Life Cycle Assessment of Aluminium Alloys for Sustainable Building Materials and Components

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Abstract. Aluminium has become a cornerstone of sustainable architectural design due to its lightweight properties, structural strength, corrosion resistance, and high recyclability. However, its primary production remains energy-intensive and a major contributor to greenhouse gas (GHG) emissions. This study presents a comparative Life Cycle Assessment (LCA) of commonly used aluminium alloys in architectural components, evaluating them across key stages—production and end-of-life—based on energy consumption, emissions, and recyclability. The analysis covers 3000, 5000 and 6000-series alloys, as well as recycled, anodized, and coated variants. The study contributes a parameterized LCA-based framework to support sustainable material selection in façade and structural design. It highlights the importance of incorporating recycled content, optimizing alloy use based on application, and adopting circular economy strategies such as closed-loop recycling. These findings offer practical guidance for architects, engineers, and policymakers striving toward low-carbon, net-zero building goals.

Introduction

Aluminium is widely used in architecture for façades, claddings, brackets, and structural components due to its light weight, corrosion resistance, and durability [1]. However, its production is energy-intensive and a major source of greenhouse gas (GHG) emissions [2]. As sustainability and circular economy principles gain importance, assessing aluminium's environmental footprint has become crucial [3]. Life Cycle Assessment (LCA) offers a systematic method to evaluate impacts such as energy use, emissions, and recyclability across a product's life cycle [4]. This study applies an LCA-based approach to classify aluminium alloys according to their environmental performance in construction.

Research Problem

Aluminium is valued for its durability, light weight, and recyclability, but its environmental impact varies with alloy type, processing, and end-of-life treatment [5]. Most LCA studies focus on transportation and packaging, offering limited insights for architectural alloys [6]. Furthermore, many studies apply Cradle-to-Gate or Cradle-to-Grave approaches, often neglecting the full recycling potential assessed through a Cradle-to-Cradle (C2C) framework [7]. This research addresses that gap by applying a C2C-based LCA to commonly used architectural aluminium alloys. It provides comparative evidence on energy consumption, greenhouse gas (GHG) emissions, and recycling efficiency, supporting sustainable material selection in the construction industry.

Analysis Methodology

Life cycle assessment (LCA) is a standardized framework for evaluating environmental impacts across product stages. The four main approaches are Cradle-to-Grave, Cradle-to-Gate, Cradle-to-Cradle, and Gate-to-Gate [11]. For aluminium in construction, key parameters include energy use, GHG emissions, recycling rates, material efficiency, and resource depletion [4]. This study adopts the Cradle-to-Cradle (C2C) framework, which emphasizes continuous recycling and closed-loop flows, aligning with circular economy principles [11]. The analysis encompasses four main life cycle stages, as depicted in Fig. 1:

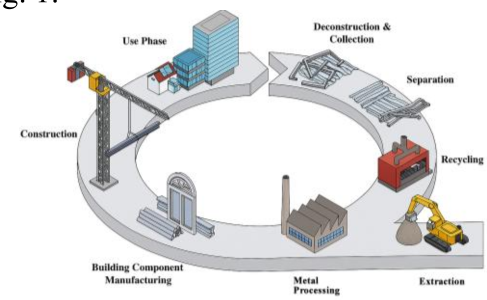

Fig 1. Aluminium Life Cycle Stages

(1) Raw material extraction (bauxite mining and aluminium production), (2) Manufacturing & processing (alloying, forming, surface treatments), (3) Use phase (applications in façades and structural elements), and (4) End-of-life & recycling (demolition, sorting, closed-loop recovery) [8–10]. The functional unit is 1 kg of aluminium alloy in architectural applications.

System boundaries include extraction, alloying, processing, finishing, and recycling; transport and maintenance are excluded due to low contribution. Recycling credits follow the avoided burden method, where secondary aluminium offsets primary impacts.

Five alloy categories are studied: 3000-series (cladding), 5000-series (corrosion-resistant structures), 6000-series (structural frameworks), recycled aluminium (low-impact secondary material), and anodized/coated aluminium (finishing impacts). The analysis focuses on two critical stages: (i) production, focusing on energy and GHG emissions, and (ii) end-of-life, focusing on recycling efficiency and circular material flows. Energy consumption strongly influences aluminium's environmental profile. Primary production, especially alumina refining and electrolytic smelting, is highly energy-intensive, whereas recycling requires only ~5% of that energy [8,14,15]. Table 1 summarizes energy demand across life cycle stages, with extraction contributing ~0.2%, production ~186 GJ per tonne, and recycling ~8.3 GJ, leading to ~95% energy savings compared to primary aluminium [13–15]. As shown in Table. 1, these differences highlight the need to integrate recycled content in architectural applications.

Al Life Cycle Stages	Included Processes	Energy Consumption	Energy Observations
Extraction Phase	Bauxite mining and raw material transport [13].	~0.373 GJ (≈0.2% of total) [13].	Low energy demand
Production Phase	Alumina refining, smelting (Hall-Héroult), casting [8].	~186 GJ [14]	Highly energy-intensive
Use Phase	Use, maintenance and replacement [8].	Minimal for static uses	Reduces indirect energy in transport
Recycling Phase	Demolition, sorting, collection and re-melting	~8.3 GJ (≈5% of primary production energy) [15].	~95% energy saving

Table 1. Aluminium Life Cycle energy consumption

GHG emissions are dominated by the production phase, with an average of 16.1 t CO_2e per tonne of primary aluminium, depending on energy sources [16]. Total emissions can be estimated as: Total GHG Emissions = Aluminium Production × Emission Factor. Figure 2 illustrates the overall distribution of GHG emissions across the aluminium life cycle stages. Recycling emits less than 5% of this total, confirming its role in reducing aluminium's carbon footprint [8,10,16].

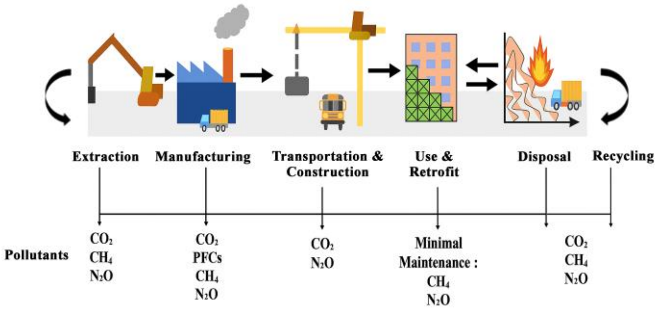

Fig 2. Greenhouse Gas (GHG) Emissions Across Aluminium's Life Cycle

Aluminium Life Cycle Stages	GHG Emissions (Million tonnes of CO_2e)	Key Pollutants	Emission Observations
Extraction Phase	**~5.3** (Electricity-Indirect: 1.7 Thermal Energy (Direct/Indirect): 3.5)	CO_2 (diesel, electricity), CH_4, N_2O	Low share of total
Production Phase	**~1,087** (Refining: 166 Electrolysis: 791 Anode Production: 71 Casting and Semi-Production: 47 PFC-Direct: 54 Process (CO_2-Direct): 115.	CO_2 (fuel, anode), PFCs (CF_4, C_2F_6), CH_4, N_2O	Main emission source
Use Phase	Minimal	CH_4, N_2O (maintenance)	Negligible for static uses
Recycling & End-of-Life Phase	Internal Scrap Remelting ~12 (Electricity-Indirect: 3 Thermal Energy (Direct/Indirect): 9) Recycling~ 24 (Electricity-Indirect: 4 Thermal Energy (Direct/Indirect): 20)	CO_2 (remelting, transport), CH_4, N_2O	Much lower than production

Table 2. Aluminium Life Cycle GHG Emissions

Recycling pathways further affect sustainability. Conventional methods involve melting and casting scrap into ingots, while emerging solid-state processes (extrusion, rolling) avoid melting losses and cut energy demand [17,18]. Fig. 3 illustrates these routes, emphasizing that improving collection and scrap quality directly enhances circularity.

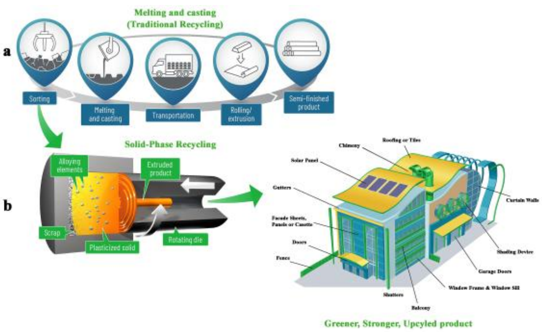

Fig 3. Aluminium recycling methods: melting and casting vs. solid-state processing

Aluminium is widely used in construction for cladding, brackets, and structural elements because of its light weight, durability, and versatility. Commonly used alloys include the 3000, 5000, and 6000 series, as well as recycled and anodized or coated variants. Each offers different levels of strength, corrosion resistance, and workability suited to architectural applications [19]. Table 3 summarizes key characteristics, applications, and case studies of these alloys [19–26].

Alloy Type	Key Characteristics	Typical Applications	Case Study Example	
3000-Series	Good formability, corrosion resistance, easy to weld [19].	Roofing, siding, gutters, cladding [19].	Titanic Museum Cladding – anodized aluminium with silver finish [20].	
5000-Series	High magnesium, strong corrosion resistance, marine-grade [19].	Façades, roofing, coastal structures[19].	Manetti Shrem Museum Canopy – marine-grade aluminium louvers [21].	
6000-Series	High strength, weldability, extrudability [22].	Beams, frames, railings, decorative structures [22].	Connecticut Project – 6061 alloy for structural strength and aesthetics [23].	
Recycled Al	Energy-efficient, sustainable, slightly lower mechanical properties [24].	Façades, sustainable building components [24].	Mercator One Façade – Hydro CIRCAL 75R with 75% recycled aluminium [25].	
Anodized/ Coated	Durable, corrosion/wear resistant, aesthetic flexibility [13].	Window frames, curtain walls, façade panels [13].	Capita Mall LuOne – custom anodized aluminium panels with dynamic façade [26].	

Table 3. Aluminium alloys in architecture: key traits, uses, and case study examples

The comparative LCA results for architectural aluminium alloys across extraction, production, use, and end-of-life are shown in Table 4, including energy use, GHG emissions, and recyclability [19].

Alloy Type	Energy Consumption	GHG Emissions	Recyclability
3000-Series	Low to moderate; due to high formability and no heat treatment [27].	Moderate; Cold working reduces processing emissions. Mn refining adds slightly [27].	Highly recyclable (~5% of primary energy) [27].
5000-Series	Moderate to high, due to Mg content, though no heat treatment is required [28].	Higher than 3000; Mg refining adds emissions [28].	~95% GHG reduction from recycling [29].
6000-Series	Moderate to high; due to heat treatment and extrusion [30].	Moderate–high; Heat treatment and forming processes add emissions [31].	Efficient with clean scrap; needs sorting (e.g., LIBS, XRF) to avoid downcycling [32].
Recycled Al	Only ~5% of primary energy [33].	~0.5 t CO_2/t Al; 95% less than primary	Infinitely recyclable without property loss [33].
Anodized Al	High due to electrolytic process, voltage demands, cooling systems, and sealing steps [34].	11.8 kg CO_2/kg aluminium; reduced to 7.8 kg CO_2/kg when accounting for end-of-life recycling [35].	Fully recyclable
Coated Al	Lower than anodizing Powder coating is energy-efficient [36].	0.3–0.6 kg CO_2/m² depending on coating type and thickness [37, 38].	Fully recyclable; ~15% loss as dross [39].

Table 4. Comparative LCA of aluminium alloys: energy use, emissions, and recyclability

This comparison suggests practical strategies: prioritize recycled aluminium in cladding and façades, reserve 5000- and 6000-series for demanding structural roles and prefer powder coating over anodizing to reduce finishing impacts. Recycling efficiency depends on alloy compatibility and sorting, making design-for-recycling essential. The analysis is limited to energy, GHG emissions, and recycling potential, while other impacts such as water use and toxicity are excluded. Regional differences in electricity mix also affect results. Future work should extend analysis to building-scale LCAs and assess new recycling technologies under industrial conditions.

Conclusion

Overall, recycled aluminium is confirmed as the most sustainable option, delivering up to 95% energy savings and drastic emission reductions [33]. Primary alloys remain necessary for strength and durability, but their use should be minimized or balanced with recycled content. Coated aluminium offers a relatively low-energy surface treatment, while anodizing provides durability at higher cost to the environment. Integrating recycled content, refining scrap sorting technologies, and designing for closed-loop reuse are therefore critical to achieving circularity and supporting net-zero construction goals.

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