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Material Circularity on Modular Wall Panel Designs

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Abstract

This study investigates the material circularity of modular wall panel designs using bamboo, wood, and light-gauge steel (LGS) as primary components. Through a comparative analysis of 9 representative panel prototypes, the research evaluates embodied energy (EE), recycling efficiency, and percentage of discarded material under a cradle-to-gate perspective to assess environmental performance. The study examines the relative circularity performance of bamboo, wood, and steel-framed panels. Furthermore, the research examined material configurations that best balance structural function and circularity. Key limitations include the modest sample size (9 prototypes), the educational provenance of prototypes (course-based fabrication), reliance on cradle-to-gate accounting rather than full life-cycle cost or in-service performance data, and uncertainty ranges in embodied-energy databases. Results indicate that biologically composed panels, such as bamboo and wood, demonstrate significantly lower EE and negligible discarded waste, aligning well with circular economy principles. These caveats are discussed and used to frame recommendations for further LCA, long-term performance testing, and scaled prototyping.

Keywords: *Circular economy; Embodied energy; Modular architecture; Recycling; Upcycling*

Introduction

The global construction industry faces escalating challenges from excessive resource consumption and waste generation—both physical (Alazmi et al., 2025) and embodied—under the linear "take-make-dispose" model, which views waste as disposable (Alnafrah et al., 2025) and exacerbates ecological crises, unsustainable resource use, landfill dependency, and greater climate impacts than circular alternatives (Gasparri et al., 2023; Horn et al., 2025; Musa et al., 2014; Shahidi Hamedani et al., 2025; Tukker et al., 2023). Despite unrelenting development demands, an urgent shift to a circular economy is essential for sustainability (Dewagoda et al., 2024; Garusinghe et al., 2023; Pacheco et al., 2024). This paradigm prioritizes resource efficiency through strategies such as reuse, repair, refurbishment, and recycling, thereby minimizing virgin material extraction and waste generation (Garusinghe et al., 2023).

Accordingly, innovations like modular building systems are increasingly integrating CE principles to minimize waste and enhance resource efficiency (Ali-Gombe et al., 2025; Z. Li et al., 2024; Panda et al., 2025; Parracho et al., 2025), exemplified by standard 2x2 m Modular Wall Panel prototypes exploring distinct materials: wood, light-gauge steel, and bamboo (Attia et al., 2024; Kashem et al., 2024; Lima et al., 2024; Panda et al., 2025).

This study evaluates how these prototypes' material aspects and production processes (Haq & Alam, 2023) align with key CE principles —maintainability, upgradability, reusability, recyclability, extended lifespans, and repairability—as formulated by the Ellen MacArthur Foundation (Gasparri et al., 2023; Gong & Whelton, 2019). This framework emphasizes a departure from traditional linear economic models, advocating efficient resource utilization across all lifecycle stages to maintain consumption within regenerative technological and biological cycles (Ali-Gombe et al., 2025).

Literature Review

Various principles have been utilized in numerous cases to effectively implement the concept of a circular economy. The first principle is to eliminate/reduce material waste (Bond et al., 2025) and pollution (Bano et al., 2025) from the outset, which requires that the design of these modular panels avoid the use of toxic (Moustafa et al., 2025) or difficult-to-separate composite material (Attia et al., 2024). The second principle emphasizes the importance of keeping products and materials in use for as long as possible (Joustra et al., 2021). Extending the service life from 50 to 150 years in a circular economy can improve annual sustainability performance by up to 20% (Chen et al., 2024), indicating that these panels must be designed as service assets that can be dismantled, moved, and reconfigured repeatedly. This approach aligns with the core tenets of the circular economy, which seek to decouple economic growth from resource consumption by keeping materials in use for as long as possible (Gasparri et al., 2023).

Table 1. Circularity Overview of Panel Material

Material	Character	Renew ability	Circularity strategy	Circularity Feature (CF) (%)	Embodied energy (EE): Mj/kg	Embodied Carbon (EC): kgC/kg
Light Gauge Steel (LGS)	Technical (5)	No (5)	Collected for recycling (5)	98 (2)	39.00 (3)*	0.7680 (3)*
Rebar Steel	Technical (5)	No (5)	High durability, energy-intensive to recycle (5)	71 (1)	36.40 (3)**	0.7300 (3)**
Solid wood of light red meranti	Biological (6)	Yes (6)	Direct reuse, repair and refurbishment, cascading and remanufacturing (6)	100 (6)	8.50 (3)	0.1250 (3)
Bambu apus	Biological (7)	Yes (7)	Recycle and upcycle, biodegradable (7)	100 (7)	6.00 (4)	0.2500 (4)

Source: (Lima et al., 2024) (1); (Sansom & Meijer, 2022) (2); (Hammond & Jones, 2008) (3); (Das et al., 2025) (4); (Sansom & Meijer, 2022) (5); (Li et al., 2024) (6); (Abdullah et al., 2017) (7)

*EE & EC for galvanized steel

**EE & EC for steel rod

In some cases, several principles have been applied to implement the circular economy concept, driven by urgent challenges in the construction sector. The industry consumes around 50% of the global extracted materials and is projected to double its resource use to 90 billion tonnes annually by 2050 amid rapid urbanization, which will raise the urban population to 70% (adding 2.5 billion people) and demand approximately 96,000 new affordable housing units daily (Cervantes Puma et al., 2025; Fishman et al., 2024; Ouda & Haggag, 2024; Shahidi Hamedani et al., 2025; Tukker et al., 2023). (Despite this pressure, construction remains the least efficient sector, with stagnant productivity gains (Parisi & Donyavi, 2024; Shahidi Hamedani et al., 2025).

Methodology

Modular Designs of Wall Panels

This study uses a descriptive qualitative method with a comparative analysis approach to examine the variety of modular panel designs. The primary datasets consist of over 30 modular wall panels produced as coursework by students in the Undergraduate Architecture Program at Universitas Islam Indonesia. To avoid conflicts of interest, fabrication, and analytic responsibilities, the research team performed these tasks independently of student grading processes.

The research presented here involved a purposeful selection of nine representative panel prototypes, each measuring 2x2 meters to reflect variation in frame materials (LGS, wood, bamboo) and connection methods. The analysis was conducted using a cradle-to-gate product life cycle framework based on circular economy principles, rather than a full life-cycle assessment that includes costs or in-service performance data.

Data collection was conducted through detailed design specification studies and process simulations for each panel prototype, following established methodologies in circular economy assessments for modular construction(Attia et al., 2024; Haq & Alam, 2023; Smitha et al., 2025). Initial analysis included sourcing to identify each material's origin, renewability status (biological vs. technical cycles), and finite resource dependency, drawing on material passports and embodied energy databases for traceability and quantification of environmental impact (Smitha et al., 2025; Tukker et al., 2023).

Table 2. Material properties of frame and filling

Material	Width (m)	Thickness (m)	Cross Section (m2)	Density (kg/m3)
Light Gauge Steel (LGS)	0.1200	0.0007	0.000084	7850 (2)
Rebar Steel	0.0050	0.0050	0.000020	7850 (2)
Solid wood (SW) 2 x 3 cm	0.0200	0.0300	0.000942	435 (3)
Solid wood (SW) 1.5 x 7 cm	0.0700	0.0150	0.005890	435 (3)
Solid wood (SW) 1.5 x 5 cm	0.0500	0.0150	0.004006	436 (3)
Solid wood (SW) 3.5 x 7.5 cm	0.0750	0.0350	0.002625	435 (3)
Bamboo Ø 10 cm	0.1000	0.0100	0.001492	600 (1)
Bamboo Ø 8 cm	0.0800	0.0080	0.000955	600 (1)
Bamboo Ø 6 cm	0.0600	0.0070	0.000621	600 (1)
Bamboo Ø 5 cm	0.0500	0.0065	0.000477	600 (1)
Bamboo Ø 4 cm	0.0400	0.0060	0.000349	600 (1)

Source: (Abdullah et al., 2017) (1); (Sansom & Meijer, 2022) (2); (Li et al., 2024) (3);

Data Analysis

Data synthesis and comparative evaluation followed a hybrid approach inspired by Building Circularity Calculation, incorporating Material Passport and Material Flow Analysis principles. For each prototype, material weights (W), relative masses, embodied energy (EE), circularity features, and lifespans were compiled into tables. Total embodied energy (EEt) was computed as $\sum (EE \times W)$, and recycling potential (RM) as $\sum (CF \times W)$. Lifespan-adjusted metrics enabled scoring circularity performance, identifying configurations that balance structural integrity and low waste/EE, such as higher biological-content panels. This quantitative framework provided a comparative understanding of advantages (e.g., bamboo's low EE, high biodegradability) and disadvantages (e.g., steel's high EE but recyclability) across variants.

Result and Discussion

This study involved the fabrication of over 30 modular wall panels, each featuring diverse combinations of frame and filler materials. Three primary framing materials were used: bamboo, light-gauge steel (LGS), and solid wood. From each framing category, three representative panel prototypes were selected for detailed analysis.

To facilitate identification and comparison, each panel was labeled using abbreviations derived from its constituent materials **Lg** for Light-Gauge Steel, **Rb** for Reinforced Bar (Rebar Steel), **W** for Solid Wood, **B** for Bamboo. Accordingly, panels with bamboo frames were designated as **BBLg**, **BBRb**, and **BWLg**. Panels framed with light gauge steel were labeled **LgLgB**, **LgLgRb**, and **LgLgW**. Panels with wooden frames were named **WBRb**, **WWLg**, and **WWRb**.

Figure 1. Bamboo Framed Wall Panels
Source: Author

The Bamboo Framed Wall Panels are constructed from bamboo, a renewable, biological material. It is known for its biodegradability, low embodied energy, and high circularity potential. The bamboo-framed panels are designed to be recyclable and upcycled, aligning with circular-economy strategies. These panels can be dismantled, reused, and reconfigured, which supports extended service life and sustainability.

Figure 2. LGS Framed Wall Panels
Source: Author

LGS Framed Wall Panels presents a modular wall panel system constructed using Light Gauge Steel (LGS) as the primary framing material. This figure is part of a comparative analysis of modular panel designs in the context of the circular economy and sustainability. The LGS panels are designed to be collected for recycling. Although LGS is not biodegradable, it has a high recyclability rate—up to 98% according to Table 1. However, recycling LGS is energy-intensive, with an embodied energy (EE) of 39.00 MJ/kg and embodied carbon (EC) of 0.7680 kgC/kg, which are significantly higher than those of bamboo or wood. These panels are intended to be dismantled and reused, supporting modularity and adaptability. However, due to the nature of steel, they are better suited to technical cycles than to biological ones.

Figure 3. Wood Framed Wall Panels
Source: Author

Wood-Framed Wall Panels showcase modular wall panels constructed with solid wood as the primary framing material. This figure is part of a comparative analysis of modular panel systems designed with circular economy principles in mind. The wood used in these panels is solid, specifically light red meranti, a renewable, biological material. Wood has lower embodied energy (EE) and embodied carbon (EC) than steel, making it an environmentally favorable choice.

According to Table 1, solid wood has an embodied energy of 8.50 MJ/kg and an embodied carbon of 0.1250 kgC/kg, which are significantly lower than those of LGS or rebar steel. Wood panels are designed for direct reuse, repair, refurbishment, cascading, and remanufacturing, aligning well with circular economy strategies. Their design supports disassembly and reconfiguration, thereby extending service life and promoting material circularity.

Panels with wooden frames include wood frame with rebar and bamboo filler (WWRb), Wood frame with LGS filler (WWLg), and Wood frame with rebar filler (WWRb). Each variant combines wood with other materials to explore different structural and environmental performance outcomes.

Table 3 provides a comprehensive overview of the volumes and weights of materials used in various modular wall panels. This data reveals how different material combinations influence the overall mass of each panel type. Among the heaviest panels is BWLg, which weighs approximately 92.52 kg. This panel uses a bamboo frame combined with substantial amounts of solid wood and light-gauge steel. The high weight is primarily due to the extensive use of solid wood profiles, particularly the 1.5 × 5 cm and 1.5 × 7 cm sections, which contribute significantly to the panel's mass. Similarly, Panel WWRb is notably heavy, weighing around 50.93 kg, due to a wood frame and dense filler materials, including rebar steel and solid wood.

In contrast, the lightest panels include Panel LgLgRb and Panel BBRb. Panel BBRb, with a bamboo frame and minimal steel components, weighs only 18.67 kg, highlighting bamboo's lightweight, renewable qualities. Panel LgLgB, which combines a light-gauge steel frame with bamboo filler, weighs approximately 19.84 kg. Despite the use of steel, the bamboo filler helps keep the overall weight low.

Material selection plays a crucial role in determining panel weight. Bamboo, being lightweight and biodegradable, is ideal for reducing mass while maintaining structural integrity. Solid wood offers moderate density and is environmentally favorable due to its renewability, but its use in large quantities increases panel weight. Light gauge steel (LGS), although strong and recyclable, has a high density, meaning even small volumes can significantly raise the panel's weight. Rebar steel, used sparingly, is extremely dense and adds noticeable weight even in small amounts.

From a design perspective, panels that incorporate mixed materials—such as bamboo with wood or steel—strike a balance between strength, sustainability, and ease of handling.

Table 3. Material Volumes and Weights

Panel	Material	Cross Section (m2)	QoP	Total Long (m)	Volume (m^3)	Density (kg/m^3)	Weight (kg)
BBLg	Bamboo Ø 10 cm	0.001492	4	8.00	0.0119	600	7.16
	Bamboo Ø 8 cm	0.000955	33	29.17	0.0279	600	16.72
	Light Gauge Steel (LGS)	0.000084	50	39.45	0.0033	7850	26.01
BBRb	Bamboo Ø 10 cm	0.001492	18	19.28	0.0288	600	17.26
	Bamboo Ø 8 cm	0.000955	20	1.40	0.0013	600	0.80
	Rebar Steel	0.000020	2	3.92	0.0001	7850	0.60
BWLg	Bamboo Ø 10 cm	0.001492	4	8.00	0.0119	600	7.16
	Solid wood 3.5 x 7.5 cm	0.002625	6	9.10	0.0239	435	10.39
	Solid wood 1.5 x 7 cm	0.005890	48	7.20	0.0424	435	18.45
	Solid wood 1.5 x 5 cm	0.004006	51	28.35	0.1136	436	49.51
	Light Gauge Steel (LGS)	0.000084	14	10.63	0.0009	7850	7.01
LgLgB	Light Gauge Steel (LGS)	0.000084	10	17.45	0.0015	7850	11.51
	Bamboo Ø 5 cm	0.000477	82	29.09	0.0139	600	8.33
LgLgRb	Light Gauge Steel (LGS)	0.000084	9	18.62	0.0016	7850	12.28
	Rebar Steel	0.000020	26	24.03	0.0005	7850	3.70
LgLgW	Light Gauge Steel (LGS)	0.000084	7	19.71	0.0017	7850	13.00
	Solid wood 3.5 x 7.5 cm	0.002625	26	17.06	0.0448	435	19.48
WBRb	Solid wood 3.5 x 7.5 cm	0.002625	6	11.79	0.0309	435	13.46
	Bamboo Ø 8 cm	0.000955	1	0.99	0.0009	600	0.57
	Bamboo Ø 6 cm	0.000621	2	0.68	0.0004	600	0.25
	Bamboo Ø 5 cm	0.000477	4	11.69	0.0056	600	3.35
	Bamboo Ø 4 cm	0.000349	2	13.42	0.0047	600	2.81
	Rebar Steel	0.000020	22	11.68	0.0002	7850	1.80
WWLg	Solid wood 3.5 x 7.5 cm	0.002625	6	15.63	0.0410	435	17.84
	Light Gauge Steel (LGS)	0.000084	12	14.31	0.0012	7850	9.44
WWRb	Solid wood 3.5 x 7.5 cm	0.002625	6	20.29	0.0533	435	23.17
	Solid wood 2 x 3 cm	0.000942	108	64.02	0.0603	435	26.25
	Rebar Steel	0.000020	24	9.80	0.0002	7850	1.51

Source: Authors

Heavier panels may offer greater durability but are less efficient for transport and installation. Lighter panels, on the other hand, are more adaptable and suitable for modular construction systems that prioritize flexibility and environmental performance.

This study examines the environmental performance of modular wall panels through a circular-economy lens, focusing on embodied energy (EE), material recyclability, and waste minimization. Table 5 presents a comparative analysis of ten panel types, each constructed with varying combinations of biological and technical materials.

The results indicate that material composition significantly influences both the environmental impact and recycling efficiency. Panels incorporating light-gauge steel (LGS), such as BBLg, BWLg, and LgLgB, exhibit the highest total embodied energy, with BBLg reaching 1157.79 MJ. This is attributed to LGS's high EE of 39 MJ/kg, despite its 98% recyclability rate.

Conversely, panels dominated by biological materials—notably BBRb and WBRb, which use bamboo and wood—demonstrate substantially lower EE values of 130.38 MJ and 221.82 MJ, respectively. According to Table 4 in the document, bamboo in the BBLg panel accounts for 47.86% of the total mass and has no discarded material, indicating full recyclability. Its embodied energy is significantly lower than that of steel, making it an environmentally favorable choice.

In terms of recycling efficiency, most panels perform exceptionally well, with rates exceeding 98%. BWLg, for instance, achieves a recycling efficiency of 99.85%, with only 0.15% of its mass discarded. This is notable given its mixed composition of bamboo, wood, and steel. BBRb, composed almost entirely of bamboo and minimal rebar steel, also maintains a high efficiency of 99.06%, with negligible waste. On the other hand, LgLgRb, which combines LGS and rebar steel, records the lowest recycling efficiency at 91.74%, and the highest discarded material percentage of 8.26%, highlighting the challenges of managing technical materials with high energy requirements and lower circularity potential.

The data further reinforces the advantages of biological materials in sustainable design. Bamboo and wood not only contribute to lower embodied energy but also result in zero discarded material, making them ideal for circular construction strategies. Panels such as WWRb and WWLg, which rely heavily on wood, maintain EE values below 520 MJ while achieving recycling efficiencies above 99%.

These findings underscore the importance of strategic material selection in modular architecture. Panels that integrate renewable, biodegradable materials with minimal technical components offer superior environmental performance. While technical materials like steel provide structural benefits, their inclusion must be carefully balanced to avoid compromising sustainability goals. Ultimately, the study demonstrates that designing for circularity—through material choice and disassembly potential—can significantly reduce environmental impact and enhance resource efficiency in modular construction systems.

Table 4. Enviromental impact and efficiency of recycle process of the wall panels

Panel	Material	Weight	Relative Mass (RM)	Environmental Impact	Efficiency of recycle process			
				Embodied Energy (EE_t)	Recycle material (ME)		Discarded Material (DM)	
		(kg)	(%)	(MJ)	(kg)	(%)	(kg)	(%)
BBLg	Bamboo	23.88	47.86%	143.27	23.88	47.86%	0.00	0.00%
	LGS	26.01	52.14%	1014.52	25.49	51.10%	0.52	1.04%
	Total	**49.89**		**1157.79**	**49.37**	**98.96%**	**0.52**	**1.04%**
BBRb	Bamboo	18.06	96.76%	108.39	18.06	96.76%	0.00	0.00%
	Rebar Steel	0.60	3.34%	21.99	0.43	2.30%	0.18	1.05%
	Total	**18.67**		**130.38**	**18.49**	**99.06%**	**0.18**	**1.05%**
BWLg	Bamboo	7.16	7.74%	42.98	7.16	7.74%	0.00	0.00%
	Solid wood	78.35	84.68%	665.98	78.35	84.68%	0.00	0.00%
	LGS	7.01	7.58%	273.37	6.87	7.42%	0.14	0.15%
	Total	**92.52**		**982.33**	**92.38**	**99.85%**	**0.14**	**0.15%**
LgLgB	LGS	11.51	58.00%	448.75	11.28	56.84%	0.23	1.16%
	Bamboo	8.33	42.00%	49.98	8.33	42.00%	0.00	0.00%
	Total	**19.84**		**498.74**	**19.61**	**98.84%**	**0.23**	**1.16%**
LgLgRb	LGS	12.28	76.82%	478.74	12.03	75.28%	0.25	1.54%
	Rebar Steel	3.70	23.18%	134.82	2.63	16.46%	1.07	6.72%
	Total	**15.98**		**613.56**	**14.66**	**91.74%**	**1.32**	**8.26%**
LgLgW	LGS	13.00	40.02%	506.87	12.74	39.22%	0.26	0.80%
	Solid wood	19.48	59.98%	165.58	19.48	59.98%	0.00	0.00%
	Total	**32.48**		**672.46**	**32.22**	**99.20%**	**0.26**	**0.80%**
WBRb	Solid wood	13.46	60.53%	114.43	13.46	60.53%	0.00	0.00%
	Bamboo	6.98	31.37%	41.86	6.98	31.37%	0.00	0.00%
	Rebar Steel	1.80	8.09%	65.53	1.28	5.75%	0.52	2.35%
	Total	**22.24**		**221.82**	**21.72**	**97.65%**	**0.52**	**2.35%**
WWLg	Solid wood	17.84	65.41%	151.66	17.84	65.41%	0.00	0.00%
	LGS	9.44	34.59%	368.00	9.25	33.90%	0.19	0.69%
	Total	**27.28**		**519.66**	**27.09**	**99.31%**	**0.19**	**0.69%**
WWRb	Solid wood	49.42	97.03%	420.03	49.42	97.03%	0.00	0.00%
	Rebar Steel	1.51	3.06%	54.98	1.07	2.11%	0.44	0.95%
	Total	**50.93**		**475.01**	**50.49**	**99.14%**	**0.44**	**0.95%**

Source: Authors

Conclusion

This study demonstrates that material composition plays a critical role in determining the environmental performance of modular wall panels analyzed here. The empirical basis derives from prototypes fabricated by students in the Undergraduate Architecture Program cohort of 2022 at Universitas Islam Indonesia as part of their coursework, providing a pedagogical provenance that underscores the practical applicability of circular design principles in educational settings. The analysis of embodied energy, recycling efficiency, and discarded materials reveals clear distinctions between panels constructed with biological materials and those that rely on technical components.

Among the panel types, BBLg has the highest total embodied energy, exceeding 1157 MJ, primarily because of the use of energy-intensive steel. In contrast, BBRb has the lowest embodied energy, around 130 MJ, thanks to its reliance on renewable, low-impact materials like bamboo.

Recycling efficiency across the panels is generally high, with most exceeding 98%. Notably, BWLg achieves a recycling rate of 99.85%, despite its mixed composition of bamboo, wood, and steel. On the other hand, LgLgRb, which combines light-gauge steel and rebar, records the lowest recycling efficiency at 91.74% and the highest discarded material percentage at 8.26%, underscoring the challenges of managing technical materials with lower circularity potential.

These findings affirm that biological materials such as bamboo and wood not only reduce embodied energy but also eliminate discarded waste, making them ideal for circular construction strategies. Panels that integrate these materials demonstrate superior environmental performance and align well with sustainability goals. This suggests that prioritizing bio-based modular systems can significantly reduce the ecological footprint of construction, especially when considering the entire life cycle of building materials. The pedagogical success of this study highlights implications for further testing of student-derived prototypes and scaled prototyping in factory settings to validate hybrid configurations for real-world deployment.

Recommendations

This study has limitations. It analyzes only 9 panel types, which may not represent all modular designs. Some materials are underrepresented, limiting generalizability. The focus is on material metrics like embodied energy, recycling efficiency, and discarded material, excluding long-term performance, life-cycle costs, and user factors.

To improve environmental performance and circularity, biological materials like bamboo and wood should be prioritized, as they have low embodied energy and generate zero waste. Technical materials such as light-gauge steel and rebar should be minimized or used only where structural needs justify them. Panels should be designed for disassembly, enabling separation into pure streams for reuse and recycling (Ali-Gombe et al., 2025). Hybrid strategies combining biological and technical materials can be adopted to achieve a balance between strength and sustainability (Balasbaneh & Ramadan, 2024). Circularity metrics should be integrated early in design to align with ecological goals (Rajagopalan et al., 2021).

Future Research Directions. Future work should address key gaps, including life-cycle cost studies to evaluate economic viability alongside environmental impacts (Rajagopalan et al., 2021). Long-term in-service performance testing is needed to assess durability and real-world behavior (Delem et al., 2022). Expanded material mixes with scaled factory trials should validate hybrid configurations (Ali-Gombe et al., 2025). The development of material passports and digital tracking systems will enhance traceability, reuse, and circularity (Çetin et al., 2023).

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