COMPARATIVE STUDY OF UNITISED CURTAIN WALL AND UNITISED TIMBER ENVELOPE SYSTEMS: PATHWAYS TO REDUCING EMBODIED CARBON AND ENHANCING CIRCULARITY IN FACADE DESIGN

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ABSTRACT: The construction sector accounts for approximately 40% of global greenhouse gas emissions and nearly one-third of global material consumption. Modern facade systems significantly contribute to these impacts due to their reliance on energy-intensive materials such as aluminium, high-performance glass, insulation, sealants, and adhesives. Reconsidering material choices to facilitate the transition toward a circular economy is crucial for reducing embodied carbon emissions and material waste. This study comparatively evaluates widely adopted Unitised Curtain Wall systems and emerging Unitised Timber Envelope systems using Life Cycle Assessment and circularity metrics, examining global warming potential, material recovery, and end-of-life scenarios. Results indicate that Unitised Timber Envelope systems reduce embodied carbon by up to 49.3% compared to Unitised Curtain Wall systems, primarily due to timber's biogenic carbon storage. In contrast, while aluminium recycling supports material recovery in Unitised Curtain Wall systems, their total embodied carbon remains considerably higher due to energy-intensive primary aluminium production. For both cases, the low recyclability of laminated glass and insulation constrains circularity. Findings also highlight that current circularity assessment tools inadequately capture the complexity of circular facade strategies, underscoring the need for improved frameworks. Future research should develop integrated design guidelines to embed circular economy principles from early design stages.

KEYWORDS: LCA, Circularity, Unitised Timber Envelope, Unitised Curtain Wall, GWP

1 – INTRODUCTION

The 2024 Circularity Gap Report indicates that approximately 40% of global greenhouse gas (GHG) emissions are attributed to construction, operation, and deconstruction, with nearly one-third of global material consumption linked to a linear model [1]. Adopting Circular Economy (CE) principles is essential for mitigating environmental impacts, minimising waste, and reducing embodied carbon in construction [2]. Over recent decades, sustainable facade design has primarily aimed to enhance building energy efficiency and reduce operational carbon emissions [3]. This has pushed the facade industry towards novel high-performance solutions, including double-skin facades, adaptive and kinetic facades, and integrated photovoltaic technologies [3]. However, these advancements have unintentionally increased embodied carbon due to their complexity and reliance on energy-intensive materials like aluminium and laminated glass [4].

Unitised Curtain Walls (UCWs), widely adopted in high-rise buildings, exemplify these trends. UCWs consist of prefabricated modules incorporating aluminium frames, laminated glass, spandrels, insulation, and sealing materials [5]. These systems offer rapid installation, factory-controlled quality, customisability, and relatively low weight [6]. However, their reliance on carbon-intensive materials, limited recyclability, and dependence on linear model (take-make-waste)

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contribute to significant embodied carbon emissions. At end-of-life (EOL), the multi-material complexity and reliance on chemical bonds often necessitate landfill disposal or energy-intensive recycling processes, limiting their overall circularity [4, 6].

Unitised Timber Envelopes (UTEs) emerge as potential alternatives integrating timber components, typically cross-laminated timber (CLT), with aluminium and glass to leverage prefabrication benefits while aiming to reduce environmental impacts. Timber's renewable nature and carbon sequestration properties offer notable environmental benefits [7]. However, engineered wood products (EWPs) like CLT present circularity challenges at end-of-life due to adhesives and coatings limiting recyclability and reuse options [8]. End-of-life scenarios—reuse, recycling, energy recovery, and landfill—critically impact timber systems' circularity. While timber sequesters carbon, energy recovery processes may offset this benefit, raising concerns about long-term carbon retention [7].

Despite advancements, facade systems follow linear models, limiting material recovery and circularity potential. While prior studies focus on individual materials or operational efficiency, comparative lifecycle assessments between Unitised Curtain Walls (UCWs) and Unitised Timber Envelopes (UTEs) remain scarce. This study addresses this gap by evaluating UCWs and UTEs using Life Cycle Assessment (LCA) and circularity metrics. Given the need to reduce embodied carbon and improve end-of-life strategies, understanding their environmental impacts is essential. This comparative analysis provides a novel contribution by integrating sustainability and circularity metrics, guiding informed design strategies, enhancing material recovery, reducing embodied carbon, and promoting circular practices in facade systems.

2 – BACKGROUND

2.1 CIRCULAR ECONOMY AND SUSTAINABILITY IN FACADES

Between 2024 and 2050, new construction projects will consume approximately 7 million tonnes of resources annually, with 91% associated greenhouse gas emissions arising from embodied carbon, spanning all material lifecycle stages from extraction through disposal [9]. Transitioning to a circular economy extends the lifespan of materials, promotes reuse and recyclability, and reduces waste generation [9]. Facade systems incorporate various materials with differing recyclability potentials. While aluminium is widely recycled, materials such as laminated glass and insulation present challenges due to their composite structures and separation complexities [4, 10].

Implementing circularity in facades necessitates strategies like modularity and reversibility from early design stages, facilitating material reuse, disassembly, and effective waste management [11]. Prefabrication significantly supports circular approaches, embedding modularity and enabling reversible design processes [12]. Yet, despite these potential advantages, widespread adoption of Design-for-Disassembly (DfD) remains limited. Many facade systems, including UCWs, depend heavily on chemical bonding, complicating component separation and hindering efficient end-of-life recovery [6]. Modular facade systems, particularly UCWs, are preferred in high-rise construction due to their standardisation, rapid installation, and quality assurance benefits. However, these systems predominantly follow linear economy principles, resulting in high rates of virgin material usage and low recycling efficiency. End-of-life disposal frequently involves landfilling or energy-intensive recycling, underscoring the urgent need for design improvements to facilitate circularity [4, 6, 10].

2.2 FACADE SYSTEMS AND THEIR ENVIRONMENTAL IMPACT

Facade systems significantly influence buildings' operational energy use and embodied carbon emissions. Optimising facade design and material selection is critical to reducing these environmental impacts throughout the building lifecycle [4, 13]. While UCWs provide notable benefits in construction speed, consistency, and installation efficiency, their extensive use of aluminium and laminated glass results in substantial embodied carbon emissions. Aluminium production, in particular, is highly energy-intensive, and although recycling rates are relatively high, much of the aluminium used in facades still originates from virgin sources [14, 15]. Laminated glass further complicates end-of-life recycling efforts due to difficulties separating glass from interlayer materials, thereby contributing to material inefficiencies and environmental burdens at disposal [16].

In response, timber-based facade systems, including UTEs, have emerged as environmentally favourable alternatives due to timber’s renewability and carbon sequestration potential—however, engineered wood products (EWPs) such as CLT present end-of-life recovery challenges. Adhesives and coatings in EWPs may present difficulties for recycling and reuse, influencing circularity potential [7]. To overcome timber’s limitations and leverage its environmental advantages, hybrid timber-aluminium facade systems

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have been developed, integrating the structural and performance benefits of aluminium with the lower environmental impact of timber. These hybrid systems promise reduced embodied carbon and enhanced sustainability performance, but the complexity of material combinations introduces challenges in recycling and end-of-life management [7].

Recent advances, such as Slanina and Moravec's [17] timber-only unitised facade frames and Gasparri's [18] Rapid-installation UTE prototypes illustrate potential improvements in structural performance and prefabrication efficiency. However, comprehensive lifecycle assessments exploring these hybrid and timber-based systems' environmental impacts, circular economy potentials, and end-of-life implications remain limited. Addressing this research gap is crucial to fully understand the comparative sustainability of emerging facade technologies and circular economy performance.

2.3 LIFECYCLE ASSESSMENT AND CIRCULARITY METRICS

Evaluating the environmental sustainability of façade systems necessitates robust assessment methodologies such as Life Cycle Assessment (LCA) and circularity metrics. LCA systematically quantifies environmental impacts—including global warming potential, resource consumption, and waste generation—across all lifecycle stages: raw material extraction, production, construction, operation, and end-of-life [20]. It is particularly effective at highlighting embodied carbon implications inherent in façade materials and manufacturing processes.

Conversely, circularity metrics precisely measure the potential for material recovery, reuse, recycling efficiency, and waste minimisation. These metrics help quantify the extent to which façade systems can maintain value and material quality after the initial lifecycle, enabling strategies aligned with circular economy principles [1]. Current tools for evaluating circularity do not fully account for the differences between recycled and virgin aluminium in façade systems, pointing to the need for improved methodologies [19].

Existing façade research mainly evaluates operational energy performance or singular lifecycle stages rather than comprehensive circularity across the entire lifecycle, particularly in hybrid façade systems. Consequently, comparative LCA and circularity assessments for hybrid timber-aluminium façades—such as UCWs and UTEs—are notably lacking. Addressing this gap, this research uniquely combines LCA and circularity metrics, offering a comprehensive evaluation that informs strategic design decisions to improve environmental sustainability and material recovery across diverse façade systems.

3 – PROJECT DESCRIPTION

Unitised facade systems are a widely used curtain wall solution composed of prefabricated and pre-glazed panels. These panels are assembled in a factory setting and transported to the construction site for installation [5]. Prefabrication in a controlled environment enhances quality control and reduces on-site labour [5]. Each panel features an aluminium frame with glass or aluminium panels. Aluminium is preferred for its lightweight nature, high strength-to-weight ratio, and corrosion resistance [18]. It also includes other advantages, such as reduced field labour, enhanced quality control due to factory assembly, and improved capacity to resist environmental loads and structural movements, resulting in significantly shorter construction timelines than traditional stick-built systems [20, 21]. Overall, unitised facade systems present a modern, efficient building envelope solution by combining the benefits of factory-controlled production with streamlined on-site installation.

Case Study 1: The Unitised Curtain Wall (UCW) System features prefabricated modules incorporating aluminium framing, double-laminated glass, and opaque spandrels designed to meet thermal performance and rapid installation requirements. The Schüco UCC 65 SG is selected for this project, with each module measuring

Table 1 Overview of facade materials, parts, mass, lifespan, and end-of-life (EOL) scenarios.

Material/Part Information						**UCW**		**UTE**	
Level	***Material Type***	***Lifespan (years)***	***Replacement (Yes/No)***	***EOL scenarios***	***Source***	***Mass kg***	***Mass %***	***Mass kg***	***Mass %***
Frame	Aluminium	50	No	Recycling	One-click	54	38%	27	11%
	Framing Timber	60	No	Landfills	[24], One-click	-	-	15.84	6%
	EPDM	40	No	Landfills	One-click	8.85	6%	6.6	3%
IGU	Laminated Glass	30	Yes	Landfills	[5], One-click	50	35%	50	20%
	Spacebar	30	Yes	Landfills	One-click	4.4	3%	4.4	2%
	Silicone sealants	20-25	Yes	Landfills	One-click	2.5	2%	1.25	1%
Spandrel	CLT	60	No	Landfills	[24], One-click	-	-	100.8	41%
	Aluminium Panel	60	No	Recycling	One-click	15.93	11%	7.83	3%
	Stone wool Insulation	50	No	Landfills	One-click	8	6%	8	3%
	Calcium silicate board	40	No	Backfilling	One-click	-	-	27	11%
	Weather barrier	30	Yes	Landfills	One-click	-	-	0.01	0.04%

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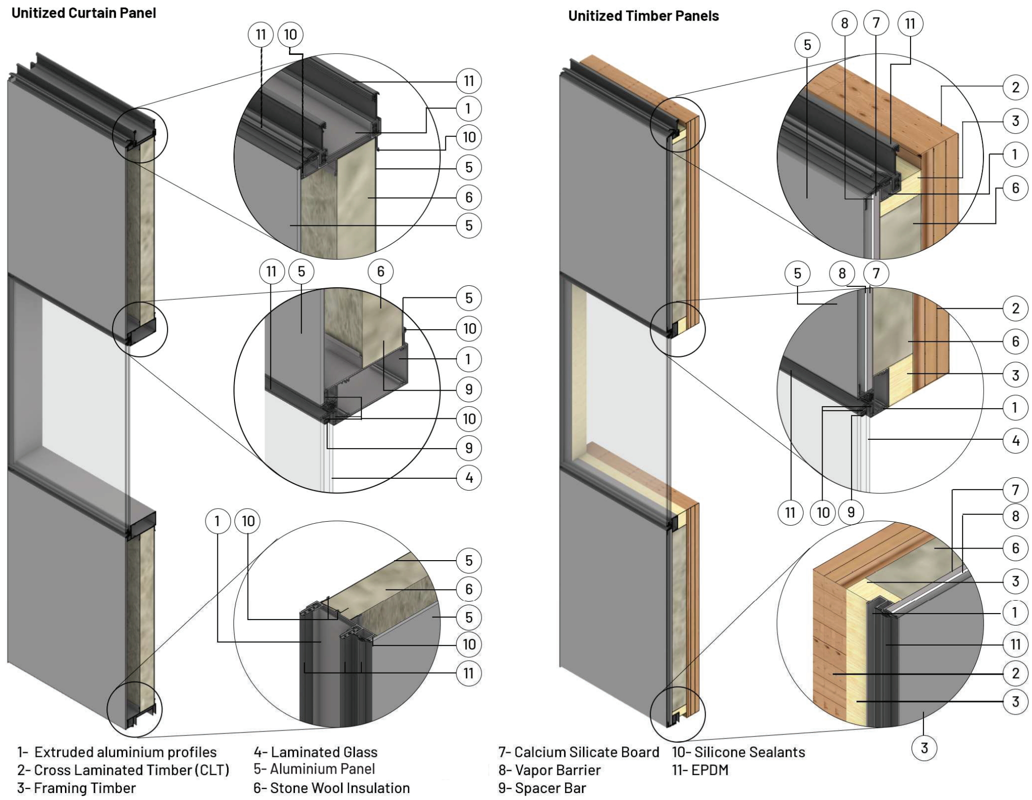

Figure 1 Illustrates the system's technical drawing for UCW and UTE.

3.2m × 1.2m. The system integrates 33% double-laminated glass and 66.6% opaque spandrels, which consist of stone wool insulation and aluminium exterior and interior panel. The prefabricated panels are transported to the site and installed using mounting brackets and cranes, facilitating quick assembly with reduced labour requirements. Table 1 presents the material's mass, component, lifespan, and end-of-life (EOL) scenarios, while Figure 1 illustrates the system's technical drawing.

Case Study 2: The unitised timber envelope (UTE) is a prefabricated facade system that integrates engineered timber into a modular format and is designed for both load-bearing and non-load-bearing applications [18]. This system incorporates cross-laminated timber (CLT), framing timber, aluminium components, and laminated glass, offering an alternative to conventional UCWs while maintaining prefabrication benefits. The project adopted a modified Schüco UCC 65 SG system, integrating engineered timber with a Unitised curtain wall approach developed in [18]. Each UTE module measures 3.2m × 1.2m and consists of a hybrid timber-aluminium frame, 33% double-laminated glass, and 66.6% opaque spandrels. The Spandrels include over-interior CLT, stone wool insulation, a calcium silicate board, a weather barrier and exterior aluminium panel. Like the UCW system, the prefabricated UTE panels are transported to the site and installed using cranes, ensuring fast and efficient construction. Table 1 presents the material's mass, component, lifespan, and end-of-life (EOL) scenarios, while Figure 1 illustrates the system's technical drawing.

4 – METHODOLOGY

4.1 STUDY FRAMEWORK

This study conducts a comparative Life Cycle Assessment (LCA) and Circularity Assessment to evaluate the environmental performance of two facade systems: a Unitised Curtain Wall (UCW) and a Unitised Timber Envelope (UTE). The analysis adopts a cradle-to-grave approach, examining the impacts of material extraction, transportation, construction, usage, and end-of-life (EOL) stages. A functional unit of 3.84 m² was selected to match the standardised dimensions of unitised panels in the case study, ensuring consistency in material quantification and environmental impact assessment.

4.2 SYSTEM BOUNDARIES

The LCA follows EN 15804+A2 standards and evaluates all lifecycle stages of each facade system, which include material extraction and manufacturing (A1-A3), transportation (A4), construction and installation (A5), replacement and maintenance (B4-B5), and end-of-life processes (C2-C4). This study focuses on embodied emissions and material circularity by evaluating each stage's carbon footprint, and material flows in UCW and UTE while excluding operational energy to ensure a robust sustainability analysis.

4.3 DATA SOURCES AND IMPACT ASSESSMENT METRICS

LCA calculations were performed using OneClick LCA (https://oneclicklca.com/), a recognised software for environmental impact assessments. Material-specific emission factors were obtained from Environmental Product Declarations (EPDs) and OneClick databases. The environmental impact assessment primarily focuses on Global Warming Potential (GWP, kg CO_2e).

4.4 CIRCULARITY ASSESSMENT

The circularity performance of UCW and UTE was assessed using the OneClick Building Circularity V2 tool, which evaluates material flows, potential for reuse, and end-of-life scenarios. The tool quantifies circularity based on predefined formulas, measuring the percentage of materials sourced from recycled inputs and the proportion recovered at end-of-life. A circularity score (0-100%) is assigned, where 100% represents a system with no waste and complete material reuse.

4.5 LIFESPAN AND END-OF-LIFE (EOL) SCENARIOS

The study integrates material lifespan and replacement cycles into the Life Cycle Assessment (LCA) framework to evaluate environmental impacts. Table 1 offers a detailed overview of material lifespan, replacement requirements, and end-of-life pathways. The aluminium frame, an essential UCW and UTE systems component, is designed to last 50 years. In comparison, the framing timber used in UTE has a lifespan of 60 years. Insulated glass units (IGUs) in both systems necessitate replacement every 30 years because of sealant degradation. Other significant materials, such as EPDM sealants (40 years), spacebars (30 years), and aluminium panel (60 years), adhere to industry-standard lifespans. UTE-specific materials, including CLT (60 years), calcium silicate board (40 years), and weather barriers (30 years), enhance its circularity potential and contribute to long-term performance. By integrating these lifespans, the study accounts for replacement impacts over a 40-year building lifecycle. By examining these lifespans, this study evaluates their effect on material efficiency, replacement frequency, end-of-life pathways, and overall environmental performance.

At the end-of-life stage, the disposal and recovery pathways for UCW and UTE materials were assessed to determine their impact on facade circularity and environmental performance. Aluminium components are highly recyclable, yet their energy-intensive reprocessing contributes to embodied emissions.

In the Australian market, CLT and framing timber are typically disposed of in landfills (100%) due to reuse and recycling infrastructure limitations. However, alternative end-of-life scenarios recommended by [22] Suggest two additional strategies to improve circularity:

- Reuse (73%) + Landfill (27%): A portion is repurposed for future construction applications, reducing waste disposal.
- Energy Recovery (100%): Incineration recovers energy but releases stored carbon, offsetting potential sequestration benefits.

Insulated glass units (IGUs) pose a significant challenge in both systems due to the complexity of laminated glass separation. Consequently, IGUs are commonly landfilled. Similarly, silicone sealants and EPDM are landfilled due to their chemical composition. Calcium silicate boards in UTE are backfilled, while weather barriers are disposed of in landfills.

5 – RESULTS AND DISCUSSION

The life cycle assessment (LCA) of the Unitised Curtain Wall (UCW) and the Unitised Timber Envelope (UTE) evaluates their global warming potential (GWP) across key stages. These stages include material extraction (A1-A3), transportation (A4), construction (A5), replacement (B4-B5), end-of-life scenarios (C2-C4) and net benefits and loads (Modules D). The results are presented to underscore the significant differences in emissions between these two cases.

5.1 GLOBAL WARMING POTENTIAL (GWP) ACROSS LIFECYCLE STAGES

Material Extraction and Manufacturing (A1-A3): Material extraction and manufacturing contribute 83% of UCW's total emissions (1,026.54 kg CO_2e) and 72% of UTE's total emissions (701.61 kg CO_2e). Figure 2 shows the global warming potential (GWP) of UCW and UTE systems across various life-cycle stages and detailed material contributions to the total CO2e. UCW's high

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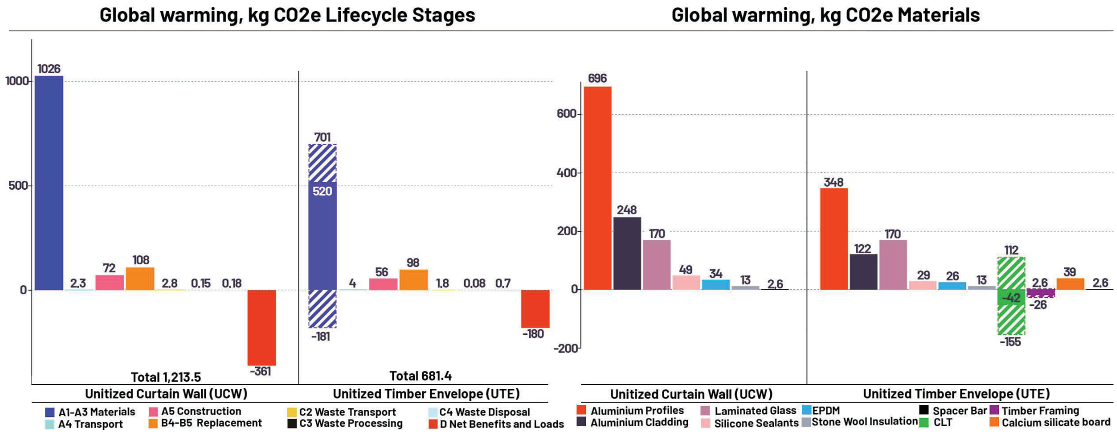

Figure 2 Shows GWP (kg CO2e) for UCW and UTE systems; the left chart breaks down life-cycle emissions, and the right chart details material contributions, any value >1 is excluded from the GWP for materials figure.

emissions are mainly due to aluminium (644.08 kg CO_2e) and laminated glass (84.47 kg CO_2e). In contrast, UTE benefits from timber's biogenic carbon storage (-181.47 kg CO_2e bio), which reduces its net emissions to 520.14 kg CO_2e. Its hybrid aluminium-timber frame lowers aluminium dependency while incorporating CLT as a structural element. Despite requiring additional layers like calcium silicate board and a weather barrier for durability, UTE still achieves a 49.3% GWP reduction compared to UCW when biogenic storage is considered. If disregarding biogenic storage, UTE maintains a 31.7% reduction. These findings emphasise the importance of integrating renewable materials to lower embodied carbon.

Transportation (A4): Transportation emissions are minimal, with UTE at 4.13 kg CO_2e and UCW at 2.30 kg CO_2e. UTE's higher emissions stem from its heavier timber modules than UCW's lighter prefabricated aluminium and glass components. However, transportation remains a minor contributor to total GWP, reinforcing the efficiency benefits of prefabrication in minimising logistics-related emissions.

Construction (A5): Emissions from the construction phase amount to 72.51 kg CO_2e for UCW and 56.41 kg CO_2e for UTE. While both systems are prefabricated, their material composition significantly influences emissions. UCW requires specialised lifting equipment and energy-intensive aluminium and glass installation tools, increasing energy demand. In contrast, UTE benefits from lighter timber components, reducing on-site energy use. Although UTE incorporates calcium silicate boards and stone wool insulation, these materials require less energy-intensive handling than UCW's aluminium-heavy modules. Additionally, UTE's hybrid aluminium-timber design reduces reliance on high-impact materials such as aluminium and laminated glass, which have high embodied carbon and require energy-intensive manufacturing, leading to a 16.1 kg CO_2e reduction in construction emissions compared to UCW.

Replacement (B4): UCW and UTE require the replacement of insulated glass units (IGUs) due to the degradation of sealants and spacers, which cannot be repaired on-site. UCW emits 108.98 kg CO_2e from IGU replacements, whereas UTE emits 98.55 kg CO_2e. The higher emissions in UCW stem from its greater reliance on EPDM, silicone sealants, and spacebars, totalling 15.75 kg compared to 12.25 kg in UTE. Additionally, UCW's aluminium-heavy design increases embodied emissions during replacement. The energy-intensive laminated glass manufacturing process further compounds emissions. These findings highlight the need for more durable sealants, spacer materials, and alternative glazing technologies to reduce lifecycle replacement impacts.

End-of-Life Stages (C2-C4): At the end-of-life stage, UCW exhibits higher emissions than UTE due to differences in material composition and disposal methods. Waste transport (C2) emissions are 2.88 kg CO_2e for UCW and 1.79 kg CO_2e for UTE, reflecting variations in material mass and transportation distances. Waste processing (C3) emissions for UCW are 0.146 kg CO_2e, exceeding UTE's 0.0821 kg CO_2e, as timber components require minimal processing compared to aluminium and laminated glass. Waste disposal (C4) emissions remain low for both systems, recorded at 0.181 kg CO_2e for UCW and 0.709 kg CO_2e for UTE. However, UTE's timber components (CLT and framing timber) are fully landfilled (100%) under Australian market conditions, preventing material recovery [22]. This disposal pathway poses potential long-term environmental concerns due to the slow degradation of timber in landfills.

Net Benefits and Loads (Modules D): credits in UCW are primarily derived from aluminium recycling, providing a total offset of -361.39 kg CO_2e (-268.9 kg CO_2e from aluminium profiles and -92.5 kg CO_2e from aluminium panel). In contrast, UTE's post-use recovery remains limited, with a lower Module D benefit of -180.53 kg CO_2e, mainly attributed to aluminium (-134.4 kg CO_2e) and calcium silicate board (-46.5 kg CO_2e). This highlights the need for improved timber recycling infrastructure and increased circularity in engineered wood products to enhance UTE's end-of-life sustainability.

The LCA results reveal significant differences in GWP between UCW and UTE across all lifecycle stages, primarily driven by material composition and end-of-life treatment. UCW demonstrates the highest emissions in material extraction and manufacturing (A1-A3) at 1,026.54 kg CO_2e, primarily due to aluminium (644.08 kg CO_2e) and laminated glass (84.47 kg CO_2e). In contrast, UTE benefits from a 29% reduction in A1-A3 emissions (701.61 kg CO_2e) due to timber's biogenic carbon storage (-181.47 kg CO_2e). However, while UTE incorporates additional calcium silicate board and stone wool insulation, their impact on embodied emissions remains lower than UCW's aluminium-heavy composition, ensuring an overall reduction in environmental impact.

At end-of-life (C2-C4), UCW incurs higher emissions than UTE, reflecting its reliance on materials with limited recovery potential. Waste transport (C2) emissions amount to 2.88 kg CO_2e for UCW and 1.79 kg CO_2e for UTE, mainly due to differences in material mass and transportation distances. Waste processing (C3) emissions are 0.146 kg CO_2e for UCW and 0.0821 kg CO_2e for UTE, as timber requires minimal processing compared to aluminium and laminated glass. Waste disposal (C4) emissions remain low for both systems, recorded at 0.181 kg CO_2e for UCW and 0.709 kg CO_2e for UTE. However, UTE's landfill dependency is notable, as 100% of CLT and framing timber are landfilled under Australian market conditions, preventing material recovery and limiting circularity benefits.

Module D credits highlight UCW's advantage in aluminium recycling, which offsets -361.39 kg CO_2e (-268.9 kg CO_2e from aluminium profiles and -92.5 kg CO_2e from aluminium panel). In contrast, UTE's post-use recovery remains lower, with a Module D credit of -180.5 kg CO_2e, attributed mainly to aluminium (-179.91 kg CO_2e) and calcium silicate board (-0.616 kg CO_2e). The comparison demonstrates that while UTE has lower upfront embodied emissions, its reliance on landfill disposal significantly limits material recovery, negatively impacting its long-term carbon performance. These findings emphasise the importance of material selection and recovery in determining the sustainability of façade systems. While UCW benefits from a well-established aluminium recycling market, UTE's circularity remains constrained by current disposal practices, necessitating improved recycling pathways for engineered wood products to enhance lifecycle sustainability.

5.2 GLOBAL WARMING POTENTIAL (GWP) FOR MATERIALS

The material composition of each facade system significantly influences its total GWP. In Unitized Curtain Wall (UCW), aluminium and laminated glass are the primary contributors to emissions. Extruded aluminium profiles alone account for 696 kg CO_2e, while aluminium panels contribute 230.13 kg CO_2e, bringing total aluminium-related emissions to 926.13 kg CO_2e. Laminated glass further increases UCW's footprint, contributing 84.47 kg CO_2e. Additional materials such as EPDM (31.71 kg CO_2e), silicone sealants (23.25 kg CO_2e), and stone wool insulation (11.64 kg CO_2e) contribute smaller but notable amounts to overall emissions.

In contrast, the Unitized Timber Envelope (UTE) reduces aluminium usage by 50%, decreasing its associated emissions to 470.14 kg CO_2e. However, laminated glass emissions remain unchanged at 84.47 kg CO_2e due to its presence in both systems. The key distinction in UTE lies in timber's biogenic carbon storage, which offsets emissions. Cross-laminated timber (CLT) stores -155.4 kg CO_2e while framing timber stores -26.07 kg CO_2e, partially compensating for their combined emissions of 29.84 kg CO_2e. Other materials in UTE, such as calcium silicate board (38.98 kg CO_2e), EPDM (25.68 kg CO_2e), and stone wool insulation (12.68 kg CO_2e), contribute to system performance while maintaining relatively low emissions.

Although aluminium in UCW benefits from a high recycling rate (90%), its production remains highly energy-intensive, making it the dominant source of embodied carbon. Likewise, laminated glass and stone wool insulation present recycling challenges, often leading to landfill disposal. UTE mitigates these effects by optimising frame design and leveraging timber's carbon storage capabilities, reducing its reliance on aluminium. However, further advancements in low-impact insulation materials and glazing configurations could minimise lifecycle GWP. Additionally, increasing

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the recycled content of aluminium in both UCW and UTE could significantly reduce emissions while maintaining structural integrity.

5.3 CIRCULARITY RESULTS

The circularity potential of UCW and UTE varies significantly due to differences in material composition, recycling rates, and EOL strategies. Figure 3 presents the circularity assessment results, while Figure 4 highlights the Module D benefits, emphasising aluminium recycling in UCW and emissions reduction from CLT reuse in UTE. UCW exhibits a moderate level of circularity, with 24% circularity, primarily driven by aluminium recycling. While 33.9% of its material mass enters the recycling stream, a substantial 66.1%to landfills, particularly laminated glass, EPDM, and stone wool insulation, have limited recovery potential. This reliance on landfill disposal contributes to higher long-term GWP impacts, with total EOL emissions reaching 3.207 kg CO_2e (C2: 2.88 kg CO_2e, C3: 0.146 kg CO_2e, C4: 0.181 kg CO_2e). However, UCW benefits significantly from aluminium recycling, which provides a Module D credit of -268.9 kg CO_2e from aluminium profiles and -92.5 kg CO_2e from aluminium panel, resulting in a total offset of -361.39 kg CO_2e. Despite this advantage, UCW's sustainability performance remains heavily dependent on increasing secondary aluminium content and improving recovery rates for non-metallic components.

The UTE landfill scenario, reflecting current market conditions, assumes that 100% of CLT and framing timber is sent to landfills, resulting in a low circularity rate of 29% and a high disposal rate of 89.5%. While timber inherently retains biogenic carbon storage, landfill disposal limits its circularity by preventing reuse and recycling, leading to potential methane emissions. According to [22] only 0.1% of degradable organic carbon (DOCf) decomposes in landfills, with 27% of resulting landfill gas released as methane, contributing to long-term emissions rather than maintaining stored biogenic carbon. The total EOL emissions in this scenario are 2.581 kg CO_2e (C2: 1.79 kg CO_2e, C3: 0.0821 kg CO_2e, C4: 0.709 kg CO_2e). A key limitation of assessment tools is that methane emissions from timber degradation remain underrepresented, leading to potential underestimations of landfill-related climate impacts. Despite UTE's lower embodied carbon compared to UCW, this scenario highlights the risks of inadequate recovery infrastructure, reinforcing the need for improved timber recycling pathways. UTE's Module D credit is -180.5 kg CO_2e, significantly lower than UCW's aluminium-driven offset of -361.39 kg CO_2e. This difference highlights UTE's limited post-use recovery potential in landfill-dominant scenarios.

The UTE-Reuse scenario adopts a more circular approach by repurposing 73% of CLT and framing timber, reducing landfill dependency to 58.6% and increasing overall circularity to 44%. By extending the service life of timber materials, this scenario delays carbon release and reduces demand for virgin materials, leading to substantial improvements in circularity and lifecycle carbon footprint. The total EOL emissions in this scenario are 1.864 kg CO_2e (C2: 1.61 kg CO_2e, C3: 0.0821 kg CO_2e, C4: 0.172 kg CO_2e). The reuse of timber provides a significant Module D benefit of -405.07 kg CO_2e, with key contributions from aluminium (-180.5 kg CO_2e) and CLT reuse (-207.3 kg CO_2e). As a result, reuse emerges as the most effective strategy for minimising GWP impacts while preserving circularity benefits. However, widespread adoption remains constrained by

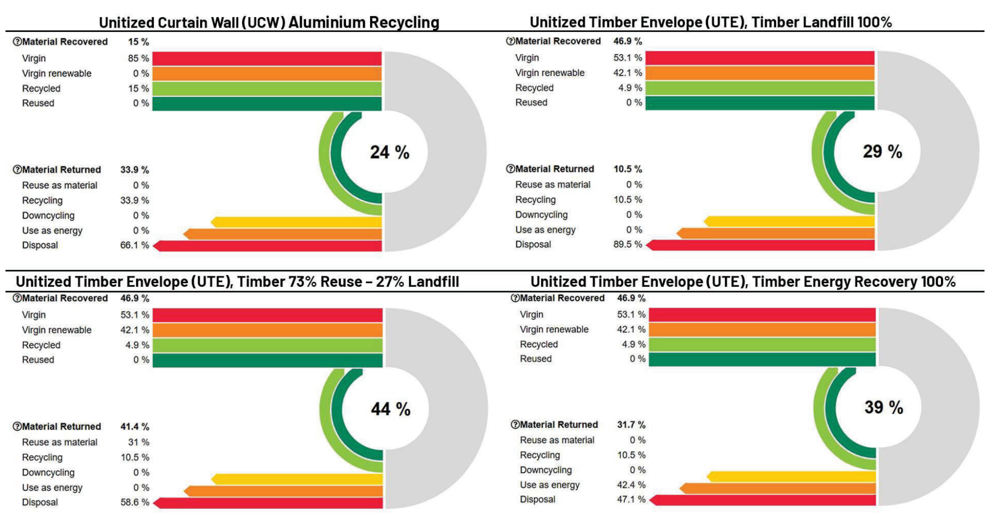

Figure 3 Circularity assessment results under different EOL scenarios using the Building Circularity v2 tool.

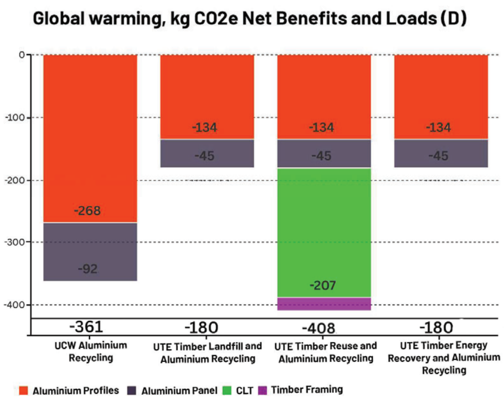

Figure 4 GWP benefits under different EOL scenarios, highlighting Module D emission offsets.

several factors. Disassembly challenges present a key barrier, as current facade systems do not consider easy deconstruction, necessitating improvements in design-for-disassembly (DfD) strategies to facilitate material separation and reuse. Additionally, market infrastructure limitations hinder large-scale timber reuse, as existing recovery systems predominantly focus on recycling rather than repurposing engineered wood products [22].

The UTE-Energy Recovery scenario prioritises biogenic energy substitution, where 100% of timber is incinerated (replace fossil-based energy sources). This approach reduces the circularity rate by 39%, reduces landfill dependency by 47.1%, and recovers 42.4% of material mass through energy conversion. Unlike landfill scenarios, this pathway prevents methane emissions. However, total EOL emissions in this scenario are 3.802 kg CO_2e (C2: 2.05 kg CO_2e, C3: 1.58 kg CO_2e, C4: 0.172 kg CO_2e). A key limitation of current assessment tools is that they do not fully account for the emissions released during timber combustion (C3). This results in potential underestimations of real GWP impacts, as stored biogenic carbon is immediately released rather than retained within material cycles. As per EN16485:2014, biogenic carbon flows are accounted as -1 kg CO_2e/kg at entry and +1 kg CO_2e/kg at release, resulting in timber's net-zero contribution to Module C3 and D [23]. While this pathway generates a Module D credit of -180.5 kg CO_2e, driven by aluminium profile (-134.4 kg CO_2e) and aluminium panel (-46.5 kg CO_2e), it lacks the long-term carbon storage benefits of reuse. Unlike aluminium, which maintains circularity through recycling, timber used for energy recovery is permanently removed from material loops, limiting its future sustainability contributions.

Assessing façades reveals key limitations in current tools, particularly their inability to fully capture emissions released from landfill decomposition and energy recovery, especially in C3 (waste processing). A key limitation of the Building Circularity v2 tool is its restriction to single-pathway EOL scenarios, preventing the evaluation of mixed recovery strategies like partial reuse and recycling. Additionally, OneClick Circularity focuses primarily on quantitative material recovery but overlooks essential qualitative circular design strategies, including modularity, disassembly, and flexible reuse, which are critical for optimising façade circularity. Future research should expand circularity indicators and KPIs to integrate material recovery efficiency and design-based circularity strategies, ensuring a more comprehensive and practical approach to evaluating the circular potential of façade systems.

6 – CONCLUSION

This study evaluated the environmental performance and circularity of Unitized Curtain Wall (UCW) and Unitized Timber Envelope (UTE) facade systems using OneClick LCA and Building Circularity v2. The results demonstrate that UTE achieves lower global warming potential (GWP) and higher circularity potential than UCW, primarily due to its integration of renewable materials and carbon sequestration benefits. UCW, by contrast, exhibits significantly higher embodied carbon, mainly from its aluminium and laminated glass components, which require energy-intensive production and have low recovery rates at end-of-life (EOL).

The circularity assessment underscores the critical influence of EOL pathways on material recovery efficiency. UCW achieves a circularity score of 26%, constrained by its reliance on virgin materials and the limited recyclability of glass and insulation. UTE's circularity performance varies based on timber disposal strategies, reaching 29% for 100% landfill, 44% for 73% reuse, and 39% for 100% energy recovery. These findings highlight that maximising material reuse leads to more significant circularity gains and environmental benefits than incineration or disposal.

However, both systems face limitations in recycling laminated glass and insulation materials, and existing tools remain inadequate in assessing circular design strategies such as modularity, flexibility, and disassembly potential. To bridge these gaps, future research should refine assessment frameworks, integrate multi-pathway EOL scenarios, and enhance methodologies for evaluating long-term circularity performance, ensuring more circular and resource-efficient facade systems.

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