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Embodied emissions of hempcrete wall systems in residential buildings: A comparative case study from Australia

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Abstract: In Australia, embodied greenhouse gas emissions associated with the extraction, production, transportation, and disposal of building materials accounted for 16% of building-related emissions in 2019 and are projected to rise to 85% by 2050 as operational emissions decline. This shift underscores the urgent need to decarbonise material lifecycles. Among various biobased alternatives, hempcrete has drawn growing interest for its renewable, carbon-sequestering properties and thermal performance benefits. However, limited empirical studies have quantified its embodied emissions performance under real-world conditions. This study aims to evaluate and compare the embodied emissions performance of hempcrete external walls against two common wall systems (brick veneer and lightweight steel cladding) by using a process-based life cycle assessment. A real-world case study of a single-storey dwelling in Narara Ecovillage, New South Wales, was used to quantify cradle-to-grave emissions across production, transport, construction, use, and end-of-life stages. Results show that the hempcrete wall system emitted 49.57 t CO_2e, 19.9% lower than brick veneer (61.81 t CO_2e) and 92.5% lower than lightweight steel cladding (927.34 t CO_2e). The dominant source of emissions was long-distance material transport, although substantial carbon sequestration occurred during manufacture (growing), construction and use stages. The comparative analysis highlights the potential of hempcrete in reducing embodied emissions, especially when paired with local sourcing and prefabrication strategies. This study contributes to evidence-based decision-making in low-carbon residential design and supports the inclusion of biobased materials in Australia's decarbonisation efforts.

Keywords: Hempcrete wall; embodied emissions; life cycle assessment; residential buildings.

1. Introduction

The global building sector is responsible for approximately 28% of total greenhouse gas (GHG) emissions and 38% of energy-related emissions (United Nations Environment Programme and Yale Center for Ecosystems + Architecture, 2023). In Australia, the construction industry accounts for around 18.1% of national GHG emissions (Yu et al., 2017). With the national population projected to exceed 30 million by 2030 and 46 million by 2050 (from 27.4 million in 2024), growing demand for housing and urban infrastructure is placing increased pressure on the environment (Australian Bureau of Statistics, 2018). In response, federal and state governments have invested heavily in reducing energy consumption and emissions through initiatives such as energy-efficient technologies, rooftop solar incentives, and net-zero building policies. However, most of the policy and technological efforts have focused on reducing operational energy (OE), but the embodied energy used in the extraction, production, transportation, and construction of building materials throughout the building life cycle has received less attention. As buildings become increasingly efficient in their operations, the share of embodied

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emissions will increase. In Australia, embodied emissions accounted for 16% of total building emissions in 2019 and is projected to increase to 85% by 2050 under a business-as-usual scenario (Vickers et al., 2021).

To reduce embodied emissions, current Australian practice often adopts lightweight construction materials, such as timber framing with plasterboard or insulated steel frames. Although these building materials offer lower embodied emissions, they are frequently associated with reduced thermal comfort, increased energy use for heating and cooling, higher maintenance needs, and energy-intensive manufacturing processes (Lu et al., 2017). This trade-off highlights a key challenge: how to achieve both low embodied emissions and high functional performance in buildings. Hempcrete is an alternative building material which may meet these challenges since it is a biobased material composed of hemp shiv (the woody core of the hemp plant), lime binder, water, and occasionally sand, as shown in Figure 1 (Essaghouri et al., 2023).

Figure 1: Composition and mixing process of hempcrete materials. (source: Authors)

1.1. Hempcrete benefits and challenges

Compared with conventional building materials, hempcrete masonry has demonstrated multiple benefits, such as excellent thermal insulation, moisture regulation, vapour permeability, and acoustic and fire resistance. Its low thermal conductivity (0.06-0.08 W/m·K) contributes to reduced heating and cooling demand by maintaining stable indoor temperatures (HempToday, 2021). Laboratory studies have also shown that its compressive strength (typically 0.2-3.5 MPa) is adequate for use as a non-load bearing wall material (Carbon Futures, 2024). From an environmental perspective, it can support carbon sequestration during cultivation and curing, due to the rapid growth rate and low-input requirements of industrial hemp. Many studies indicate that hempcrete can offset part of its embodied emissions through biobased carbon storage across its life cycle (Arrigoni et al., 2017, Arehart et al., 2020). In addition, hempcrete's natural texture and vapour-permeable properties offer architectural design opportunities such as exposed wall finishes. Its thermal inertia also makes it suitable for temperate and warm Australia climates, although careful detailing may be needed in regions with high rainfall and cyclonic conditions to ensure durability (Carbon Futures, 2024). However, hemp has not been adopted widely in construction markets, perhaps due to public misconceptions around marijuana, despite industrial hemp containing less than 0.3% Tetra-Hydrocannabinol (THC) and legally distinguished from marijuana under both Commonwealth and state legislation in Australia. Therefore, the Australian Hemp Council, established in 2020, continues to advocate for policy support and market development. Despite these advantages and advocacy, the Australian hemp industry remains nascent.

1.2. Study objectives

Academic research on hempcrete in Australia has primarily centred on its thermal comfort and vapor control characteristics, with limited studies addressing its embodied emissions reduction potential (Arrigoni et al., 2017). Significantly, there is a lack of empirical evidence comparing hempcrete to conventional Australian construction systems such as brick veneer and lightweight steel-framed structures, which is a popular construction in high fire risk areas.

This study addresses this gap by evaluating an as-built residential building in Australia using a hempcrete wall and comparing its environmental performance to common wall material alternatives with the specific objectives to:

- Identify embodied emissions boundary across the building's life cycle,

- Quantify the embodied emissions of a residential case study using hempcrete, brick veneer, and lightweight steel-framed wall systems,
- Compare and evaluate the embodied emissions across these systems to determine the potential of hempcrete as a low-emissions building solution.

By quantifying and comparing the embodied carbon emissions of hempcrete with conventional building systems, this research aims to provide actionable insights for architects, builders, and policymakers. The findings will support the integration of hempcrete into mainstream construction and contribute to the adoption of biobased materials within Australia's evolving regulatory frameworks for sustainable development.

2. Methodology

To date, three major methods are commonly used to calculate embodied emissions: bottom-up process-based LCA (Process LCA), top-down input-output LCA (IO-LCA), and hybrid LCA, which combines the two (GBCA and thinkstep-anz, 2021, Vickers et al., 2021). Given the research aim and the dwelling-scale focus, this study adopts a bottom-up, process-based life cycle assessment (LCA) method to quantify and compare the embodied emissions of different wall systems. The process-based LCA was selected for its ability to provide detailed and component-specific insights, making it suitable for comparative analysis across distinct construction systems. This method integrates standardised calculation procedures with context-specific case study inputs, ensuring transparency, consistency, and practical relevance. Figure 2 illustrates the overall research steps.

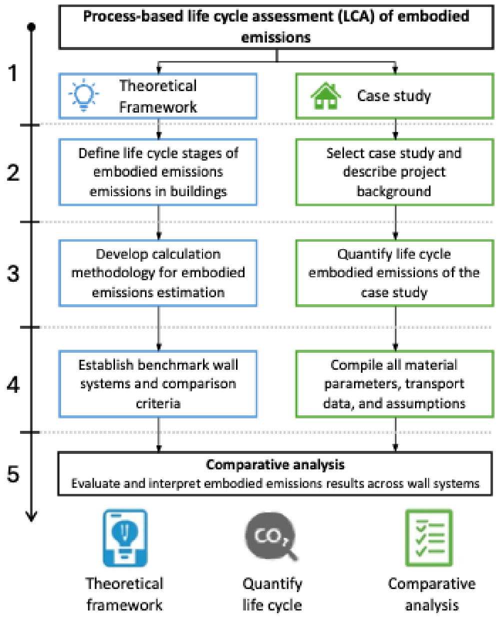

Figure 2: Structured process-based LCA framework for embodied emissions evaluation.

2.1. Establishing embodied emissions scope

The scope of this study covers the full life cycle embodied emissions of the hempcrete wall system and is aligned with the modular structure of EN 15978, as shown in Figure 3. To suit the practical constraints of this research, some modules were aggregated, but all relevant life cycle phases are included. Specifically:

- Product stage (A1-A3): Includes raw material supply (A1), transport to processing facilities (A2), and manufacturing of lime binder and hemp shiv processing (A3). Hemp cultivation sequesters CO_2, while lime production emits CO_2 through limestone calcination.
- Construction Stage (A4–A5): Covers transport of materials to site (A4) and construction/installation emissions (A5). Hempcrete continues to absorb CO_2 during curing, and excess hempcrete can be reused during construction.
- Use Stage (B1): Includes direct CO_2 absorption through ongoing carbonation during building use. Maintenance, repair, and operational energy/water (B2–B7) are excluded due to their negligible contribution to wall system emissions in this case study.

- End-of-Life Stage (C1–C4): Covers demolition (C1), transport of waste (C2), waste processing (C3), and final disposal (C4).
- Beyond the Life Cycle (Module D): Accounts for environmental benefits from recycling and natural degradation of hempcrete components, resulting in negative emissions credits.
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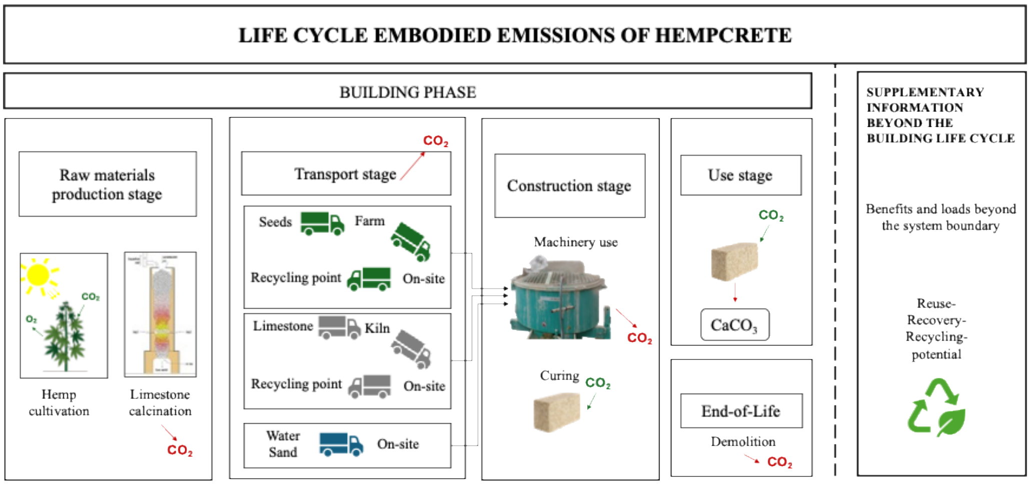

Figure 3: Life cycle embodied carbon emission processes of hempcrete (source: Authors)

2.2. Determining calculation method

This section outlines the specific calculation approach applied to quantify the embodied carbon emissions at each life cycle stage, which refers to GBCA and thinkstep-anz (2021). The equations below reflect a modular breakdown aligned with the system boundaries defined in Section 2.1.

2.2.1. Estimate equations

Production stage (A1-4, and C2)

$$C_p = \sum_{i=0}^{i=n}\left(m_{building,i} \times f_{material,i}\right) \quad (1)$$

$$C_t = \sum_{i=0}^{i=n}\left(m_{building,i} \times f_{mat,transport}\right) \quad (2)$$

Construction, use, and end of life stages (A5, B1, C1, and C3)

$$C_c = \sum_{i=0}^{i=n}\left(\left(f_{area} \times \mathrm{A}\right) + m_{c,waste,i} \times \left(f_{mat,transport} + f_{material,i} + f_{waste,transport} + f_{waste,i}\right)\right) - C_{c,c} \quad (3)$$

Beyond the building life cycle stage (D)

$$C_e = \sum_{i=0}^{i=n}\left(\frac{1}{4} m_{building,i} \times \left(f_{waste,i} + f_{waste,transport}\right)\right) \quad (4)$$

Where:

- C_p = the amount of embodied emissions in the production stage
- i = building wall material, where n=(0,1,2) for each wall type
- $m_{building,i}$= mass of material (i) used in the construction of buildings
- $C_{p,c}$ = carbon sequestration during the hemp growing period in the production stage
- $f_{material,i}$= emission factor of material (i) production
- C_t= the amount of embodied emissions in the transport stage
- $f_{mat,i,transport}$= emission factor of transporting material (i)
- C_c= the amount of embodied emissions in the construction, use and end of life stages
- f_{area}= emission factor of the construction of a building per area constructed (t CO_2e/m^2 constructed)
- A= area of wall constructed (m^2)
- $m_{c,waste,i}$= mass of construction waste of material (i) (kg)

- $f_{waste,i,transport}$= emission factor of transporting waste of wall material (i) from the building site to the end-of-life or recycling location
- $f_{waste,i}$= emission factor of the waste processing and landfilling of material (i) (where applicable)
- $C_{c,c}$= carbon sequestration during the hempcrete curing period
- C_e= the amount of embodied emissions in the beyond the building life cycle stage
- 1/4= used as it is assumed that currently for every four buildings constructed in Australia, one is demolished.

This modular structure ensures accurate attribution of emissions to each stage and facilitates comparison between systems.

2.2.2. Building materials identification

To determine the embodied emission impacts of hempcrete, this study utilise the external wall structure of a case study to compare two traditional and popular construction assemblies in Australia: brick veneer and lightweight cladding on steel frame, as shown in Table 1. Internal timber and steel are modelled as load-bearing part, and brick, fibre cement cladding, and hempcrete serve as non-structural enclosure elements. Additionally, the study adopted a flexed wall thickness of 300mm based on the actual design of the case study building, although some studies use equivalent R-values to standardize thermal performance for comparison. One of the main reasons is that the same R-value as a 300 mm hempcrete wall may require unreasonably thick walls for other systems, which cannot reflect real-world construction practice on wall thickness. However, to maintain this fixed thickness and standardized comparison, some compromises were made in initial material proportions. The detailed layer structure and thickness of the three comparative external wall systems are presented Figure 4. The thicknesses of all components are based on reasonable assumptions. Overall, this standardized and unified external wall structure ensures consistency in evaluating and comparing embodied emissions across all systems.

Table 1: Comparative building structure and basic components.

Wall system	Brick veneer on timber frame	Lightweight cladding on a steel frame	Hempcrete
Components	• Clay bricks • Mortar • Timber • Plasterboard	• Fibre cement • Timber • Steel • Plasterboard	• External lime render • Timber • Hemp shiv • Lime binder • Water • Internal lime render

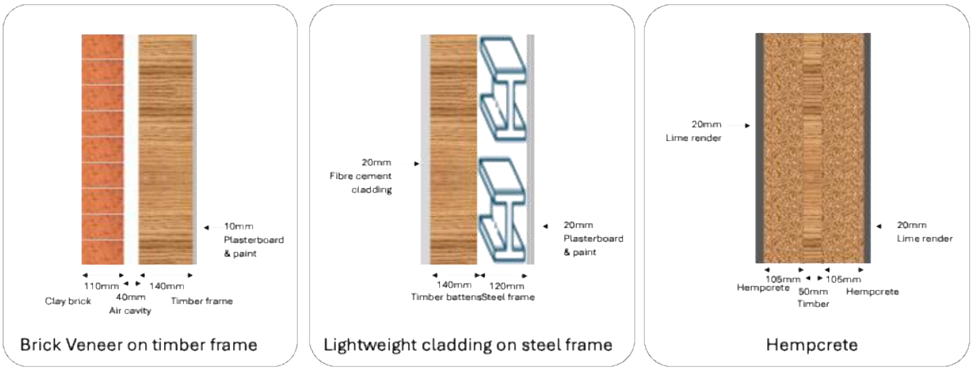

Figure 4: Key components of external non-bearing wall systems (brick veneer, lightweight cladding, and hempcrete). (source: Authors)

2.3. Case study

2.3.1. Case information

This case study examines a completed residential house located in the Narara Ecovillage in New South Wales (NSW), Australia. The house was designed and built with a focus on sustainability, incorporating passive solar design, renewable energy integration, and biobased construction materials. The dwelling is a split-level single-storey home with a veranda and carport. In this study, only the external wall system is adopted for the comparison, as only this part is constructed using in-situ cast hempcrete. Other structural and internal components are excluded from analysis. Figure 5 presents the 3D views of the northeast and southwest elevations of the building, showcasing the full extent of the hempcrete walls. Figure 6 provides the building's floor plan, wall segment measurements, and calculated wall areas. The gross external wall area is 118.00 m², and after deducting windows and doors (19.69 m²), the net hempcrete wall area assessed is 98.31 m².

Figure 5: Exterior views of the case study building from northeastern and northwestern perspectives. (source: Authors)

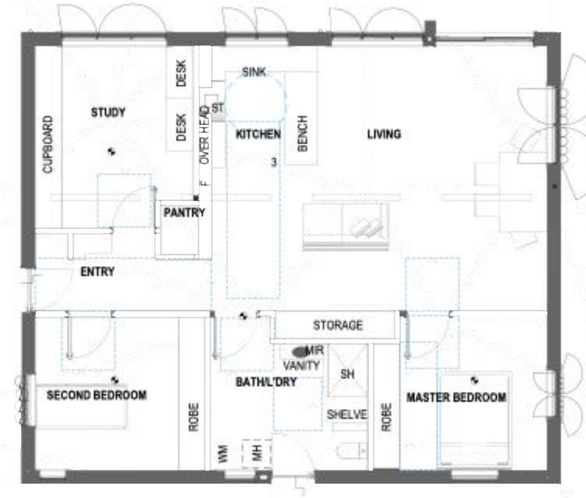

Figure 6: Floor plan and external wall area data of the case study building. (source: Authors)

Table 2: External wall dimensions (including windows and doors) of the hempcrete house in Narara Ecovillage.

Item	Detail	Length	Height	Are
		m	m	m2
External Hemp Walls	N edge	12.2	2.7	32.
	S edge	12.2	2.7	32.
	N edge	9.65	2.7	26.
	S edge	9.65	2.7	26.
Ext Windows/Doors	W1	2.4	1.2	2.8
	W2	1.45	1.2	1.7
	W3	2.11	0.772	1.6
	D1	2.238	2.1	4.6
	W4	1.8	0.772	1.3
	W5	1.1	1.1	1.2
	W6	1.09	0.6	0.6
	D2	1	2.1	2.1
	W7	0.61	2.1	1.2
	D3	1	2.1	2.1
Actual areas (less doors & windows)				98.

2.3.2. Data collection

The life cycle embodied emissions data of the hempcrete wall system is obtained based on the dwelling case at Narara Ecovillage, as shown in Figure 7, which presents emissions at each stage of the life cycle of hempcrete, in particular:

- The hemp cultivation sequestration was estimated based on UK field data, given the lack of peer-reviewed Australian field studies (Vosper, 2021). High-yield hemp grown in the UK can sequester 1.37 kg CO_2 per kg of hemp stem (Vosper, 2021). Since hemp shiv accounts for roughly 60% of the stem's dry weight, this equates to 2.28 kg of carbon dioxide sequestered per kg of hemp shiv.
- The main areas where hemp is grown and trialled in NSW include Northern Rivers Region, Riverina Region, Central West NSW, and Hunter Valley (NSW Department of Primary Industries, 2013). Based on proximity principles, the hemp would usually be sourced from Muswellbrook, NSW, approximately 176 km from the site.
- Mix ratios for 1m³ of hempcrete were based on Hempcrete Australia's product specifications (Hempcrete Australia Pty Ltd, 2013), using 100 kg hemp shiv, 250 kg lime binder, and 325 kg water. Some builders use another 200 kg of washed river sand to strengthen the mix.

- Transport emissions were calculated using national averages for fuel use and diesel emission factors from the 2024 National Greenhouse Accounts Factors (Department of Climate Change, 2024).
- There are assumed to be no emissions during the construction and demolition due to the use of on-site renewable solar energy and community battery at Narara Ecovillage.

In comparison, two selected wall systems (brick veneer and lightweight cladding) were modelled using equivalent life cycle data, as shown in Table 3.

- **Brick Veneer**: Emissions were based on the Environmental Performance in Construction (EPiC) Database for clay brick production, with a 25% reuse/recycling rate. Transport and waste handling distances were based on typical NSW manufacturers (Brickworks and Steel Builders, NSW).
- **Lightweight cladding**: Data for steel and cement render components were sourced from Jai Kant Pandit et al. (2020) and Cement Industry Federation (2022), respectively. The emission factor for steel production was used alongside standard transport and demolition data in Table 2.
- Both external wall systems include plasterboard as interior lining, and data is from (Laveglia et al., 2023).
- Some data such as material densities, fuel use, component ratios, and transport distances to drop points, were the same across systems based on the actual case study.

Overall, the collective data set provides a transparent, reliable, and replicable framework for comparing wall systems in Australia's low-rise residential construction.

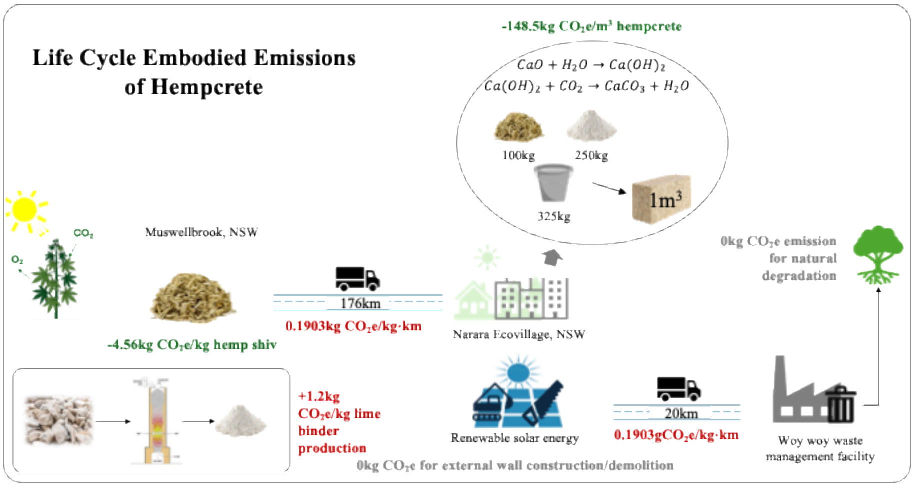

Figure 7: Life cycle embodied emissions estimate per unit of hempcrete. (source: Authors)

Table 3: Comparative building structure and emission factors.

Life cycle stage	Brick veneer	Lightweight cladding	Hempcrete
Production	Clay brick: 0.39 kg CO_2e/kg (EPiC Database) Timber: -1.6 kg CO_2e/kg (Essaghouri et al., 2023) Plasterboard: 1.12 kg CO_2e/kg	Steel: 1.83 kg CO_2e/kg (Jai Kant Pandit et al., 2020) Cement render: 0.791 kg CO_2e/kg (Cement Industry Federation, 2022) Timber: -1.6 kg CO_2e/kg (Essaghouri et al., 2023) Plasterboard: 1.12 kg CO_2e/kg	Hemp shiv: -4.56 kg CO_2e/kg (Vosper, 2021) Lime binder: 1.2 kg CO_2e/kg (Laveglia et al., 2023) Timber: -1.6 kg CO_2e/kg (Essaghouri et al., 2023)
Transport (Diesel Truck)	Truck: 28.6 L/100km (Australian Bureau of Statistics, 2020)		
	Energy content factor: 38.6 GJ/kL (Department of Climate Change, 2024)		
	Emission factor: 17.3 kg CO_2e/GJ (Department of Climate Change, 2024)		
	Distance from construction site to waste disposal point: 20 km (Google map)		
	150 km (Brickworks, NSW)	121 km (Steel Builders, NSW)	176 km (Muswellbrook, NSW)

Construction and demolition	Clay brick: 2,000 kg/m^3 (DGI, 2025), Timber: 500 kg/m^3	Steel: 7,850 kg/m^3 (Australian Building Codes Board, 2022)	1 m^3 of hempcrete consists of: • 100 kg of hemp shiv • 250 kg lime binder • 325 kg of water (Hempcrete Australia Pty Ltd, 2013) Carbon sequestration of hempcrete: 148.5kg CO_2e/m^3
End of life	25% reusable or recyclable (bricks reused/crushed for fill)	Steel is fully recyclable, saves 75% energy compared to virgin production	Fully biodegradable (0 kg CO_2 from natural degradation)

3. Results and Discussion

Figure 8 presents the life cycle embodied emissions of the hempcrete external wall across five life cycle stages. The materials transportation stage is the most emissions-intensive, reaching 51.04 t CO_2e due to the 176 km haul of hemp shiv and lime binder from Muswellbrook to Narara Ecovillage. In contrast, the waste transportation stage only emits 6.29 t CO_2e, reflecting the much shorter 20 km distance to the disposal site. Significantly, the construction and use stage shows a net-negative emission of –7.51 t CO_2e, highlighting the carbon sequestration potential of hempcrete during curing and usage. Additionally, the village's renewable energy reduced reliance on fossil fuel-based construction equipment. Although hemp and timber cultivation absorb CO_2, the production stage still contributes 3.56 t CO_2e, primarily from lime binder and render. The recycling/reuse stage offsets approximately 3.80 t CO_2e, mainly through the reuse of lime render and the biodegradable nature of hempcrete. Overall, the main opportunity for reducing total emissions lies in minimising transportation-related emissions. This may be addressed by having more hemp growers and processing hubs or shifting to electric vehicles. Construction time could be dramatically reduced with the use of prefabrication, such as hempcrete panels.

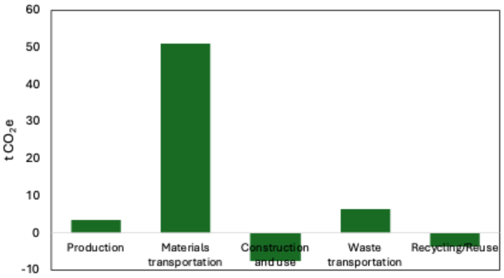

Figure 8: Embodied emissions of hempcrete external wall, by life cycle stage.

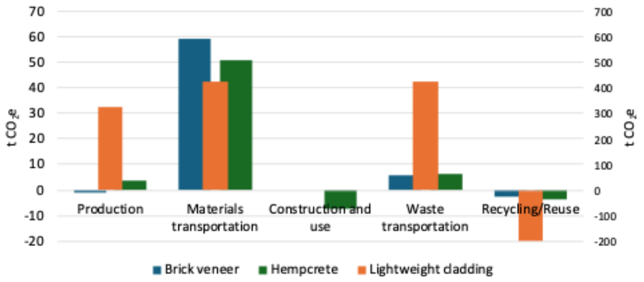

Figure 9: Comparative life cycle embodied emissions of external walls, by life cycle stage.

Error! Reference source not found. illustrates the differences in embodied emissions between the three wall s ystems. Lightweight cladding shows a disproportionately high total emission (927.34 t CO_2e), largely driven by the intensive use of steel and associated transport and demolition emissions. Although steel materials are high-emission, they can be reused effectively. It was found that three quarters of the emissions is offset, and passed to the next dwelling. In contrast, brick veneer and hempcrete have comparable total emissions (61.81 t and 49.57 t CO_2e, respectively), but both are distinctive. Significantly, brick veneer achieved zero emissions in the production stage due to the combined carbon effects of clay bricks (lower carbon emission) and timber framing (higher carbon storage). However, it still performs less favourably in transportation and waste stages. As green building materials, the hempcrete wall demonstrates substantial sequestration benefits during the construction and use stages due to the CO_2 sequestration of hempcrete and lime carbonation. It also performs well in the end-of-life stage due to its biodegradability and reuse potential. Overall, it was suggested that combining hempcrete with timber can be a promising pathway to achieving net-zero emissions in the production stage, but local cultivation and prefabrication are needed to reduce the overall footprint.

Figure 10 compares the total embodied emissions of the three external wall systems. It was found that the hempcrete system outperforms both alternatives in terms of embodied emissions, emitting only 49.57t CO_2e, compared to 61.81 t CO_2e for brick veneer and significantly higher 927.34 t CO_2e for lightweight cladding (steel structure). It indicates a 92.5% reduction in emissions when lightweight cladding is replaced by hempcrete and a 19.9% reduction when substituting brick veneer with hempcrete. Such differences demonstrate the substantial emissions-saving potential of adopting hempcrete in mainstream construction. An assumption to convert just 10 lightweight-clad houses to hempcrete can save over 8700 t CO_2e. In addition, the biodegradable and recyclable end-of-life characteristics of hempcrete support circular economy goals in Australia. The use of equal wall thickness confirms that the observed emissions savings are attributable to differences in material characteristics and life cycle performance, rather than structural simplification or reduced material volume. Combined with local sourcing, electric transport, and prefabrication methods, hempcrete offers a transformative opportunity for net-zero construction and climate-resilient building practices.

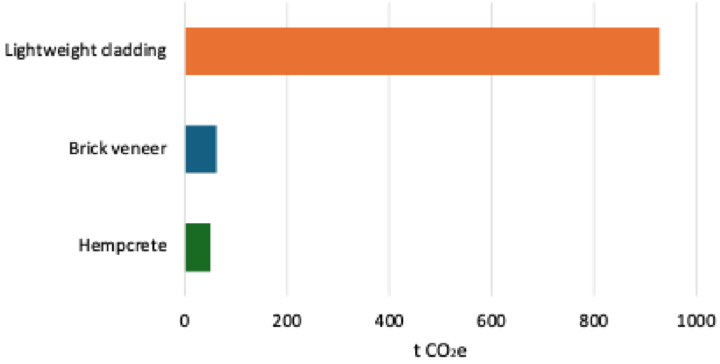

Figure 10: Comparison of total embodied emissions of three external wall systems.

4. Limitations and future directions

Broader hempcrete environmental impacts remain partially unexplored, particularly regarding operational emissions. Since thermal insulation directly affects heating and cooling demands, the exclusion of operational performance limits the holistic assessment of hempcrete's environmental performance. Future research should incorporate operational energy data from case studies to evaluate full life cycle environmental impacts. Research should also consider reducing hempcrete embodied emissions by 1) reducing the render thickness, 2) adopting a low-emissions binder such as one that is unfired, or 3) using organically grown hemp without fertilisers or pesticides.

Another limitation is the scope of the case study. The analysis is based on a single residential dwelling with a simple structural layout, one mix ratio and hemp grown and processed locally, which restricts the generalisability of the findings. Although this study contributes to the growing body of empirical hempcrete research in Australia, future studies should include diverse building types such as apartments, commercial offices, and public facilities to improve relevance to national construction practices. Additionally, the current research focuses solely on external wall systems, overlooking other critical components such as roofing and flooring, which also play a significant role in overall embodied emissions performance.

In addition, the study employed a process-based LCA method, which can suffer from system boundary truncation and data omission (such as capital goods, services). A hybrid LCA approach may be more suitable for capturing both direct and indirect emissions in future analyses. Addressing these limitations will help refine hempcrete's role within sustainable construction frameworks and support its broader implementation across Australia's built environment.

Lastly, future work can explore integration with innovative construction approaches, such as a laminated timber walling and roof CNC cut kit that can take several biogenic materials including hempcrete, light straw and earth. It is currently being prototyped at Narara Ecovillage in Australia, and projects to significantly reduce construction time, improve quality control, and further minimise emissions through prefabrication.

5. Conclusion

This study conducted a streamlined life cycle assessment (LCA) to evaluate the embodied emissions of hempcrete external walls in comparison with conventional brick veneer and lightweight cladding systems in

Australian residential construction. Drawing on a real-world case study at Narara Ecovillage, the results demonstrate that hempcrete offers substantial emissions reduction benefits, achieving a 92.5% decrease in total embodied emissions compared to a lightweight steel wall and a 19.9% reduction relative to a brick veneer wall. Although material transport emerged as the dominant emission contributor, hempcrete's carbon sequestration during curing and biodegradable end-of-life properties significantly offset its embodied emissions footprint. Despite its promising performance, the study also highlighted key limitations, including reliance on a single dwelling case, exclusion of operational energy, and the use of a process-based LCA method subject to truncation errors. Nonetheless, the findings support hempcrete as a viable low-emissions alternative in external wall systems and reinforce the importance of integrating local sourcing, electric transport, and prefabrication to further reduce emissions. Future research should expand to diverse building typologies and incorporate whole-of-life emissions, including thermal performance and operational emissions, to inform Australia's transition toward net-zero and climate-resilient building practices.

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