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Embodied Carbon in Australian Residential Houses: A Preliminary Study

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Abstract: Embodied carbon is a buzzword in the construction industry. Australia is committed to achieving Net Zero 2050 targets, and minimizing embodied carbon (EC) is inevitable. Owing to the population growth, there will be a significant demand for residential construction. Therefore, the material consumption in residential construction should be evaluated and proper strategies should be in place to minimize EC. The aim of this research is to undertake a preliminary study of EC in the Australian residential sector, with an emphasis on new residential home construction. This research presents a preliminary study on EC in residential buildings in Australia. Three case study residential buildings were used in this study. All three case studies are single -story residential units, with a gross floor area between 200 and 240 m^2. One Click LCA software was used to calculate the EC. The EC of three case study residential homes is between 193 and 233 $kgCO_2e/m^2$. Based on the findings of this study, 'other structures and materials' contribute to a large amount of EC in residential construction. Concrete and aluminum are considered significant contributors to EC. Therefore, it is vital to either introduce low-EC material to replace aluminum windows or introduce various design options to minimize the use of aluminum in windows. There are various sustainable concretes available with low EC. It is essential to explore these low-EC concretes in residential homes as well. This research identifies the importance of adopting strategies to reduce the carbon impact from other sources, including concrete. It is also essential to consider the EC through transportation related to construction and promote locally sourced building materials in residential construction. Therefore, the results of this research indicate the necessity of reducing raw material consumption in Australian residential construction by implementing approaches such as a circular economy in order to circulate building materials throughout the construction supply chain and reduce raw material extraction.

Keywords: building materials; circular economy; embodied carbon; residential construction

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1. Introduction

Climate change is a buzzword across many sectors. There are several contributing factors to climate change, and greenhouse gas emission (GHG) is one of the most significant. Buildings play a significant role in carbon dioxide (CO_2) emissions, accounting for approximately 40% of the overall energy consumption, and as a result, they contribute as much as 30% of the annual total GHG emissions worldwide [1]. The lifecycle carbon emission of a building has two components: operational carbon and embodied carbon (EC). Operational carbon is emitted during the operational phase and EC refers to carbon emissions that occur during the manufacturing process of the product/materials [2], transportation to the site, construction, and end-of-life stage. The growing emphasis on decreasing the environmental impact of buildings has prompted the adoption of zero-carbon buildings to reduce operating costs [3]. Over the last few decades, reducing operational energy and carbon has gained much prominence. In Australia, there are mandatory requirements focusing specifically on the energy efficiency of buildings, which regulates the operational carbon in buildings. For example, in New South Wales (NSW), residential homes have a minimum BASIX (building sustainability index) score that needs to be fulfilled [4]. Due to these mandatory requirements, the building sector is now on track to achieve the targets set out by Net Zero 2050. However, when considering the total carbon emissions, EC also plays a major role, yet EC mitigation still lags behind. If no action is taken, the contribution from EC will rise up to 85% of total emissions from buildings in 2050 [5]. Therefore, currently, there is an increasing focus on EC and its mitigation, yet prior to mitigation, it is essential to identify the EC in buildings and its contribution to elements. There is always a trade-off between EC and operational carbon [6].

Measuring EC has become increasingly important for reducing EC in building construction, and hence, the environmental effect of construction. Various tools are used to measure EC in construction, including the Construction Carbon Calculator, Athena Impact Estimator, and One Click LCA. The Construction Carbon Calculator was developed by the Build Carbon Neutral Organization. It covers from cradle to construction, and estimations are limited to multi-family and commercial projects [7]. The Athena Impact Estimator is a lifecycle assessment tool and freeware that facilitates cradle-to-grave carbon estimation and is mostly applicable for North American projects such as commercial, residential, industrial, and institutional buildings [8]. These tools have several limitations, including their applicability to a specific context and building type. On the other hand, as a subscription-based lifecycle assessment software, One Click LCA offers access to the world's largest material Environmental Product Declaration database and has the ability to integrate automation in order to estimate EC in construction [9]. EPiC is also an Australian database data providing EC data in construction. There is also more sophisticated software such as SimaPro and GaBi that are used to conduct lifecycle assessment, which also can be used to calculate the EC considering certain building lifecycle stages. The most accurate calculations should extract information from the Environmental Product Declarations (EPDs) of each material/product used. However, this can be a time-consuming task. When estimating EC, it is essential to clearly define the lifecycle stages of a building. According to EN15978, a building lifecycle can be mainly classified into four stages, including (1) the product stage (A1–A3: raw material supply to manufacturing); (2) the construction process stage (A4: transportation to the construction site and A5: onsite construction); (3) the use stage (B1–B7: use, maintenance, repair, replacement, refurbishment, and operational energy and water usage); and (4) the end-of-life stage (C1–C4: deconstruction, waste processing, and final disposal). Accordingly, cradle-to-grave includes all these building lifecycle stages, from A1 to C4.

The Australian Bureau of Statistics [10] has estimated that there will be a population of 31 million in 2030, requiring a significant increase in building construction to accommodate people. This will lead to an increase in annual carbon emissions from the building sector and challenges in achieving the net-zero targets. With the population growth in Australia, there will be a high demand for residential units in the future, and the challenge is to minimize the EC whilst catering to the demand for residential units. There are regulatory requirements such as BASIX to mitigate operational carbon. However, currently, there are no regulatory/policy requirements for mitigating EC in residential homes. However, due to the significant contributions from EC emissions to lifecycle carbon emissions, since 1 October 2023, the NSW State Environmental Planning Policy has encouraged reporting EC for all building topologies [11]. Further, it is expected that EC regulations and targets will be set up in the near future. In 2019, significant EC emissions from the building stock in Australia were from residential buildings [5]. Therefore, it is necessary to identify high-EC-intensive materials used in residential houses that contribute to high-EC outputs during the initial decision-making stages.

The aim of this research is to undertake a preliminary study of EC in the Australian residential sector, with an emphasis on new residential home construction. This paper presents the initial results and findings of the study. The remainder of this paper is divided into the following sections. Following Section 1 (the introduction), Section 2 provides a comprehensive literature review on EC in construction, EC in the Australian residential sector, and strategies to reduce EC in construction. Section 3 explains the methodology adopted in this study. Section 4 presents the case study results related to EC calculations. The implications of this research are discussed in Section 5. Finally, Section 6 concludes the present research while highlighting the key findings of this study.

2. Literature Review

2.1. Embodied Carbon in Construction

The construction industry generates carbon emissions in two ways, including energy consumption at the use stage and material production and construction stages. Carbon emissions over the building lifecycle are therefore divided into operational carbon and embodied carbon [12]. Operational carbon refers to the emissions owing to the energy consumption related to heating, cooling, and lighting during the use stage [13]. Embodied carbon is related to the carbon emissions associated with building material and component production, as well as their transportation, construction, maintenance, and end-of-life stages [14]. Nowadays, there is growing attention to the environmental influence of embodied carbon in the construction industry due to its contribution to climate change and resource depletion. Reducing carbon emissions in construction is key to combating climate change. There is also an emerging interplay between the share of embodied carbon and resource depletion. EC is becoming a key contributor to the long-term environmental effects of the construction industry due to the increased usage of materials in construction, such as double glazing, thicker insulation, and more technological applications [15]. Further, the proportion of embodied carbon is expanding as buildings become more energy-efficient [16]. However, it is challenging to measure and manage EC in construction due to the complexity of the supply chain.

In current practice, several approaches are adopted to measure the embodied carbon in construction. Among those approaches, the lifecycle assessment approach is widely adopted to quantify the embodied carbon throughout the building's lifecycle [14]. In addition, inventory-based methods are used to calculate the embodied carbon of building materials, often using emission factors through databases. For this purpose, several databases are adopted, such as the Inventory of Carbon and Energy (ICE) from the University of Bath, the Hutchins UK Building Blackbook, the Carbon Working Group [17], the EPiC database published by the Melbourne School of Design, the Integrated Carbon Metrics (ICM) Embodied Carbon Life Cycle Inventory Database published by the University of New South Wales Sydney, and the Australian National Life Cycle Inventory Database (AISLCI) currently delivered by the Australian Life Cycle Assessment Society. There are also more sophisticated and detailed databases such as EcoInvent that can be used by many LCS tools such as SimaPro and GaBi. These databases provide embodied carbon coefficients for common construction materials, which in turn facilitates measuring embodied carbon in a simple manner.

2.2. Embodied Carbon in the Residential Sector in Australia

With population growth in metropolitan and regional areas in Australia, there is a wider development in residential properties that in turn contributes to higher embodied carbon [18]. There have been several studies conducted on EC in the residential sector in Australia. Ref. [19] conducted a study on upfront carbon considering modules A1–A5 for several building typologies. In this research study, residential homes (Class 1) buildings were classified into two categories: (1) residential homes with timber/brick veneer and (2) residential homes with concrete/brick. This study provided benchmarks, and residential homes with timber/brick veneer garnered an average EC of 1270 $kgCO_2e/m^2$, yet it ranged from 762 to 1778 $kgCO_2e/m^2$. The floor area considered in this research is the net lettable area (NLA), which is a relatively smaller area considering the gross floor area (GFA) of the building.

In 2022, Slattery conducted a similar study on EC for common building types considering Modules A1–A5 [20]. In this research study, buildings were classified into four main elements, namely, (1) Substructure, (2) Superstructure, (3) Finishes, and (4) Building Services. According to this research study, for a typical project, the Substructure accounts for 10–30% of the total EC, yet it depends on the extent of the basement. The Superstructure accounts for 40–70%, Finishes for 4–8%, and Building Services for 5–8% of the total EC. Ref. [20] also concluded that it is essential to focus on the substructure, upper floors, columns, external walls, and windows, as these capture approximately 70–80% of the building's upfront EC. Ref. [21] also conducted a comprehensive study, revealing a broad range of embodied carbon emissions in residential buildings, spanning from 179.3 kg CO_2e/m^2 to 1050 kg CO_2e/m^2, which reflects a share between 9% and 80% for the total lifecycle impact in the Australian context. In this research study, the authors considered the correlation between the share of embodied energy and carbon for different levels of building energy efficiency. According to the study, for a net-zero-energy building, the share of EC in the total carbon emission amounts to 71%. Managing EC is not a one-off task in selecting the correct materials. However, attention should be paid to aspects such as reusability, longevity, and maintainability when selecting materials to minimize the overall EC. The materials have a direct impact on operation carbon emissions; thus, they should be managed holistically.

According to [22], Australian residential building construction accounted for 21.5 Mt CO_2e emissions in 2013. Ref. [18] identified that building materials such as structural steel, concrete, composite concrete, and rebar have higher levels of embodied carbon compared to timber in metropolitan areas, as opposed to regional areas, in Australia. This discrepancy was mainly attributed to the growth of residential construction in regional areas. However, the embodied emissions of Australian residential construction are lower than international averages due to the high use of timber-framed and single-story dwellings [5]. Further [22] revealed that the replacement of all reinforced concrete in new residential buildings in Australia with engineering wood products might save 26 Mt CO_2e by 2050. Due to the continued expansion of Australia's residential stock, careful material selection and strategic planning should be executed to minimize the embodied carbon in Australian residential construction.

2.3. Strategies to Reduce EC in Construction

With the growing attention to the portion of embodied carbon in construction, several strategies have been suggested by various scholars and institutions to minimize the embodied carbon throughout the building lifecycle. The World Green Building Council Ref. [23] introduced four strategies to reduce embodied carbon, namely, (1) Build nothing, (2) Build less (3) Build clever, and (4) Build efficiently. According to a 2021 census in Australia, approximately 10% of Australian homes were unoccupied or left empty [24], despite the rising growth in population. On the other hand, ref. [25] explored the 'Airbnb' effect on higher prices for housing in Australia and various suburbs—this has a direct impact on residential houses. Therefore, researchers suggest that it is essential to first focus on the first two strategies of WGBC: 'build nothing' and 'build less'. The census data suggest that there may be residential units that can be reused or re-purposed rather than building new homes to deal with the rising demand. This strategy will completely cut down the EC as there will be no new materials used in the new construction. However, the first two strategies require the involvement of governments and other institutions. There should be policies put in place to support 'build nothing' and 'build less' strategies. Further to that, the other two strategies ('Build clever' and 'Build efficiently') can be directly achieved by effective initial decision-making. Material-saving and design optimization can be considered key approaches to reducing embodied carbon, particularly during the design stage [26].

Construction materials account for 90% of embodied carbon, so an increased use of recycled and reused materials and locally sourced materials could largely reduce embodied carbon emissions [27]. Ref. [28] identified recycling building materials as the most efficient approach to reducing embodied carbon, particularly in residential building construction. A reduction in the use of cement, which contains a higher proportion of fly ash and blast furnace slag, leads to a 7–20% reduction in embodied carbon emissions [29]. Embodied carbon emissions can be considerably reduced by using local materials due to reduced transportation. For example, ref. [30] found that importing stones to the UK from other countries, such as Spain and China, significantly increases the carbon footprint from 134 to 318 $kgCO_2$/tons and 415 to 568 $kgCO_2$/tons, respectively. It has been demonstrated in a number of countries, including Australia and China, that using timber frames or structures lowers embodied carbon emissions, compared to using other building materials like concrete or steel [31,32]. Design optimization in building elements such as beams, slabs, and walls should be particularly optimized because they are responsible for more than 50% of embodied carbon emissions [33]. For example, ref. [34] identified that the embodied carbon of prismatic beams can be reduced by up to 38% when their design is optimized, compared with conventional designs. In addition to the choice of building materials and design shapes, other design factors such as the quantity and type of recycled materials and building height also have a significant influence on embodied carbon [35]. Furthermore, maintaining the existing building stock at a reasonable level, encouraging building retrofitting, and avoiding early demolition while extending a building's lifecycle could significantly reduce the demand for new materials and the carbon intensity of material production [36]. Consistent with these strategies, ref. [37] identified that EC in residential building stock can be reduced by implementing strategies such as using lightweight materials and wood products, reducing the built area, expanding the useful life span of the building, reusing and recycling building materials, and adopting offsite manufacturing methods.

Offsite manufacturing has been recognized as a promising approach for minimizing embodied carbon emissions. This is achieved by optimizing the construction process, which, in turn, leads to waste reduction, enhanced quality, and improved process efficiency. Comparing houses built using the traditional approach to those built using modular construction, ref. [38] found that the embodied carbon might be reduced by 4 to 20%. However, prefabricated buildings may emit higher embodied carbon due to the higher use of steel. Therefore, the use of recycled steel could reduce the embodied carbon associated with offsite construction [26]. In addition, several measures can be taken to minimize the embodied carbon in offsite construction, including improving the productivity of machines, redesigning supply chains, using alternative energy sources, applying lean techniques to minimize waste and improve the process, and using materials with low embodied carbon and locally sourced materials [39].

Macro-level strategies, including changes in government policies and regulations, organizational-level policies, and the decarbonization of the energy supply or grid, are also identified as potential approaches to minimizing embodied carbon emissions in construction. While revising government policy and regulations related to embodied carbon has become a recent trend, these changes are mainly focused on supporting the implementation of other strategies, such as the use of recycled materials in construction [40]. For instance, the government can promote the use of recycled materials by providing incentives to businesses and consumers [41]. Although decarbonizing the energy grid mainly contributes to minimizing operational carbon, it also reduces embodied carbon emissions [42]. The reduction in embodied carbon emissions occurs due to aspects such as lower embodied energy in building systems, minimized use of carbon-intensive materials, and improved energy efficiency of buildings.

3. Research Methodology

The research study presented in this paper is an initial stage of preliminary research conducted in Australia. The aim of this research is to undertake a preliminary study of EC in the Australian residential sector, with an emphasis on new residential home construction. The overall research process of this study is presented in Figure 1. The scope of the study, normalization and area calculations, case study selection, and details on One Click LCA calculations should be clearly defined prior to the study.

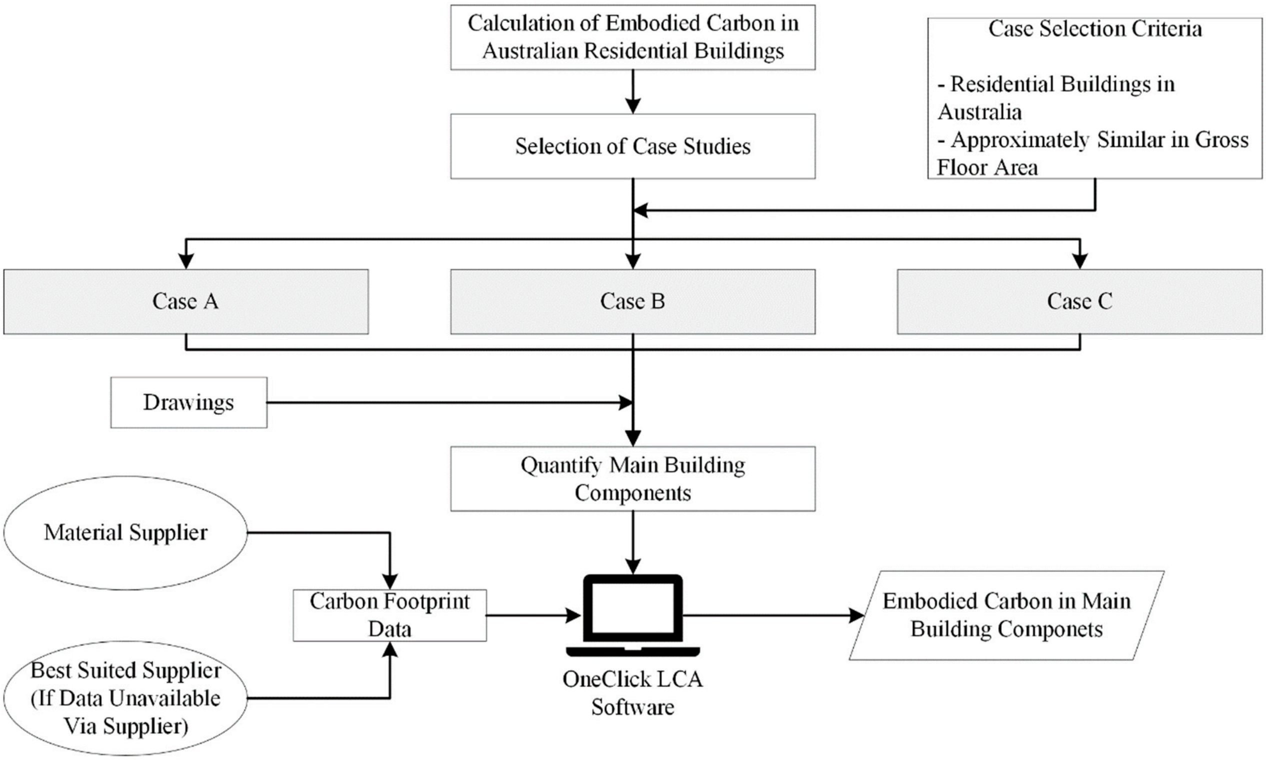


Figure 1. Overall Research Process.

Scope of the study: The embodied carbon for three case studies is calculated from A1 to A5 for all the elements considered in the study.

One Click LCA complies with the Green Star credit 19A Life Cycle Assessment and contains Green Star-specific characterization factors for Australian datapoints, and for other factors, EN 15,804-compliant characterizations are applied instead.

Case study selection: This is a preliminary study on residential homes. According to the National Construction Code, Class 1a detached residential homes are considered for this research study. The approximate area of a residential home is 233 m^2 [43]. Therefore, when selecting case studies, homes with a gross floor area of approximately 200–240 m^2 are considered. All the homes are built in the year 2021/2022 and all the homes were built with similar regulations and requirements. The estimated construction cost for each house is between AUD 300,000 and AUD 400,000 as of January 2023.

Normalization and area calculations: There is no consensus on the normalized area that should be used for EC calculations. For example, [19], used the net lettable area for area calculations, and [20] used GFA for their calculations. This research study focuses on residential homes, and when providing information on residential homes, GFA is a widely used an accepted term. Therefore, the EC figures are normalized using GFA in this research study.

One Click LCA: One Click LCA software (https://www.oneclicklca.com/) and the associated database is used for calculations. This software draws EC data from EPDs, and there are Australian EPDs available in the dataset. Using EPDs provides accurate details. This software is structured to input data in designated elements. The elements are given as (1) Foundations and substructure, (2) Vertical structures and façade (3) Horizontal structures: beams, floors and roofs, and (4) Other structures and materials. Foundations and substructure include foundation, subsurface, basement, and retaining walls (if any). Vertical structure and façade include external walls and façade. Horizontal structure includes floor slabs, ceilings, roofing deck, beams, and roof. Other structures include doors and windows and other special items. However, these calculations did not consider mechanical and electrical services. Further, any repair and maintenance work were also not considered in the calculations. Table 1 below reports the elemental sections and the relevant materials used in each of the case studies as per the One Click LCA.

Table 1. Case study details classified according to One Click LCA.

Elements	Details	Case Study A	Case Study B	Case Study C
	Gross Floor Area (GFA)	207.45 m^2	221.85 m^2	236.04 m^2
Foundations and substructure	Foundation	Waffle Pod	Waffle Pod	Waffle Pod
Vertical structures and façade	Building frame	Timber frame	Timber frame	Steel frame
Horizontal Structure	Roof	Concrete tiles on timber structure	Concrete tiles on timber structure	Concrete tiles on timber structure
	Internal walls	Timber studs with plasterboards	Timber studs with plasterboards	Steel studs with plasterboards
	Wall finishes	Wall tiles up to ceiling height in wet areas, painting in other areas	Wall tiles up to ceiling height in wet areas, painting in other areas	Wall tiles up to ceiling height in wet areas, painting in other areas
	Floor finishes	Ceramic tiles in wet areas, living, kitchen and dining. Carpets in bedrooms	Ceramic tiles in wet areas, living, kitchen and dining. Carpets in bedrooms	Ceramic tiles in wet areas and kitchen. Carpets in bedrooms, living and kitchen
	Ceiling finish	Painting	Painting	Painting
Other Structure	Doors	Timber	Timber	Timber
	Windows	Aluminum	Aluminum	Aluminum

This research study selected three residential units: single-story detached residential houses within the Sydney region.

A summary of EC results is presented in the following section. Subsequently, the complications and obstacles encountered by the researchers during the process of estimating EC were documented and deliberated upon in the research findings.

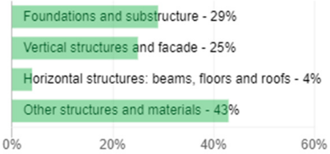
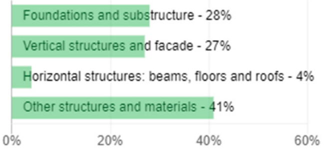
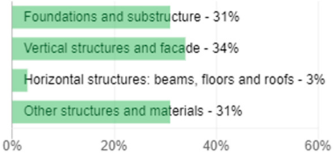
4. Results and Findings

The results are provided in Table 2. The EC from three case study residential units ranges from 193 to 233 $kgCO_2e/m^2$. The scope of analysis only focused on the elements presented in Table 1. Therefore, the EC calculated in this research is restricted to the elements used in the calculation and does not represent all the materials included in the construction. As mentioned in the methodology, there is no standard method to classify elemental sections in EC calculations. The elemental sections considered in the research study conducted by [20] concerning EC were: Substructure amounts to a total of 10–30%, Superstructure amounts to 40–70%, Finishes amounts to 4–8%, and Building Services amounts to 5–8%. The classifications put forward by these studies include their own formats, thus making it difficult to compare results.

Ref. [44] conducted a similar study to evaluate EC in 220 m^2 houses in Australia. This study revealed that timber-framed houses with timber cladding had the lowest EC of 94 $kgCO_2e/m^2$ while those with steel frames and brick cladding had an EC of 171 $kgCO_2e/m^2$. The area considered for this study was the gross dwelling area. In this research study, the EC varies from 190 to 233 $kgCO_2e/m^2$. Compared with [44], the EC calculated in this research study is higher, yet there are many reasons for this difference. Initially, the study was conducted in 2011 focusing on 5-star energy-rated buildings, and there may be regulatory changes due to which the material use may be different. According to Table 2, Case Study C, with a steel frame, has a higher EC compared to Case Studies A and B. The vertical structures represent the building frame. Both Case Study A and Case

Study B have timber frames, while Case Study C has a steel frame structure. Case Study A has an EC amount of 48.25 $kgCO_2e/m^2$ for the timber structure and Case Study B has 53.19 $kgCO_2e/m^2$. However, for Case Study C, the EC amounts to 79.22 $kgCO_2e/m^2$. This is considerably high compared to Case Studies A and B.

Table 2. Summary of EC results.

Details	Case A	Case B	Case C
GFA	207.45 m^2	221.85 m^2	236.04 m^2
EC (A1 to A5)	193 $kgCO_2e/m^2$	197 $kgCO_2e/m^2$	233 $kgCO_2e/m^2$
EC by structure			
Foundation and substructure	55.97 $kgCO_2e/m^2$	55.16 $kgCO_2e/m^2$	72.23 $kgCO_2e/m^2$
Vertical structures	48.25 $kgCO_2e/m^2$	53.19 $kgCO_2e/m^2$	79.22 $kgCO_2e/m^2$
Horizontal structure	7.72 $kgCO_2e/m^2$	7.88 $kgCO_2e/m^2$	6.99 $kgCO_2e/m^2$
Other structures (Doors and Windows)	82.99 $kgCO_2e/m^2$	80.77 $kgCO_2e/m^2$	72.23 $kgCO_2e/m^2$

Ref. [19] set up benchmarks for EC in Australian residential buildings. The benchmark ranges from 762 to 2050 $kgCO_2e/m^2$ of net lettable area (NLA), which is comparatively high compared to the figures generated in Table 2. When calculating the NLA, the circulation spaces are removed, thus a significantly lower measurement is presented compared to the GFA. This creates a higher EC value in these studies. Further to that, [19] used the Footprint Calculator (TFC) and EPiC database to conduct a hybrid analysis. However, in this study, researchers used One Click LCA, referring to Environmental Product Declaration (EPDs), for process analysis. This is one of the reasons for the changes in figures. In the same study, [19], compared the EC of a brickwork using TFC and One Click LCA. TFC reported approximately 10,000 $kgCO_2e$ of global warming potential (GWP) in absolute terms whilst One Click LCA reported only approximately 4000 $kgCO_2e$ GWP. Due to the changes in the LCA tool used and the inputs used in the EC, the calculations provide different results.

All three case studies—A, B, and C—have a higher contribution from the 'other structures and materials' element. Other structures represent windows, and in all three case studies, the windows are aluminum. Aluminum has a significantly high EC due to its manufacturing process. According to the construction material pyramid, aluminum sits at the top of the material pyramid, reflecting its high intensity of EC [45]. Therefore, it is essential to look for alternatives to aluminum to mitigate EC.

According to Table 2, the second highest contribution is from the foundation, which represents concrete waffle pods. Concrete itself is a high-carbon-emitting material. There are other sustainable alternatives provided by other suppliers. The current concrete supplier has 274.708 GWP CO_2/m^3. However, there are potential alternative suppliers with 140–160 GWP CO_2/m^3. Concrete is the highest contributing material in all three case studies. It is essential to find green alternatives to concrete to reduce the EC from the residential sector.

Case Study C has a distinct design with higher material intensity. The internal wall area is higher (approximately 5% higher after adjusting to the floor area), and therefore, the EC is higher compared with the other two case studies. Compared with Case Studies A and B, Case Study C has a higher contribution from concrete foundations. According to Table 2, 31% of the total EC is allocated to the foundation in Case Study C. In Case Studies A and B, it is 29% and 28%, respectively. The specific design required a higher footprint, thereby leading to a higher volume of concrete in the foundation. It is also important to consider the design and the material intensities when considering EC mitigation in residential homes.

5. Discussion on Possible EC Mitigation

In an attempt to minimize EC in the residential sector, it is essential to reduce the EC during the production stage. According to the [46], the global floor area of buildings will be approximately 450 billion m^2 by 2050, yet countries like Australia are committed to net-zero emissions by 2050. This presents a contradiction. The results of the case studies suggest that the use of new material contributes to EC. All the materials used in these case studies are virgin materials. This generated a considerable EC per GFA for a single-story house. When the above residential housing requirements are factored in, this implies a significant EC emission due to the use of virgin materials. As a result, the use of virgin materials should be minimized. To minimize the use of virgin materials, it is essential to introduce the circular economy concept to residential construction, as it strives to keep material in circulation by removing the waste from the process and the demand for material extraction from primary resources [47]. The circular economy principle usually facilitates the reduction of embodied emissions through strategies such as building reuse, design for deconstruction, material reuse, and design for adaptability [47].

Transportation to the site includes a considerable amount of lifecycle EC, which is approximately 5% of the total lifecycle EC. The figures presented in Table 2 considered A1 to A5 including the transportation stage. When calculating the EC using One Click LCA, transport is therefore considered. Further, none of the homes considered sourcing materials from local suppliers closer to the construction. Sourcing materials locally, from a supplier close to the site, can reduce the carbon emissions associated with transportation [48]. In residential unit construction, the builders usually use specific suppliers to purchase commonly used materials in bulk quantities. Further, in the Australian context, the user can choose specific products from different suppliers. For example, clay bricks are a commonly used material. There are several mega-scale brick suppliers within Australia. The builders usually offer the option to select the type of brick (decision on the design and color) to the client (homeowner). In such circumstances, there may be local minor-scale suppliers who are not considered even though they can provide bricks with lower EC due to less transportation distances.

The highest contribution in 'Other structures and materials' came from aluminum windows, and aluminum is one of the most widely and commonly used materials in residential construction (refer to Table 2). The [45] introduced a material pyramid positioning materials with high EC levels at the top of the pyramid. According to the [45], aluminum windows are positioned just below the top in the second tier, illustrating the high GWP. According to [49], the aluminum window manufacturing process (stage A2 of the aluminum window lifecycle) amounts to 11% of its total carbon emissions. Therefore, the researchers suggested applying alternate design options to reduce the carbon footprint of aluminum windows [49]. It may not be possible to avoid using aluminum windows in residential construction in Australia. However, there is the possibility to adopt various design options to reduce the use of aluminum windows and to change the design of aluminum windows to reduce material usage.

The cement industry emits approximately 8% of total global CO_2 emissions. In this research, it was evident that the ready-mixed concrete had the second highest impact on the EC (refer to Table 2). Due to the high carbon-emission intensity, there are various research studies underway around the world to reduce the carbon impacts of concrete. For example, [50], introduced a carbon-conditioned concrete, also known as CO_2 concrete, that uses a carbon-conditioning process to obtain high-quality recycled concrete. This process captures carbon emissions from the environment rather than emitting carbon in the process. This technique is now used by ready-mix concrete manufacturers within Australia. However, it is interesting to note that it is not very popular in residential construction. Also in this research study, the case study buildings used ready-mix concrete with a higher GWP, although there are alternate suppliers with lower GWP. Thus, it is safer to say that although net-zero targets and minimizing EC are buzzwords in the construction industry, residential construction still lags in adopting strategies to minimize the EC. The concrete use in each residential unit is less compared to a mega construction with a concrete structure. However, the significant rise in population and migration patterns suggest that there will be significant numbers of residential constructions happening in the future. Therefore, it is essential to consider concrete with low EC levels if we are to achieve a net-zero target in 2050, irrespective of the quantity used in each construction unit.

When compared with Case Studies A and B, Case Study C has a unique design. It has a lot of designated spaces separated from non-load-bearing internal walls. As a result, there is a high material intensity in this design, which is evident in the results. According to WGBC strategies, 'build clever' is another strategy introduced to reduce the EC [23]. Researchers suggest that this strategy should be introduced to residential construction. In the Australian context, homeowners/clients use ready-made designs provided by the builders. Therefore, this strategy can be introduced to the builders in residential construction.

Issues in the EC Calculation Process

When conducting the EC calculation, researchers faced several issues during the process. The main issue faced by the researchers is the non-availability of the required data. It is difficult to find certain specific materials used in residential construction. As a result, when calculating the EC, researchers had to use the next best-suited product for calculations. For example, when calculating the internal doors, data from the specific supplier were not available. Therefore, researchers used the next best-suited option in the database.

EC calculation is not a standardized process in Australia. Therefore, many suppliers follow 'their own method,' leading to various system boundaries. According to members of the [51], calculating EC is itself a complex task, and the unavailability of specific standards makes calculations less comparable. Currently, the National Australian Built Environment Rating System (NABERS), together with the New South Wales state government, is in the process of developing a framework for measuring, benchmarking, and certifying emissions from construction and building materials [52].

Due to the unavailability of a widely used and accepted standard, it is difficult to compare results. When comparing the results of this study with similar research studies, researchers faced the same issue. Ref. [19] used NLA as the area measurement and TFC with a hybrid approach to calculate EC, providing higher EC values. Further researchers used One Click LCA for calculating EC. There are many databases available that present various formats of data. Depending on the database and tools used in the calculation, there may be discrepancies in the EC results. Accuracy of measurement is another concern when calculating EC. According to [19], it is important to achieve at least 95% accuracy in measurements by abiding by a correct method of measurement. In the Australian context, detached residential houses usually have cost plans rather than detailed Bills of Quantities (BOQ). Converting the quantities of a trade-wise BOQ into materials is easier compared to a cost plan prepared according to an elemental format. This is also a challenging task for a quantity surveyor working on EC calculation.

6. Conclusions

This research presented an EC calculation for three selected case study residential units in Australia. The case studies are single-story residential units. The results of this study identified that higher EC is produced in 'other structures and materials', such as window frames. Further, aluminum windows and ready-mixed concrete were identified as the leading EC-contributing building materials in Australian residential construction. These results suggested the need to focus on the principles of circular economy in residential construction, including the utilization of recycled materials, in order to minimize the use of raw materials. Design optimization was also identified as another key strategy to reduce the use of raw materials, particularly for aluminum window manufacturing, which aligns with achieving circularity in residential construction. Moreover, this study revealed that the impact of concrete on EC is another important aspect to consider in residential construction in Australia. The findings further suggested that although green materials are available in the industry, their uptake is lower in residential construction. This was apparent from the case studies, where the builders tend to use concrete with high EC levels rather than choose more sustainable options. In terms of materials, the quantity of materials required per residential unit is less compared with a multi-story office complex. However, with the growing demand in the population, material consumption will have an upward trend, which will contribute to EC. The results of this study revealed that the early stages of the building lifecycle contribute to the highest EC in Australian residential construction. Therefore, it is essential to focus on EC by considering materials in residential construction. Future studies should investigate avenues for lowering the use of raw materials while using recycled building materials, reducing EC in transportation, and adopting sustainable material manufacturing approaches. A lack of standards and clarity in the EC calculation process is another concern that hinders the EC calculation process. Therefore, it is essential to develop tools for homeowners and builders in the residential sector to easily identify low-cost EC mitigation materials during the initial decision-making process.

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