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Life-Cycle Assessment of Fibre-Reinforced Polymers Dwellings Compared to Traditional Structures

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Abstract: Fibre-reinforced polymers (FRP) have been presented as materials that possess properties that are comparable to conventional building materials, while also being more sustainable. This study describes the material and its properties and compares the materials using a life-cycle assessment (LCA) modelling approach. The objective of this paper is to perform a cradle-to-grave (from resource extraction to the disposal stage) analysis of pultruded FRP material and compare it to conventional building materials used in a typical dwelling. This analysis was conducted in accordance with LCA standard EN15978. A streamlined LCA was conducted, whereby the major impacts observed included the global warming potential in kilograms of carbon dioxide equivalent and the embodied energy in megajoule net calorific value. The products compared with the FRP profiles were the most commonly used materials in a residential dwelling; bricks and timber. The results of the LCA modelling provided a comparative assertion of the FRPs to conventional materials by demonstrating that they perform better than double-brick dwellings and external timber framed walls in both environmental impact categories of global warming potential and embodied energy. The results shows that the FRP-walled house had the lowest emissions of carbon dioxide equivalent, which was around 17% lower than that of the double-brick wall and 1.46% less than that of the timber wall house.

Keywords: life-cycle assessment; fibre-reinforced polymer dwellings; traditional structures; global warming potential; embodied energy

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1. Introduction

The world currently faces major environmental problems such as climate change, ozone layer depletion, resource availability, waste accumulation and water acidification due to anthropogenic activities [1]. The construction sector is a significant contributor to the problem owing to its consumption of resources during the operational phase. In 2010, buildings accounted for 32% of annual final energy use, 19% of energy-related greenhouse gas emissions and a third of black carbon emissions [2].

In response to these findings, various nations have signed multiple sustainability acts with the goal of reducing greenhouse gas emissions released by human activities. Thus, there is greater focus within the building sector on more sustainable products and techniques that can reduce the industry's environmental footprint [3]. The Australian construction sector has seen little or no variation in the materials used in the construction of a typical dwelling. The main materials are still masonry, timber, steel and concrete. In 1993–1994, 87% of new dwellings had outer walls of brick, 67% were double-brick and 20% were single-brick. Only 6% of new dwellings had timber outer walls [4]. As there is a need for change in the materials and processes used, a relatively new material called fibre-reinforced polymer (FRP) has been introduced to the construction industry. It possesses a variety of properties suitable for construction [5].

FRP is a composite material consisting of a polymer matrix reinforced with fibres. The combination of high-strength, high-stiffness structural fibres with low-cost, lightweight, environmentally resistant polymers creates composite materials with mechanical properties and durability superior to either of the constituents alone [5]. The fibres typically utilised include glass, carbon and aramid, with a polymer of epoxy vinyl ester or polyester thermosetting plastic [5]. FRPs offer a combination of properties that are not readily available in conventional materials such as a high strength-to-weight ratio, high impact resistance, high durability, ease of manufacture, high chemical resistance and high sound and thermal insulation [6]. The construction sector has recently increased its usage of these materials in structural applications, due to their high strength-to-weight ratio, ease of handling and installation and low production costs [7]. It is now utilised in many applications such as marine transportation, architectural cladding, aerospace transportation, weapon components, automotive components, energy generation and static structural components [8].

Among the different types of FRP materials, aramid-fibre-reinforced polymers (AFRP), carbon-fibre-reinforced polymers (CFRP) and glass-fibre-reinforced polymers (GFRP) are most predominantly used in the structural engineering field. These structural FRPs have primarily been employed to reinforce new concrete structures, to strengthen existing structures during maintenance and repair, and as building profiles for new structures [9]. The processing and fabrication of FRP can be categorised based on four main methods: pre-impregnated (pregreg), resin infusion/liquid composite moulding, filament winding and pultrusion.

Pultrusion is the preferred manufacturing method for FRPs to fit a wide scope of engineering and structural requirements [10]. The pultrusion process is a highly automated and continuous process whereby the reinforcing fibres are pulled from creels, guided to a resin bath and impregnated and wetted with liquid resin (thermosetting polymer, pigments, fillers catalysts and other additives). The fibres are then pulled through a performer that eliminates the excess resin and shapes the fibres into the desired shape. These preformed fibres then pass through the heated die where the final cross section is determined, and the resin curing occurs. The cured product is then cut to the desired lengths [10]. The major advantages of the pultrusion process are the lower production cost due to the continuous nature of the process, low raw material costs, minimal waste, simple machinery and a high degree of automation. The disadvantages include the limitation to a constant cross-sectional shape, the labour intensity of the initial machinery setup and the majority of reinforcement being orientated in the longitudinal direction [11].

FRPs have many advantages over conventional building materials but have only recently been introduced into the construction sector as a potentially competitive material. However, FRPs do have shortcomings in structural applications. These include the poor ductility of FRP relative to metals, low stiffness in comparison to many traditional/competitive materials, relatively high cost of production and the limited recyclability of the product. A previous disadvantage was the perceived lack of building knowledge for FRPs. FRPs are a relatively new material compared to steel, concrete and timber, and as such, its specifications are less mature than the other materials. There was a lack of standard building specifications and testing methods for FRPs for several decades, leading the construction sector to avoid the use of FRPs in some structural applications [9]. However, with the standardised pultruded profiles and company-provided standards on the designs for FRP materials, this is no longer an issue [12].

The relative cost of FRPs is higher than conventional materials used in construction and there is no real recyclability for FRP products [5]. However, this paper does not focus on the product's costs, but rather on its environmental capabilities and the savings that can be potentially realised with this product. To achieve this, a comprehensive life-cycle assessment is conducted, where the model presents the environmental impacts from all the relevant associated costs. FRPs may provide an environmental solution to reduce carbon emissions and energy generation and increase building lifespan, hence reducing the maintenance costs and need for refurbishment of existing structures.

2. Research Significance

As FRPs are a relatively new material, there is limited information available about the lifetime considerations of buildings comprised solely of FRP material compared to conventional brick and timber houses. To fully investigate FRP's prospective capabilities and potentially recognise FRPs as a feasible building material, a comparison must be made of FRPs and conventional building designs. Such a comparison would usually be conducted through a building life cycle, which provides a highly detailed and comprehensive report. The LCA weighs the inputs of each material and provides an output of global impacts that each design produces throughout the building's life cycle [13]. Some inputs to include during the assessments are the embodied energy costs (energy needed to produce the product and deliver it), transportation costs, human resources and operating costs over the structure's lifetime.

This study aims to complete a feasibility study of FRPs and compare the results to conventional materials such as brick and timber under various scenarios. The findings will help to determine which material is more practical in an average house design. The paper primarily focuses on the impacts each building produces over its lifetime and in different climates. Different climates have varying temperature and humidity levels and require different building methods, such as the R value or the thermal resistance for the external walls necessary for compliance with the Building Codes of Australia.

3. Literature Review

The use of pultruded FRP profiles in bridges has many advantages and long-term benefits. The lightweight properties of FRPs can significantly reduce the dead load of the bridge decking and increase the service life of the bridge. The prefabricated FRP deck panels are light and can be installed very quickly compared to the labour-intensive cast-in-place deck. This reduces weather delays, ensures that high-quality profiles are used and reduces the down time of the bridge [9,14,15].

FRPs are still not the main choice for rehabilitation for a number of reasons. First, the use of FRPs has higher initial outlays for raw materials compared to conventional materials. A lack of design specification inhibits the creation of efficient designs due to unfamiliarity with FRPs. Hence, the materials are perceived to be higher-risk, leading to higher safety factor in the design. This increases costs relative to conventional materials. The volume of FRPs traded in the current market is relatively low. If higher trading volumes can be achieved, economies of scales will increase, leading to lower production costs [15]. With further research, greater market size and the development of design specifications for the standardised pultruded profile, FRPs have the capacity to provide a great alternative to reinforced concrete and steel for structural bridges.

Adopting FRPs in construction could lead to more economic and environmentally friendly housing. The ease of assembly allows for faster construction, which would alleviate the accelerating need for housing in developing countries. There has been limited research on the use of FRP in buildings, hence this research's aim to investigate the environmental feasibility of FRP dwellings. Halliwell [16] demonstrated how the environmental credentials of FRP structures may be assessed using techniques such as life-cycle assessments.

Life-cycle assessments analyse the environmental aspects and impacts of a given product or service throughout a product's life cycle, from raw material acquisition through production, operation, end-of-life treatment, recycling and final disposal [13]. It is one of the most comprehensive analytic approaches available for assessing products. It has been endorsed by the World Summit and the EU Commission due to its more holistic approach to environmental assessments compared to other methods [17]. There are four phases in an LCA study, including the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase [18–20]. The merits of an LCA are numerous and various but the main advantages of an LCA are the identification of areas where there are potential improvements in the environmental performance of a product, the comparison of the environmental impact of two or more products and providing a quick analysis of one product as an alternative to another [21]. LCAs are governed by international standards such as ISO:14044 [22] and EN15978 [23]. These standards dictate the methodology by which an LCA is conducted. The main stages of an LCA are shown in Figure 1.

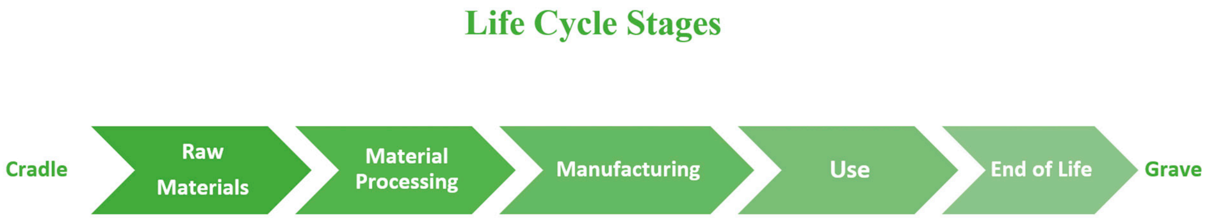


Figure 1. Life cycle stages.

Economic and environmental pressures make it necessary to change the construction industry. From an economic perspective, given more building development and infrastructure is being carried out for a growing population, the cost of repair, maintenance, refurbishing and retrofitting will increase annually; hence, there is a need for a more cost-effective approach.

Environmentally, the building sector is a significant contributor to environmental problems throughout resource mining, manufacturing processes, operational energy expenditure and waste disposal [3]. FRPs can provide a solution to these rising costs and impacts [7]. The material possesses strengths and properties comparable to conventional materials such as timber, brick, concrete and steel components in various applications. With further research, they may become more commonly used in structural applications such as bridges, houses and utility poles.

4. Life-Cycle Assessment Analysis

4.1. Methodology of the LCA

This research conducted an LCA to compare the environmental impacts of a traditionally built average Australian residential house to that of a similar structure with FRP profiles. To undertake the LCA comparison, it was necessary to define the goals and scope of the study based on the ISO14044 [22] international governing standards. The goal was to conduct an environmental assessment of conventional materials used in an average house and compare the house to a similar structure containing FRP profiles. The assessment was in accordance with the European Committee for Standardization (CEN) EN15978 [23] and the Building Codes of Australia. To highlight variations, the study used environmental impacts such as global warming potential and embodied energy to produce an observation. To assist in this comparison, the life-cycle assessment program eTool Life-cycle Design, developed by eTool, was implemented. eTool is a group of LCA engineers located in Australia that have developed an LCA design software that produces comprehensive reports on comparable sustainable building data, using outputs compliant with the international life-cycle assessment standards of ISO14044 [22] and EN15978 [23]. The program is web-based and publicly accessible. It collates data for different types of buildings, considers the main environmental impacts, provides a user-friendly interface and generates thorough reports.

However, in the case of construction works, the predicted design performance of the models was limited by the influence of:

- Occupant behaviour or asset management decisions during the life of the asset. For example, the amount of energy used in the operation cycle may vary due to extreme use of heating, venting and air-conditioning (HVAC) operations and appliances.
- The actual asset lifespan deviating significantly from the estimated value in this assessment on a project-by-project basis. The actual lifespan of the building can vary from the model, as an increase in lifespan will decrease the amount of impacts per occupant per year. This also holds true for the reverse.

- Future changes in background life-cycle inventory (LCI) assumptions intensities, such as electricity primary energy sources and changes in the amount of resources consumed during maintenance, transport, energy and/or water use.

The eTool software presents the performance of the building at a snapshot of time, holding all other variables equal.

4.2. Scope of the LCA

The scope of the LCA is the stage where the system boundary of the model is drawn and the level of detail required by the models is given. At this stage, the study considered the total impact of the product or service over its life from the cradle to grave, and wherever possible, from cradle to grave. In the case of buildings and infrastructure, the inputs were taken from the key life-cycle phases defined in EN15978 [23]. eTool categorised these into 5 main phases: product stage, construction stage, building use, end of life and benefits with loads beyond post end of life. To establish the system boundary, the study must select a functional unit to enable a comparison of any variations between products or services under analysis. For this model, the functional unit was derived from an arbitrary selected house design from a popular Western Australian home designer located in the suburb of Crawley, Perth; Figure 2. The functional unit automatically corrects for any dimensions and the design life of the house. The functional unit selected for the study is the impacts of the house divided by the number of occupants and service life. Therefore, the number of occupants and the design life must be specified, as both will have a significant impact on the functional unit and thus the comparison between the different designs. The number of occupants the study used per house was 2.6 occupants per household [24].

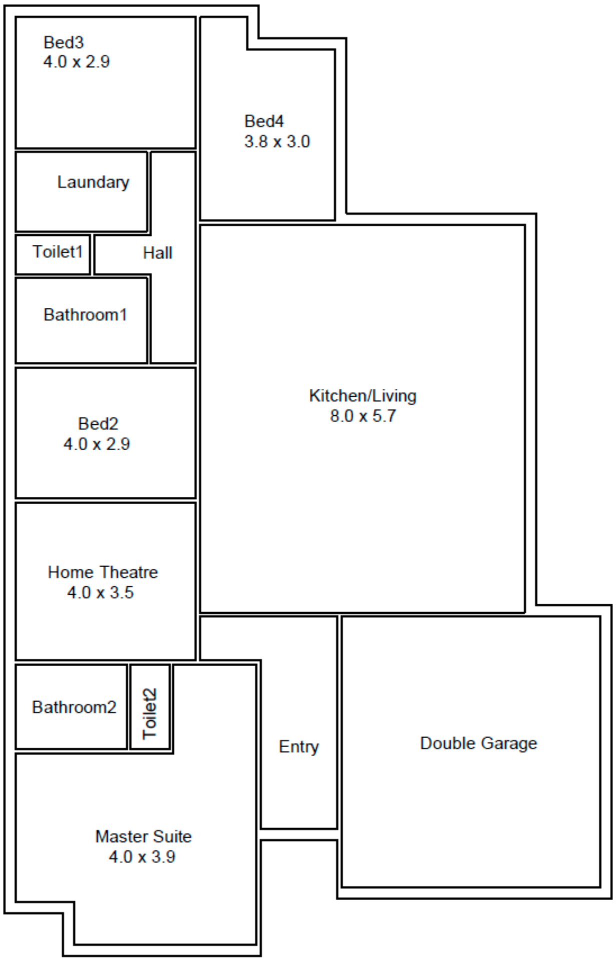


Figure 2. Diagram of house design.

The default lifespan for the average house was 40 years. This value was selected as there seems to be a curve from an eTool research observation that, for a house to last 100 years, it must initially last 30–50 years [25]. The reasons why a house may not exist for a long period may be due to redevelopment, such as the demolition of the building for site suite redevelopment; the dwelling no longer fulfilling the owner's need or the building becoming unserviceable. The value for the service life is not of major significance in itself; rather, the significance stems from consistency of the design life that leads to a more fair and comparable result. Equation (1) is the formula for a functional unit and the floor plan of the house. The function of this structure is to act as a multiple-bedroom family residence.

$$\text{Impact catergory per occupant per year} = \frac{\text{Impact category}}{\text{Occupants } \times \text{Service life}} \tag{1}$$

Another important aspect of the house requiring definition is the services including heating, ventilation, cooling and lighting. The area for heating and cooling was designated as 170 m^2.

The thermal demand was in accordance with the Nationwide House Energy Rating Scheme, where all new houses, by law, must fulfil the requirement of a 6-star building in a specific climate zone. The maximum thermal demand of the house was 70 MJ/m^2 per year or 35 MJ/m^2 for both heating and cooling in Perth, as seen in Table 1.

Table 1. NatHERS-required energy loads for different climate zones.

Climate Zone	Location	Energy Rating (Stars)																			
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**	**10**
13	Perth	483	387	311	251	204	167	139	118	102	89	79	70	61	52	44	34	25	18	9	4

For lighting service, the average run time was an eTool default value of 2500 h per year, which was approximately 6.85 h per day. The brightness or lux level of each light source was set at 150 lumen/m^2. This reflects the required lighting level of a house in accordance with Table 2. Therefore, the final inputs for the function of a house were as shown in Table 3.

Table 2. Illuminance levels.

Activity	Illumination (Lux, Lumen/m^2)
Public areas with dark surroundings	20–50
Simple orientation for short visits	50–100
Working areas where visual tasks are only occasionally performed	100–150
Warehouses, Homes, Theatres, Archives	15
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Office Landscapes	1000
Detailed Drawing Work, Very Detailed Mechanical Works	1500–2000
Performance of visual tasks of low contrast and very small size of prolonged periods of time	2000–5000
Performance of very prolonged and exacting visual tasks	5000–10,000
Performance of very special visual tasks extremely low contract and small size	10,000–20,000

Table 3. Inputs for the function of a house.

Building Function			**Description**	**Function Unit**	**Time Frame**	
Multiple Bedroom Family Residence			**Dwelling**	**Occupant**	**Per Year**	
Name	Dwelling			Services:		
Characteristics:						
Dwelling	1	Mechanical Ventilation	Treated Area (m^2)	Thermal Demand (MJ/m^2/Annum)	Average Run Time (h/year)	Lux (lx)
Bedrooms	4	Cooling	170	35		
Occupants	2.5	Heating	170	35		
Floor Area:		Mechanical Ventilation	170		2500	
Usable Floor Area	191.5 m^2	Lighting	170		2500	150
Fully Enclosed Covered Area	170 m^2			Functional Unit:		
Unenclosed Covered Area	0 m^2	Function	Occupant			
Gross Floor Area	170 m^2	Time Frame	Per Year			

4.3. Life-Cycle Inventory

The next step of the LCA was to compile a life-cycle inventory (LCI). This creates an inventory of the input and output data of the system being studied, which was the building itself. In the assessment, the eToolLCD included all the upstream and downstream processes needed to provide the primary function of the building for construction, maintenance, operation and finally demolition/disposal. The inventory included the extraction of raw materials or energy and the release of substances back to the environment to the point where the inventory item exits the system boundary either during or at the end of the project life cycle. The default materials and energy database for the inputs eTool used were provided by life-cycle strategies and comprised LCI processes from the following sources:

- AusLCI: Primary database where initial process values were obtained.
- Australasian Database: Secondary database utilised for values not obtained in AusLCI.
- EcoInvent: Shadow database utilised for making up the minor flows for the processes in the above data sources.

The inputs selected were building systems that were necessary to the house and provided a significant portion of impacts to the model. It was noted that the inputs eToolLCD used were industry averages. For example, in reality, a specific product is used to construct a wall. However, there may be a discrepancy as the input for this specific product is different from the average owing to a superior method of manufacturing the material. Below are some of the model templates, which contain other material and process templates needed for each building system. A life-cycle inventory list is displayed in Figure 3, whilst a subset nested template for concrete floors is shown in Figure 4.

A comparison was made by changing the materials of the external walls of the house, in order to maintain a consistent and fair comparison between the models. The walls were altered to equate to a thermal resistance (R) value of 3 as per the requirements of the Building Codes of Australia. The project comparison was based on the impact of the amount of inputs (energy, materials and labour) needed to construct a wall with a thermal resistance value of 3. The input values of the building system were based on the house plan shown in Figure 4. Three different wall materials were shown and compared in this assessment, including a double-brick wall, timber frame wall and wall constructed using FRP materials. The double-brick wall used for the model used 90 mm-width bricks separated by a 50 mm cavity. The cavity was filled with polybat insulation to meet requirements. High-density polyethylene coating for waterproofing and aluminium flashings were also included. The embodied energy requirements and CO_2 emissions for this component are included in the eTool database, and these figures were utilised for the model.

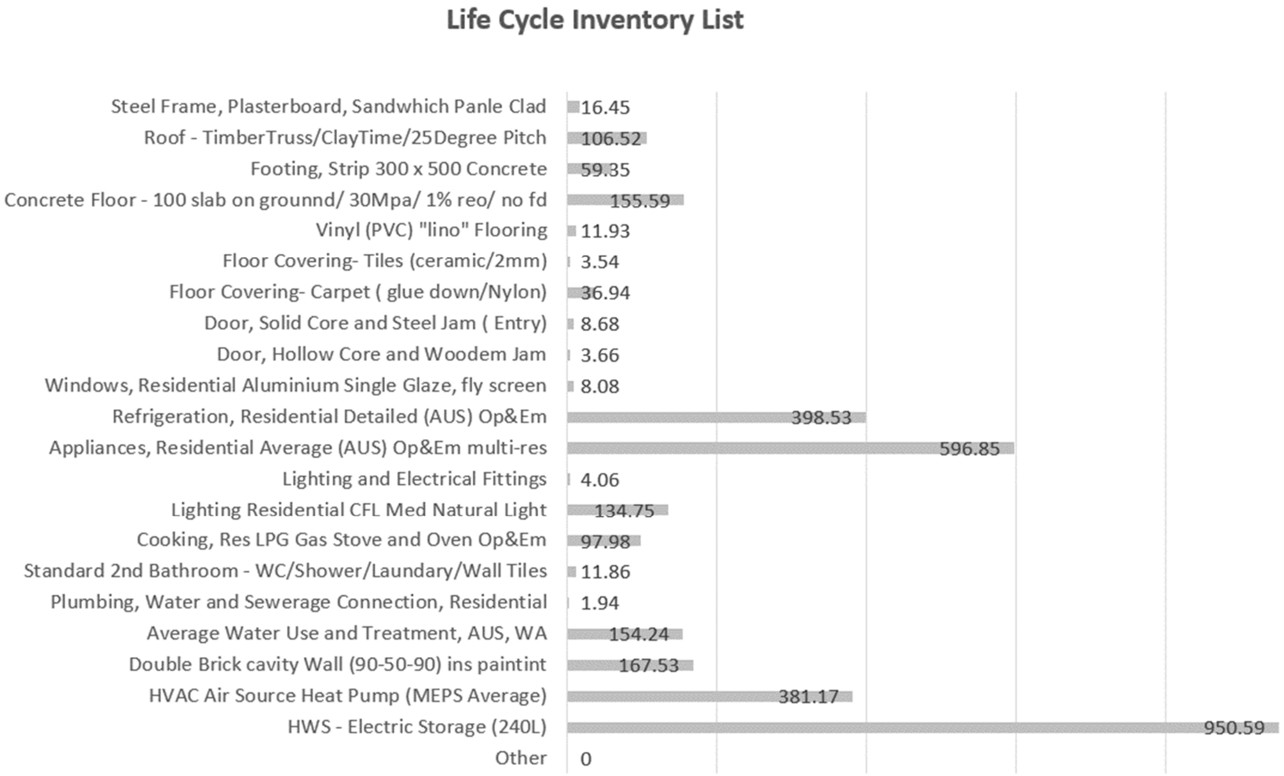


Figure 3. Life-cycle inventory list.

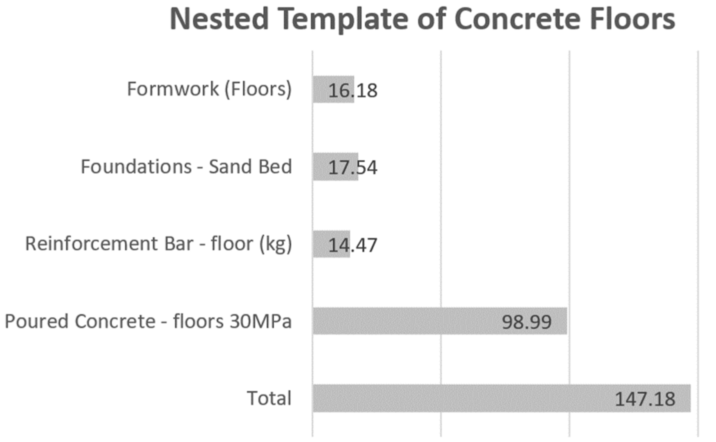


Figure 4. Nested template of concrete floors.

The timber frame wall used in this assessment is made of soft wood timber framing with a fibre cement weatherboard exterior and painted plasterboard internal finish. The wall also has polyester insulation to meet building requirements. The embodied energy requirements and CO_2 emissions of this component are included in the eTool database, and these figures were used for the model.

For the FRP building system, a custom template was created in the program. This was necessary because the eToolLCD did not have a suitable template for FRPs. The fibre glass material in the program did not match the material and process inputs consistent with the FRP product. As a replacement, the research acquired previous life-cycle assessments or environmental product disclosures for FRP products and entered these values. These inputs were the best available data for the study. The data was taken from another life-cycle assessment that focused on FRP material. The FRP material used in this LCA was comparable to the FRP elements used in the external walls of the model. The LCA was prepared by a certified professional and the results are tabulated below. However, the data did not include the recyclability of the product or the differentiation of the energy consumed at different stages of the life cycle.

However, the study needed to convert this into a usable number. Hence, the calculation below was used to convert SAFRAIL FRP (Table 4), a similar product used in the walls of the FRP model, to impact the unit per kilogram of FRP material. The final impacts per kilogram of FRP materials are shown in Table 5.

Table 4. External LCA impact values for 100 linear feet of SAFRAIL FRP.

Environmental Indicator	Unit	SAFRAIL of 100 Linear Feet
Global Warming	kg CO_2 eq	2.063932671
Acidification	H+moles eq	1.290360308
Eutrophication	kg N eq	0.000671859
Ozone Depletion	CFC-11 eq	0.0000000403
Smong	kg Nox eq	0.009176991
Metered Water	kg	15.7654338
Energy	MJ-eq	40.35463631

Table 5. Impact values for 1 kg of FRP material.

Environmental Indicator	Unit	SAFRAIL FRP HANDRAIL-100 Linear Feet-Revision 6-2-09
Global Warming	kg CO_2 eq	280.85583
Acidification	H+moles eq	175.58965
Eutrophication	kg N eq	0.09142527
Ozone Depletion	CFC-11 eq	0.00000548
Smong	kg Nox eq	1.2487866
Metered Water	kg	2145.3287
Energy	MJ-eq	5791.3782

The FRP material used to build the external wall was Strongwell's Durashield composite. The material was a tongue-and-groove fibreglass pultruded panel consisting of a pultruded skin over a foam core. A 3-inch panel was selected to simulate the external wall comprised of FRPs as it provided the sufficient R value of 3. The R value in America employs an imperial system to Australia, where metric R values were used. The properties of the panel are from Strongwell's Durashield composite [26].

The durashield panel used in the construction was manufactured by Strongwell, which is located in Bristol, Virginia, USA [26]. As such, transportation energy requirements and emissions must include both the sea freight from the United States to Australia and land transportation to the construction site. Assuming an approximately 20,700 km sea journey from Portsmouth, Virginia, to the Port of Fremantle in Perth and a 50 km combined land journey based on figures taken from the Australia Institute, Table 6, the embodied energy and emission information can be extrapolated for the durashield panel. The data is shown in Table 7. It is assumed that a rigid truck is used for land transportation.

Table 6. Energy and emission intensity of freight transport modes.

Mode	Energy Intensity (MJ-FFC/tkm)	Emission Intensity (g CO_2-e/tkm)
Road transport		
Light commercial vehicles	21.07	1532
Rigid trucks	2.95	209
Articulated trucks	0.98	71
Rail	-	-
Hire and reward	0.32	24
Ancillary	0.09	6
Coastal shipping	0.17	15
Pipeline	0.89	54

Table 7. Energy and emission costs for different transport modes of durashield panels.

Durashield Panel Transport Mode	Embodied Energy (MJ/kg)	CO_2 Emissions (kg CO_2/kg)
Light Commercial Vehicles	1.0535	0.0766
Rigid Trucks	0.1475	0.01045
Articulated Trucks	0.049	0.00355
Sea Freight	3.519	0.2898

For the construction and lifetime phase, it was assumed that, during the 40-year lifetime of the dwelling, the FRP panels required no maintenance. The operational energy of the dwelling was based on the average water consumption, heating requirements, appliance use etc. of the house over the course of its lifetime. These energy requirements, however, remained constant over the three sample dwellings, as they were to be used for the same purpose. Furthermore, the three walls were constructed to comply with insulation studies. As such, they have similar R-values, meaning that there were no differences based on heating or cooling requirements. For this reason, the operational energy for the modelled dwellings was omitted from the analysis, as they provided no significant change in the results.

Currently, the accepted end-of-life options for FRP products include being sent to landfill or incineration with energy recovery. Although these methods are lower down the waste hierarchy, little or no information is available pertaining to the embodied energy cost and CO_2 emissions for other waste management options such as re-use, material recycling etc. Incineration with energy recovery yields 16.7 kJ/kg of FRP waste material [27].

It is necessary to input information about the emissions and embodied energy data for the durashield panels into eTool. This can be done in two ways. One is to edit an existing template to fit the data of the durashield panel. Editing an existing template is the easier option, but also runs to the risk of compromising the existing data on eTool. In addition, there is potential for leftover information to remain on the template, potentially compromising the results. The alternative option is to create a custom environmental product declaration (EPD). An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impacts of a product. Creating a fresh EPD allows us to custom input all the embodied energy and emissions for the durashield panel. This EPD can then be input into the eTool model for our dwelling, and it calculates the total environmental impact depending on the weight of the product required. The inputted information can be seen in Table 8.

Table 8. EPD data as inputted into eTool.

	Manufacturing	Transport	Construction	End-of-Life Transport	Recovery
Global Warming (kg CO_2-eq)	2.064	0.01407	0.03059	0.01045	-
Embodied Energy (MJ NCV)	40.35	0.19426	0.34362	0.1475	−0.0167

The eTool model exclusions were the same as exclusions in EN15978 [23]. These include impacts related to:

- Transportation of trade-staff during construction and maintenance.
- Operational energy of non-integrated technical loads (appliances, computers and monitors).
- Operational transportation (transportation of occupants to and from the building during the user phase).
- Operational waste exiting the project during its lifespan (paper and food waste) apart from replacement materials during repair, maintenance and replacement refurbishment of construction components.
- Goods and services consumed within the bounds of the project not directly relating to maintenance or operation itself.

Table 9 provides an illustrated view of the exclusions. The following cut-off criteria were used to ensure that all relevant potential environmental impacts were appropriately represented.

Table 9. Chart of system's boundaries used by eTool software.

<table>
<tr><th colspan="5">eTool LCA Normal LCA System Boundary</th></tr>
<tr><td colspan="5">EN 15978 System Boundary</td></tr>
<tr><td rowspan="12">eTool LCA Normal LCA System Boundary</td><td rowspan="12">EN 15978 System Boundary</td><td rowspan="3">Product Stage (A1–A3)</td><td>A1: Raw Materials Extraction</td><td rowspan="3"></td></tr>
<tr><td>A2: Transport</td></tr>
<tr><td>A3: Manufacturing</td></tr>
<tr><td rowspan="2">Construction Stage (A4–A5)</td><td>A4: Transport</td><td rowspan="2">Transport of Construction Labour</td></tr>
<tr><td>A5: Construction & Installation</td></tr>
<tr><td rowspan="7">Use (B1–B7)</td><td>B1: Use</td><td rowspan="7">Operational Energy</td></tr>
<tr><td>B2: Maintenance</td></tr>
<tr><td>B3: Repair</td></tr>
<tr><td>B4: Replacement</td></tr>
<tr><td>B5: Refurbishment</td></tr>
<tr><td>B6: Operational Energy</td></tr>
<tr><td>B7: Operational Water</td></tr>
</table>

Table 9. *Cont.*

eTool LCA Normal LCA System Boundary		
	End of Life (C1–C4)	C1: De-construction/Demolition
		C2: Transport
		C3: Waste Processing
		C4: Disposal
	Benefits and Loads Beyond the Building Life Cycle (D)	Reuse
		Recovery
		Recycling
		Exported Energy

Mass and energy flows—if a flow was less than 1% of the respective category at either a product level or individual-process level, it was excluded. The sum of the neglected material flows should not exceed 5% of total mass, energy or environmental relevance, at a product level or individual-process level. In the interest of time, this study focused on the bare necessities of a house with the largest impacts.

4.4. Life-Cycle Impact Assessment

At the impact assessment stage, this study selected the environmental indicators or impacts associated with the studies. These included climate change, embodied energy, ozone depletion, acidification potential, eutrophication potential, mineral and fossil depletion, water use and human toxicity (Table 10). The primary focus of the study was on global warming potential and the embodied energy required for the construction processes owing to:

- Climate change impacts resulting in adverse effects on the earth due to the release of greenhouse gases into the atmosphere. This was measured in mass of carbon dioxide equivalent. eTool used a software system called CML-IA baseline V4.5 to quantify global warming potential. The program contains a database with characterisation factors for all of the baseline characterisation methods mentioned in the handbook on LCA. All substances were multiplied by a factor that reflected their relative contribution to the environmental impact, thus quantifying the impact of a product or service on each category. To ensure a fair comparison, the different greenhouse gases were characterised to carbon-dioxide-equivalent effects (kg CO_2 equiv).
- Embodied energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery. The combustion of fuels led to the generation of greenhouse gases, which was relevant to the goal of this study. This indicator was also calculated using the CML-IA baseline V4.5. It was measured in mega joule net calorific value (MJ, NCV), where the energy required through the combustion of various fuels were characterised to allow a better comparison.

4.5. Benchmark Checks

eToolLCD uses established benchmarks in the software to create common measurements against which all projects are assessed. This makes it possible to compare any project to another and creates a starting point, or "average, business as usual case" from which to measure improvements. The benchmark used in eTool was an average dwelling built in a developed country [27]. The benchmark dwelling took statistics from a range of developed countries, population-weighted and combined into a single theoretical average dwelling. The data are regularly updated wherever possible to ensure reliability.

Table 10. The list of reported environmental indicators from the LCA standards EN15978 [23].

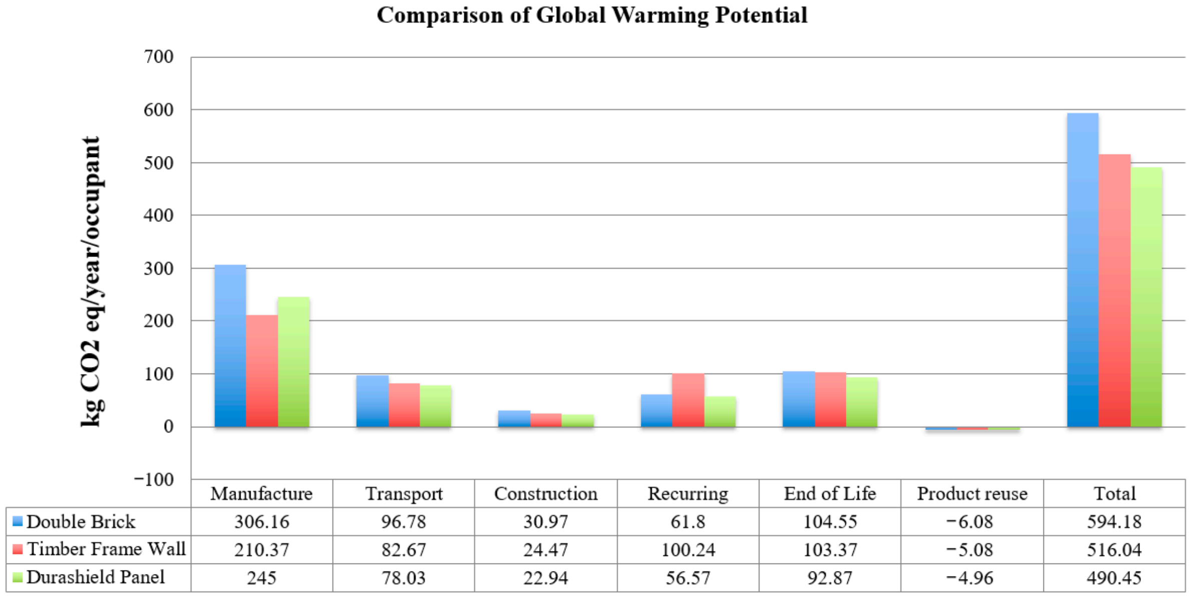
	Indicator	Unit
Impact Assessment	Global warming potential, GWP	kg CO_2 equiv
	Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv
	Acidification potential of land and water, AP	kg SO_2 equiv
	Eutrophication potential, EP	kg $(PO_4)_3$ equiv
	Formation potential of tropospheric ozone photochemical oxidants, POCP	kg Ethene equiv
	Abiotic Resource Depletion Potential for fossil fuels, ADP_fossil fuels	kg Sb equiv
	Abiotic Resource Depletion Potential for elements, ADP_elements	kg Sb equiv
Resource Use	Use of renewable primary energy excluding resources used as raw material	MJ, net calorific value
	Use of renewable primary energy resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy excluding resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
	Use of secondary material	kg
	Use of renewable secondary fuels	MJ
	Use of non-renewable secondary fuels	MJ
	Net use of fresh water	m^3
Waste	Hazardous waste disposed	kg
	Non-hazardous waste disposed	kg
	Radioactive waste disposed	kg
Output Flows	Components for re-use	kg
	Materials for recycling	kg
	Materials for energy recovery (not being waste incineration)	kg
	Exported energy	MJ for each energy carrier

5. Results and Discussion

5.1. Global Warming Potential Results

Figure 5 shows that the FRP-walled house had the lowest emissions of kilograms of carbon dioxide equivalent. The emission released by the FRPs was around 17% lower than the double-brick wall and 1.46% less than the timber wall house.

The largest amount of carbon dioxide was generated in the manufacturing stage of the life-cycle assessment (LCA), where the double-brick wall generated the highest volume of emissions. FRPs produced approximately 50 kg less than double brick, while timber produced the least, at 209.68 kg CO_2 equivalent. During the transportation stage, the double-brick house had the highest emissions of kilograms of carbon dioxide, followed by the timber walls. The FRP walls produced the lowest emissions. During the construction stage, the FRP released the highest emissions, closely followed by the double wall and the timber wall. In the recurring phase, the timber released the highest emissions, followed by the double-brick walls. The Durashield wall required the lowest maintenance. The FRP had the lowest emissions, followed by the timber walls, at the end-of-life stage.

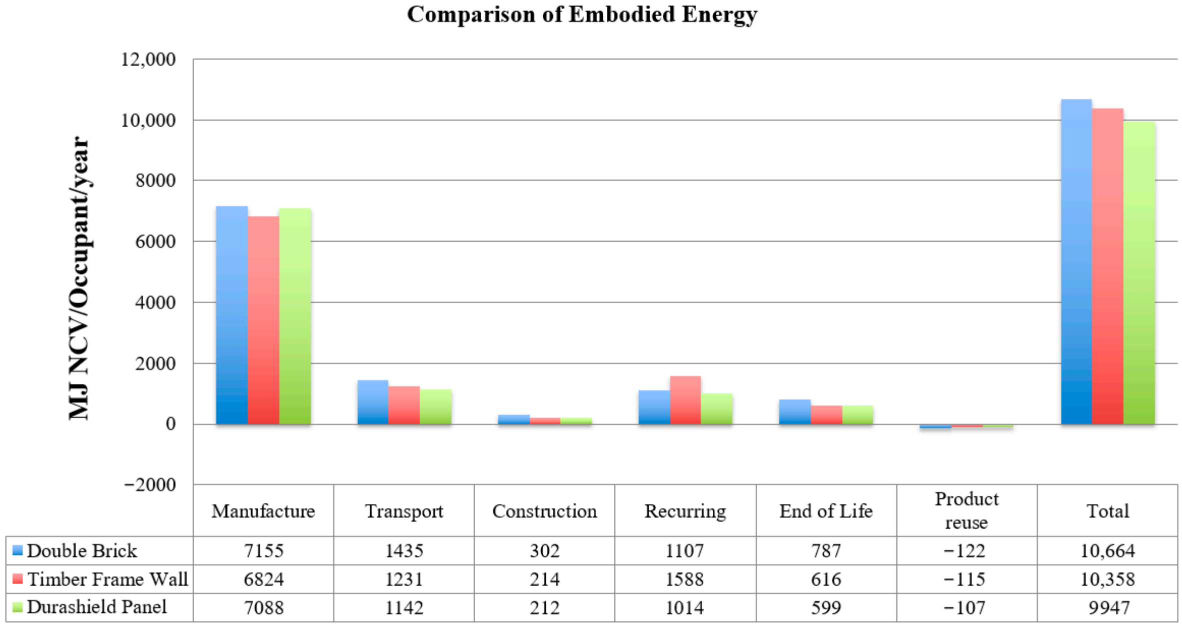


	Manufacture	Transport	Construction	Recurring	End of Life	Product reuse	Total
🟦 Double Brick	306.16	96.78	30.97	61.8	104.55	−6.08	594.18
🟥 Timber Frame Wall	210.37	82.67	24.47	100.24	103.37	−5.08	516.04
🟩 Durashield Panel	245	78.03	22.94	56.57	92.87	−4.96	490.45

Figure 5. The global warming potential comparisons of CO_2 released from different life-cycle phases.

5.2. Embodied Energy Results

Figure 6 shows that the FRP walls consumed the least amount of energy in the life cycle. However, variations in the energy consumed by the different wall materials were miniscule. The difference between the double brick and FRPs was 3.4%, while the difference between the timber walls and the FRP walls was less than 1%.



	Manufacture	Transport	Construction	Recurring	End of Life	Product reuse	Total
🟦 Double Brick	7155	1435	302	1107	787	−122	10,664
🟥 Timber Frame Wall	6824	1231	214	1588	616	−115	10,358
🟩 Durashield Panel	7088	1142	212	1014	599	−107	9947

Figure 6. Comparison of embodied energy.

During the manufacturing stage, the FRP product consumed the most energy. This result was closely followed by the double brick, whilst timber consumed the least energy in the production process. The transportation of bricks required the most amount of energy, followed by timber and FRPs. The observation made in the construction cycle was that the FRP product consumed the highest amount of energy, the double brick consumed a smaller amount of energy than FRP and timber consumed the least amount of energy during the construction stage. In the recurring phase of the life cycle, timber walls consumed the largest amount of energy by a significant amount of 481 MJ NCV, compared with the double brick. FRPs consumed the least energy in the recurring phase. At the end of the life stage, the difference in energy required to dispose of the materials was insignificant. However, the double-brick walls still required the largest amount of energy for disposal, followed by timber and then FRPs.

5.3. Implications of the Results

Based on the overall outputs of the graphs, the FRP product was the most sustainable material in comparison to the double-brick and timber walls. These results show that FRPs were more sustainable than the conventional materials of brick and timber when assessed for environmental indicators of global warming potential and embodied energy. The implication of these results is to increase the incentives for parties such as construction firms and governments to place greater focus on sustainability and provide more impetus for further research and development of FRPs. This would allow lower-cost FRPs and a reduction in conventional brick and mortar structures.

5.4. Manufacturing Cycle

During the manufacturing stage, the material's global warming potential was less than that of brick by a substantial amount. This was contrary to expectations, as the FRP construction process was originally thought to have a greater impact than conventional materials such as brick and timber. Hence, the finding that FRPs produce less impact during the manufacturing process will place greater importance on FRP materials and increase recognition of their sustainability. The embodied energy consumed in the manufacturing cycle was expected due to the high costs of setting up and starting the pultrusion process.

5.5. Transport Phase

The FRPs possessed a comparative advantage over the conventional materials as, the results show that the FRPs outperformed brick and timber. This implied that the FRPs can be transported at a faster rate than the other materials, allowing for more rapid build times due to their prefabricated state. This can benefit developing countries experiencing high demand for housing.

5.6. Construction Phase

An unexpected result showed that the FRP walls had the highest values of all of the materials during the construction phase, with timber walls recording the lowest. This result was not expected, most likely because in the model, heavy machinery was included for the FRPs. In reality, such heavy machinery would not be utilised as FRPs are lightweight and simple to construct solely through labour. The removal of the heavy machinery would have significantly lowered the impact and increased the accuracy of the results.

5.7. Recurring Costs

The observed values for the recurring costs of the three materials were in line with the predicted results. The maintenance cost of timber was highest, and that of FRPs was the lowest. This implied that the maintenance needed for FRP profiles was significantly less than that for either timber or double brick. Therefore, where FRPs are employed in long-lifespan structures, maintenance costs will be significantly lower than for other conventional materials. This also applies to houses. The longer an FRP dwelling exists, the lower the functional unit will become over time, constantly improving the amount of impact. The reduction in the costs associated with structural aging can lead to significant savings in corporate and government expenditure. These savings can then be diverted to more studies or research.

5.8. End-of-Life Costs

The FRPs' end-of-life costs were the lowest in both impact categories. This was due to the non-existent recycling process for the material. In reality, the FRP elements would simply be dismantled and transferred to plastic waste fill, implying ease of dismantling, transportation and disposal of FRPs. However, this is not ideal as resources are finite. Given the durability of FRPs, instead of disposing of these elements after their initial use, they could be repurposed into another structure where compatible with the house design.

5.9. Model Accuracy

However, certain areas of the model require improvement. The model utilised in the life-cycle assessment possessed a great consistency of factors across the different materials. However, the model was limited as the house design uses different construction methods for each respective material. As the basis of the house structure was a double-brick design, the mandatory substructure of a double-brick design was applied to the timber and FRP designs used in the theoretical models. This would not be the case in reality, as timber and FRP designs may not require the same substructure. If such a variable was accounted for in the modelling, the results may have been more accurate.

The lifespan of the materials was another variable that restricted the model. The lifespan of the material affects the functional unit of the house design. In the modelling, the lifespan of the buildings was kept consistent with a value of 40 years, but in reality, the materials have different lifespans. Based on these different values, the functional unit of the models would have been greatly affected, increasing the accuracy of the models. The environmental impact per occupant per year would differ in a longer-lifespan material compared to a shorter-lifespan material. This is because the initial impacts would be spread out over the material's lifespan.

The accuracy of the model would have been significantly increased if the impact data for the input of the FRP material was given for each stage of the life cycles. From the external LCA input, the emissions were normalised to a functional unit and all temporal characteristics which were needed to assess local environmental impacts were lost. The modelling of the impacts was also conducted using a different model to eTool. eTool employs a different characterisation calculation to project its impact, but greater accuracy could have been achieved had the external LCA used similar characterisation models.

6. Conclusions

This study compared fibre-reinforced polymers to conventional brick and timber materials to conduct a comparison of their respective environmental impacts. A life-cycle assessment was undertaken to provide a holistic and comprehensive comparison between the different construction materials. This was done by employing the life-cycle assessment program eTool to model the environmental feasibility of FRP materials compared to brick and timber. eTool is a software package whose modelling adheres to the EN15978 life-cycle assessment standard, lending reliability to the findings.

- The comparison conducted was based on the global warming potential released and the embodied energy consumed by each of the materials. The model utilised was set up as accurately as possible. However, certain values had to be extrapolated due to limited and possibly subpar information being used as inputs.
- Overall, the model evaluated FRPs to have the lowest overall global warming potential over their entire life cycle. FRPs also consumed the least amount of energy in their life-cycle stages. Hence, these two indicators show that FRPs are the most sustainable material of the three investigated.
- It must be stressed that the comparison was undertaken purely to investigate environmental and sustainability factors rather than cost.
- The FRPs released the highest emissions during the construction stage, closely followed by the double wall and the timber wall.
- The timber released the highest emissions in the recurring phase, followed by the double-brick walls.

- The results of this study provide an extra incentive for additional research. This would assist in reducing the construction sector's footprint, and thus reduce or reverse the effects of anthropogenic climate change.

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