urban development [12]. Urban Building Energy Modelling is an efficient, low-cost, and scalable workflow that can be used to model the energy performance of buildings in urban areas [13]. UMI is a "multi-scale, multi-physics platform that allows users to simulate and visualize the performance of buildings and urban areas at various scales [14].

Rapid urbanization is taking place in developing countries at an unprecedented rate, with the majority of the world's population projected to live in urban areas by 2050 [15]. The redevelopment approach aimed to revitalize deteriorating inner-city neighbourhoods through the demolition of substandard housing, commercial buildings, and other structures [16]. Dense neighbourhood redevelopment has become a popular strategy for addressing urban sprawl and improving urban liveability [17].

Using energy-efficient building materials such as low-emissivity glass, insulation, and reflective roofing can significantly reduce the energy consumption of buildings. Using energy-efficient building materials in high-rise residential buildings reduced the cooling load by 15%, reducing energy consumption and carbon emissions [18]. Sources such as IPCC, India's construction material database for embodied energy data that is used in the construction industry for analysis. The Global Warming Potential (GWP) of construction materials can depend on several factors, including material composition, extraction and production, transportation and maintenance, and end-of-life disposal [19].

Methodology

According to the figure below, the methodological framework for this research study is organized into four steps. A broad area of interest was identified before beginning the main research, and related literature was reviewed to find areas for improvement.

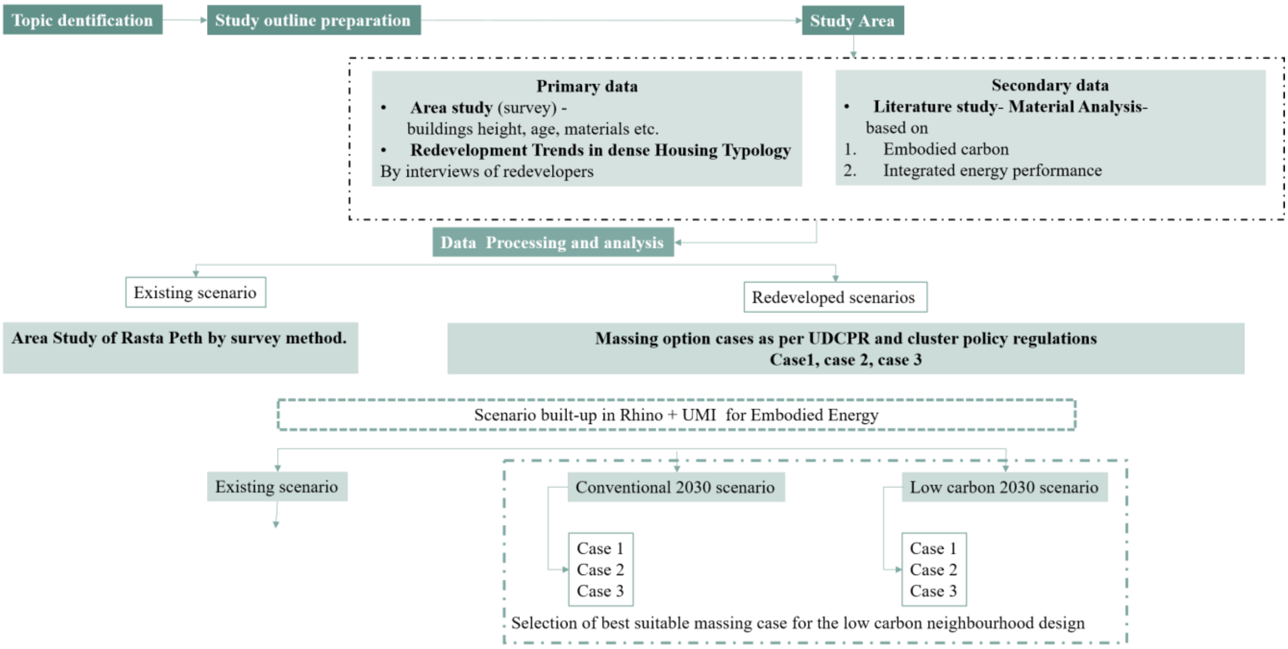

Figure 1: A methodological framework for the research study.

The following steps can formulate this research:

Step 1: Topic identification and generate the study's basic outline

The first step was to define the purpose of the study, as well as its expected outcomes, goals, and objectives.

Step 2: Finalizing study area and data collection

Data gathering focused on embodied energy. Primary data was gathered using QGIS with the Kobo tool application for mapping and field surveys. To understand how construction material trends have changed, information on redevelopment was collected in addition to secondary data for embodied emissions from the India Construction Materials Database. In this study, only structural systems with envelopes with floor finishes were considered. Considering scenarios for 2030 when analyzing EE is essential as it will help to anticipate and assess potential changes in technology, materials, and practices within construction and manufacturing industries.

Step 3: Data processing and analysis

The data collected in Step 2 was processed by developing scenarios and then simulated in UMI (Urban Modelling Interface) using a Rhino plug-in. Rationalized densities and house types were taken into account to simulate a redevelopment scenario in Rasta Peth. Based on UDCPR guidelines, simulations of the Rasta Peth redevelopment scenarios were performed. The service life of buildings is considered to be **60 years**. To finalize the massing layout for low-carbon redevelopment and comply with UDCPR regulations, many massing cases were generated and evaluated. The built-up area for all redeveloped cases is constant. Products used were manufactured within a radius of 200-800 km, and the transportation distances from distribution from distributor to site were in the range of 25-130 km were considered.

Step 4: Recommendations and results

The simulation results were thoroughly examined and visually presented, resulting in significant findings and recommendations. By comparing conventional and low-carbon 2030 scenarios, it will be possible to understand the potential impact of shifting towards more sustainable practices.

Study area

The proposed study area is Rasta Peth in Pune, Maharashtra. It has mixed-use typology buildings with a distinct planning character of grid-iron road networks segregating access and service road networks. For the proposal of Urban Renewal Schemes, the study area is divided into 12 blocks named Block A-L, as shown in Figure 2.

The existing scenario of neighbourhood type is Low Rise- High Density.

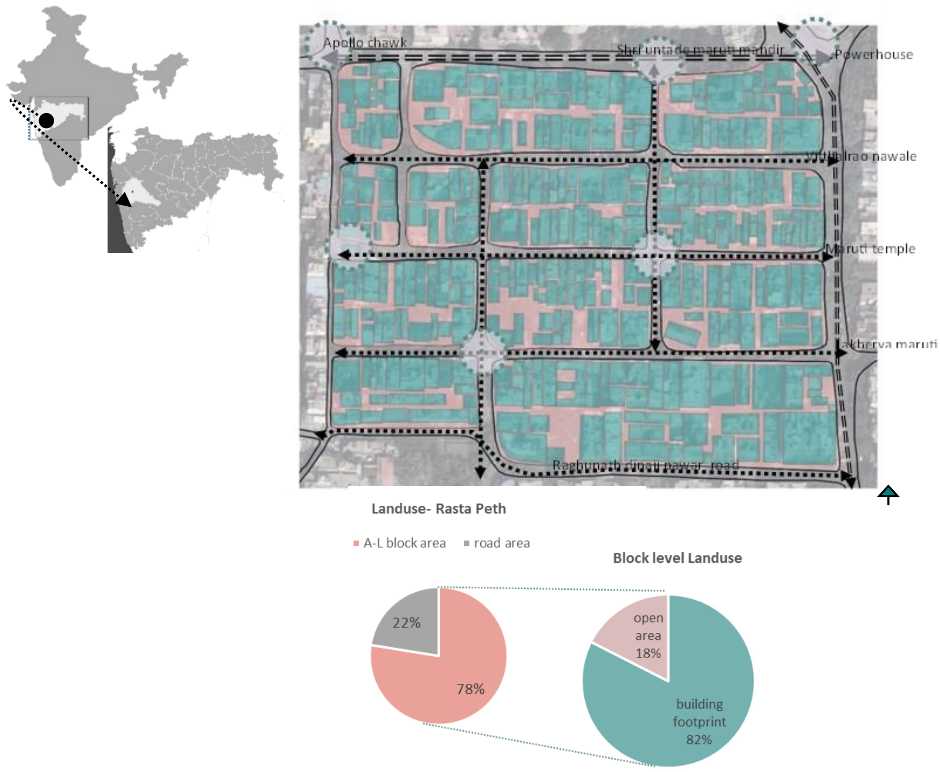

Figure 2: Site plan- Rasta Peth, Pune- An existing scenario with area distribution

• Total site Area- 105303 m^2 Total No. Of existing structures- 326 Total no. of blocks- 12

Primary data collection by gathering data related to existing site development was field study and survey and building level mapping with the help of software like QGIS. The mapping attributes were Building footprint, building typology, no. of floors, age range of buildings, building envelope materials, and structural type.

Data processing

Existing scenario generation

The existing scenario for embodied energy analysis is modelled and simulated based on the existing material assembly of Rasta Peth. The study scope was limited to structural systems, envelopes, and floor finishes.

- Site Area- 105303 m^2
- No. of Households-2187 Nos.
- Max. Building Height- 18 m

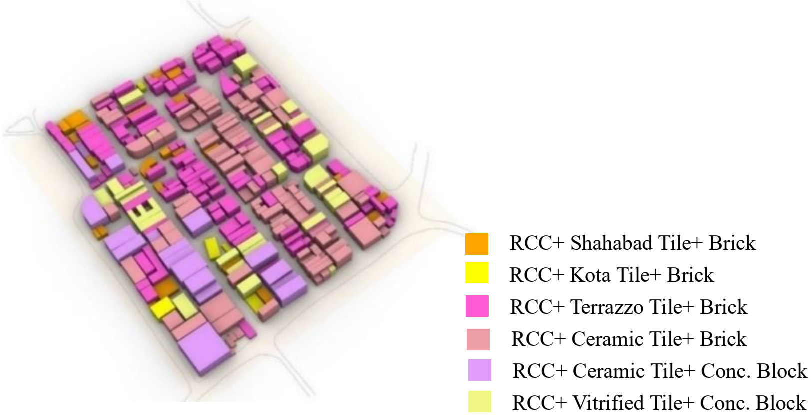

Figure 3: Embodied energy and embodied carbon for the existing scenario

Table 1 presents the material template for the existing scenario.

Table 1: Existing material inventory *source- India construction material database*

Elements	Materials	Embodied energy (MJ)	Embodied carbon (kg CO_2 eq.)
Wall	Bricks (common/facing)	4.40	0.39
	Concrete block- AAC	3.70	0.50
Floor Slab/ Roofing	RCC	2.12	0.24
	Reinforcement	30	2.60
Flooring	Terrazzo Tile	4.60	0.51
	Shahabad Tile	0.44	0.056
	Kota tile	0.79	0.056
	Ceramic Tile	7.80	0.67
	Vitrified tile	8.20	0.68
Windows	Aluminium Frame	280	26
	MS frame	51	3.50
Glass	Single glazed opaque glass	191.80	10.10
	Single glazed clear glass	191.80	10.1 0

Redevelopment scenario generation- Calculations as per UDCPR and Cluster policy regulations.

The proposed redevelopment project aims to revitalize the core area of the city by replacing outdated buildings with high-rise, high-density structures that maximize the available floor space. The project site is located in a strategic location, surrounded by key commercial and public amenities, making it an ideal location for a mixed-use development that caters to the diverse needs of the community.

Overall, for the redevelopment area calculations considering various factors and variables, developers and local governments can work together to determine the appropriate size, shape, and scope of the redevelopment project, ensuring that it meets the needs of the community while complying with relevant regulations and building standards.

The proposal was developed block-wise. The massing cases were based on the UDCPR and cluster policy guidelines. The intent of sustainable development was mainly based on embodied carbon as the built structure will exist there for the next 60 years, and embodied energy will be locked for a long time. Along with this, the environmental quality parameters were considered for the user's health and well-being.

Redevelopment scenario- Massing cases for site development, Rasta Peth

For redeveloped scenarios, massing cases were referred from the Handbook of Replicable Designs for Energy Efficient Residential Buildings published by BEE. However, slight modifications may be necessary during the detailed design

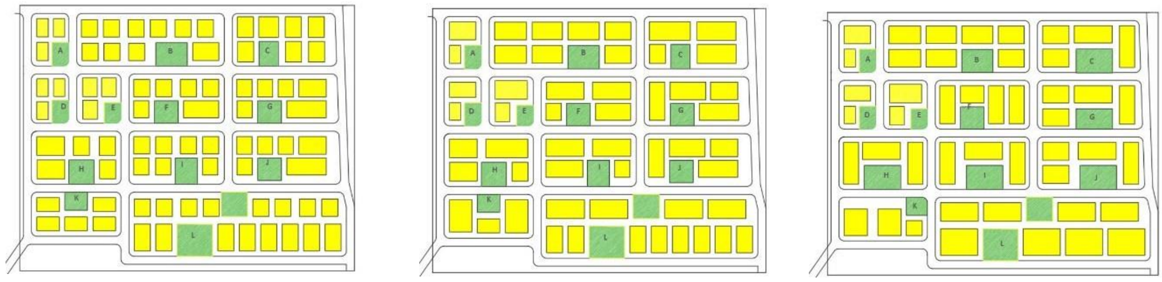

Figure 4: Massing cases 1, 2, and 3 for the Redeveloped scenario

stage. Here, the total built-up area for all 3 cases is considered the same, i.e., 4,30,960.15 m^2 by altering the massing modules.

Case 1: The first scenario features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 43% of the net plot area. The building footprints of blocks are comparatively smaller, have a height ranging from 8-13 stories, and consist of a combination of residential and commercial units. (Considered commercial floor height is 4.5 m and residential floor height is 3m). The lower levels are dedicated to retail and commercial space, while the upper levels are for residential apartments.

Case 2: The second scenario features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 49% of the net plot area. The building footprints of blocks are comparatively wider and rectangular by amalgamating 2 blocks from option 1, have a height ranging from 7-12 stories, and consist of a combination of residential and commercial units.

Case 3: The third case also features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 45% of a net plot area. The building footprints of blocks are comparatively wider and rectangular by amalgamating 2 blocks from option 1, have a height ranging from 8-11 stories, and consist of a combination of residential and commercial units.

Conventional EE 2030 scenario generation

Table 2: Material inventory for Conventional 2030 scenario *source- India construction material database*

Elements	Material	Embodied energy (MJ)	GWP (kg CO_2 eq)
Walls	AAC blocks	3.7	0.50
Slab/ Roofing	200 mm RCC slab	12.2	1
	Steel reinforcement	30	2.6
	Cement plaster	4.8	0.44
Flooring	Vitrified tile flooring	8.2	0.68
	Ceramic tile flooring	7.8	0.67
	RCC	2.12	0.24
Windows	Single glazed clear glass	191.80	10.1
	Al. Frames	280	26

A conventional embodied scenario is to evaluate the environmental impact of a building's materials and construction processes. This scenario is based on current material trends after conducting informal interviews with developers in Pune, which includes a comprehensive assessment of the materials used in buildings, such as their extraction, transportation, manufacturing, installation, and end-of-life disposal. This material palette is identified from the materials used for the current redevelopment building construction in Rasta Peth.

With the help of this knowledge, it will be possible to spot opportunities for a building's environmental impact to be reduced by choosing more green building materials and enhancing construction procedures, as well as to make educated decisions for a building's overall carbon footprint reduction. The above is the material template for the conventional 2030 scenario.

Low carbon EE 2030 scenario generation

In this scenario, as per the research, it was realized that the use of low-carbon materials helps to reduce EE. Hence, for this scenario, regionally available materials with recycled contents were preferred. These materials will be produced using renewable energy sources, which will reduce the carbon footprint of the manufacturing process. By using electric vehicles and improving supply chain logistics, there will also be an emphasis on lowering the amount of energy needed for transportation. The following is the material template for the low carbon 2030 scenario. Total item-wise material quantities were calculated and used as input for the EE calculations.

Table 3: Material inventory for Conventional 2030 scenario *source- India construction material database*

Elements	Material	Embodied energy (MJ)	GWP (kg CO_2 eq)
Walls	FaLG blocks with fly ash content 30% (200 mm)	0.83	0.20
	AAC blocks with fly ash content 30% (100 mm)	0.97	0.34
Slab/ Roofing	Prefabricated 200 mm RCC Filler slab	0.87	0.45
	Reinforcement 50% recyclable content	14.8	1.05
	Cement 30% Flyash content	1.87	0.11
Flooring	Ceramic tile flooring	7.80	0.65
	Cement mortar with 30% fly ash content	1.87	0.11
Windows	Single glazed low E glass	96	5.06
	UPVC Frames	61	3.70

Results

Embodied energy for the existing scenario

Site Area- 105303 m^2

Gross Floor Area- 225101 m^2

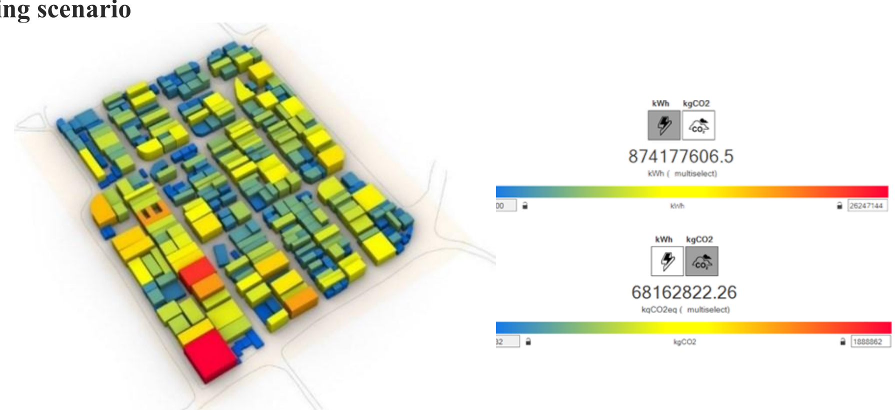

Figure 5: Embodied energy and embodied carbon for the existing scenario

The results of UMI simulations are carried out for the existing scenario of the low-rise, high-density area of Rasta Peth, Pune.

The existing scenario was run by inputting the existing material inventory given in Table 1; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 5.

The total embodied energy for the existing scenario is 874177606.50 kWh. i.e., 874 GWh, and total embodied carbon is 68162822.26 kg CO_2eq.

As shown in the following results, the building assemblies with bigger footprints have higher EE.

Conventional building wall material assemblies like red brick have relatively higher EE than concrete blocks.

The conventional terrazzo tile flooring with RCC construction has relatively lower EE than ceramic tile flooring with a similar building footprint area.

Block L has relatively newer constructions with mostly more than G+4 height structures; hence, the EE for the L block is higher.

Embodied energy (EE) for redeveloped conventional 2030 scenario

All massing cases were run by inputting the conventional 2030 material inventory given in Table 2; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 6. Gross floor area- 4,30,960.15 m^2.

The total embodied energy for the conventional 2030 scenario for case 1 is 1249 GWh, and the total embodied carbon for the conventional 2030 scenario is 91961217.89 kg CO_2 eq. For case 2, EE is 1100 GWh, and total embodied carbon is 81198000.65 kg CO_2 eq. For case 3, EE is 998 GWh, and the total embodied carbon for the conventional 2030 scenario is 73529667.14 kg CO_2 eq.

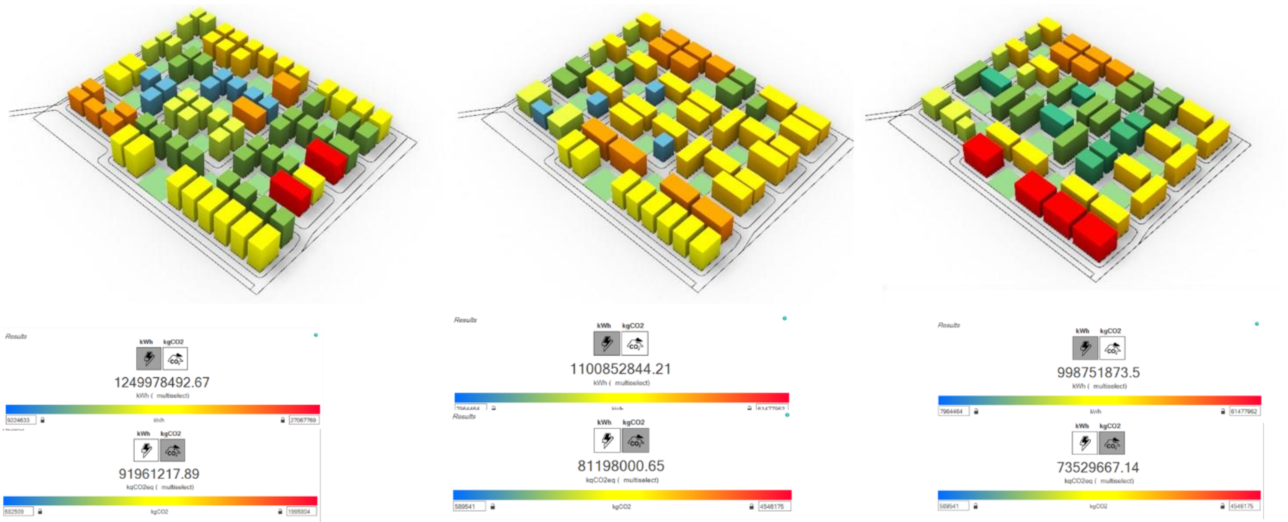

Figure 6: EE and EC of cases 1, 2, and 3 for conventional 2030 scenario

The comparative analysis is done for all cases for the total embodied energy for the conventional 2030 scenario and is shown in Figure 7.

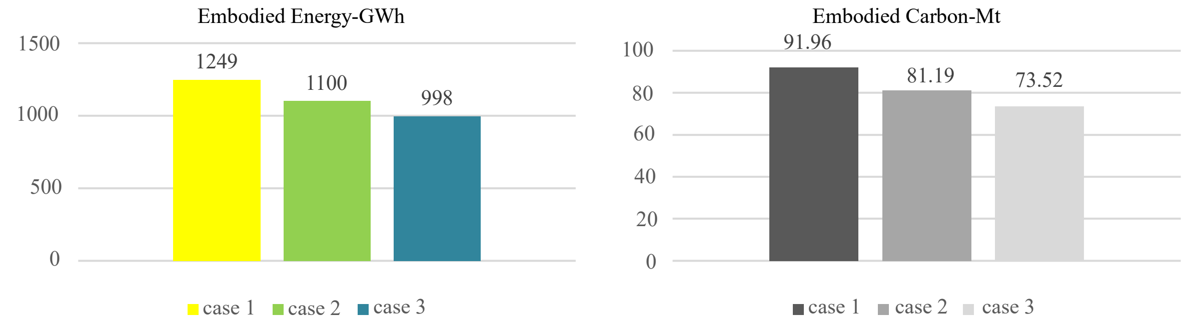

Figure 7: Comparative analysis for EE and EC of all 3 cases for conventional 2030 scenario

From the comparative analysis (Figure 7), it is seen that there is a 20% reduction in the embodied energy of case 3 from case 1 and a 21% reduction in embodied carbon of case 3 from case 1.

Embodied energy (EE) for redeveloped low carbon 2030 scenario

All massing cases were run by inputting the low carbon 2030 material inventory given in Table 3; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 8.

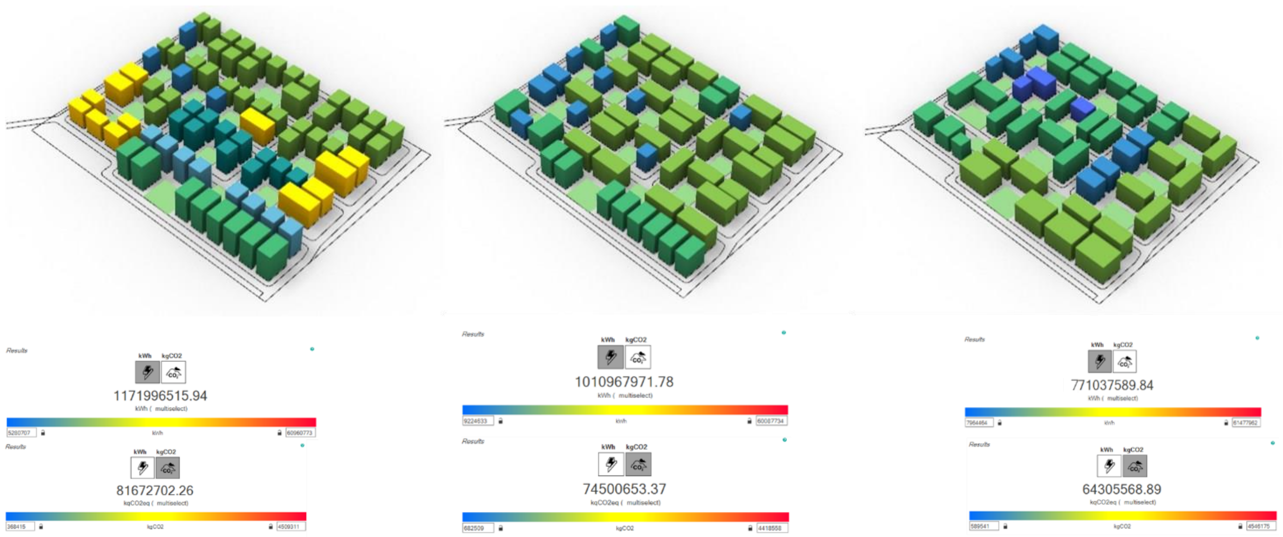

Figure 8: EE and EC of cases 1, 2, and 3 for the conventional 2030 scenario

The total embodied energy for the low-carbon 2030 scenario for case 1 is 1171 GWh, and the total embodied carbon for the low-carbon 2030 scenario is 81672702.26 kg CO_2 eq. For case 2, EE is 1010 GWh, and the total embodied carbon is

74500653.37 kg CO_2 eq. For case 3, EE is 771 GWh, and the total embodied carbon for the conventional 2030 scenario is 64305568.89 kg CO_2 eq.

The comparative analysis is done for all cases for the total embodied energy for the low carbon 2030 scenario, as shown in Figure 9.

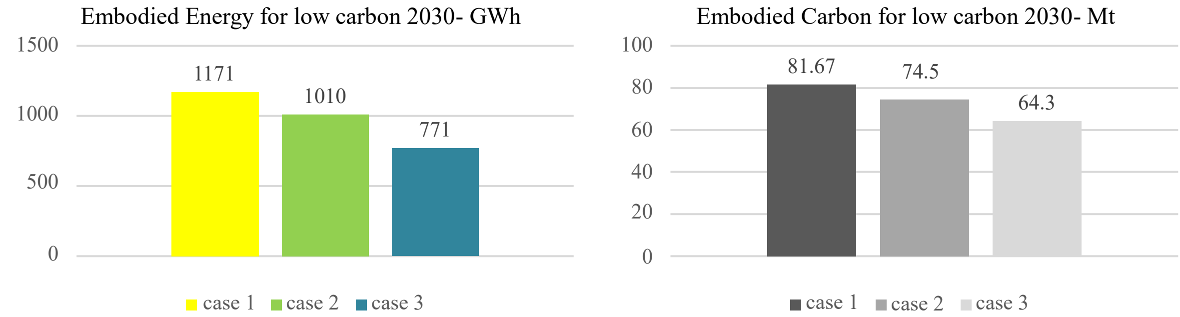

Figure 9: Comparative analysis for EE and EC of all 3 cases for the low carbon 2030 scenario

From the comparative analysis (Figure 9), it is seen that there is a 34.1 % reduction in embodied energy of case 3 from case 1 and a 21% reduction in embodied carbon of case 3 from case 1.

Data Analysis

For redeveloped scenarios- conventional 2030 and low carbon 2030, 3 massing cases were designed according to UDCPR and cluster policy rules. The simulation results showed that case 3 had the lowest embodied energy and embodied carbon among the three cases in both scenarios.

This is because case 3 requires comparatively less building materials quantity compared to massing cases 1 and 2. Additionally, the wider shape design of the building allows for more efficient use of space, with the reduction in areas of circulation spaces, further reducing the amount of building materials required.

Comparative analysis of existing vs. conventional 2030 vs. low carbon 2030 scenarios for total EE and EC

Existing systems refer to products and systems as they are available today in the given context. In contrast, conventional 2030 refers to a scenario where products and systems still use conventional techniques and technologies for redevelopment.

The low carbon 2030 scenario has the least amount of average embodied energy as well as embodied carbon, respectively. It has 22.7% less Embodied Energy and 13% less Embodied carbon than the conventional 2030 scenario.

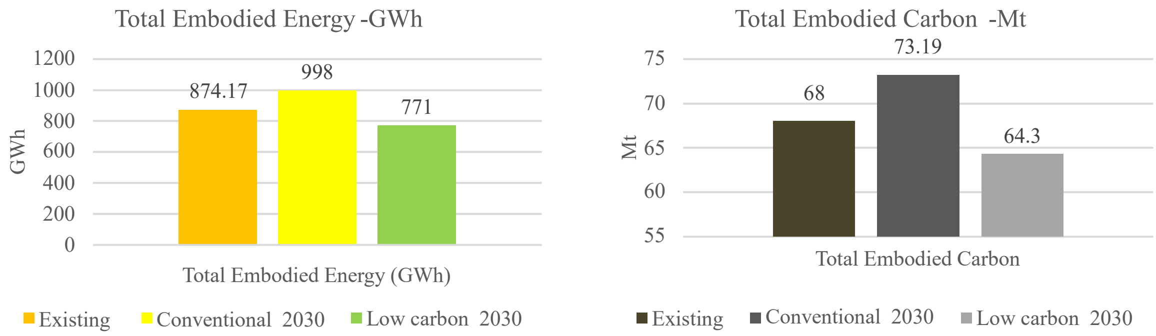

Figure 10: A comparative analysis of existing vs. conventional 2030 vs. low carbon 2030 scenarios for total EE and EC

- The total embodied carbon values are not rising exponentially in the low carbon scenarios despite the predicted densification of the building stock in the future scenarios.
- Variations in the total amounts of embodied carbon can be observed with changes in the materials selected.

Overall, the findings imply that, compared to the conventional 2030 scenario, switching to a low-carbon 2030 scenario would significantly reduce the embodied energy and embodied carbon per unit area.

Discussions

This paper addressed the UBEM tool and strategies that can encourage the construction industry to effectively incorporate embodied carbon considerations and thus reduce its contribution to global greenhouse gas emissions. The success of these reduction strategies depends on the understanding and proper execution of all stakeholders involved in a project. Rising awareness among manufacturers and industry professionals will result from more research and information sharing, such as carbon labeling, eventually reducing the instances of missing data.

Scenarios like materials with a higher percentage of construction and demolition waste and recycled content can be built to analyze further reduction from conventional scenarios. Exploring a range of low-carbon alternatives that can contribute to sustainable urban development is imperative. One such consideration involves refurbishing existing buildings. While the low-carbon benefits of refurbishment are evident, it's essential to acknowledge certain challenges like structural limitations, meeting modern building codes, and addressing potential hazardous materials. A thorough lifecycle assessment is crucial to quantify the environmental impact of both options.

Conclusions

This study conducted a comprehensive evaluation of the design and construction sector to assess the industry's current status and scope regarding its impact on embodied emissions.

A comparative analysis of embodied energy in redeveloped scenarios was performed to provide insights into the potential environmental impacts of various building designs and materials. According to the study, a conventional 2030 scenario would result in higher embodied energy than a low-carbon 2030 scenario. This suggests that to achieve carbon neutrality by 2070, efforts to lower embodied energy in building materials and construction methods will be required.

By selecting materials with a low carbon footprint, initiating recycled content products, and using renewable energy sources for manufacturing can reduce embodied emissions. For the low carbon 2030 scenario, low-carbon materials like AAC Blocks with fly ash contents significantly reduce embodied energy by 22% and embodied carbon by 13%.

The densification of the building stock and the material inventory are both factors that affect total embodied carbon. Hence, changes in total embodied energy are based on massing layouts.

As different layouts may require different amounts of materials and energy for construction, factors like massing layouts can have a significant impact on embodied energy. The kind of materials used, the location of the construction site, and the modes of transportation employed to move materials and goods are additional elements that can impact embodied energy.

For the proposed scenario, regionally available materials were preferred. Considering the lifespan of construction materials is in the range of 30-60 years, the end of the lifecycle of a product and preventing it from going to landfills will reduce the embodied energy of the material.

These results demonstrate the importance of considering Embodied energy in building design and how careful planning and consideration can result in more sustainable neighbourhoods.

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