



Aluminium Sector Greenhouse Gas Pathways to 2050

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world-aluminium.org

International Aluminium Institute (IAI)

Current IAI membership represents the major producers of bauxite, alumina and aluminium in all significant regions, including China. Since its foundation in 1972, members of IAI have been companies engaged in the production of bauxite, alumina, aluminium, the recycling of aluminium, or fabrication of aluminium, or as joint venture partners in such. The key objectives of IAI are to:

- Increase the market for aluminium by enhancing worldwide awareness of its unique and valuable qualities;
- Provide the global forum for aluminium producers on matters of common concern and liaise with regional and national aluminium associations to achieve efficient and cost-effective cooperation;
- Identify issues of relevance to the production, use and recycling of aluminium and promote appropriate research and other action concerning them;
- Encourage and assist continuous progress in the healthy, safe and environmentally sound production of aluminium;
- Collect statistical and other relevant information and communicate it to the industry and its principal stakeholders; and
- Communicate the views and positions of the aluminium industry to international agencies and other relevant parties.

Through IAI, the aluminium industry aims to promote a wider understanding of its activities and demonstrate both its responsibility in producing the metal and the potential benefits to be realised through their use in sustainable applications and recycling.

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1. Aluminium: central to a sustainable future

Aluminium products are essential enablers of a low carbon future and the increased use of the metal will lead to reduced economy-wide emissions.

Fleets of lightweight, autonomous, electric vehicles delivering leased mobility services to a growing global population, powered by renewable energy grids; net positive, modular, intelligent buildings, producing more energy than they consume and adapting in real time to the varied needs of their occupants; lightweight and protective packaging solutions, bringing nutritional and pharmaceutical benefits to ten billion people by 2050, minimising wastage and reducing burdens on logistics – all will require the material and energy benefits that aluminium brings...and in increasing quantities.

While aluminium is part of the solution for a sustainable future (because of its unique combination of properties: lightness, strength, durability, electrical and thermal conductivity, formability and recyclability), the industry recognises that it has the potential to be part of the problem if the sector does not plan and act quickly to reduce its greenhouse gas emissions in line with societal climate goals. Increasing demand for aluminium will only be enhanced by transitioning to a low carbon trajectory and such paths will be different for different actors within the aluminium sector around the world and along the value chain.

This is a challenge. Not just an environmental challenge, but an economic, political, social, logistical and technological one, made even more complex by differential access to the solutions that will be required to deliver it (and the fact that many of these solutions are currently on the drawing board while others do not yet exist).

It is, however, a challenge that the aluminium sector is poised to address, in part through the work of the International Aluminium Institute (IAI), which is exploring realistic and credible technological pathways for 2050 sector-wide greenhouse gas emissions reduction. These pathways are in line with the Paris Agreement goal to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels.

With unrivalled industrial and material data and analyses, the IAI has mapped out the three main routes for the aluminium industry to achieve global climate goals (while addressing other sustainability issues). The technology needed in many cases is in the final stages of development and deployment, however, significant investment is required. The greatest need is for policies to support and accelerate that investment.

2. The International Aluminium Institute: a scientific authority & enabler of change

The Greenhouse Gas Pathways Working Group, made up of IAI member companies and regional associations, has worked collaboratively to understand and articulate:

- The emissions benefits delivered by the use and recycling of aluminium products;
- The sector's footprint and sources of emissions;
- How this footprint might change over the next thirty years if no action is taken, given changing demand for aluminium products;
- What the industry as a whole (and individual actors along the value chain) would need to achieve under a below 2-degree warming scenario;
- The range and mix of decarbonisation technologies, including existing, new, under-development and yet-to-be-developed solutions, available to different actors with varying processes and emission profiles;
- Policy (and investment) drivers and barriers to decarbonisation – through production process emissions mitigation and through recycling savings.

All of this is underpinned by the IAI's mature emissions models, built on its member companies' data and analytical expertise.

The pathway choices made by aluminium industry actors will depend on their unique energy endowments, raw material and scrap availability, regional policies, investment options and the availability, speed and cost of technology development and implementation.

There is a need for sector-wide and inter-sectoral partnerships to address the huge challenge of reducing GHG emissions, while satisfying growing demand. Partnerships will be required among and between producers, as well as with the public sector and academia, power generators, semi-fabricators, customers/original equipment manufacturers (OEMs) and end users. Due to its relative homogeneity in terms of processes and products, along with its scale and global scope, the aluminium industry can meet this need, with the IAI uniquely placed to initiate, facilitate and inform such partnerships.

3. What is the aluminium sector's carbon footprint?

The IAI has collected data on industry emissions for more than two decades, recently publishing a 15-year [database of sector emissions](#) (IAI, 2020a), which covers all processes cradle-to-gate. That means ALL the emissions that the sector generates in its own facilities (primary and recycling), but also those embedded in the raw materials, ancillary materials and energy that the sector consumes. This is the most comprehensive, detailed and up to date sector-wide dataset that exists for aluminium, but also any material, today.

According to this 2018 data, the sector is responsible for 1.1 billion tonnes of greenhouse gas emissions per annum, around 2% of all global anthropogenic emissions¹. More than 90% of this footprint is from primary production processes, while primary aluminium currently makes up around 70% of annual metal demand.

	Bauxite mining	Alumina refining	Anode production	Electrolysis	Casting	Recycling*	Semis production	Internal scrap remelting	Total
Electricity (indirect)	0.6	16.9	-	670.6	-	3.1	9.5	2.5	703
Non CO ₂ GHGs (direct)	-	32.2	-	35.4	-	-	-	-	68
Process CO ₂ (direct)	-	-	6.4	92.6	-	-	-	-	99
Ancillary materials (indirect)	-	14.8	19.3	6.4	-	-	-	-	41
Thermal energy (direct/indirect)	2.6	124.3	6.4	-	6.4	15.6	19.0	8.4	183
Transport (indirect)	-	15.4	-	18.7	-	-	-	-	34
Total (cradle to gate)	3	204	32	824	6	19	29	11	1,127

*Figure 1 2018 total aluminium sector emissions (Mt CO₂e) heat mapped, by process and source (*recycling of pre- and post-consumer scrap), (IAI, 2020a)*

In the IAI's [material flow analysis](#) (IAI, 2021a) demand for aluminium is expected to grow by 80% by 2050. This will be met by a combination of recycled and primary aluminium. Aluminium products already have high recycling rates. Yet, even with further improvements in collection, the long lifetimes of durable aluminium products, a growing population and a broader range of applications mean there will not be enough post-consumer scrap to meet this demand alone and primary metal will still need to be produced until at least the second half of the century.

Collection rates of end-of-life products are currently above 70%, having increased by 10% in the past 10 years (IAI, 2020b). However, there are still significant opportunities to increase the collection, sorting and recycling of post-consumer products to reduce (to some extent) the need for primary aluminium.

Primary aluminium production is an [energy intensive process](#) (IAI, 2020c), requiring huge amounts of electricity to break the strong oxygen bonds of the input chemical - alumina². The reactivity of

¹ Expressed as CO₂ equivalents – CO₂e (or 4% of carbon dioxide (CO₂) emissions)

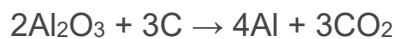
² Alumina is a chemical compound of aluminium and oxygen with the chemical formula Al₂O₃

aluminium is a function of its atomic structure, which is also the source of its valuable physical qualities, such as lightness, strength, durability and conductivity, making it the material of choice for so many applications.

The [production of primary aluminium](#) (IAI, 2018) begins with the mining of bauxite ores. Around 5.5 tonnes of bauxite is required on average to produce one tonne of aluminium. The mining process itself is relatively low emitting (compared to other processes in the value chain) representing one quarter of a percent of total sector emissions, mainly from mobile equipment. Transport of bauxite (and all other intermediate products) amounts to around 3% of emissions.

Alumina is extracted from bauxite in [the Bayer Process](#), which requires energy in the form of heat and steam, as well as ancillary materials such as sodium hydroxide, all of which come with a carbon footprint. Alumina production represents just under 20% of all sector emissions.

The [smelting](#) of aluminium currently takes the form of a reduction-oxidation reaction between the raw material, alumina, and carbon anodes, in which three electrons are provided to each aluminium ion to reduce it to its metal form, while the carbon atoms of the anodes are oxidised to form carbon dioxide, according to the reaction:



Thus, direct carbon dioxide emissions from this process are proportional to the production of aluminium. This electro-chemical process (electrolysis) requires electricity, carbon anodes and ancillary products, such as cryolite (sodium aluminium fluoride), as well as thermal energy to cast liquid metal into solid products. Electricity-related emissions dominate the 75% of sectoral emissions that smelting represents. And yet, this is the source with the greatest variation across the industry, depending on the smelter [power mix](#) – historically dominated by hydropower, but now increasingly by coal and gas combustion (IAI, 2020d).

Recycling on the other hand, requires much less energy – essentially only that needed to melt the aluminium scrap. It also has no need to reduce aluminium oxide to aluminium metal and so emissions of carbon dioxide from the chemical reaction mentioned above are eliminated.

Thus, the emissions profile of the industry is dominated by primary aluminium production, with a kilogram having a carbon footprint of anywhere between less than 5 and more than 25 kg CO_{2e}, depending on the [source of energy used to generate the electricity](#).

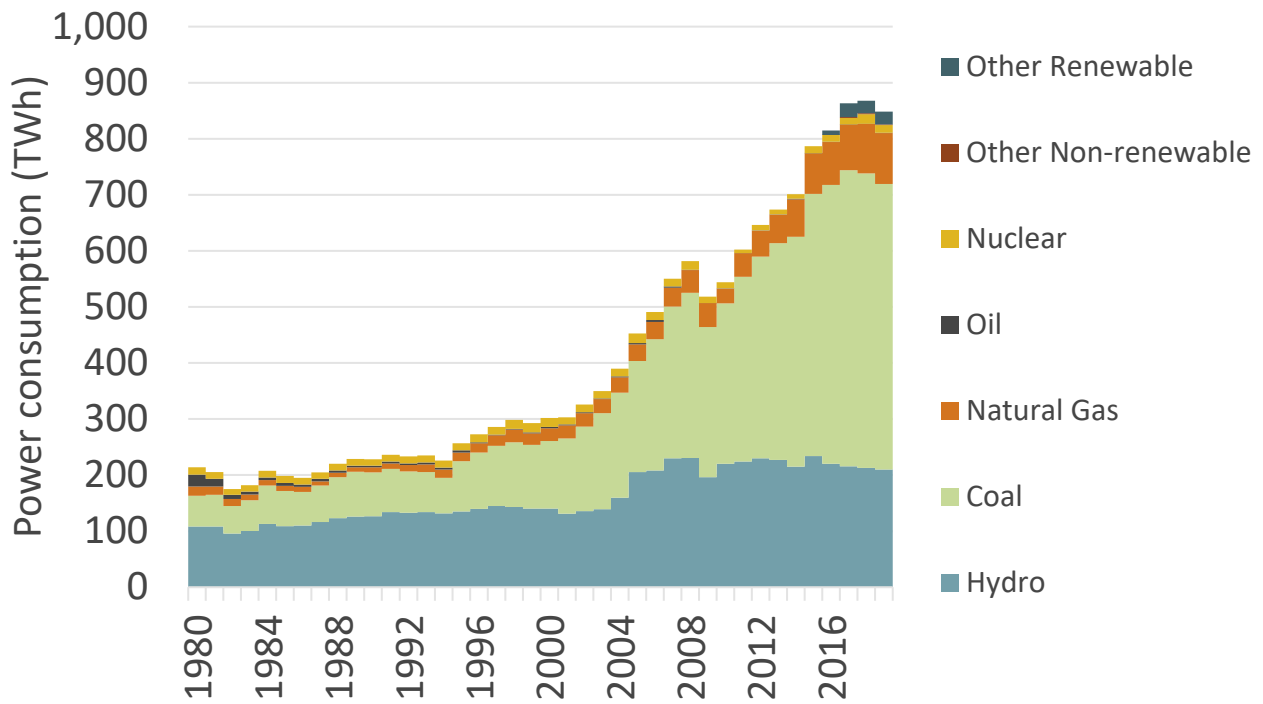


Figure 2 Global primary aluminium smelting power mix, TWh per annum (1980-2019), (IAI, 2020d)

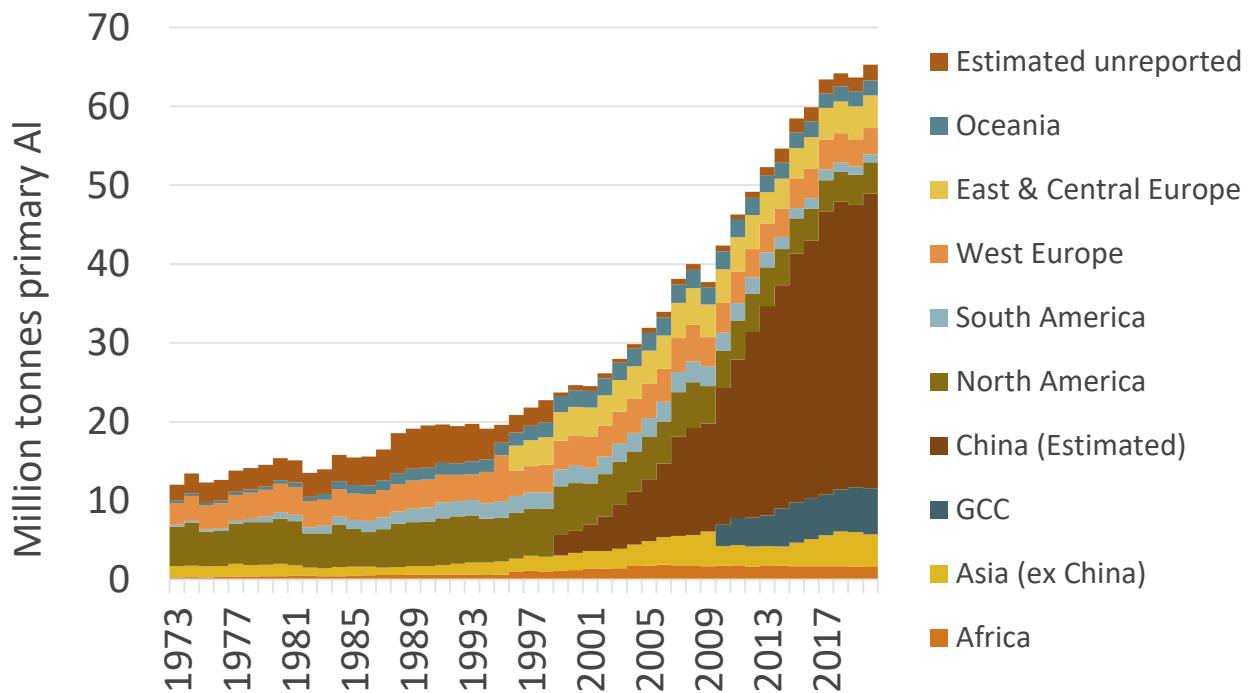


Figure 3 Global primary aluminium production by region, Mt Al per annum (1973-2019), (IAI, 2021b)

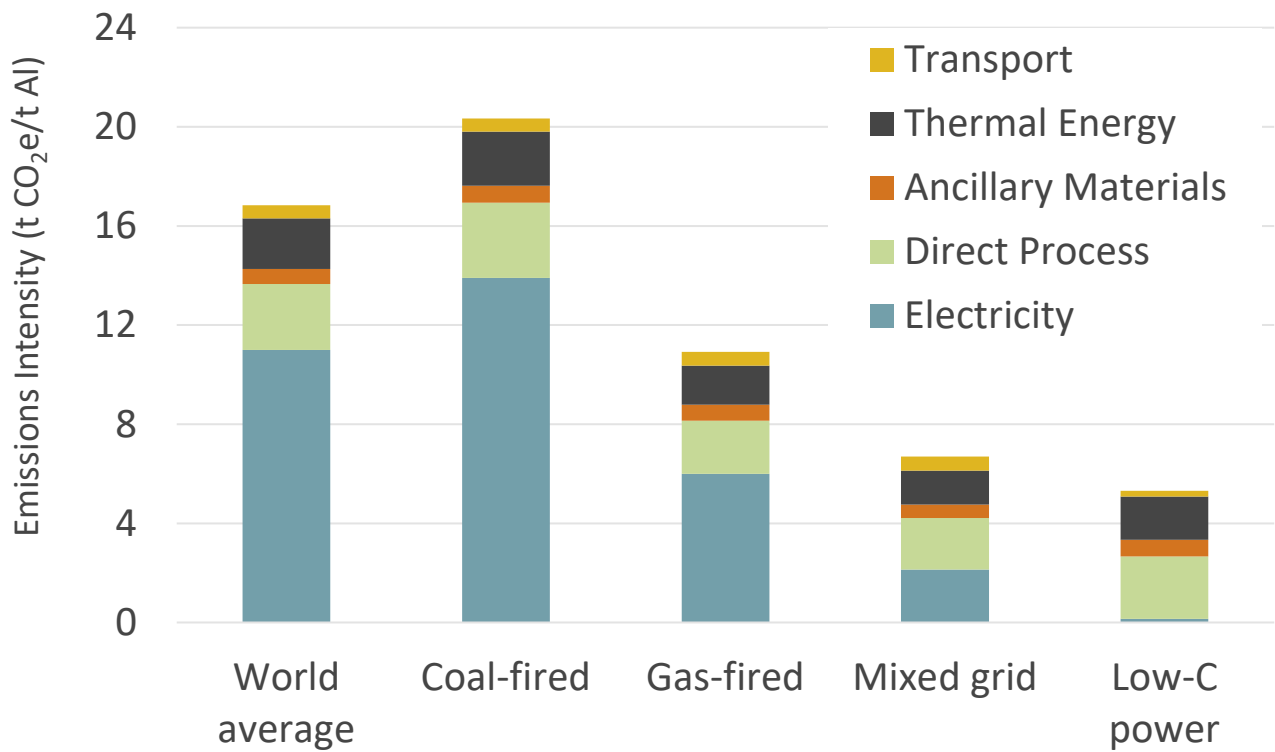


Figure 4 World average 2018 & example power mix cradle-to-gate emissions intensity of PRIMARY aluminium, t CO₂e/t Al

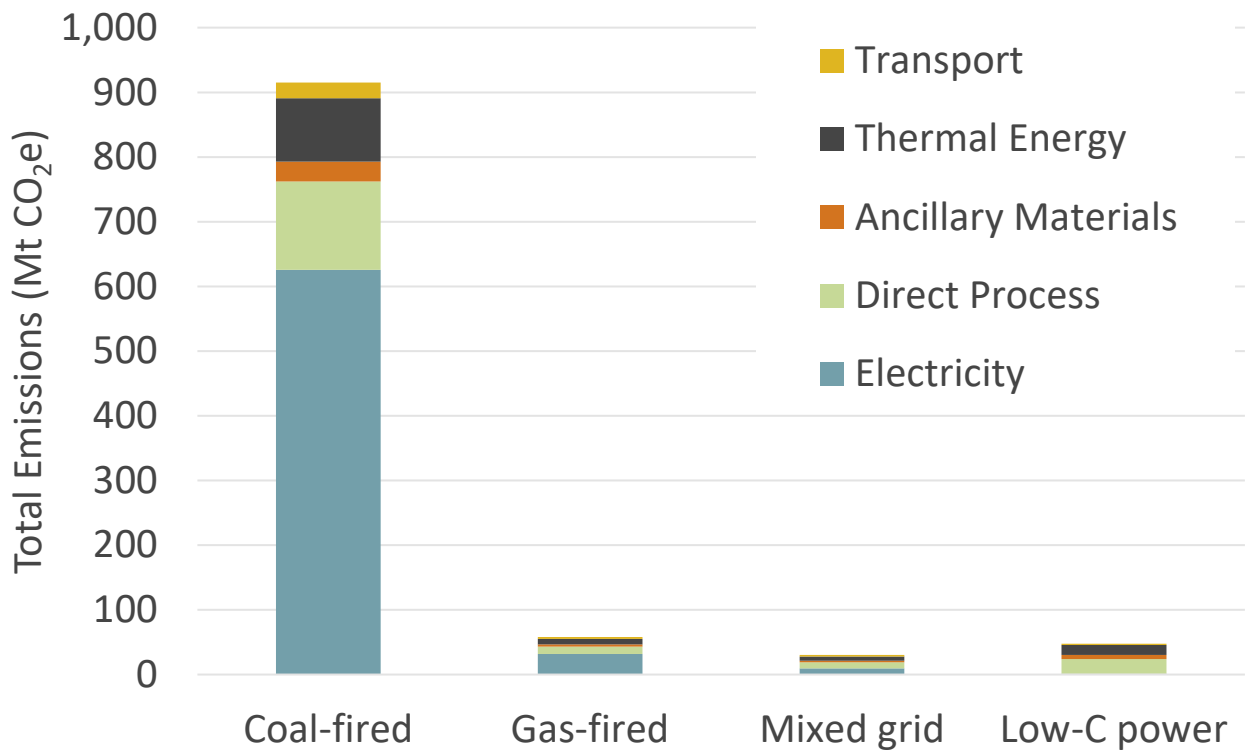


Figure 5 Total 2018 cradle-to-gate emissions from PRIMARY aluminium by power source, Mt CO₂e

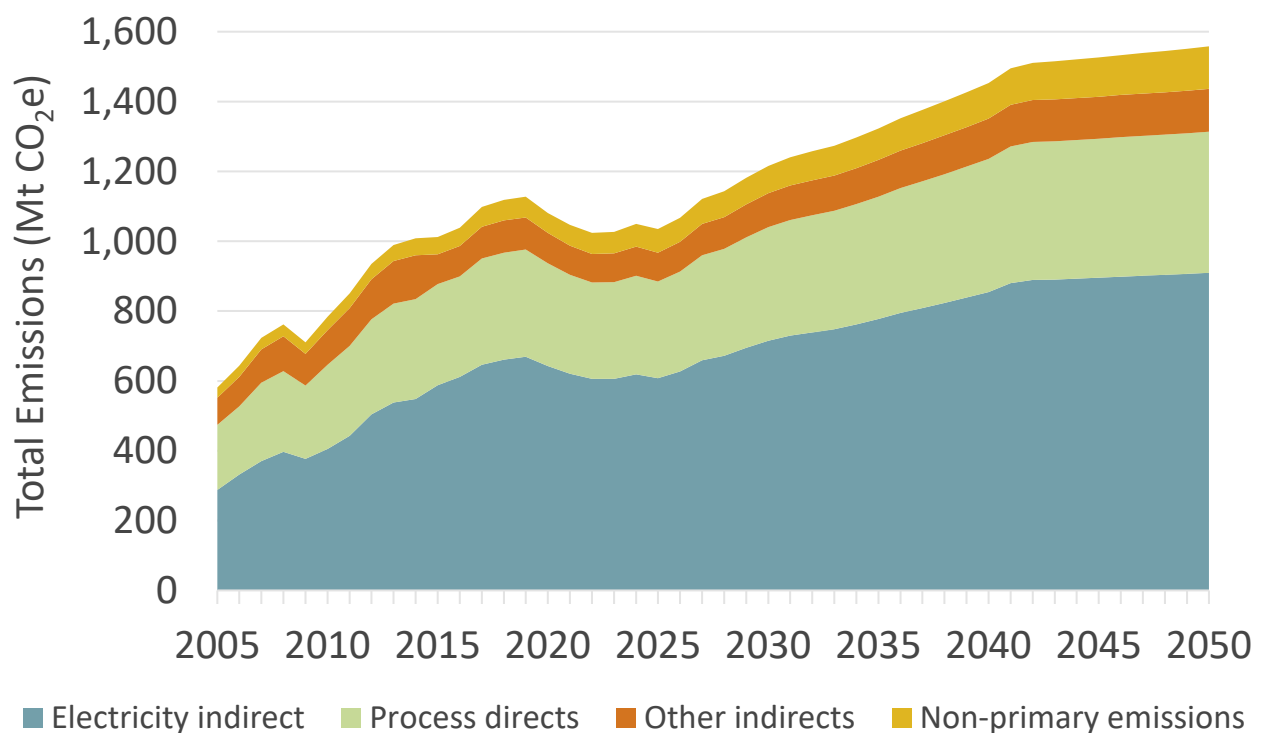


Figure 6 Historic (2005-2018) and forecast (2019-2050) global aluminium sector emissions under the BAU scenario, Mt CO₂e per annum

Driven by the expected growth in demand for aluminium applications, and even with recycling forming a significant proportion of supply (up to 60% by mid-century), Business As Usual emissions for the sector are forecast to reach 1.6 Gt CO₂e by 2050, the majority (1.5 Gt) from primary production.

4. What would a Paris-aligned 2050 aluminium footprint look like?

The *International Energy Agency* (IEA) recognises the contribution of aluminium to a decarbonising world and has therefore given the sector a 2050 allowance for greenhouse gas emissions that is above zero, even as the world would need to be at net zero by the second half of the 21st century.

The IEA has published two below 2°C warming scenarios: the [Beyond 2°C Scenario \(B2DS\)](#) (IEA, 2017) and the [Sustainable Development Scenario \(SDS\)](#) (IEA, 2020). Under B2DS, the IEA forecasts that by 2050 there should be a reduction in total anthropogenic CO₂ emissions from 34.3 Gt CO₂ (2014) to 4.8 Gt CO₂, whilst the SDS requires a reduction from 35.7 Gt (2019) to 9.4 Gt CO₂ (2050). The IAI decided to work under the B2DS scenario framework due to the availability of regional electricity datasets and the lower overall global CO₂ emissions budget by 2050. Nevertheless, the IAI will continue to work on improving its scenarios based on material flow modelling and updated climate science.

The IEA's B2DS budget for the aluminium sector includes a subset of the industry's direct emissions, with separate regional pathways for the electricity consumed by the industry. The IAI has therefore

brought together the IEA scenario for direct CO₂ emissions generated by the aluminium sector and its power consumption and developed B2DS-aligned pathways for the emissions not included in the IEA's dataset. The result is a B2DS-aligned pathway for the entire aluminium sector, which indicates that by 2050:

- Total aluminium sector emissions covering the entire chain (bauxite, alumina and primary aluminium production, pre- and post-consumer aluminium scrap recycling and semi-finished aluminium production processes, cradle-to-gate) would need to be reduced to 250 Mt CO₂e (from a 2018 baseline of 1,100 Mt CO₂e and a projected Business as Usual (BAU) 2050 pathway of 1,600 Mt CO₂e).
- Out of this 250 million tonnes, the emissions from electricity consumed in all primary processes (but in particular smelting) would account for near zero emissions. Today this source accounts for 700 Mt CO₂e and in 2050 would emit 900 Mt CO₂e under BAU.
- Non-electricity primary aluminium emissions (cradle-to-gate) would need to be reduced from 400 Mt CO₂e today (over 520 Mt in 2050 under BAU) to below 200 Mt CO₂e.
- Fuel combustion and electricity emissions from recycling and fabrication processes would need to be reduced by 55% compared to BAU, from over 120 Mt CO₂e to 50 Mt CO₂e.

In 2018, global demand for aluminium was 95 million tonnes per annum; two-thirds of which was met by primary aluminium and one third from recycled scrap.

Rapid population and economic growth over the coming decades means global demand for aluminium is set to increase by up to 80% (to 170 Mt) by 2050 ([material flow model “2020 IAI Reference Scenario”](#) (IAI, 2021a) and this will still be met by a mix of both recycled and primary metal.

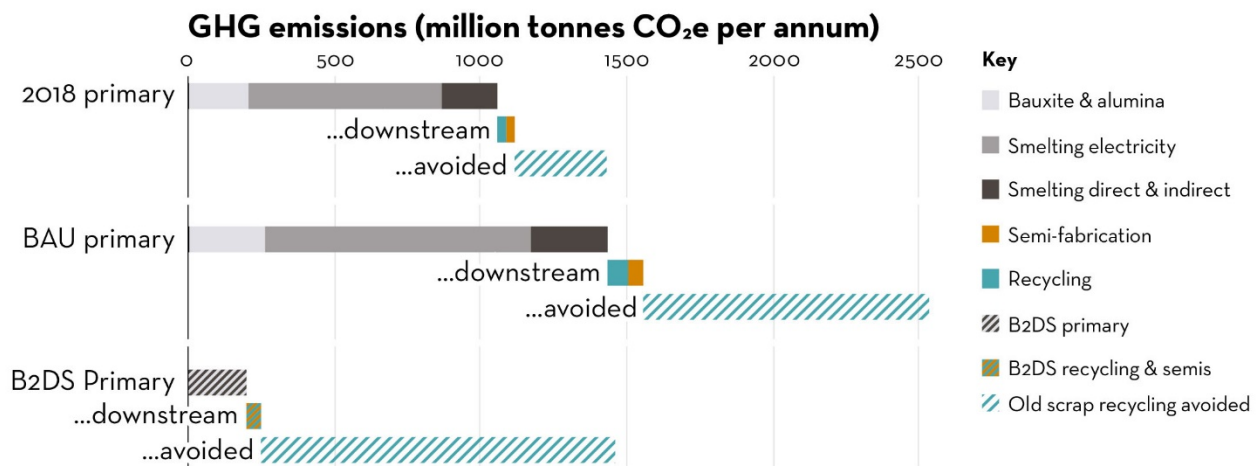


Figure 7 Sector-wide emissions in 2018 and 2050 under BAU and B2DS, Mt CO₂e

The global average emissions intensity of a tonne of aluminium (semi-fabricated) product would therefore need to be around 1.5 t CO₂e/t Al (cradle-to-gate) in 2050 to be B2DS aligned:

$$(2050 \text{ B2DS-aligned sectoral "allowance"}) / (2050 \text{ aluminium semis demand})$$

$$(\text{million tonnes CO}_2\text{e}) / (\text{million tonnes aluminium})$$

$$250 / 170$$

$$= 1.5 \text{ t CO}_2\text{e/t Al semis}$$

Despite increased projected recycled metal supply, the IAI estimates that between 75 and 90 million tonnes per annum of primary aluminium will still be required in 2050. Assuming a primary aluminium “allowance” of 200Mt (80% of the 2050 budget, compared to 95% today), the average emissions intensity of primary aluminium would need to be 2-3 t CO₂e/t Al (cradle-to-gate) to be B2DS aligned:

$$(2050 \text{ B2DS-aligned primary "allowance"}) / (2050 \text{ aluminium primary demand})$$

$$(\text{million tonnes CO}_2\text{e}) / (\text{million tonnes aluminium})$$

$$200 / 80$$

$$= 2.5 \text{ t CO}_2\text{e/t Al primary}$$

Broadly these numbers assume a 100% reduction of electricity-related emissions over the next 30 years - a significant challenge for primary producers. This also assumes a 50% reduction in direct (process and thermal energy) emissions and those embedded in raw materials and ancillary processes – a challenge common to all players along the value chain, including the downstream industry.

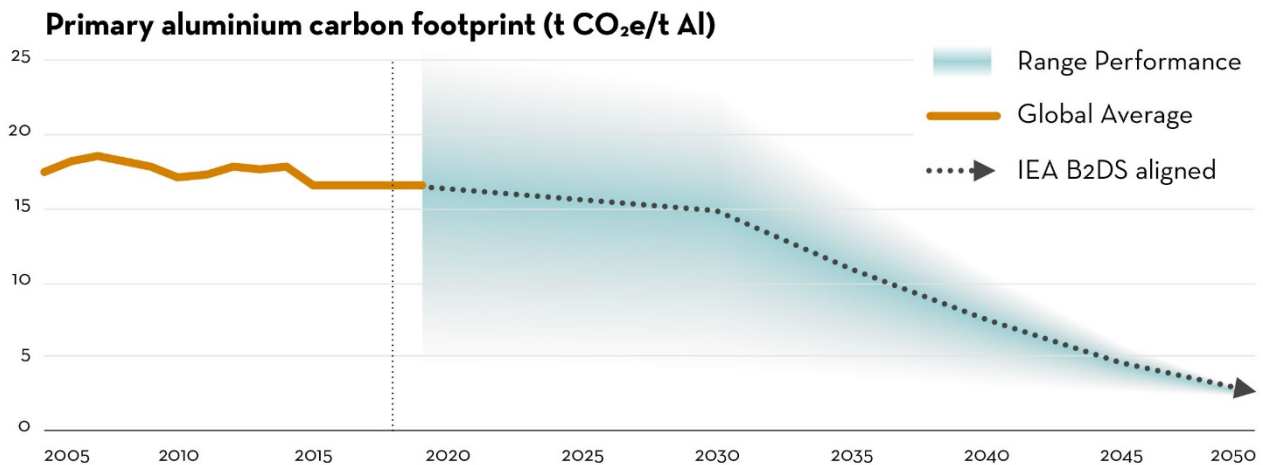


Figure 8 Global average primary aluminium carbon footprint under B2DS aligned 2050 scenario, t CO₂e/t Al

5. GHG emission reduction pathways

There are three broad areas that have the potential to contribute to this delinking of growth and emissions, each with distinct innovation, policy and financial drivers, barriers, costs and materiality:

1. Electricity decarbonisation
2. Direct emissions reduction
3. Recycling & resource efficiency

The following exploration of greenhouse gas emissions pathways identifies the most significant (greatest emissions reduction potential) technological and policy changes that can/may be implemented in order to realise sectoral B2DS-aligned decarbonisation.

Depending on where they sit within the aluminium value chain, the processes currently employed and the future availability of energy and material resources, different corporate actors will follow different (or a range of different) pathways, at different rates and from different starting points.

Electricity decarbonisation

The generation of electricity was responsible for 60% of the sector's emissions in 2018.

Decarbonised power generation and the accelerated deployment of carbon capture utilisation and storage (CCUS) offer the most significant opportunity for emissions reduction.

Decarbonisation of electricity grids (currently supplying a third of the industry's power needs) and a shift in captive (self-generating) power plants to low/near-zero emissions sources will require significant investment, both for the existing 45 million tonnes of primary aluminium currently powered by fossil fuel-generated electricity, and for the additional 20-25 million tonnes of aluminium production capacity required to meet 2050 demand.

Existing producers are presented with a wide range of significantly different opportunities, technologies and pathways depending on local circumstances and energy endowment.

Aluminium production in fossil fuel heavy regions is predominantly powered by self-generated electricity. In some cases, this is due to grid power being unreliable during the construction of smelters, which require 24/7 power. [IAI data](#) indicates that 97% of electricity in Asia (ex-China), for instance, is self-generated (IAI, 2020d).

Depending on the pathway(s) followed, the capital investment required for electricity decarbonisation is in the range of US\$ 0.5 to 1.5 trillion over the next 30 years.

Aside from this capital investment, it is recognised that the sector (and society in general) will likely pay more per unit of energy and that further investments will be required to upgrade or install new aluminium production facilities.

Hydropower was the dominant source of electricity for aluminium smelters [throughout the 20th century](#) (IAI, 2020d). While hydro-based production has remained relatively flat since the 1970s, recent years have seen plans for significant growth. This has occurred as a number of aluminium producers in China begin to replace coal-fired capacity (much of it relatively young, less than 10 years old) in central and eastern China with new capacity in Yunnan Province. Three million tonnes of aluminium have relocated in the last year with a further 3-5 million tonnes scheduled to shift in the coming years. This is part of a broader plan for [low carbon aluminium production](#) proposed by the largest Chinese producers (China Hongqiao & China Aluminum Corporation, 2021).

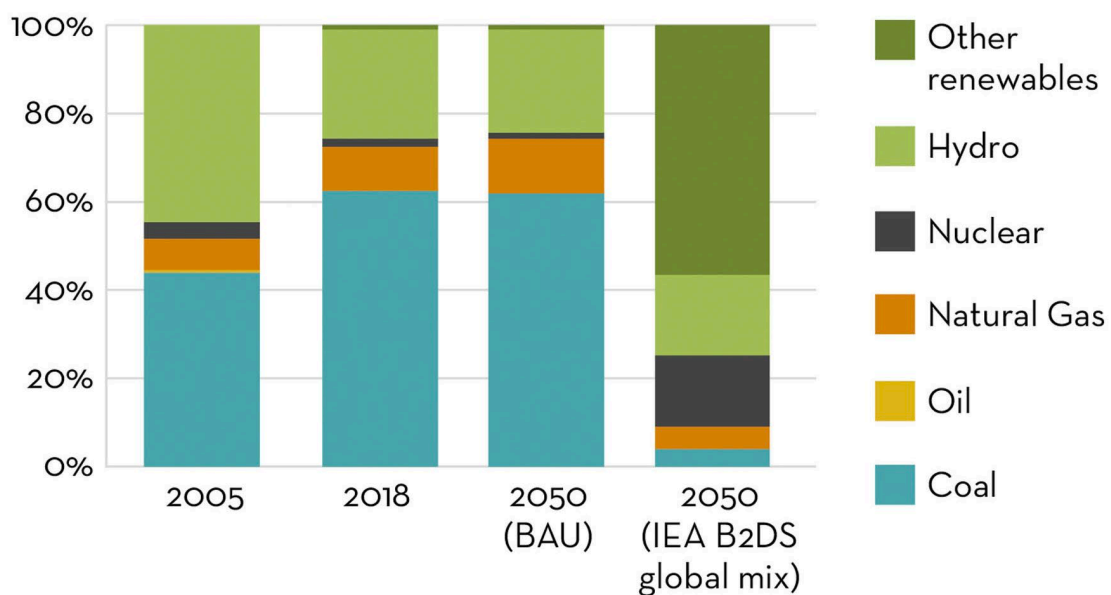


Figure 9 Changing smelter power mix under 2050 BAU compared to IEA Beyond 2 Degree Scenario (B2DS). (Fossil fuel in B2DS predominantly with CCUS).

The United Arab Emirates (UAE) [Energy Strategy 2050](#) (UAE Government, 2017) aims to reduce the carbon footprint of power generation by 70% (with an energy mix that combines renewable, nuclear and other clean energy sources). It will also improve the energy efficiency of consumers by 40%, through an AED 600 billion (USD\$ 165 bn) investment over the next 30 years, while delivering savings of AED 700 billion (USD\$ 190 bn).

Carbon capture utilisation and storage (CCUS) from power plants has the potential to reduce emissions from electricity supply at a similar level as grid decarbonisation at similar costs per tonne of carbon, with the [IEA identifying](#) costs of US\$ 40-80/tCO₂ for coal- and gas-fired power plants (IEA, 2019).

Energy efficiency gains in existing facilities through incremental improvement (“creep”) and retrofitting and installing new capacity would contribute only 10% to emissions reduction.

As grids transition to lower inertia (intermittent renewable electricity generation sources, with a changing demand base including more electric vehicles that lead to peak loads at given times), large and consistent electricity consumers, like aluminium smelters, will play an increasingly important role in stabilising grids. This enabling role will be important in giving smelters access to renewables grids – in the same way that many 20th century smelters enabled the development of new power networks in regions such as Brazil and southern Africa.

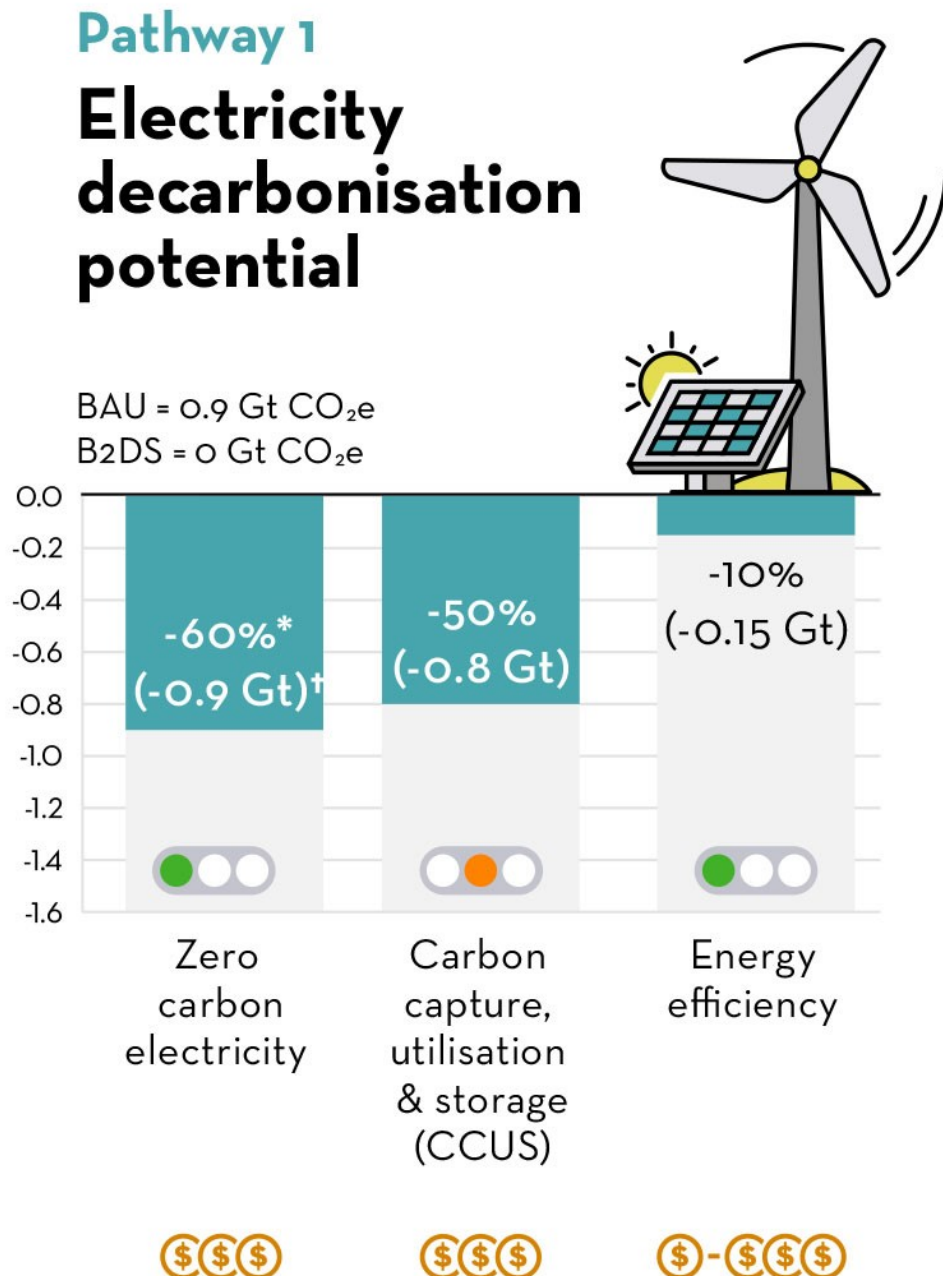


Figure 10 Pathway 1: Electricity decarbonisation

Direct emissions reduction

The past 20 years have seen a dramatic reduction in the proportion of sectoral emissions that are directly emitted from the aluminium production process (as opposed to the electricity and raw materials they consume) and of that share, those which are evolved from the combustion of fuels (to provide heat and steam) and other sources.

This is partly a consequence of the growth in fossil fuel power and the focus of the industry on eliminating process-related emissions, such as the high global warming potential gases perfluorocarbons (PFCs) from anode effects, improving energy efficiency and adding new (and best available) refining and smelting technologies.

In 1990, with sector-wide emissions at less than 300 Mt CO₂e per annum, direct emissions made up around two-thirds of this total. Of this approximately 200 Mt CO₂e, PFCs constituted 100 Mt CO₂e (33%).

Today, direct emissions constitute less than one-third of the total sectoral emissions (300 Mt CO₂e of the 2018 total of 1.1 Gt CO₂e), with PFCs making up only 35 Mt CO₂e (3%) (IAI, 2020a). This is due to a concerted effort to improve management of the smelting process in the 1990s and 2000s, as well as the addition of new technologies in the 2000s and 2010s. Anode consumption in the smelting process and fuel combustion across all production processes make up almost all of the direct emissions from the sector.

Thus, the promising pathways to emissions reduction in this category are focused on two things:

- novel (inert anode) technologies that eliminate the need for carbon anodes in smelting, and
- the development of technologies that can provide heat and steam without the combustion of fossil fuels (e.g. electrification with renewable power sources, combustion of renewables-produced hydrogen, concentrated solar thermal as a share of the energy mix and mechanical vapour re-compression of steam).

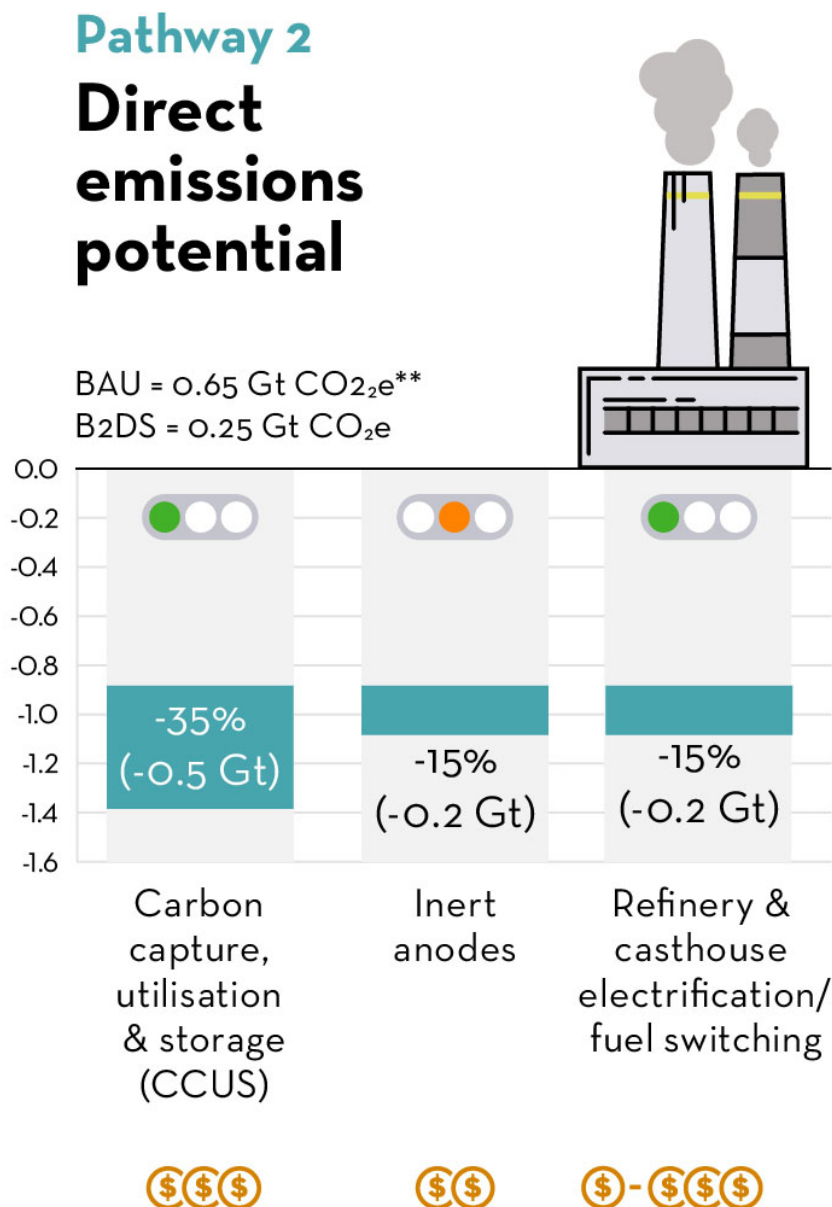
In addition, the capture and sequestration of greenhouse gases from each source at point of emission or evolution is another potential pathway.

Challenges with CCUS are not unique to the aluminium sector and costs reflect wider issues that emitters will face in developing and deploying these technologies appropriately. For aluminium smelting however, the low concentration of CO₂ in the flow of gases from electrolytic cells at 500-15,000 ppm presents an additional challenge, requiring redesign or retrofitting of cells and consequent costs of design, realisation and deployment. This is without counting the cost of scrubbing the other contaminants before the carbon is captured (to reduce contamination of captured CO₂).

Removal of direct emissions from the electrolytic smelting process (transforming alumina into aluminium) is a challenge common to all primary aluminium producers and will require a step change in technology to realise. Novel cell technologies, such as inert anodes, will play an important role in

emissions reduction, but it should be noted that the sources they mitigate make up around 15% of global sector-wide emissions.

These technologies will also need to operate at similar or better energy intensity than existing carbon anodes during the transition to zero-carbon power environments. This is because any reductions in direct emissions could be outweighed by indirect electricity-related emissions if deployed at a higher energy consumption in fossil fuel powered grids. However, in the long-term, inert anodes will be an important component of a B2DS-aligned sectoral pathway.



** includes 0.15 Gt CO_{2e} from indirect emission sources (predominantly input materials & transport)

Figure 11 Pathway 2: Direct emissions

Alumina production (from bauxite ore) requires [significant amounts](#) of heat and steam (IAI, 2020e). The challenges associated with technologies to decarbonise these energy carriers are not unique to the aluminium industry.

For these thermal processes, electrification with renewables offers a potential pathway to decarbonisation. Fuel switching to green hydrogen, concentrated solar thermal energy and carbon capture utilisation and storage (CCUS) are opportunities where electrification is not feasible, such as alumina calcining, where direct replacement of fossil fuel-fed boilers with electric boilers could have product quality implications and thus higher emissions downstream.

Other fuel combustion processes (mobile equipment in mining, ovens for baking anodes, casthouse furnaces, remelting & recycling) will follow similar pathways (electrification, fuel switching and CCUS), while already electrified processes (extrusion, rolling, etc.) will require renewables deployment at the same rate as smelting (zero emissions by 2050).

Ancillary materials and transport emissions (representing around 8% of sector emissions under BAU) will be reduced at the same rate as direct emissions through pathway changes in other sectors and purchasing choices by aluminium producers.

Recycling & resource efficiency

Infinite [recyclability](#), without loss of properties, is one of aluminium's unique benefits, making it an enabling material for circular economies (IAI, 2018). Current end-of-life (post-consumer) recycling (collection) rates for the metal in its largest market segments (transport, building and construction) are high – above 90%. However, these applications tend to have long lifetimes (taking advantage of aluminium's durability) and so scrap availability is as much constrained by product life as it is by recycling rates.

Thus, [three quarters of the more than 1.4 billion tonnes of aluminium ever produced](#) is still in productive use, providing services globally today and available for collection and recycling/reuse in the future (IAI, 2021a).

Aluminium in packaging applications has a much shorter lifetime and a range of collection and recycling rates depending on the application (cans tend to be higher than flexible packaging) and local market, consumer behaviour and political conditions.

The aluminium scrap that is collected at the end of product life also has a diversity of qualities, depending on the constituent alloy classes and how well the scrap has been sorted. Lower quality, mixed scrap, while of use for certain applications today, will have fewer “places to go” in a future that will require higher value, wrought alloys (in applications such as electric vehicle light-weighting).

The onus is on producers and consumers (and waste management actors) to ensure that material is brought back into the system at end of life. It is also a responsibility of those who design and transform the metal into products to create applications from which aluminium components can be

easily and efficiently separated, collected and sorted to ensure that the metal's value and its alloys are retained.

The recycling of post-consumer scrap today avoids the need for almost 20 million tonnes of primary aluminium and thus around 300 million tonnes of CO₂e. Once collected, metal losses during scrap processing (3%) and melting (6%) are relatively low.

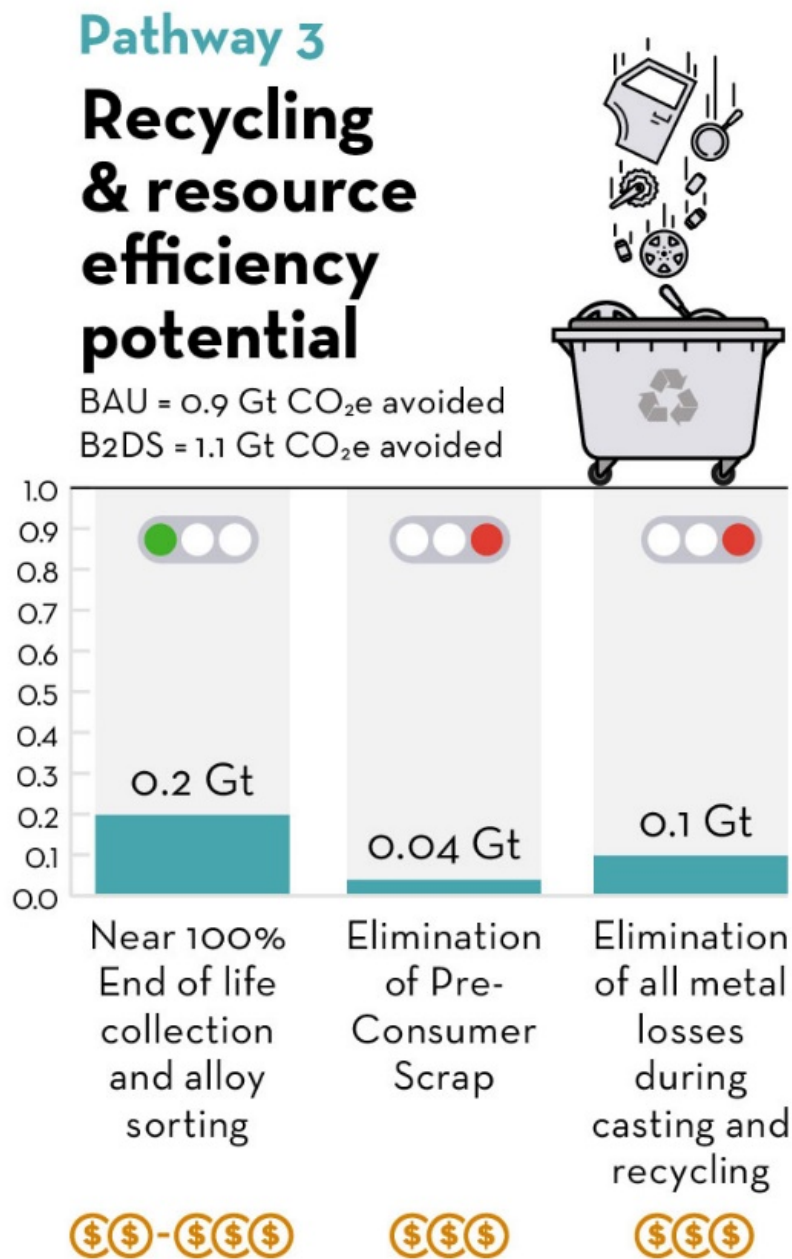


Figure 12 Pathway 3: Recycling & resource efficiency

There are high recycling rates (>90%) in building and construction and automotive segments. In some regions recycling of cans is almost 100%, though lower rate regions consume significant volumes of metal. In 2018, 1.2 million tonnes of aluminium in the form of used beverage cans and other rigid packaging was not collected at end of life.

Across all segments, around 7 million tonnes of aluminium is not recycled every year due to collection and processing losses at the end of its life (2018), and this will rise to 17 million tonnes per annum by 2050 with no change to current recycling rates (IAI, 2021a).

When this metal is not retained in the economy, it must be replaced by primary aluminium. Primary production today has a greenhouse gas emissions profile on average twenty-five times higher than recovery of metal from post-consumer scrap.

Recovery of 95% of this material through improved collection, sorting and recycling processes would reduce the need for primary aluminium by 15% and deliver 250 million tonnes of absolute CO₂e emissions reduction per year, second in magnitude only to the decarbonisation of smelter electricity.

New and internal scrap (the scrap that is generated in the various production and fabrication processes prior to final product manufacture) has a very high collection rate and low post-collection losses. This is due to the fact that it tends to be a clean, well-sorted material stream, already under the management and control of producers, who understand its value and for whom material losses impact profitability. Thus, while the volumes of new scrap generated today (13 million tonnes in 2018) and in 2050 (24 Mt) are high, losses are extremely low.

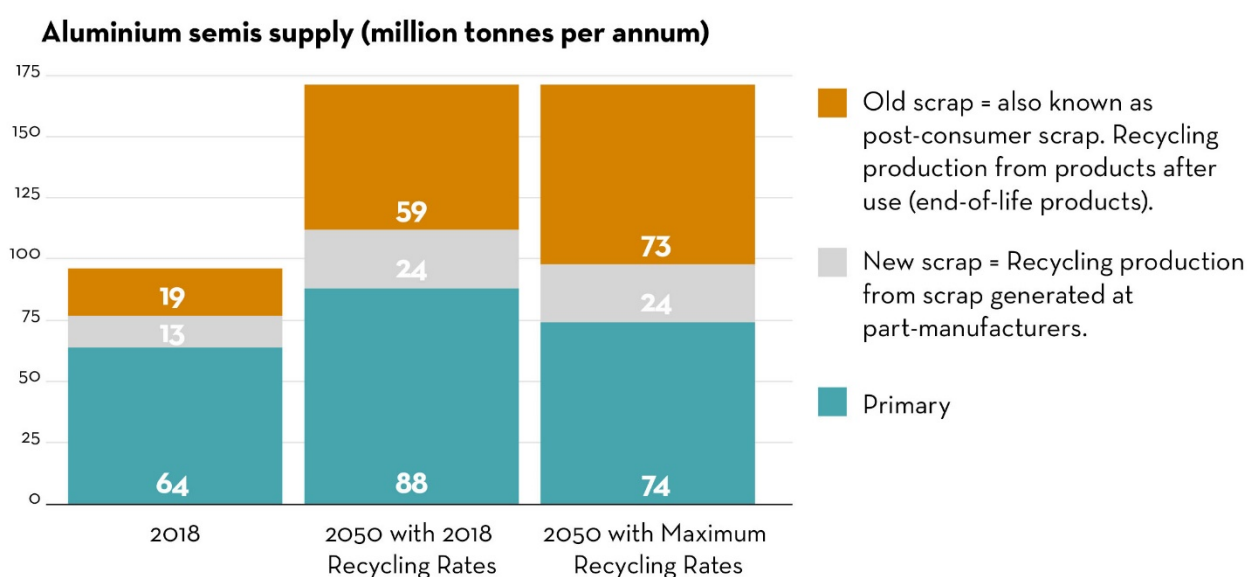
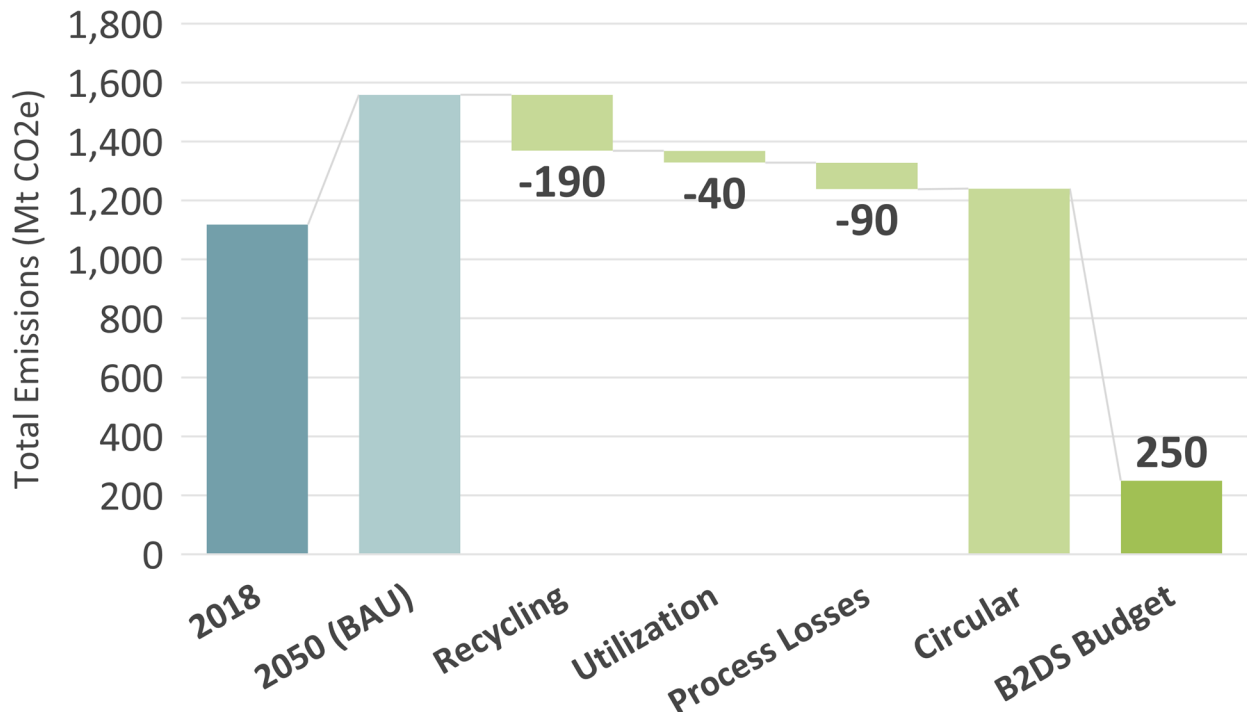


Figure 13 Aluminium supplied from primary and recycled sources in 2018 and 2050, under alternative recycling rate scenarios, Mt Al

New and internal scrap is remelted (through a thermal process), which generates CO₂, albeit at a very low level compared to primary production (IAI, 2020a). The reduction in new scrap generation, through some yet unknown processes (e.g. 3D printing), while seemingly attractive to reduce the number of internal scrap loops, has a limited impact (1.5% or 38 Mt CO₂e) on emissions reduction.

A fully circular system without any (collection, process and melt) losses and no generation of new and internal scrap would deliver a 20% reduction on BAU sector emissions.



2050 (BAU)	with 2018 recycling rates
Recycling	with maximised recycling rates
Utilization	zero new scrap generation
Process Losses	zero pre-melting and melting losses
Circular	maximum recycling & resource efficiency potential

Figure 14 Cumulative impacts of recycling & resource efficiency potential, Mt CO₂e

This transformation of the supply of aluminium requires action from all actors along the value chain - including consumers - and policy frameworks that incentivise circularity, including investments in scrap recycling capacity and design for disassembly/recycling, including novel metal/material joining technologies.

6. *What is needed to deliver a Paris-aligned aluminium industry?*

As an integrated and global industry, supplying energy-saving and emissions-reducing lightweight, recyclable products to some of the highest GHG emitting sectors, a full value chain approach to emissions reduction is critical for the aluminium sector. This lifecycle approach requires that, in addition to reducing the global industry's footprint, the in-use benefits of aluminium products and savings from recycling are maximised.

As an industry, moving from a 1.1 Gt CO₂e base to 250 Mt CO₂e by 2050, while growing production by up to 80%, will require action from all actors along the value chain, including technology providers, governments and investors.

Commitments from producers to mid-century targets that are B2DS or SDS aligned will need to be bolstered and enabled by policies that secure long-term aluminium sector access to competitively priced renewable electricity and drive increased investment in research, development and the deployment of electrified processes, green hydrogen, inert anode and CCUS (in concert with co-located industries). In addition, circular economy policies that promote both improved scrap collection (particularly in packaging) and scrap alloy sorting (particularly in automotive) will be critical to ensuring that the value of aluminium (and the significant energy required in its initial production) is not lost at the end of products' life.

Here, customers have a role to play too in designing aluminium containing products in a way that maximises metal recovery and recycling, as well as sorting production scrap by alloy class at the point of generation.

Finally, and crucially, with the cost of decarbonisation of the aluminium sector in the order of trillions of dollars, the key enabler of a 2050 low carbon aluminium sector is investment:

- to deliver up to 25 million tonnes of new smelting capacity and the decarbonisation of an existing 65 Mt capacity.
- for the 180 million tonnes of alumina capacity required to meet smelter demand.
- in the new carbon-free or CCUS technologies that currently make up less than 1% of aluminium production, but by 2050 will need to fulfil over 50%.
- in the electrification of operations all along the value chain and the renewables grids that power them.
- in an industry that is critical to the global achievement of net zero emissions across all sectors by the end of this century.

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