Low-carbon Aluminium is a Great Start – Next, Aluminium's Journey to Further Optimise Sustainability

Bill Wyllie[1,a]

[1]Arhitectural Anodised Finishes (AAF), Queensland

[a]bill@aafonline.com.au,

Abstract. Architectural aluminium is a growing and vital part of our built environment, providing a compelling building material for growing cities and regional areas due to its lightweight and strength properties and being infinitely recyclable. Starting with 'low-carbon' aluminium reduces carbon (dioxide) emissions from manufacturing.

This paper reviews the opportunities to further optimise sustainability of aluminium after manufacture. With Life Cycle Assessment (LCA), extended serviceable life will maximise the sustainability benefit calculations before the next recycling process. Finishing condition plays a key role in the serviceable life of aluminium, not only from a corrosion point of view, but also in maintaining the original aesthetic design and appearance of the building or structure. Warranty on finishes can provide a guide to serviceable life. However, empirical studies, such as the World Aluminium study *Aluminium and Durability* and several heritage buildings in Australia, provide some remarkable examples of life well beyond the warranty period. Reviewing highlights from the world study, this paper provides some examples of CO_2-e calculations by comparing finishes to assist in optimising the sustainability benefits of low-carbon aluminium to its full life cycle potential.

From Bauxite to Building

We begin with a brief overview of the aluminium product lifecycle.

- Aluminium is on the Strategic Metal list for the global net zero transition
- Australia is the world's largest producer of bauxite and second largest producer of alumina
- Aluminium is used extensively and has many advantages over other common metals
- It's 100% recyclable – recycling requires only 5% of the original energy used in its creation, and it's infinitely recyclable without deterioration

When selecting aluminium and finishes for a building, an Aluminium for Architecture & The Built Environment paper summarises six primary qualities:

1. Durable
2. Recyclable
3. Flexible
4. Light yet Strong
5. It's Efficient, and
6. It's Economical

Fig. 1 shows the various transformative stages in converting bauxite to finished aluminium products. With aluminium's very high levels of recycling, it also shows their return, transformed, as other aluminium products.

The Power Mix in the global manufacture of aluminium is now of major importance for sustainability. Initial decisions about power source were made for commercial cost reasons and availability of power, as opposed to environmental drivers. Today, hydro-power manufactured aluminium offers major environmental advantages creating this metal from green energy.

Today, companies such as Capral, one of Australia's largest extruders and aluminium distributors, are offering a choice of low carbon sourced aluminium products [2]. Raw billets/ingots of aluminium are measured by CO_2e emission per kg. CO_2e emissions have fallen from a world average of 13.9 CO_2e kg per 1 kg of aluminium, to as low as 4 CO_2e per kg. These suppliers and product choices support our national drive to net zero emissions.

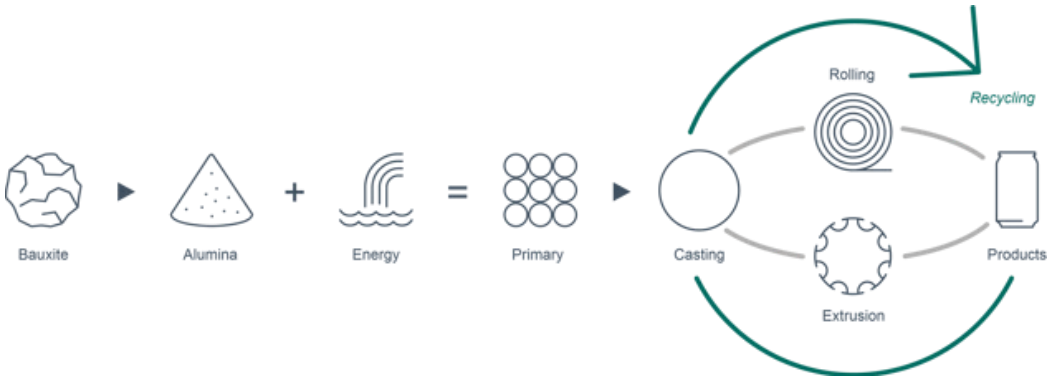

Figure 1: Bauxite to product life cycle [1]

Comparing CO_2e emissions -Per kg - and SQM surface area. Once aluminium is extruded or processed into sheet form, it presents a substantial surface area requiring finishing. This extensive surface coverage means that finishing processes—whether anodising, powder coating, or other treatments—play a significant role in the overall carbon footprint of aluminium products. With around 9 million kg of powders sold annually in Australia, plus emissions due to anodising, emissions produced by finishing are also critical in the environmental conversation. So, how can sustainability outcomes be improved by selecting appropriate finishes?

The Role of Coatings and Finishes

Most architectural use of aluminium is finished in some form, either for decorative or protective purposes. Finishes are often described as 100 % of the visibility, but less than 1% of costs. Decisions about the finish specified are extremely important since the life cycle for aluminium use is highly likely to be determined by the durability of the finish. High grade decorative and protective properties are needed to ensure optimal life and lower lifetime maintenance.

In this section we review four studies from around the world and the role of coatings and finishes to aluminium, in ensuring both durability and delivering strong aesthetic value.

International Aluminium Institute. Working mainly in Europe, The International Aluminium Institute funded a three-year research programme "Towards Sustainable Cities." The programme was led by Professor Michael Stacey, who toured and lectured in Australia in 2023. There were five separate studies, which document the evolution of aluminium in the building industry and how it performs. We'll focus first on the original study undertaken, called "Aluminium and Durability" [3].

The report details 50 examples of buildings from some of the earliest use of aluminium and finishes. All are high-quality architecture, incorporating a significant use of aluminium.

Figure 2: Key observations from Stacey's research in 5 reports [3]

Stacey illustrates the importance of lifecycle analysis in sustainability. It correlates directly to durability. As a self-confessed believer in aluminium, he describes aluminium as the servant of sustainability. In the seven key qualities identified for sustainability in buildings, number one is durability. This is followed by flexibility. Stacey refers to the "infinite possibilities for architects and designers to shape aluminium" and "the freedom to create imaginative colours and structures for both environmental and aesthetic outcomes."

The first building had the second oldest anodised aluminium windows ever installed in the world, - back in 1940, the New Bodleian Library at the University of Oxford (Fig. 3). Its windows were manufactured in Wolverhampton in the UK.

In 2015, the library was completely renovated, at a cost of some 50 million pounds. On inspecting the original anodised window frames, the refurbishment team determined, after they were washed and cleaned, that the frames were in fine condition and would be reusable, reglazed, with new double glazing. The design life of the renovation project, plus the time since original installation, would forecast a useful life of the anodised window frames at 135 years. It was described as “a great example of sustainability solutions & the planet”. The report stated: *“the quality of the aluminium was so good that the micron thicknesses recorded on the seventy-year-old aluminium were very similar to what you would expect to find on new anodised aluminium.”*

Figure 3: The New Bodleian Library at the University of Oxford was built in 1940. The anodised window frames remain in fine condition with a useful life forecast to be 135 years [3]

A 30-year-old building, finished with polyester powder coating, was also assessed. Three different blue finishes were employed. Filiform corrosion was found on the east facade. The report highlighted the significant advances in powder coating durability since this building was completed. Nonetheless all three blues, exposed to prolonged sunshine, had faded, particularly noticeable on the light blue surfaces.

In a third example, a London building with a bronze anodized finish was performing well, after 28 years of service. Measurement of material thickness was only slightly below current standards and there was minimal colour variation.

In reinforcing the comments in the evaluation of sustainability, Professor Stacey also focused on manufacturers' warranties as a useful measure of durability. He referred to suggested 40-year warranty periods, now proposed in the UK for Class 2 super durable powder coatings. While deemed to be useful, the study was not designed to quantify CO_2e emission factors when assessing aluminium or their coatings. An assessment was made of the condition and appearance of the finishes to determine durability, and thus, the sustainability of the buildings.

USA & Canada Research. In North America the journey of standards has been backed by work of the Aluminum Extruders Council. In 2022, as a service to their members, with the growing importance of sustainability, the AEC commissioned an Environment Product Declaration. The preface noted that aluminium extrusion is extensively used by product designers, engineers, and architects. As one of the most recycled industrial materials, it also makes a substantial contribution to sustainability efforts, despite high initial energy usage.

To maintain independence, Consultants, Underwriters Laboratories (UL Environment), were commissioned to undertake the Environment Product Declaration. The study was separated into three categories: Mill Finish, Anodized and Painted/Powder. It was based on information supplied by 100 extrusion presses in the US and Canada. In addition, 10 anodizing and 10 paint-powder facilities completed the study.

When compared to mill-finish aluminium, anodising adds 18% and Powder/Paint 43% to the quantity of CO_2e emissions (Fig. 4). This reinforces the need to consider the finishing of aluminium as an important element in overall carbon emissions assessment. Secondly, it's an indicator of the emission advantages in anodising.

ENVIRONMENTAL PRODUCT DECLARATION

ALUMINUM EXTRUDERS COUNCIL

Aluminum Extrusions

Mill Finished, Painted, and Anodized

According to ISO 14025 and ISO 21930:2017

Date of Issue:	Nov-22		
Life Cycle Assessment independently verified			
In accordance with ISO 14025: 2007; Cooper McCollum, UL Environment			
(Sample"US & Canada: 100 extrusion presses; 10 anodizing; 10 paint facilities)			
LIFE CYCLE IMPACTS ASSESSMENT(LCIS) RESULTS			
	Category 3		
	Finishing (eg extrusion)		
	Anodized; Painted/Powder		
	Unit 1 - Metric ton		
	UNITS - kg CO_2 eq.		
Global warming potential (GWP 100)	MILL FINISH	ANODIZED	POWDER/ PAINT
Kg CO_2 eq.	2.44	2.87	3.48
Percentage of Mill Finish	0%	18%	43%

Figure 4: AEC Environmental Product Declaration for coated aluminium [4]

Case Studies – Australia. Here in Australia, the KMH environmental scientists' research [5] is very important. It's unique, by:

- solely focusing on sustainability and carbon emission elements.
- making a direct comparison between the major aluminium finishes.

It was ahead of its time in 2010. Not until 12th December, 2015 in Paris did the world reach a global agreement to limit temperature rise to 1.5 degrees C. The KMH survey was also undertaken in a period when aluminium finishing was changing. For over 30 years aluminium finishing had been dominated by anodising. Then, wet paints started being converted to powder coatings. With this came major advantages of zero VOC's (volatile organic compounds). Powder coating is a one-coat efficient process, delivering a vast new colour range and the market steadily increased its use of powder coatings, as a result.

Some powder manufacturers, in promoting their products, were also making unrealistic "green-washing" statements. As a result, the KMH environmental scientific lifecycle report was commissioned to clearly document the environmental impacts of the different types of finishes.

The study was completed using Life Cycle Analysis guidelines on Green Marketing and compliance with the Trade Practices Act. It uses the current world metrics and expresses carbon dioxide and its equivalents (CO_2e) to assess greenhouse gas footprints. It specifically states that it does not address any other environmental elements such as chemical waste etc, common in both anodising and powder coating pre-treatment systems.

The report was also referenced by the AAC (American Anodizing Council) at their Annual Conference in October 2023 and quoting “Over a 100-year life cycle, PVDF & Polyester powder coatings consume almost twice the energy compared to anodising, resulting in a generation of 20 - 40% more Greenhouse Gases (GHG) than anodising”.

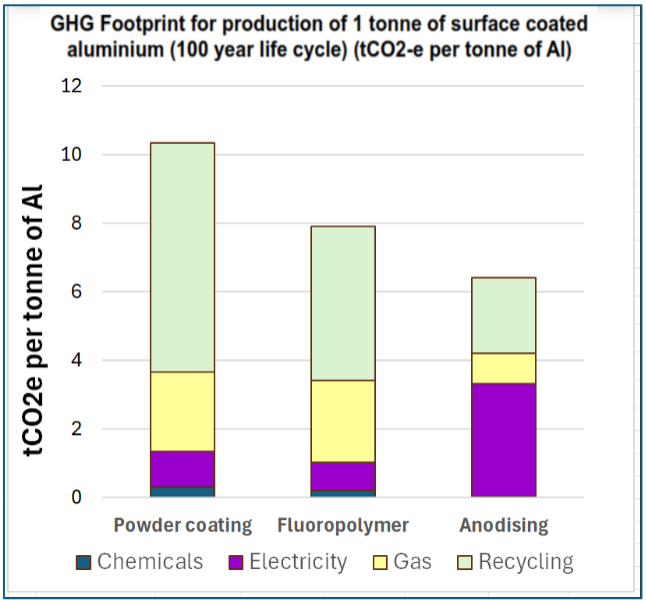

Figure 5: KMH study illustrates the emissions for anodising are significantly lower than powder coating [5]

Two Australian Heritage Buildings – Leading facade development. The International Aluminum Institute reports [3] did not look south of the equator. In 1955, Australian miners and industrialist turned the first bauxite soil in Weipa, Queensland, leading the way for Australia to become the world’s largest bauxite producer. Equally prominent, Australian architecture at the same time was very adventurous in building design. In the 50’s and 60’s there were lots of different ideas. Two significant buildings evolved and were modelled on New York buildings. They symbolised progress and modernity in post-war Australia.

ICI House in Melbourne, now the Orica Building (Fig. 6), was designed with the Architectural golden rule dimensions of 1 to 1.61. Architects for both buildings, Bates Smart and McCutcheon, modelled their designs on the best of façade design pioneered in the US at that time, employing an all-anodised aluminium curtain wall and glass. The facade was based on the United Nations building (1948-1952) and Lever House (1950-52), both in New York. At the opening of ICI House, around the time of the 1956 Olympic Games in Melbourne, the British ICI Chairman, Alexander Fleck, spoke of “an Australian landmark”, “a Commonwealth occasion”. It was far higher than any building allowed in the city of London at that time. Not everyone was so enthusiastic. Artist Norman Lindsay denounced the ICI glass box as “a final triumph to modernistic art, with its cry of death to all beauty”. Australian Aluminium Finishing sent a Quality Officer to inspect and measure coating thicknesses. While the facade is not well maintained one cursory test at a low level showed anodised thickness remained at a quite serviceable level.

A second building was the MLC in North Sydney, also heritage listed in January 2024. However, the facade is similarly not well maintained. Melbourne-based Prime Minister Sir Robert Menzies commented on opening the Sydney MLC building "the view from the top floor gives me such a new conception of Sydney that, quite frankly, I'm beginning to like the place!"

Finishing and Australian Standards

In this section, we address the actual standards used to support finishing materials decision making at the design stage.

Figure 6: ICI House in Melbourne, now the Orica Building, is an example of an anodised aluminium façade.

The key steps in the decision-making process flow for aluminium coatings:

A. What National Construction code applies?
B. Define the Environmental zone from C1 to C5
C. Consider the type of finish, anodised or powder coated and colours
D. Now consider overall economics and budget vs. aesthetics to determine the optimal material - anodising or powder coat
E. Finally: Review the environmental journey and required outcome

Australian Standards. Disseminating information about carbon emissions from Australian Standards is not obvious. The current stated objective of Australian Standards is "to ensure products, services, and systems are safe, consistent, and reliable". At this time, measuring emissions is not part of Standards role.

The Australian Standard for architectural powder coatings, is officially named "Metal Finishing – Thermoset powder coatings for architectural applications - AS 3715:2025" [6]. It is 20 years since it was last reviewed and this standard has now been significantly updated. To determine the suitability of various types of powder coatings, the structure is:

1. Assess the type of building structure: The National Construction Code covers this. Underlying the standard: Will the type of building use and conform to the NCC specifications?
2. Then consider the grades of powder rating for durability. Film integrity and colour and will be measured in terms of:
   - The AAMA or American Architectural Manufacturers Association performance requirements for architectural aluminium, and
   - QUALICOAT, the European performance specification for architectural aluminium.
3. Finally, environment is added to the equation. This assesses and groups atmospheric environment zones, as per Australian Standard AS-4312 [7].

The current Anodising Standard is named "Aluminium and aluminium alloys – Anodic oxidation coatings", AS 1231-2000 [8]. It has also commenced review in 2024. While early days, it is anticipated the same type of categorisation will take place for that standard when finally issued, AAMA 611 [9] will be the appropriate guide.

Finishing Technology and Improvements

Powder coatings – Polyester. This process transfers paint in the form of powder. It utilises electrostatic powder guns to attract the powder to the metal. The metal is pre-treated prior to coating. Once the powder is applied, it is then cured at considerable heat, depending on manufacturers' specifications. The finish is purely an in-house factory process. It's harder and a tougher finish than conventional paint.

Aluminium extrusions can be racked either horizontally or vertically. The increased investments in vertical line capacity have reduced unit costs, albeit restricted to extrusions lengths as opposed to formed sections or sheets, as examples.

The performance and development of the actual powders by local manufacturers in the Australian market has been outstanding. There are now many varieties, with choices of lustres, colours and a range of finishes. Warranties have been extended as the technology has improved.

Despite advantages like low VOC output and minimal waste, (as opposed to wet coatings) powder coatings still present environmental drawbacks as they are predominantly embodied with resins and additives and derived from petrochemical sources such as crude oil and natural gas.

Fluoropolymer Powder Coatings. Fluoropolymer technology is based on the chemistry of combining the carbon to fluorine atom (C-F) bond energy, labelled the strongest in organic chemistry, and stronger than the effect of UV rays.

The benefits of fluoropolymers powders are evidenced by:

- A requirement to meet the AAMA standard 2605 [10]
- Extensive warranties offered by the powder manufacturers.
- Measurements of years of service life in the KMH report.

In summary, there is a distinct advantage in the durability over the super durable polyester powders. They offer the longest performance and warranties - and thus an improved emissions performance.

In terms of cost, fluoropolymer in powder form is a more expensive to process, the cost of powder per kg is very much higher, and is combined with extended production and cure time compared to polyester powders.

The performance is demonstrated in the supporting powder manufacturer warranties. Dulux Fluoroset® offer the longest warranty period, 35 years film integrity and 30 for colour. Interpon Fluoromax® is more conservative with 30 year integrity and 20 colour. The new AS 3715 requires – L3 - ultra durable, to be specified in any C5 Environmental zone (AS4312) – or 100 metres from the coast. The coatings are also available in liquid form. A further example of their durability is in 2005 the Japanese Government Specification for the top coating of all bridges was changed- and now requires liquid FEVE coatings on all structures.

From an environmental assessment perspective, the increased durability of these fluoropolymer coatings, as with polyesters, is offset by their petrochemical origins.

Additionally, there are growing concerns with the chemistry of combining the carbon to fluorine atom (C-F) bond energy regarding the presence of PFAS—so-called 'forever chemicals'—which may remain throughout the life and recycling process.

Anodising. The anodising process was first used commercially 100 years ago. It's probably the least understood of all finishes. In all the case studies referred to, anodising is a superior solution for durability. Anodising was first used for the protection of flying boats from saltwater corrosion and the rigours of take-offs and landing.

For chemists, anodising is a classical type of electro-chemical conversion coating and the electro-chemistry is booming with green technology. It underpins newer technologies to avoid the use of fossil fuels, drawing on batteries and hydrogen fuel cells now in development.

The main difference from other coatings, such as electro-plating or powder/paints, is that the finishing process does not require the addition of another product onto the substrate to create the coating (Fig. 7).

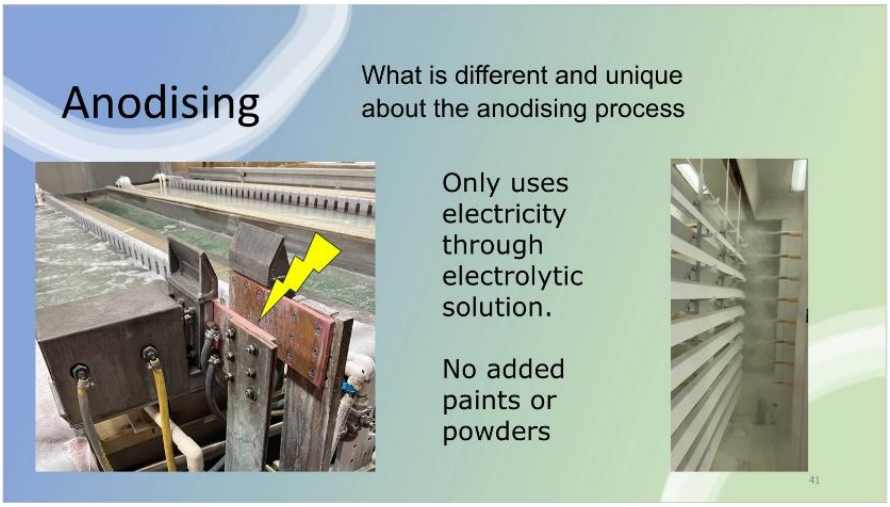

Figure 7: Key features of anodising aluminium surface

In the anodising process, aluminium is immersed back into an electrolytic (salt) bath - and connected to a very specific electric current. The process is similar to a huge battery. The process transforms the aluminium by creating nano-pores in the surface. These can then be imbedded with colouring. With high grade anodising processes, it is then sealed for the projected lifecycle of the aluminium.

In summary, anodising is an electro-chemical process that enhances aluminium without the addition of paints or petrochemical-based coatings. Key benefits include:

- Lower CO_2e emissions compared to Powder and PVDF coatings
- All-electric processing, ready to benefit from renewable energy
- Exceptional durability, supporting longer service life
- Zero added cost or waste in recycling

Although anodising has been used architecturally for over 80 years, its relevance is now stronger than ever. As electricity grids decarbonise, anodising's footprint will fall further, aligning with the direction of low-carbon aluminium production.

Technology eco-friendly improvements for anodising are also emerging to reduce energy use, incorporate green energy, and support closed-loop resource conservation. For example, current as opposed to voltage controlled processes reduce energy consumption and offer more precise control.

Why Local Finishing Elevates Projects and Lowers Risk

There are many reasons to source local finished products:

- Compliance with Stringent Standards: With multiple updated local standards, local supplier compliance is easier to confirm.
- Independent Auditing & Quality Assurance**:** Providers via the AISF Qualisure™, make available independently verified quality performance.
- Lower Transport Emissions: Local sourcing reduces carbon emissions associated with long-distance shipping, supporting overall project sustainability goals.
- Support for Local Industry & Innovation: Sourcing locally supports Australian manufacturing, fosters innovation, and strengthens supply chain resilience.
- Faster Lead Times & Better Communication: Local coordination ensures quicker turnaround times, better project support, and reduced risk of delays.
- Australia’s unique environment presents multiple challenges to architectural specifiers.
    - Harsh UV lighting.
    - Temperature/Humidity variations.
    - Large percentage of buildings in coastal, saline environment fringe.

Legislation for Measuring Emission Costs Changes in CO_2e

The year 2025 marks the continued transition toward several key changes in emissions reporting, reflecting evolving standards and greater accountability in environmental performance. For example, the IFRS (International Financial Reporting Standards) is now in effect. This requires reporting for emissions in IFRS S1 and IFRS S2 and are effective for annual reporting periods beginning on or after 1 January 2024.

In Australia, companies will need to disclose climate-related information as part of their general financial reporting, starting as early as July 2024 for some companies. Australian Security & Investments Commission ASIC chair Joe Longo described the shift as the 'biggest change to corporate reporting in a generation'. The Australian Government Energy Regulator has established National Greenhouse and Energy Reporting requirements, all staging in to more and more users with required reporting by 31st October each year. Infrastructure Australia also announced it will consider Australia's greenhouse gas (GHG) emissions reduction target under the Climate Change Act 2022.

Key Consequences of the New Legislation. These new reporting requirements are shifting industry priorities—placing equal emphasis on carbon emissions and financial performance. As detailed environmental science reviews become standard practice, Life Cycle Assessments (LCAs) will play an increasingly critical role in evaluating the long-term impact of building materials in our built environment.

While the adoption of low-carbon aluminium marks an important step, future CO_2e legislative assessments will also focus on the aluminium's serviceable life. In this context, the durability and performance of aluminium finishes will be essential factors in determining true environmental cost over time.

Highlights Summary

- Aluminium has a significant embodied carbon footprint as a virgin material. Coatings contribute to the emissions intensity of the final finished architectural product.
- Coatings play a crucial role in extending the lifetime of aluminium products in building applications. International and Australian standards apply to the robustness, performance, and specifications of finishes.
- Anodising offers emission reduction benefits by eliminating almost all petrochemical process emissions; by contrast powder coatings have a lower energy footprint, but much higher overall emissions.
- The decision factors for specifying aluminium product coatings involve identifying trade-offs relating to performance, aesthetics and lifecycle environmental costs. EPDs and warranties provide valuable information to support footprint analysis and final specification decisions.

Seven years after the last AAEC Conference, the drive to reduce carbon emissions in aluminium production has only grown. These improvements are amplified many times over when the finishing of aluminium achieves a greater serviceable life, and anodising is the preferred finish when carbon reduction is the main priority [19].

References

[1] Hydro, "Aluminium value chain", https://www.hydro.com/en/global/aluminium/about-aluminium/aluminium-life-cycle/

[2] Capral, "Lower-Carbon Aluminium", LocAl, https://www.capral.com.au/capability/lower-carbon-aluminium/

[3] M. Stacey, *Aluminium and Durability,* International Aluminium Institute, https://international-aluminium.org/wp-content/uploads/2024/03/Aluminium-and-Durability-TSC.pdf, (2015)

[4] AEC, "Environmental product declaration"

[5] KMH Sustainable Infrastructure, "Environmental Impact Comparison of Fluoropolymer Powder Coating, Polyester Powder Coating and Anodising Processes", Australian Anodising Association, (2010)

[6] Standards Australia, "Metal finishing - Thermoset powder coatings for architectural applications of aluminium and aluminium alloys", AS 3715:2025 (2025)

[7] Standards Australia, "Atmospheric corrosivity zones in Australia", AS 4312:2019 (2019)

[8] Standards Australia, "Aluminium and aluminium alloys - Anodic oxidation coatings", AS 1231:2000 (2000)

[9] American Architectural, "Specification for Anodized Architectural Aluminum", AAMA 611 (2024)

[10] American Architectural, "Voluntary Specification, Performance Requirements and Test Procedures for Superior Performing Organic Coatings on Aluminum Extrusions and Panels (with Coil Coating Appendix)", AAMA 2605-20 (2020)

[11] J.D. Morris and D. Slaton, "Modern Metals: Finishes, Investigation, and Conservation Considerations", ATP Bulletin: The Journal of Preservation Technology, Vol. 46, No. 1, (2015) p. 29-38

[12] X. Flandro and H.M. Thomas-Haney, "A Survey of Historic Finishes for Architectural Aluminium, 1920-1960", ATP Bulletin: The Journal of Preservation Technology, Vol. 46, No. 1 (2015), p. 13-21

[13] R. Piper, "The "White Metals" of Early-Twentieth-Century American Architecture", APT Bulletin: The Journal of Preservation Technology, Vol. 46, No. 1, (2015), p. 23-28

[14] J. Ashby, "The Aluminium Legacy: The History of the Metal and its Role in Architecture, JAMES ASHBY, Construction History, Vol. 15 (1999), p. 79-90

[15] A. Pense, "Metallurgy 102: Structure and Degradation of Metals", ATP Bulletin: The Journal of Preservation Technology, Vol. 46, No. 1, (2015), p. 5-11

[16] H. Leth-Olsen and K. Nisancioglu, "Filiform Corrosion Morphologies on Painted Aluminium Alloy 3105 Coil Material", Corrosion, Vol. 53, No. 9 (1997) p. 705-717

[17] A. W. Brace and P. G. Sheasby, *The Technology of Anodizing Aluminium*, Stonehouse Technicopy Limited, (1979)

[18] M. Stacey, *Aluminium: A Studio Design Guide*, UCL, RIBA Publishing, (2023)

[19] Australian aluminium Finishing, "Meeting Architectural Design Goals For Finishing Aluminium, While Reducing Environmental Impacts", Architectural Professional Development, (2024), https://cpdlive.com.au/courses/meeting-architectural-design-goals-for-finishing-aluminium-while reducing-environmental-impacts/