ARUP

Buildings & Infrastructure Priority Actions for Sustainability

Embodied Carbon

Aluminium

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Introduction

In 2022, approximately 60 million tonnes of aluminium were produced in 10 main countries, represented in Figure 1. Global demand is expected to continue to grow in response to an increasing global population, with aluminium used within several technologies important to the transition to a net zero economy.

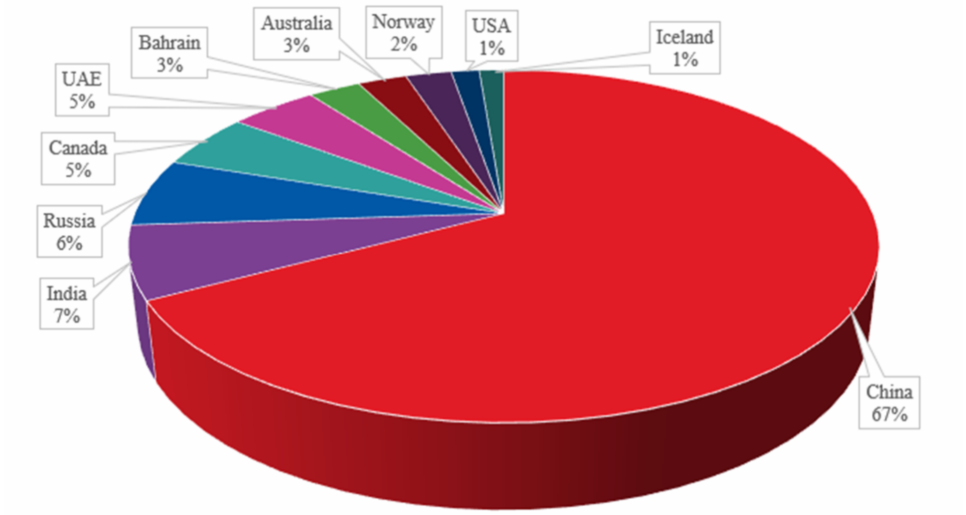

Figure 1 - Countries with the largest smelter production of aluminium, 2022 [1]

Aluminium is used in a wide range of products across the construction industry, ranging from architectural components, to structural framing and mechanical parts. This document provides information on aluminium products used primarily in buildings, which commonly include roofing sheets, cladding, facades (extrusions and sheets for unitised curtain walling), window and door frames, structural member connections (typically in timber construction), heat pumps and radiators, and renewable energy technology such as solar panels.

Aluminium production generates around 1.1 billion tonnes of CO_2 each year [2]. The production of aluminium is an energy intensive process, responsible for 2% of global greenhouse gas (GHG) emissions [2], accounting for 3% of worldwide direct industrial CO_2 emissions in 2021 [3]. Of the 2%, emissions from fuel combustion contribute to 15% and process emissions make up a further 15%. Aluminium production was originally developed based on hydroelectric power, and renewables continue to play an important role in the sector – however, the industry has moved away from renewable energy sources in some countries.

The greenhouse gas emissions (referred to in this document as 'carbon') and the carbon factor (the quantity of greenhouse gas emitted per kg of material) for aluminium can vary depending on raw material extraction, processing and manufacturing techniques, transportation mode and distance, and recycled content of the product.

As designers, we are responsible for specifying the extent and application of aluminium used on our projects; we need to understand the carbon emissions associated with each stage of the aluminium manufacturing process and work collaboratively with contractors and clients to meet increasingly critical carbon targets to ensure that the impact of our decisions is felt throughout the supply chain.

This document sets out the factors that contribute towards the emission of carbon through each stage of the whole life cycle of aluminium products used in the construction sector. It also highlights the potential route to decarbonising the production of these materials through identifying the principal constituents and their individual carbon journeys.

Stages

The stages referred to in this document align with the life cycle assessment set out in ISO 14040, where Stage A is 'up-front', Stage B is 'in-use', Stage C is 'end-of-life' and Stage D is 'beyond life-cycle'. Figure 2 illustrates how the lifecycle of aluminium products used in a building fit into the lifecycle assessment stages and the approximate proportion of carbon associated with each.

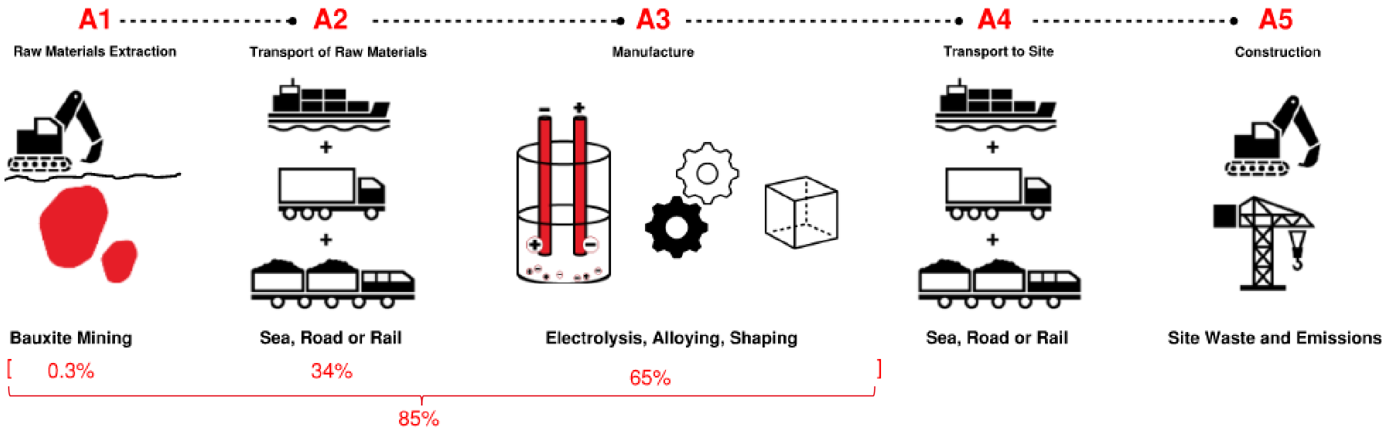

Figure 2 - Structural aluminium product lifecycle and approximate attributed emissions

Stage A

A1 – Raw material supply

Module A1 includes the carbon emissions associated with extracting and supplying the raw materials to manufacture aluminium. Bauxite ore is the main raw material, whilst sodium hydroxide, aluminium hydroxide and cryolite are used in the processing stages:

Bauxite

Bauxite is a sedimentary rock and primary ore of aluminium. It is a mixture of hydrous aluminium oxides, aluminium hydroxides, clay minerals, and insoluble materials such as quartz, hematite, magnetite, siderite, and goethite. [4]

In order to produce 1 tonne of aluminium, the extraction of 4-5 tonnes of bauxite is required. [5]

Bauxite is extracted worldwide, as shown in Figure 3; 90% of the world's bauxite reserves are found in tropical and sub-tropical areas [6] because bauxite of these origins contain the highest quantities of alumina [7]. Bauxite is mostly sourced through open cast mining, which involves clearing land of vegetation and soil. The soil is kept for replacement, and seeds or saplings may also be stored. The extraction of bauxite is carried out by blasting, drilling and ripping with bulldozers. [6]

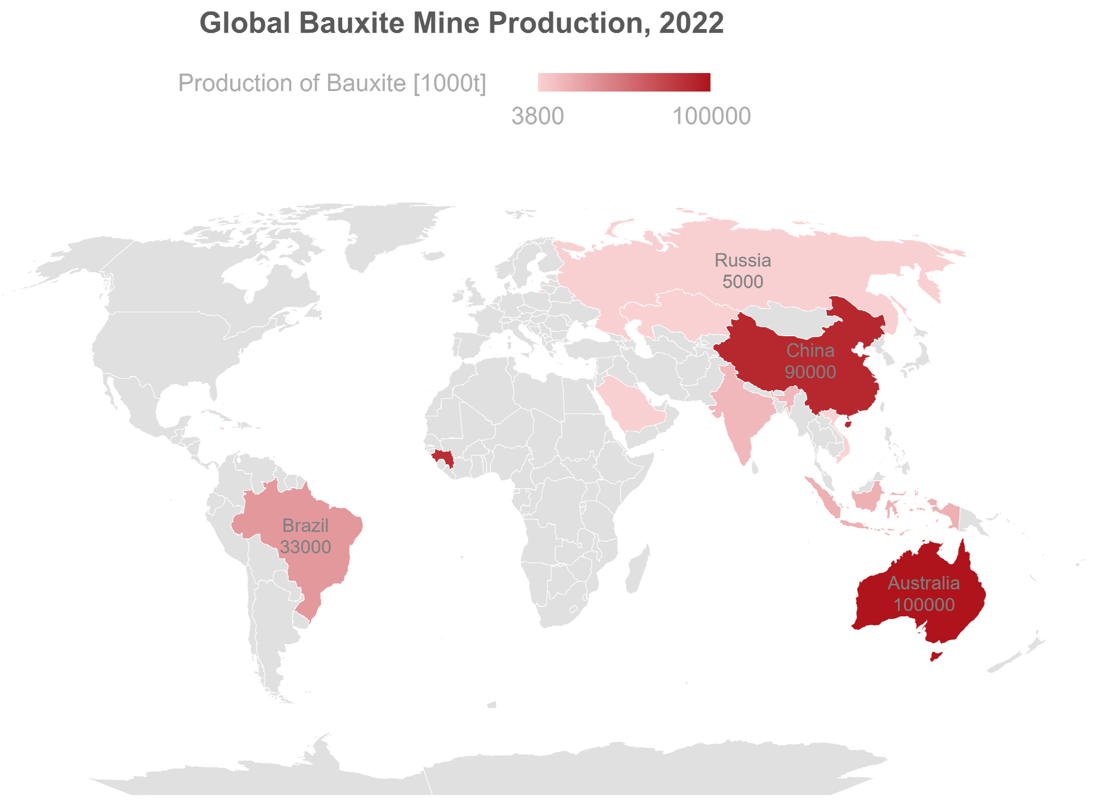

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Figure 3 - Global bauxite mine production, 2022 [8]

The global trade of aluminium has grown year on year; assuming no changes in techniques, this suggests that known bauxite reserves could be exhausted by 2055 and shortages of product can be anticipated. [9]

Sodium hydroxide

Sodium hydroxide (caustic soda) has the chemical formula NaOH. It is produced via the chloralki process, which involves electrolysis of an aqueous solution of sodium chloride. There is 0.6329kgCO_2e per 1kg of sodium hydroxide [10]. The major source of energy consumption for one kg of sodium hydroxide is electricity used for electrolysis, contributing around 93% of the fossil fuel consumption in the production of sodium hydroxide. The process consumes 3.5 MJ per one kg of sodium hydroxide [10].

Cryolite

Natural cryolite is a very rare mineral, first discovered in 1799 in southwest Greenland; in 1987 the mine was abandoned and effectively deemed to be exhausted [11]. Other pockets of cryolite have been identified, but natural cryolite is not commonly used in modern processes [12]. Typically, synthetic cryolite (typically sodium cryolite) is used in modern day aluminium production [13].

Recycled aluminium

Recycling of aluminium is commonplace, with 75% of all aluminium ever produced still in circulation [14]. The recycling process is outlined in stages C & D, later in this document. As presented in Figure 4, there is a significant difference between the average European and worldwide embodied carbon depending on the recycled aluminium content. Figure 5 explores how using recycled aluminium is less emission-intensive than primary production.

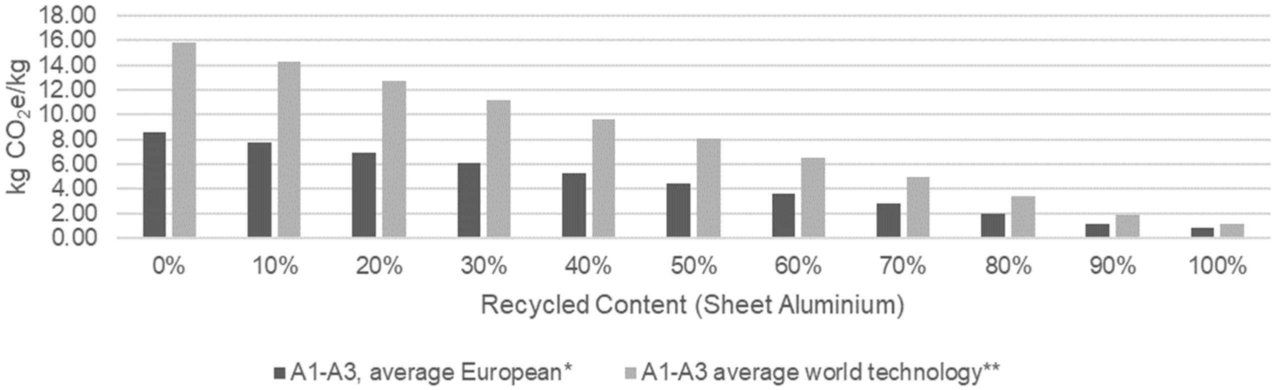
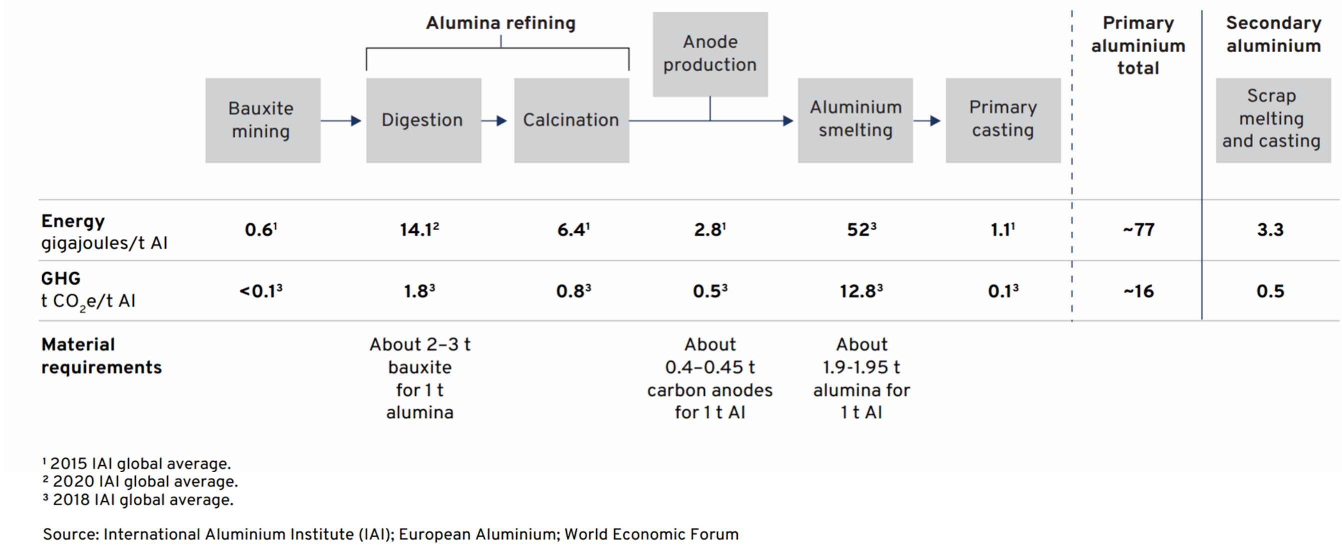


Figure 4 - European and worldwide recycled aluminium rates and associated embodied carbon. All the data is based on Ecoinvent resource for production of cast aluminium slab that is then rolled to produce sheets. Manufacturing energy inputs are electricity, burned diesel and district heating. Modelled with Ecoinvent resources [15]



		Alumina refining					Primary aluminium total	Secondary aluminium
	Bauxite mining	Digestion	Calcination	Anode production	Aluminium smelting	Primary casting		Scrap melting and casting
Energy gigajoules/t Al	0.6[1]	14.1[2]	6.4[1]	2.8[1]	52[3]	1.1[1]	~77	3.3
GHG t CO_2e/t Al	<0.1[3]	1.8[3]	0.8[3]	0.5[3]	12.8[3]	0.1[3]	~16	0.5
Material requirements		About 2–3 t bauxite for 1 t alumina		About 0.4–0.45 t carbon anodes for 1 t Al	About 1.9-1.95 t alumina for 1 t Al			

[1] 2015 IAI global average.
[2] 2020 IAI global average.
[3] 2018 IAI global average.

Source: International Aluminium Institute (IAI); European Aluminium; World Economic Forum

iii Total GHG cradle-to-gate emissions generated in bauxite mining, alumina refining, anode production, electrolysis, and casting; includes process, thermal energy, electricity, and ancillary materials emissions; 2018 global average.

Figure 5 - Embodied carbon of primary vs secondary aluminium production [16]

A2 & A4 – Transport

Stage A2 includes the carbon emissions attributed to the transport of constituent materials from their source or factories to the manufacturing site. Module A4 includes the carbon emissions attributed to the transport of the fabricated aluminium from the manufacturing site to final destination.

Typically, A2 transportation emissions are minimal, with aluminium refineries constructed near bauxite mines. However, over time these mines have been depleted and new sources are being utilised, sometimes further from the refinery [17]. Bauxite is generally transported to refineries by conveyor, rail, or ship [18] although the use of pipelines is beginning to gain traction [17]. Figure 6 shows typical emissions associated with transport via sea, rail and road.

Stage A4 transportation is typically a longer journey for customers, particularly in the UK. As shown in Figure 1, primary aluminium is not widely produced in the UK. There are some UK aluminium processors – however, they are typically responsible for intermediate and finishing processes such as shaping. The raw material feeding these processes is typically imported.

The electrification of railways, and development of hydrogen powered heavy goods vehicles (HGVs) are two changes which could enable the reduction of transport emissions associated with aluminium products.

Figure 6 - Transportation CO_2e values

A3 – Manufacture

Module A3 includes the carbon emissions resulting from manufacturing aluminium products. This can be split into two parts: the processing of the raw materials to create pure aluminium (extractive metallurgy), and the processing or fabrication of aluminium into finished products.

Steps 1 to 6 of Figure 7 are referred to as the 'Bayer process' and produce alumina powder. Step 7 is concerned with processing the alumina to aluminium metal using the Hall-Heroult process. At this stage, effectively pure aluminium ingots are produced.

		Percentage of A3 process emissions [2] [37]
Bauxite mining Crush & grind	Mining of bauxite ore as per Stage A1 Processing plants typically close to mining locations to reduce transportation. Bauxite is crushed, dried & ground.	0.2% – 2.5%
Pressure vessel Settling tank Precipitation Rotary kiln	The ore is pumped into large pressure tanks (digestor) with sodium hydroxide solution and steam heat is applied. Sodium aluminate - $Na[Al(OH)_4]$ – slurry is produced. The hot slurry is passed through flash tanks that reduce the pressure and recover heat that can be reused. It is then pumped into a settling tank. Impurities that did not dissolve in the NaOH will settle (forming "red mud*") and are removed. It is then pumped through cloth filters to remove fine impurities. The sodium aluminate solution is cooled and pumped into precipitators. Aluminium hydroxide seed crystals are added to the solution to start the precipitation process. Large aluminium crystals are formed, settle & are removed. The crystals are heated in rotary kiln to above 960°C. This extracts the last impurities and creates a white powder known as aluminium oxide or alumina.	10.5% – 32.5%
Smelting	The alumina is added to a reduction cell with 950°C molten cryolite. 400kA electrical currents are passed through the mixture to break the (alumina) bond between the aluminium and oxygen. The result is 99.8% pure aluminium.	20% – 80%

Figure 7 - Production of pure aluminium methodology

* At least 120 million tonnes of red mud is produced worldwide each year [19] [20]. It contains a mixture of oxides and potentially toxic heavy metals; there is a huge hazard associated with water and soil contamination due to high alkalinity. There is also a need for large storage areas for disposal, with ongoing maintenance and monitoring. This waste product can be used in road construction and production of cement, although only 3% red mud produced is currently recycled [21].

Processing of aluminium metal

Depending on the design of the smelting facility, aluminium is either cast into ingots for further processing, or remelted for alloying. In some cases, molten aluminium is transferred directly into furnaces (gas or electric powered) where alloying additions are made. Pure aluminium is a soft metal used in pure form in a limited number of applications, however most engineering uses require alloying to improve the mechanical properties.

Aluminium ingots are melted in a gas or electric furnace and alloying additions are made. Aluminium alloys are defined by an international numbering system as shown in Table 1, based on the main alloying element(s). There are hundreds of iterations of aluminium alloys of different compositions preferred for different applications.

Table 1 - Aluminium alloy series [1] [22] [23] [24]

Series	Principle alloying element	Possible benefits	CO_2 footprint of alloying metal ($kgCO_2e/kg$)	Possible Application
1000	99% pure aluminium	Good corrosion resistance High thermal and electrical conductivity Low mechanical properties Excellent workability		Packaging Electronics Heat exchangers Electrical conductors
2000	Copper	Heat treatable Increased strength	3.44-3.79	Fuselages for aeronautics Truck wheels & suspension
3000	Manganese	Moderate strength Food safe	3.8-4.19	Storage tanks Heat exchangers
4000	Silicon	Lower melting point Low thermal expansion High wear resistance	4.78-5.27	Welding wire Architectural applications Engine pistons
5000	Magnesium	Good corrosion resistance Good weldability	44.2-48.7	Welding wire Nautical applications
6000	Magnesium & Silicon	Good formability and weldability Good corrosion resistance Responds well to heat treatment Moderate strength	See above	Facades and extruded profiles Architectural applications Bridge railings Welded structures
7000	Zinc	High strength Heat treatable	3.46-3.82	Aeronautical industry High strength forgings
8000	Other elements (Fe, Li etc)	High strength Lightweight High elastic modulus	2.18-2.4 (Fe)	Aerospace industry

Fuel combustion and process emissions are responsible for the largest share of aluminium's embodied carbon, whereas the impact of alloy content on carbon emissions is comparatively minor.

Finishing

- **Product casting:** aluminium is suited to a range of casting processes; sand, gravity die and pressure die casting applications are often used where finished shapes of varying degrees of complexity can be cast.
- **Extrusion:** aluminium ingots, blooms or billets are squeezed at elevated temperature through dies to form long profiles.
- **Forging:** aluminium ingots or slabs are shaped at elevated temperatures in open or closed dies to form shapes.
- **Rolling:** aluminium slabs or ingots are hot and cold rolled to form plates and sheets, sometimes with patterned surfaces.

Recycled Content

As aluminium is easily recycled in closed-loop recycling processes, many aluminium products contain recycled material. This has a large effect on the carbon counting in product life cycle assessments in stages A1-A3. Using recycled aluminium results in products that are manufactured with less carbon associated with sourcing, transporting, and procuring of bauxite.

A5 – Site construction

Module A5 includes the carbon emissions of the construction related activities associated with the aluminium elements. This includes the emissions of the equipment used for installation, as well as the emissions associated with the waste material.

Site waste

The volume of site waste, and the associated carbon emissions, varies depending on the aluminium element and processes used by the contractor. The amount of site waste is often linked to the amount of manufacturing waste (part of module A3).

Waste, or scrap, from fabrication and manufacture is variable depending on individual processes. For example, cutting of aluminium sheet produces significant amounts of scrap while casting aluminium parts produces little scrap. Scrap from fabrication and manufacture of finished goods is generally recycled and is called “new scrap”. The main end uses, or classes, of aluminium-bearing goods include buildings (construction), durable goods, electrical (power), machinery, packaging, and transportation. Old, or post-consumer, scrap is generated at varying rates for different types of goods depending on the in-service life of the goods and the economics of collecting and recovering aluminium from the goods.

One element of site waste is packaging waste. This is typically cardboard, wooden pallets and plastic film. The plastic film is unlikely to be recyclable, however cardboard packaging usually is. Wooden pallets can be reused, and some contractors opt to convert these materials for site use.

Site emissions

Site emissions can vary depending on the installation preferences of the contractors and sub-contractors involved. An aluminium cladding panel will nearly always involve the use of at least one crane, which are typically powered by electricity or occasionally by a diesel generator.

Other typical equipment used during the construction of a building include: access lifts, static/mobile working platforms and plasma cutters. As the majority of these are powered by electricity, if the site is powered by renewable energy (or a decarbonised local electricity grid), the carbon emissions of these processes could theoretically be zero.

B – Use

Aluminium used in the construction sector typically has a service life of 50 years [25]. Stage B has a small contribution to the material's embodied carbon. For example, an EPD on 100m^2 of roll formed aluminium panel [26] gives the global warming potential over 100 years (GWP 100) of stage B2 as 83.7 kgCO$_2$ eq, based on the estimation that a panel requires re-painting two to three times after installation. For this product, stage B2 only makes up 6% of the GWP 100 of stages A1-A3, at 1580 kgCO$_2$ eq. The embodied carbon at stage B is highly dependent on the specific aluminium product [27], therefore it is typically not addressed in EPDs.

Corrosion

The corrosion rate of aluminium in most environments is very low, and finishes are typically only provided for aesthetic reasons. Different methods to prevent or limit corrosion of aluminium are outlined in Table 2.

Table 2 - Aluminium finishes

Process	Benefits	Carbon Impact	Life Cycle
Mill Finish	No surface treatment carried out after processing. Passive aluminium oxide layer forms on surface when exposed to air or moisture, protecting the material beneath from corrosion. Low maintenance option for applications not requiring a decorative finish.	Zero carbon impact of achieving this finish in stage B. If the material needs replacing, full carbon impact from Stages A1-A5.	Essentially corrosion resistant in architecture. Expected to last the design life of the building without maintenance, typically 50-60 years
Anodising	Thin, durable conversion coating comprising aluminium oxide Resistant to most atmospheric conditions. Can be coloured for aesthetic purposes. No use of VOCs or EPA-listed toxic organics during processing.	7 kgCO$_2$/kg (A1-A3) for an aluminium profile with anodized finish composed of 75% recycled content [28].	Typical life cycle for anodised aluminium elements in building is typically 50-60 years
Powder Coating	Organic coating applied electrostatically but thermally cured. Typically more durable and resilient than liquid applied organic coatings, with exception of fluoropolymers. Common in architecture	4.11 kgCO$_2$e/m^2 (A1-A5)	Typical coating life is typically 30-40 years

Architectural anodising requires high consistency and appearance of the finish, achieved through close quality controls over alloying and physical properties. As a result, little, if any, recycled aluminium is used in architectural anodising quality aluminium sheet. This could influence the embodied carbon associated to architectural anodised aluminium, resulting in additional stage A1-A5 emissions. [29]

B2 – Maintenance

As outlined in stage B1, aluminium is essentially corrosion resistant, so maintenance during the life cycle is generally limited to light cleaning of the finish, similar to glazing. Anodised and powder coated finishes cannot be readily repaired or maintained in-situ, thus the decorative appearance of finishes is a common reason for replacement. Due to limitations of surface preparation, manually painted aluminium elements are typically not suitable for architectural applications.

The embodied carbon associated with stages B3-B5 (repair, replacement and refurbishment) is considered to be included in values of stage B2.

C & D – End of life & re-use

Stage C includes the emissions associated with removing aluminium components from a building, while Stage D includes emissions associated with re-using or recycling aluminium elements.

C1 & C2 – Deconstruction, demolition and transport to waste processing

Information on the carbon impact associated with deconstruction and dismantling (C1) of aluminium on site is sparse and therefore taken as zero in an EPD for aluminium profiles [30]. This EPD conservatively assumes 10% of aluminium used in construction is sent to landfill, which can require transport over 200km to a disposal location by lorry. For 1kg of this mill finished aluminium profile, the total global warming potential for Stage C2 is 0.0329 kg CO_2 eq.

C3 & C4 – Waste processing and disposal

When an aluminium product reaches the end of its life (post-consumer scrap), it is systematically and selectively collected and sent to recycling facilities for secondary billet production. For example, a collection rate for aluminium products next to 95% is well documented in construction sector. [27]

With a low proportion of aluminium becoming a waste product, there is limited information on the carbon impact of stages C3 and C4. If reported in EPDs, this would include aluminium shredding, transport, incineration, and landfill. EPD data ranges from 0.12 kgCO_2e to 0.25 kg CO_2e for combined C3 and C4.

D – Recycling and Circular Economy

Recycling scrap aluminium requires only 5% of the energy used to make new aluminium [3]. Recycled aluminium is sorted, cleaned and remelted to form molten aluminium. The molten aluminium is then formed into ingots for rolling, casting or extruding. The value and possibilities for use of re-melted aluminium depend strongly on the extent of separating, cleaning and processing of scrap material. Aluminium products are highly recyclable, and all finishes applied for decorative purposes (see Table 2) do not alter the ability to recycle. During aluminium profile and sheet production, all process scrap (extrusion drop-offs from cutting, unfit material and discards, etc.) is fed back into remelting. When an aluminium product reaches the end of life phase (postconsumer scrap), it is systematically and selectively collected and sent to recycling facilities for secondary billet production.

Globally, 95% of manufacturing scrap aluminium (from stage A3) is collected whereas 70% of end-of-life scrap aluminium is collected [3]. In the construction industry over 90% of the aluminium used in building applications is being recycled, while the remaining 10% is being disposed or landfilled. The recycled aluminium from building applications is then used to make up 50% of the raw materials feed in further aluminium production [30]. Increasing the recycling and reusing rates to 100% by 2050 could reduce the need for primary aluminium by 25% which reduces the annual emission of the sector by avoiding the loss of 15 million tonnes of metal at end-of-life [31]. Key enablers to increase the efficiency of secondary production include technologies into improving scrap quality, scrap sorting and purification, in addition to switching to cleaner energy sources for the secondary production process when available.

Promoting the manufacturing and design of aluminium products with deconstruction in mind can foster the industry's reuse of the material or as a minimum high value recycling. Initial studies estimate a 49% saving in embodied carbon by designing for deconstruction [32]. Some barriers to deconstruction are:

- Existing perception towards reused materials
- Economic consideration
- Lack of incentives to deconstruct
- Re-certifications of materials for reuse
- Insurance/legal constraints
- Lack of supply/demand chains

Route to Net Zero

Demand for aluminium is predicted to increase by 80% by 2050. As engineers, designers and specifiers we can reduce this demand through implementing material efficiency in our designs to ensure aluminium is used effectively. [16]. Figure 8 shows the emissions reduction potential, subject to the whole industry engaging in decarbonisation:

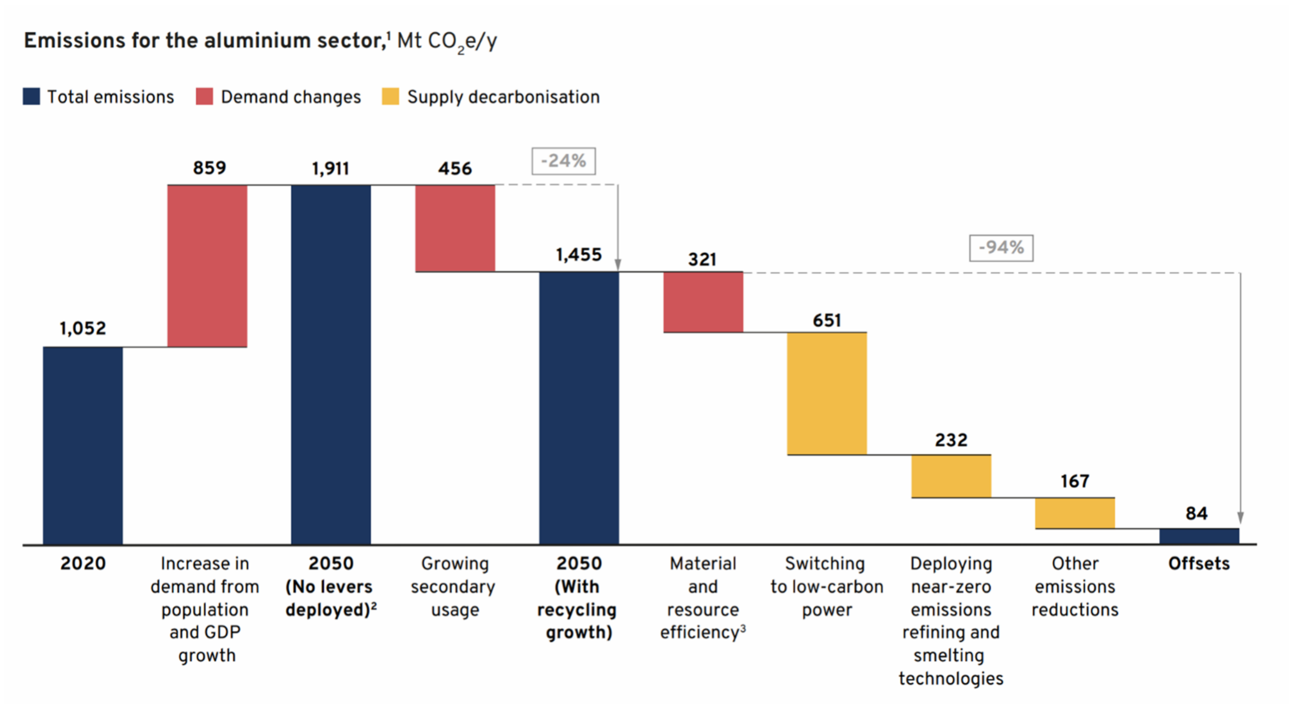


Figure 8 - Overview of emissions reduction potential by decarbonisation lever [16]

[1] Includes all direct and indirect emissions along the value chain for primary and secondary aluminium production (i.e., mining, alumina refining, aluminium smelting, anode production, casting, fabrication, recycling, and transport).

[2] Based on the IAI's Reference scenario, except for primary/secondary production ratio, which is assumed constant between 2020 and 2050; 2020 carbon intensity of aluminium assumed constant.

[3] Based on demand projections from the IAI's 1.5°C scenario.

Source: IAI Material Flow Model (2021); Aluminium Sector Transition Strategy Model (2022)

There are multiple ways to reduce the emissions for aluminium in our projects. Maximising material and resource efficiency in the design stage (lightweighting and focus on ease of repair) is the first step. It is also the only route to deal with the possibility that bauxite reserves could be exhausted by 2055 [9]. Other options to reduce emissions from aluminium production include:

- **Make good design choices**, such as finishes and processes required, with the design life, environment and de-constructability of the aluminium element in mind. For example, aluminium is an inherently a corrosion-resistant material, anodising and coating aluminium is typically used for aesthetic purposes only. Removing or minimising these processes will reduce the embodied carbon as well as the need for replacement due to defects or degradation of these finishes and coatings. This will also improve the efficiency and potential for using circular economy principles on aluminium products. Alternative materials should be assessed – aluminium is not always the answer and lower carbon solutions should be evaluated with care.
- **Discover new technology** for low carbon anodes and commercialise by 2030 [16]. For example, major industry pioneers Alcoa and Rio Tinto have partnered together to form ELYSIS, which is a new technology (inert anodes) that produces oxygen instead of GHGs in

the traditional smelting process. This aids in producing low carbon footprint products [33]. Other examples of low carbon technologies aimed to be commercialised by 2030 include HalZero by Hydro.

- **Switch to a low-carbon power supply** such as switching to the grid (provided it is decarbonised or renewable PPAs are available), renewable energy sources (hydropower, solar, wind) or nuclear small modular reactors (SMRs). Certain manufacturers like Alcoa and Hydro claim a reduction in carbon emissions (maximum or below 4 kgCO_2e/ kg of aluminium which is less than a quarter of the global average) by switching to renewable energy sources. They employ sources like hydropower, solar and wind to run their smelters [34] [35]. Carbon capture, utilisation and storage (CCUS) retrofitted at fossil fuel power stations tackles emissions from the existing running plants, enabling owners to recover investment and resultantly reducing the cost of power system transformations [36]. Additionally, CCUS gives flexibility for stable power. Many regions have growing shares of power from variable renewables, driving a greater need for flexibility to ensure the stable operation of their power systems. CCUS-equipped power plants can provide this extra flexibility across broad timescales [36].
- **Move to fossil fuel alternatives** such as bioenergy and hydrogen for alumina refining. Using near zero-emission electricity for lower temperature heat processes will also be important to get on track with the Net Zero scenario. Figure 9 shows a total energy comparison between 2010 and 2020.

  In the Net Zero Scenario, the emissions intensity of the total power mix declines by roughly 65% from today’s level by 2030. The aluminium industry should aim to reduce the intensity of its power supply by at least this much, including by reducing reliance on unabated coal-generated power.

  Increasing the proportion of aluminium production from low-emission electricity should be a top priority for the industry, and represents the biggest source of potential emission reduction in the short term. If the indirect emissions from power generation are included, they accounted for 70% of total (direct and indirect) aluminium production emissions in 2021, as shown in Figure 9.

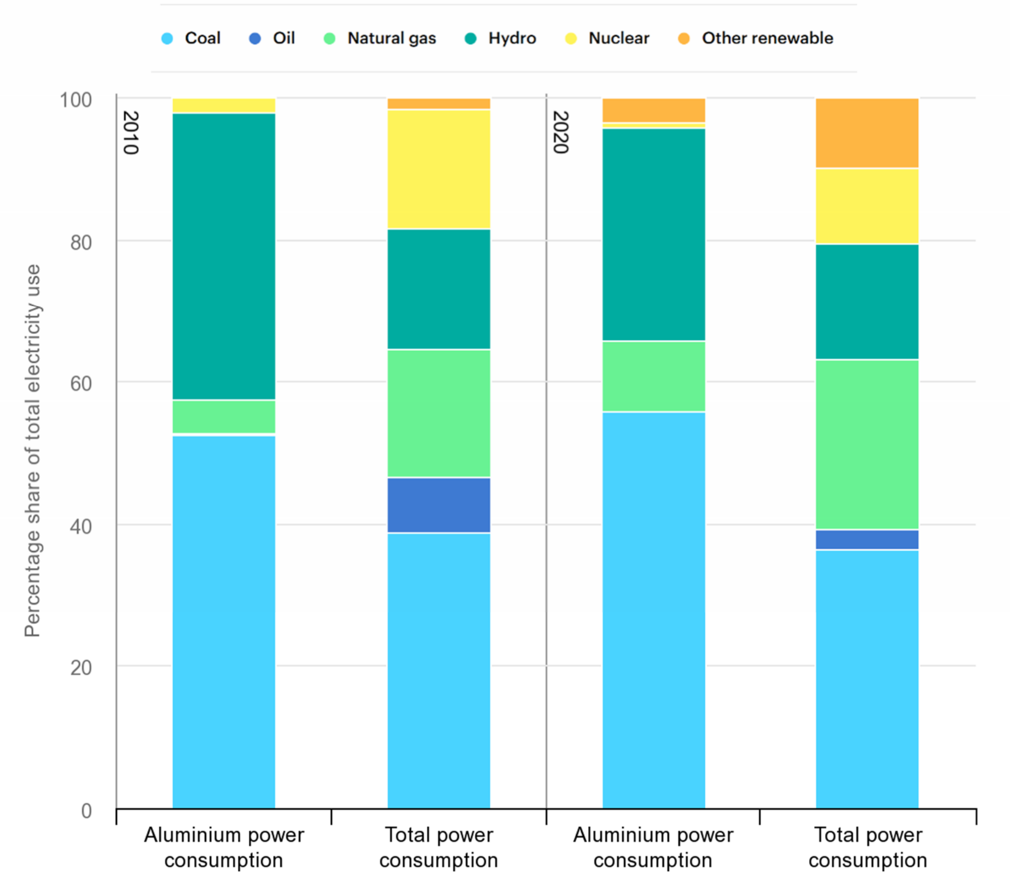


Figure 9 - Aluminium power and total power consumption (2010 to 2020 comparison) [3]

Scrap management and recovery

The International Aluminium Institute (IAI) calculates that around 15 million tonnes of aluminium will be lost each year by 2050 if no improvements are made to scrap collection and sorting. If 14.25 million tonnes were able to be recovered, it would reduce the need for primary aluminium by 15% and save an estimated 250 million tonnes of CO_2e per year (based on the 2018 carbon intensity) [36]. Efforts to increase scrap recovery should focus on:

- Advancing methods to divert aluminium from landfills.
- Improving separation techniques to decrease the mixing of alloys and address legacy material barriers - e.g. removing lead from existing aluminium alloys.
- Working with downstream partners for circular business models and closed-loop recycling.
- Supporting more complex collection and separation processes with digitization to track scrap throughout its lifetime and direct it to the correct channel to retain its value.
- Designing and creating products that are easily separated, collected and recycled.
- In-situ diagnostic tools to identify alloy composition (relates to point on separation and diversion of aluminium).
- Simplification of aluminium alloy types (related to Table 1).
- Data management and education of accurate reporting (particularly in the UK).
- Deposit return schemes and logistics (how the construction industry can emulate the packaging industry in the UK).

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