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Reducing the carbon footprint of aluminium in cars: why and how?

How to ensure an ambitious uptake of green aluminium in cars by 2040



T&E

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Executive summary

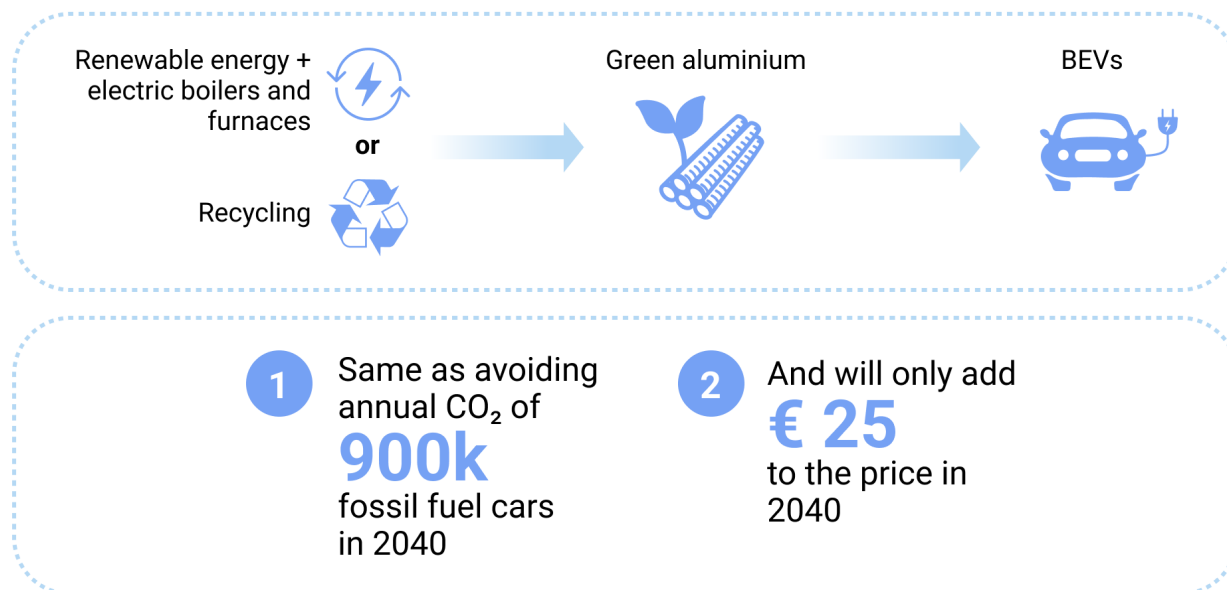
As the transition to electric vehicles gains speed in Europe and globally, leading to a reduction in the tailpipe emissions of cars, attention must now turn to the climate impact of the materials used to make a car. With use-phase emissions of an EV at close to zero, the emissions from the production phase - or a vehicle's embedded emissions - account for around 60% of an electric car's total lifecycle emissions. Aluminium makes up around 20% of these embedded emissions. The automotive sector [accounts for over a third](#) of the market for all European aluminium production. With the aluminium content of electric vehicles higher than that of an internal combustion engine (ICE) vehicle, and only expected to grow, now is the time to scale low carbon or green production and recycling of aluminium in Europe.

New research by T&E shows that we can deliver cost-competitive aluminium by 2040, with targets for green aluminium adding only 25 EUR to the price of a car. To define "green aluminium", we establish a sliding scale combining recycled and primary aluminium, with the carbon threshold decreasing over time, incentivising the transition to electrified plants.

The technology to clean up aluminium is available, and now is the time to create the conditions to scale clean aluminium production, including low carbon primary production and increased recycling. With the right policy measures in place, we can:

- Reduce residual emissions from primary aluminium in cars by 30% in 2050 (compared to business as usual), increasing to 68% with further uptake of renewable energy and deployment of technologies to reduce direct emissions from smelting, like inert anodes or carbochlorination processes. Emissions savings by 2040, would be equal to taking 900,000 ICE cars off the road.
- Reduce emissions by scaling EU aluminium recycling capabilities. By 2035, the emissions savings from increased recycling could be equal to taking 750,000 ICE cars off the road with this rising to over 2 million by 2040.
- Deliver cost-competitive aluminium by 2040, with targets for green aluminium delivering a saving of €30 by 2050 to the price of a car.

Green aluminium in cars cuts embedded CO₂ emissions at a negligible cost



Source: T&E, own modelling



Europe is heavily dependent on primary aluminium imports, with 53% of the consumption of primary aluminium in Europe in 2024 being met by imports, up from 46% in 2010. However, manufacturing primary aluminium is highly electricity-intensive. Around two-thirds of its carbon footprint stems from electricity generation, making its decarbonisation inseparable from the carbon intensity of the grid. Therefore, Europe's comparatively cleaner grid means Europe can have a significant competitive advantage when it comes to green aluminium production. Scaling green aluminium production in Europe will be a win for the climate and the economy.

Requiring green aluminium in cars therefore means we can win on all fronts. We can cut emissions, strengthen demand for green products, and if paired with smart policies, support European producers.

Scaling green aluminium production through ambitious policy

Taking into account the significant emissions reduction potential and the timeframes for innovation and aluminium plant investment cycles, now is the time to ensure robust and reliable policies to drive the transition to green aluminium and reduce the overall car carbon footprint. Ambitious policy, such as green aluminium quotas will ensure the timely scale up of green aluminium. Achieving this requires:

1

The EU should set minimum green (incl. recycling) aluminium quotas for new cars, via the upcoming Industrial Accelerator Act. Carmakers should be required to use a minimum of 60% green aluminium in new cars from 2035, increasing to 85% in 2040 and 95% in 2045, until all aluminium used in cars is required to be green by 2050. Green aluminum should be required to be made in the EU.

2

Recycled, local content targets should be introduced via a delegated act to the end-of-life vehicles (ELV) regulation, as part of the upcoming Circular Economy Act. Only post-consumer scrap should qualify to meet these targets.

3

The upcoming Circular Economy Act should include measures, including via improved waste codes, to significantly limit shipments of scrap aluminium outside of the EU.

4

The End-of-Life Vehicles Regulation (ELVR) should alleviate barriers to high quality recycling of aluminium, via dismantling requirements for certain parts and components and requirements to sort aluminium into cast and wrought alloys.

5

The Industrial Accelerator Act and Industrial Decarbonisation Bank should create strong conditions to invest into scaling green aluminium production in the EU, including via strengthened lead markets and the introduction of a carbon product label for aluminium used in vehicles.

6

Under the revision of the EU car labelling directive, the EU should establish a vehicle carbon label which would reward BEVs meeting both Made in EU and low carbon criteria. The label should focus on aluminum as well as other key vehicle emission hotspots (batteries and steel).

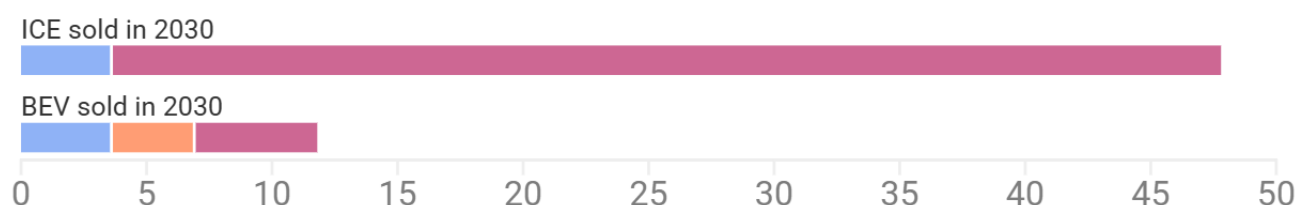
Introduction

By 2030, an average battery electric vehicle (BEV) will have one quarter of the lifetime emissions of an internal combustion engine vehicle (ICEV), shown in the figure below. With the reduction of a car's tailpipe emissions through electrification, the burden of new vehicle emissions will gradually shift to the production phase.

A BEV provides significant emissions savings over an ICEV

Lifecycle emissions for a medium passenger car in 2030

■ Vehicle production ■ Battery production ■ Use phase



Source: T&E own analysis



Decarbonising this stage is becoming increasingly important. Aluminium is responsible for around 20% of an EV's embedded emissions. This share is only expected to grow with the transition to fully electric cars and the lightweighting of vehicles. Outside the automotive sector, aluminium demand is also set to grow, due in part to aluminium's key role in other [clean energy technologies](#), such as solar panels.

This First Section of the report sets out the emissions and other impacts associated with aluminium production today. We also provide an overview of how aluminium is produced, looking at the stages of the supply chain from mining to smelting, through to recycling. Analysing the state of play of aluminium production in Europe, we explore Europe's reliance on imported aluminium.

The Second Section examines how emissions from the production of aluminium can be reduced in order to achieve green aluminium. The report assesses and compares aluminium decarbonisation pathways today, analysing emissions reduction potential, affordability and technology maturity. This section also includes recycling, its barriers and its importance as a decarbonisation lever.

Section Three models different emissions reduction scenarios, exploring the emissions saving potential of green aluminium in cars through to 2050. We explore the impact these scenarios

have on cumulative emissions, including what it means at the level of the car. We identify the additional impacts technologies such as inert anodes can have on emissions reduction.

A cost analysis, in Section Four, explores the impact green aluminium will have on a car's price point. The analysis establishes how and when green aluminium will be cost competitive with conventional aluminium and which variables are the most salient cost drivers.

Finally, we set out a range of targeted policy recommendations to enable the EU to scale up production of clean aluminium for use in cars, in order to support the shift to fully zero-emissions vehicles and support a competitive European industry.

This builds upon T&E's existing work on green steel in cars, where [analysis by Ricardo](#) showed that the annual emissions of 3.5m fossil fuel cars could be avoided by 2030, costing only €57 per car.

Section 1

1. The aluminium sector: a carbon problem?

In this chapter, we take a look at the state of play of aluminium production today; how and where is aluminium produced, and how carbon intensive is the process? By exploring the different stages of the aluminium supply chain, we identify the associated emissions, identifying hotspots along the supply chain, as well as exploring non-emissions related impacts arising from primary aluminium production.

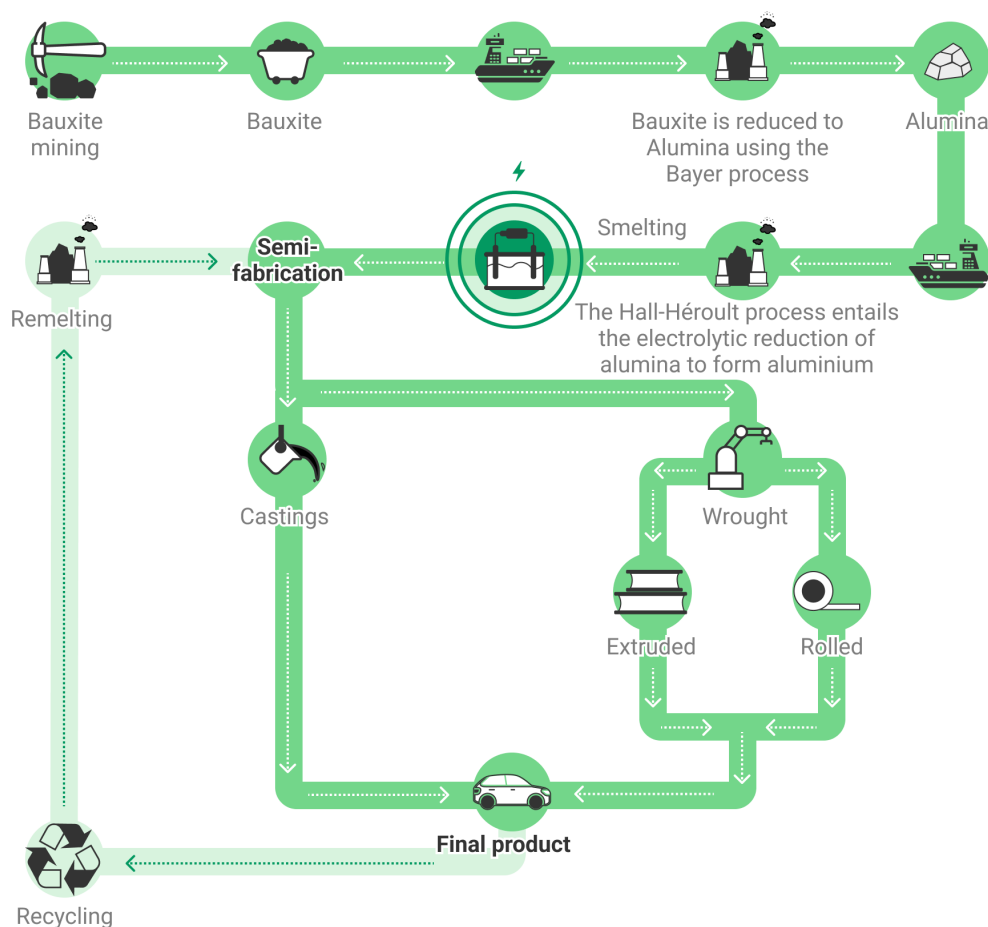
1.1 How is Aluminium produced?

Aluminium is the second most highly produced metal in the world after steel, and is used in numerous sectors, from packaging to construction.

The Figure below depicts a typical aluminium supply chain, from the mining of the bauxite ore through to refining and recycling.

Processes of Automotive Aluminium supply chain

Currently most processes along the supply chain involve the use of natural gas powered boilers and furnaces, except the use of **electricity** during the smelting stage



Source: T&E



Aluminum is rarely found in its elemental form and requires mining bauxite, with the largest reserves located in Guinea, Australia, Vietnam, Brazil and Jamaica. Bauxite ore is primarily composed of aluminium minerals such as gibbsite, boehmite and diaspor.

Bauxite is then refined using the Bayer process, where the bauxite is digested in hot sodium hydroxide under pressure, dissolving aluminium compounds while leaving behind red mud residues. The resulting solution is clarified and cooled, allowing aluminium hydroxide crystals to precipitate. These are calcined in rotary kilns or fluidised furnaces at around 1000 °C to produce pure alumina. In the smelting stage, the Hall-Héroult process, alumina is dissolved in molten cryolite, reduced by electrolysis and heated to nearly 950°C, producing molten aluminium metal.

Throughout these stages, **furnaces** provide high-temperature heat for calcination and metal casting, while **boilers** generate steam for digestion and washing. This makes the overall process both thermally and electrically energy-intensive. The smelting process requires **over 15 MWh** of electricity per tonne of aluminium, equivalent to around **ten times** the per capita annual household electricity consumption in the EU.

1.2 Aluminium - a big emitter

The aluminium sector is a big emitter; it is responsible for [2%](#) of global annual GHG emissions. The sector itself emits around 1116 million tonnes of CO₂e annually as of 2023. Global production continues to increase year on year. Therefore, without the deployment of new technologies, sector emissions are set to continue to rise.

Producing aluminium is a very energy intensive process. Smelting and alumina refining are the most energy intensive stages of production, and therefore are responsible for the majority of emissions. The electricity demand alone from smelting often represents **60% or more** of the sector's total emissions, depending on the carbon intensity of the local power grid. Additionally, the use of carbon anodes generates direct process emissions in the form of CO₂e (roughly [1.5](#) tonnes of CO₂e per tonne of aluminium). What's more, the use of carbon anodes can lead to the release of PFCs—extremely potent greenhouse gases—during anode effects that occur when alumina levels in the electrolyte become too low. Alumina refining is the next biggest emitter accounting for about 15-25% of total primary aluminium emissions depending on fuel choice and energy efficiency.

As countries and industries alike strive to achieve ambitious net-zero targets, addressing this significant industrial source of CO₂e pollution is therefore crucial. However, by using cleaner energy sources, we can produce much cleaner aluminium.

Electricity source and fuel choice play a vital role in overall emissions. As depicted in annex 3 and due to aluminium's reliance on electricity, grid emissions intensities play a vital role in influencing the overall emissions intensity of the primary aluminium produced. Depending on the location of a primary smelter, emissions could reach up to 20 tonnes of CO₂e / tonne Al produced.

1.2 Demand for Aluminium in cars set to increase

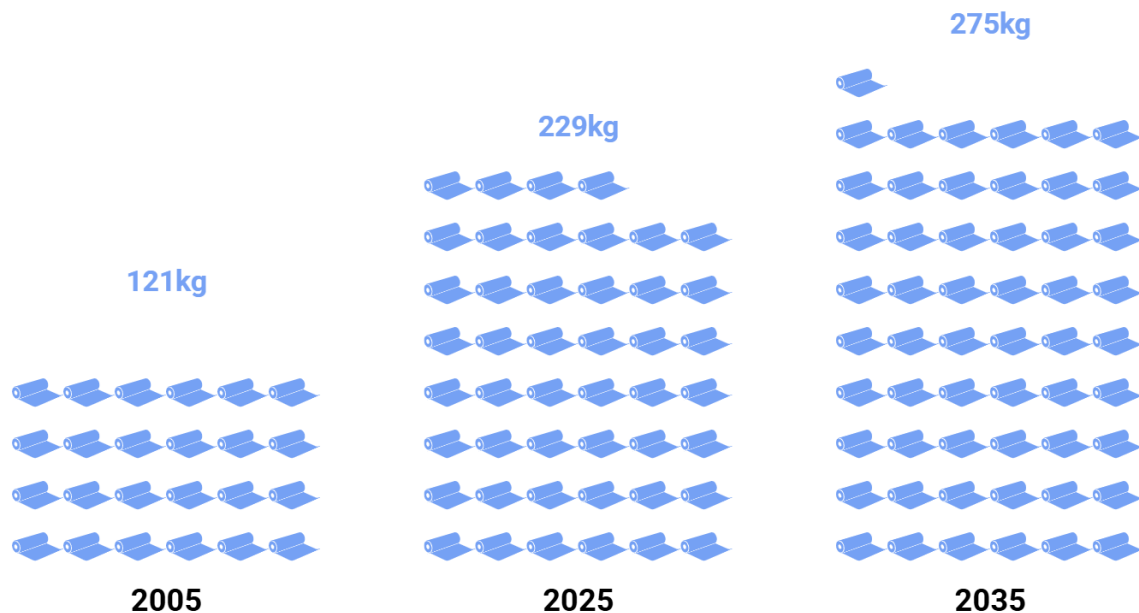
Primary aluminium has many uses from transportation to packaging and construction. The transport sector accounts for the largest use of aluminium (including both cast and wrought) in Europe, with this share expected to increase in the future. The demand for automotive aluminium has historically been driven by lightweighting, along with the growing preference of customers and manufacturers for cars in higher size segments such as SUVs and luxury cars. [Lightweighting](#) here implies substitution of steel components with aluminium due to its density being approximately one third that of steel.

Since 2005, the aluminium content of an average passenger car has almost doubled from 121kg to 229kg today. By the ICE phase out in 2035, the aluminium in an average BEV is expected to reach 275kg, as shown in the figure below. The aluminium in premium SUVs is already as high as [700kg](#) per car today, in models such as Land Rover's Range Rover Sport.

The transition to lightweight BEVs is increasing the aluminium in each passenger car

Wrought components are seeing the fastest growth

 = 5kg



Source: T&E modelling based on Ducker Carlisle data



Cast vs wrought aluminium

[Aluminium in automotive applications appears in two main fabricated forms](#), cast and wrought, depending on processing. Cast aluminium is made by pouring molten metal into moulds, allowing for complex shapes in components like engine blocks, transmission housings, and suspension parts. Cast alloys are generally high in Silicon and other alloying elements, while wrought is low. Wrought aluminium is mechanically worked (rolled, extruded, or forged), resulting in stronger, more ductile materials used in body panels, chassis structures, crash components, and forged suspension parts. Cast is preferred for complex, high-volume parts; wrought for applications requiring higher strength and durability.

1.3 Aluminium in Europe

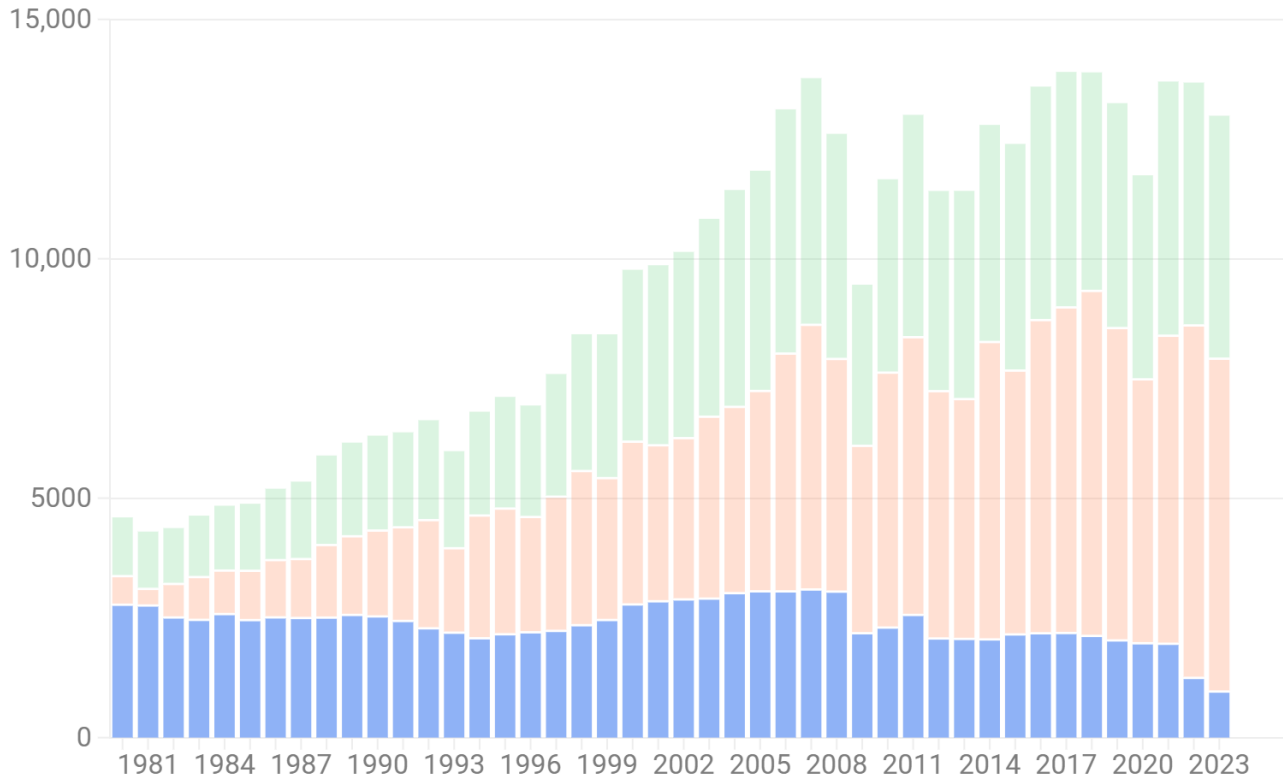
Europe is heavily dependent on primary aluminium imports. The graph below depicts how total consumption has increased almost 300% since 1980. Despite this increase, European primary production has decreased to now represent just 7% of total consumption. The transition towards a market dominated by imported aluminum is in large part the result of rising energy costs and an inability to compete globally.

Europe now imports more than half of its primary aluminum needs

European Aluminium consumption by type

European Primary Production (kt) Net Primary Production Imports (kt) Recycling (kt)

Aluminium (kt)



Source: European Aluminium



Over the last decade, Europe has seen its number of operational primary aluminium smelters significantly reduced, driven by surging energy costs, regulatory pressures, and global competition. These closures have eliminated roughly **2,000 direct jobs**. The map below depicts both current and recently closed smelters across Europe.

Aluminium smelters in Europe

● Operating ● Closed



The average emissions intensity of primary aluminium produced in Europe is significantly lower than imported primary aluminium. The average emissions intensity of a kg of primary aluminium produced in Europe was around [6.3kg](#) of CO₂e in 2023, almost 60% lower than the global average for the same year.

Therefore, this shift towards higher imports has led to “dirtier” aluminium flooding the European market. The recent drop in Russian imports, compensated by a rise in Asian and Middle Eastern imports has increased the carbon intensity of primary aluminium imports further.

In parallel, the European Union exports large amounts of scrap aluminium today. This trend has increased dramatically, rising from \$0.4 billion in 2000 to over \$2.4 billion in 2024. Approximately 84% of aluminium scrap value was exported to Asia in 2024. Historically, this has mostly benefited China, which subsidises its aluminium recycling industry, making European recyclers less competitive.

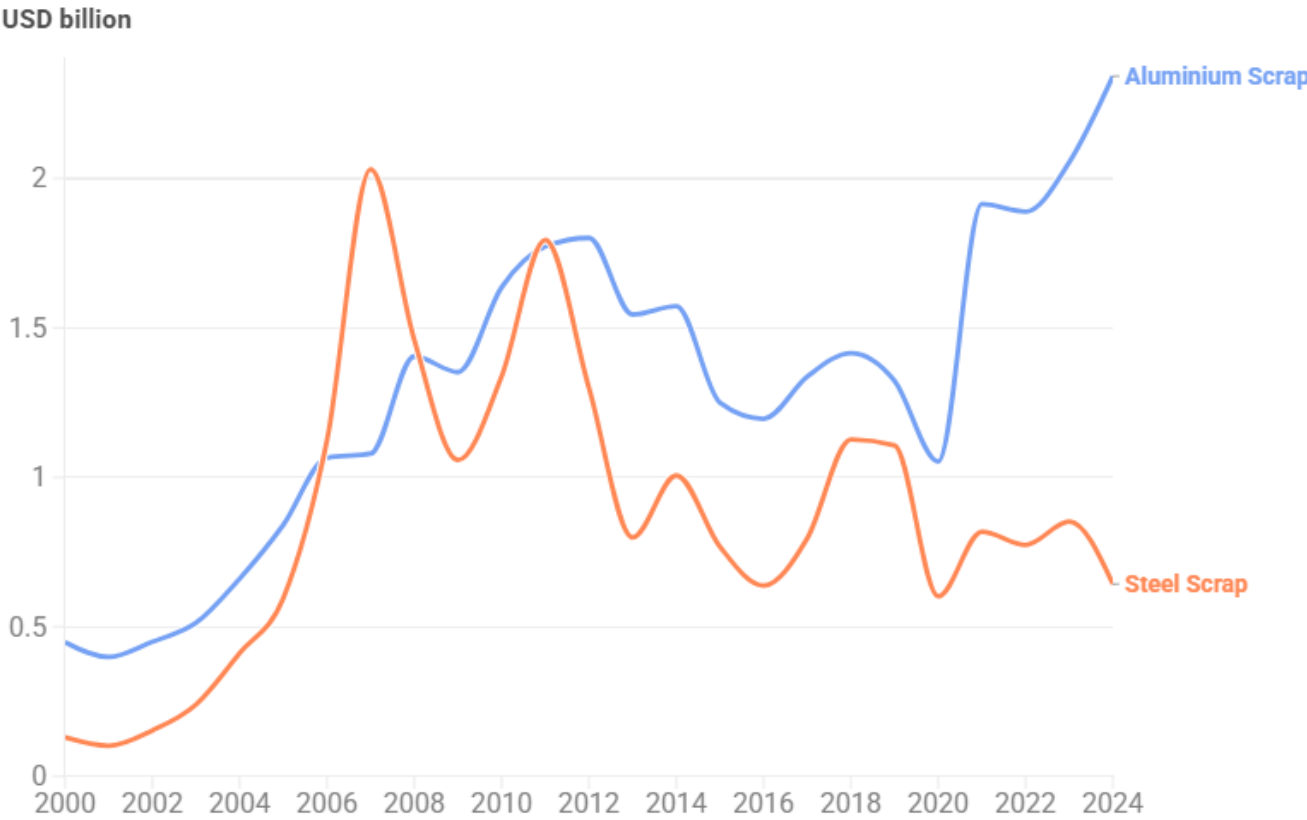
EU scrap recyclers face a crisis in 2025, encapsulated by the [BAGR](#) Berliner Aluminiumwerk filing for bankruptcy. India has grown to be the largest recipient of EU scrap relying on low labour costs for hand sorting and, in recent months, USA tariffs have made exporting scrap from the EU to America more attractive, as scrap aluminium is not included in the tariff scheme.

There has been a vicious cycle where limited investment in recycling infrastructure, especially in innovative sorting, has continually reduced the supply of appropriately treated EU scrap. This coupled with the commercial advantage of Asia (lower energy and labour costs) have resulted in the exodus of scrap leaving the EU today. This contrasts significantly with the case of EU steel, shown in the graph below, which has seen progress in keeping scrap in the EU.

The EU exported over two billion euros of scrap aluminum in 2024, with over 80% sent to Asia

Value of scrap material exported from the European Union annually

Aluminium Scrap Steel Scrap



Source: UN Comtrade

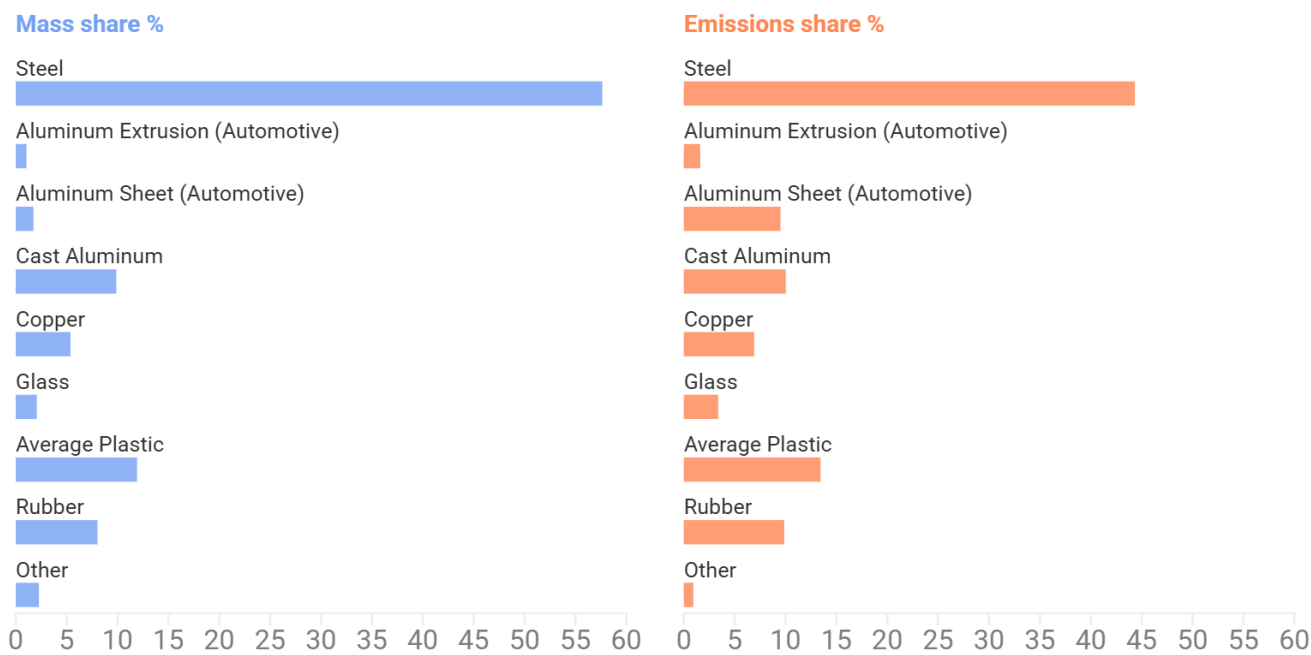


1.5 Aluminium - a growing climate problem in cars?

With tailpipe emissions reducing and on a path to zero, emissions from the production phase - also known as a vehicle’s embedded emissions - [account](#) for around 60% of an electric car’s total lifecycle emissions. Aluminium makes up an important share of this, with estimates averaging around 20% of a car’s embedded emissions, depending on the mass used in the vehicle and country of origin of the metal, as depicted in the graph below.

Breakdown of emissions and mass share of a BEV

Aluminium represents over 20% of a vehicles total embedded emissions



Source: T&E internal modelling & Greet 2



Both the mass share and the resulting emissions share are heavily dependent on the powertrain, class and type of car. For example, shifts to lightweighting can massively decrease the amount of steel used while increasing the amount of aluminium. What’s more, future shifts away from high-alloyed cast aluminium components (such as engine blocks, with a high percentage of post-consumer recycled content) and increases in the share of wrought aluminium and low-alloyed cast components with much lower recycled content values can shift the carbon can impact a car’s total embedded emissions.

The level of wrought and low-alloyed cast aluminium compared to high-alloyed cast aluminium included in the car has a significant impact on the overall emissions. Wrought and primary castings have on average the highest share of primary aluminium. Impurities may profoundly impact technical performances. This significantly increases its emission intensity and consequently increases its material carbon footprint. High alloyed cast aluminium (also commonly known as “secondary casting”) on the other hand, contains a higher proportion of

scrap, meaning it has a lower emissions intensity. Therefore, when taking into account a shift towards increased wrought and low-alloyed cast components in a car, the greening of primary aluminium and the inclusion of more scrap in wrought becomes even more vital.

1.4 Impacts across the supply chain

As previously mentioned, the final production of aluminium starts with the extraction of bauxite, with the largest deposits found in Guinea, Australia, Brazil and Jamaica. Nevertheless, as with the extraction of all manner of resources, including fossil fuels and minerals, the extraction of bauxite can have harmful impacts on the local environment and people, if not managed properly. However, with the use of the latest technologies, these impacts can be significantly reduced, and we can drive the uptake of more responsible sourcing practices. In particular, much can be done to reduce the negative impacts of bauxite mining on deforestation, water and air pollution, and human rights violations.

When it comes to **deforestation**, Bauxite mining can have a significant impact; Bauxite-linked deforestation accounts for [8% of direct mining related deforestation](#). Bauxite extraction has a large footprint as bauxite mines are mostly opencast, and deposits often cover a large area. However, according to a [JRC technical study](#), bauxite typically occurs in relatively thin layers near the surface, meaning whilst bauxite mining does disturb a significant amount of land, it does so for a short amount of time compared to the mining of other materials. With the major bauxite deposits worldwide commonly found in tropical and sub-tropical areas, they often overlap or are adjacent to areas of high conservation value. As a result, it is important that actions are taken to limit the impact, such as establishing habitat restoration and reforestation programs throughout the life cycle of the mine.

The refining of bauxite produces significant amounts of **waste**. Specifically, bauxite residue (BR), also known as “red mud”, is produced during alumina refining. It is produced in high volumes and traditionally large storage areas are needed and it is often stored in settling ponds, which can be prone to failure. For example, the [failure of a dam](#) used to store red mud in Hungary in October 2010 flooded more than 250 homes. Nevertheless, techniques exist to ensure the safer storage and management of tailings from bauxite mining and residue from the alumina refining process, including the drystacking and backfilling of the waste, which is already used in a number of contexts. For example, Hydro’s bauxite mining tailings storage facility in Paragominas in Brazil, where waste is first dried and then deposited back into the mined areas ([tailings dry backfill](#)). Backfilling or drystacking the waste increases the safety of the facilities and reduces their environmental footprint. Whilst these techniques are not mandated in the EU, the European Commission should commit to [revising the EU Extractive Waste Directive](#) to bring it in line with global best practice and mandate the use of best available techniques. In parallel, a number of global standards exist, such as the [Global Industry Standard on Tailings Management \(GISTM\)](#) or [Safety First Guidelines for Responsible Mine](#)

[Tailings Management](#). Implementing these rules can ensure the proper management of mining waste.

Bauxite extraction and refining can also have significant impacts on **water and air quality**. When it comes to bauxite residue, as it is highly alkaline and contains traces of radioactive elements and other potentially harmful elements, it can impact surface water and groundwater via the leaching of alkaline solutions. It can also impact air quality where the wind can easily disperse fine-grain particles. In addition, for bauxite mines located in areas of high water risk, where bauxite refining requires significant water use, it can have impacts on water access. However, implementing water recovery and recycling technologies, such as dry digestion & multi-stage leaching, can limit water use during refining.

Finally, there have historically been **human rights** abuses associated with bauxite extraction, including the displacement of local communities and rights holders living on or near to sources of bauxite, as evidenced by [Human Rights Watch](#). In addition, bauxite mining has also occurred on land belonging to Indigenous Peoples, leading to their displacement. As a result, ensuring the respect of human rights throughout the aluminium supply chain is vital. Standards, such as [the Initiative for Responsible Mining Assurance](#) (IRMA), can help ensure responsible practices at the mine site level. IRMA represents the most comprehensive, transparent, and credible mining sector audit standard available today.

Finally, EU legislation, such as the EU Corporate Sustainability Due Diligence Directive (CSDDD) seeks to mandate companies to identify and mitigate risks throughout their supply chain. Nevertheless, efforts to simplify this legislation risks weakening the rules. It is therefore vital that the legislation ensures a risk based approach, rather than narrowing the scope to direct suppliers, in order to ensure companies focus where harm is most likely and that harms deeper in the supply chain, such as at the mine site level, are not missed.

Section 2

2. How to reduce emissions from aluminium ?

With aluminium responsible for significant carbon emissions globally and in Europe, and making up a significant share of an electric car's total lifecycle emissions, efforts to reduce emissions from aluminium production are gaining prominence. In this chapter, we outline the pathway to achieving lower carbon, or green aluminium, and the technologies needed for emissions abatement, including the vital role recycling will play in the sector's decarbonisation.

2.1 What is green aluminium?

There is no universally agreed definition of 'green', 'clean' or 'low carbon' aluminium. For primary production today, 'low carbon' aluminium is typically considered to be between 4 to 5 tonnes CO₂e per tonne of aluminium. Hydro's [REDUXA](#) currently can reach as low as 4 tonnes CO₂e per tonne of aluminium.

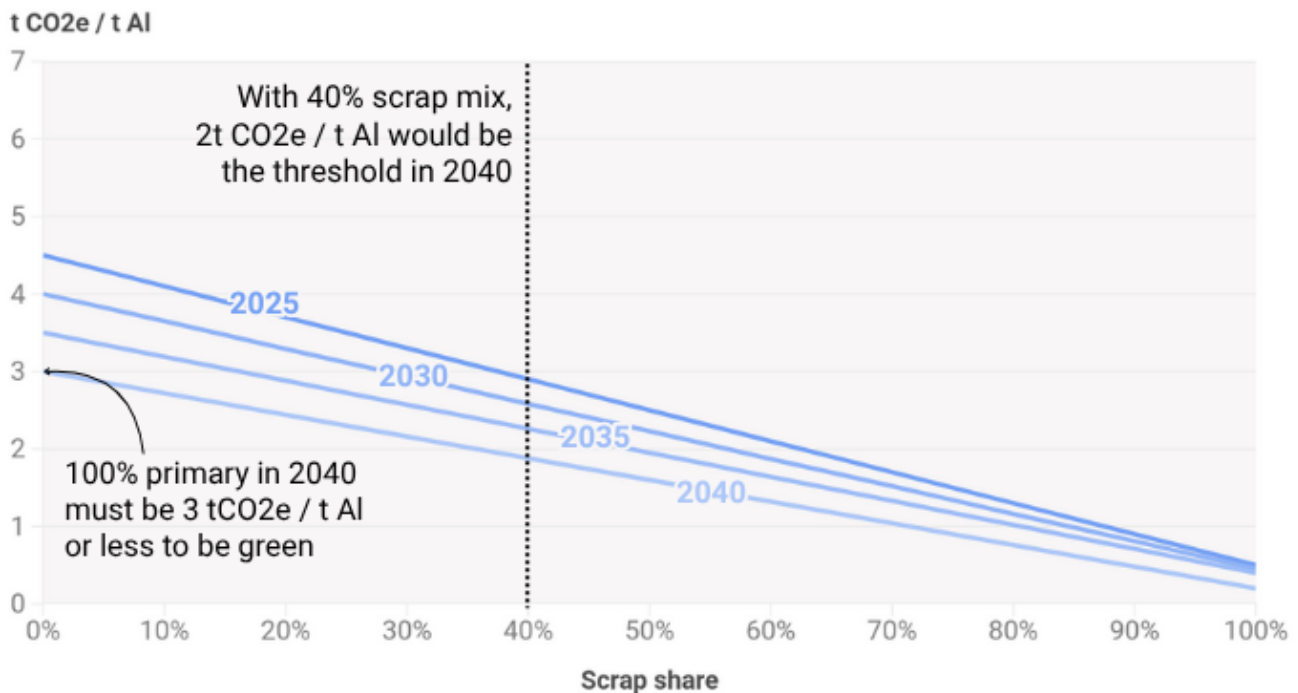
Production emissions will reduce significantly due to lower grid emissions, plant electrification and greater use of recycled materials. **By 2035, according to our modelling, a typical European electrified plant will produce primary aluminium with 3 tonnes CO₂e per tonne of aluminium.**

The [First Mover's Coalition \(FMC\)](#), companies leading the transition to low carbon materials, defines low carbon primary aluminium as containing less than three tonnes of tonnes CO₂e per tonne of aluminium. Volvo, GM and Ford are FMC members, which makes up [6%](#) of the current market share for car sales in the EU. The FMC calls for members to procure at least 10% low carbon aluminium by 2030.

A 'green aluminium' definition is complicated as most aluminium components are a mix of primary production and recycled. The mix of recycled aluminium possible varies by vehicle component. This requires a sliding scale, as with [Steel](#), with the emission threshold reducing as recycled content increases.

In the figure below, we show what an equivalent sliding scale for aluminium would look like. **To count as "green aluminium", we propose a scale based on 4.5 tonnes CO₂e per tonne of aluminium for primary production today. This would reduce to 3.5 and 3 tonnes CO₂e per tonne of aluminium in 2035 and 2040 respectively**, incentivising the transition to electrified plants. These figures are based on cradle to gate emissions.

Green aluminium can be achieved through primary, recycled or a mix of both according to the sliding scale

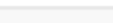
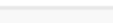
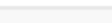
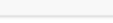
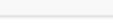
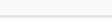


2.2 Which technologies can get us there?

The chart below shows an overview of the different aluminium production pathways and their climate potential. Hydrogen boilers and furnaces were excluded from our analysis due to their low efficiency, at almost four times lower than their electric equivalents. According to European Aluminium, their commercial viability is also several years behind. Electric boilers and furnaces are already in use at commercial scale in plants in [Brazil](#) and [Germany](#), explaining their higher technology maturity scores (with electric furnaces more challenging at higher capacity plants).

Overview and assessment of aluminium decarbonisation technologies today

Low  High

Possible pathways	CO ₂ reduction potential 	Affordability 	Technology maturity 
Direct process emission reduction technology*			
Shift to higher recycling			
Electric boilers			
Electric furnaces			
Hydrogen boilers			
Hydrogen furnaces			

Source: T&E . *This technology could be either Inert anodes or a carbochlorination process



Electrification of refining and heat processes

Along the value chain, most major process steps can be electrified as technologies mature:

- **Digestion:** Traditionally heated with steam from fossil-fired boilers. Electric boilers can replace natural gas boilers, using resistive or electrode technologies to generate process steam.
- **Calcination:** Converting aluminium hydroxide to alumina has relied heavily on natural gas. High-temperature electric calciners are now under development, with pilots demonstrating comparable efficiency to gas-fired units.
- **Casting and remelting:** Foundries and secondary aluminium operations use gas-fired furnaces to melt ingots and scrap. Induction and resistance electric furnaces can replace these, offering precise heat control and zero onsite emissions.
- **Other ancillary processes:** Drying, preheating, and annealing operations in downstream rolling and extrusion can also be electrified through resistance heating and heat pumps.

These technologies are not all available at scale today. Instead, they will follow **adoption curves** that reflect their Technology Readiness Level (TRL) and commercial rollout. We model adoption through S-curves that begin in the first year of commercial maturity and rise steadily to near-full penetration by mid-century.

Technologies to reduce direct emissions in smelting

The Hall–Héroult process, which consumes carbon anodes and releases both CO₂ and PFCs

during the reaction, is the single largest source of process emissions. Inert anodes are one option to replace consumable carbon with stable ceramic or metal composites that emit oxygen instead of CO₂. Another promising technology for removing process emissions is being piloted by Hydro. The process, denoted [“HALZERO”](#) involves the carbochlorination of alumina to Aluminium chloride. Both processes have the ability to eliminate direct GHG from electrolysis and anode baking. While both still pre-commercial, we modelled a scenario which adopts a technology which eliminates direct emissions in smelting. We modelled an sector wide uptake to start around 2035 rising gradually to full rollout by 2050 under a medium scenario. A “green-only” scenario accelerates this shift, assuming full adoption immediately once the technology is proven, representing a fast-transition pathway.

Why is electricity decisive?

Manufacturing primary aluminium is highly electricity-intensive. Around two-thirds of its carbon footprint stems from electricity generation, making its decarbonisation inseparable from the carbon intensity of the grid.

What unites all these technologies is their dependency on clean electricity. This necessitates being connected to a clean electricity grid to reap the full benefits of this shift of technology. This dependency is why Europe’s relatively clean electricity mix represents such a competitive advantage: aluminium produced in Europe can already be up to three times less carbon-intensive than aluminium from regions with fossil-heavy grids such as Central Asia or South Africa. Europe’s decarbonising grid is projected to fall below 50 gCO₂/kWh by 2035 compared to north of 250 gCO₂/kWh in the Middle East and parts of Africa.

2.3 Recycling: The state of play and avoiding a cast “cascade”

Producing primary aluminium requires up to 20 times more energy than producing recycled aluminium. Between 90–95% of the aluminium in a car can be recycled at end of [life](#). However, there are several barriers to this in Europe, both pre (design) and post (sorting) production.

One of the key barriers to closed-loop recycling in automotive aluminium lies in the difference between *wrought* and *cast* components. These materials have different tolerance levels for impurities. In current dismantling systems, wrought and low-alloyed cast products are often downcycled into high-alloyed cast products. However, high-alloyed cast scrap cannot be recycled back into wrought and low-alloyed cast components efficiently. This creates an oversupply of high-alloyed cast aluminium – a phenomenon known as the [“cast cascade.”](#) The result is an ongoing demand for primary aluminium to meet the need for high-quality wrought and low-alloyed cast products, which increases carbon emissions.

There are both policy and technical solutions to reduce the impact of the cast cascade. On the design side, pre-treatment strategies such as **uni-alloying** and **design for dismantling** can make components easier to sort and recover. Uni-alloying aids in the recycling process by reducing the need to separate multiple alloys at EOL. On the post-treatment side, alloy-sorting technologies – such as **laser-induced breakdown spectroscopy (LIBS)** and **X-ray sorting** –

show promise, but are not yet deployed at sufficient scale. These technologies must be scaled rapidly, ideally in parallel with vehicle electrification, to prevent further surplus of cast aluminium. The End-of-Life Vehicles Regulation (ELVR) should alleviate barriers to high quality recycling of aluminium. The dismantling requirement of certain parts and components before shredding vehicles is a key measure to reduce contamination of the aluminium during the shredding process. In addition to those, requirements to sort aluminium into cast and wrought alloys would significantly help reduce cast-cascade by allowing proper and separate treatment of each alloy type.

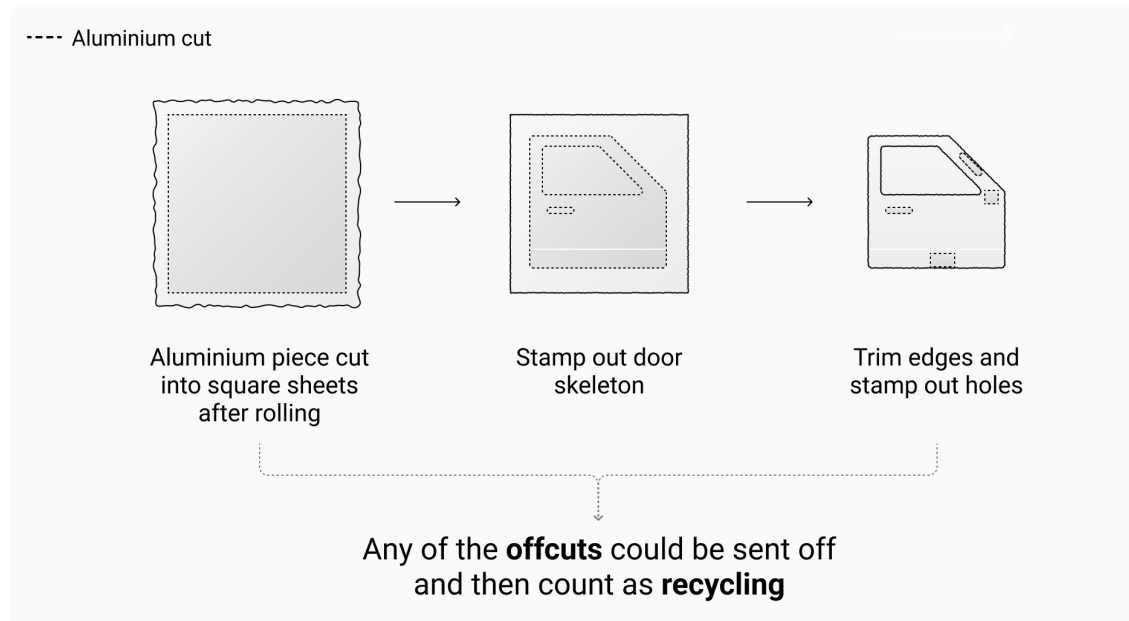
In addition, EU policies should aim to retain aluminium scrap. Currently, significant volumes are exported to countries such as China and India. Limiting scrap exports would help ensure sufficient supply for domestic recycling and support investment in dismantling and sorting infrastructure.

2.4 What is actually meant by “recycled aluminium”?

The label “recycled aluminium” is applied far too generously. [ISO 14021](#) is the international standard used for self-declared aluminium recycling. The standard is too weak and risks abuse in future emission calculations for Green Aluminium. Ambiguity in the standard includes vague definitions on what defines “process” and accounting method discrepancies for allocating emissions to pre-consumer scrap.

The figure below shows an aluminium car door being made and the scrap produced at each step. Under certain interpretations of ‘process’ in ISO 14021, scrap sent to a remelter and subsequently returned to the plant may be counted as recycled content. The leading manufacturer [Novelis states](#) that ISO 14021 “doesn’t go as far as to specify in detail what counts as recycled content as it applies to aluminum”.

Current standards are far too weak on what counts as recycled aluminium



Source: T&E



More generally, aluminium scrap can be classified into two categories.

- **Pre-consumer scrap** – relates to scrap generated within the production process. This can include scrap from the extrusion process as well as trimmings, shavings and clippings from in the production of the final product. This can be seen as an efficiency failure in the production process.
- **Post-consumer scrap** – results from after the *end-use phase* such as ELVs, building components or used beverage cans.

Things become more complicated when we break down **pre-consumer scrap**. It can be broken down into **internal scrap** – generated within the company's own production process and **external scrap** from other manufacturers' production.

Some producers only classify post-consumer as recycled content, whereas others will include external pre-consumer and even internal pre-consumer using certain accounting practices. Under the current ELV regulation, car OEMs can increase their "recycled content" by including all three types of scrap.

It is critical that going forward only post-consumer scrap can be qualified as "recycled content". Proponents of including pre-consumer scrap as recycled content point to its importance in fostering a more circular supply chain and closing the loop. Opponents cite dubious allocation emissions or potentially incentivising industrial efficiencies and disincentivising post consumer scrap collection.

Section 3

3. How fast can aluminium decarbonise?

This section explores our modelled scenarios of how to decarbonise aluminium in the European automotive industry. We modelled scenarios utilising different decarbonisation technologies applied to both primary and secondary aluminium. We present our results which show how technology uptakes impact market level cumulative emissions. This is followed by narrowing in on the unit level of primary aluminium and its emission abatement path.

3.1 How emissions will develop in the European automotive aluminium industry

Taking into account the different technologies discussed earlier, our analysis explores three different scenarios, as detailed in the methodology included in Annex.

Automotive aluminium emissions in the EU follow three distinct pathways to 2050, as shown in the chart below. The three scenarios modelled are as follows:

Business-as-usual (BAU) – No major policy or technology shifts.

Baseline decarbonisation – Electrification *without* technologies to reduce direct emissions from smelting.

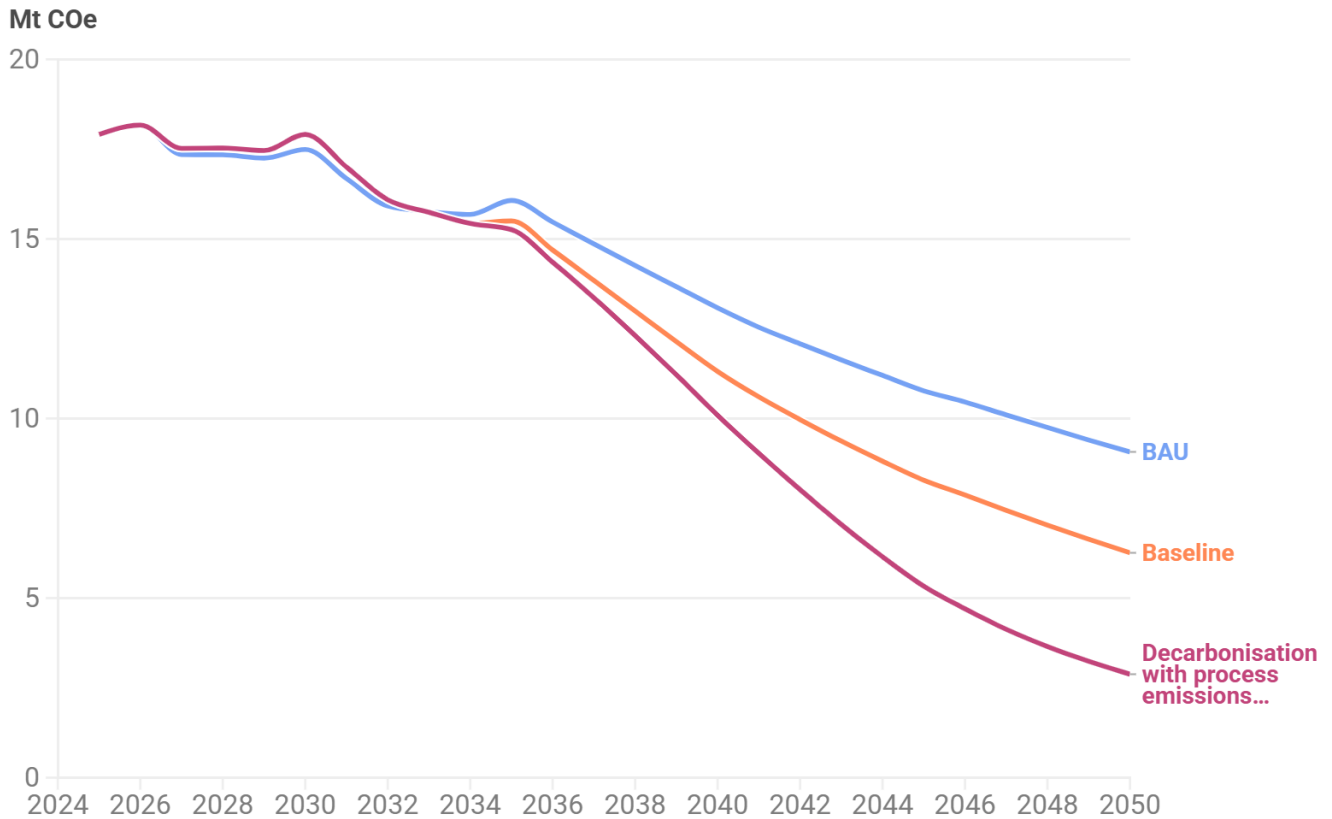
Full decarbonisation – Electrification *with* technologies to reduce direct emissions from smelting.

As shown in the graph below, in the BAU scenario, emissions peak in 2035. This is due to the projected shift to BEVs across all new car sales in Europe, which increases aluminium demand compared to ICE vehicles and other powertrains. The overall decreasing trend across all scenarios is due to the general expected reduction in global electricity grid intensities. Our baseline scenario begins to diverge from our BAU once electric furnaces and boilers begin to infiltrate the market and reach maturity. Our most ambitious scenario sees a marked divergence from the baseline once inert anodes become widespread. In our modelling, pre-consumer and post-consumer scrap are treated as recycling inline with current standards (however we recommend these standards change to exclude pre-consumer).

30% of emissions could be reduced by 2050, increasing to 68% with technology to reduce direct emissions from smelting*

Projected emissions from the European aluminium car industry

BAU Baseline Decarbonisation with process emissions reduction technology



Source: T&E analysis • *This could be achieved with inert anodes or carbochlorination technology



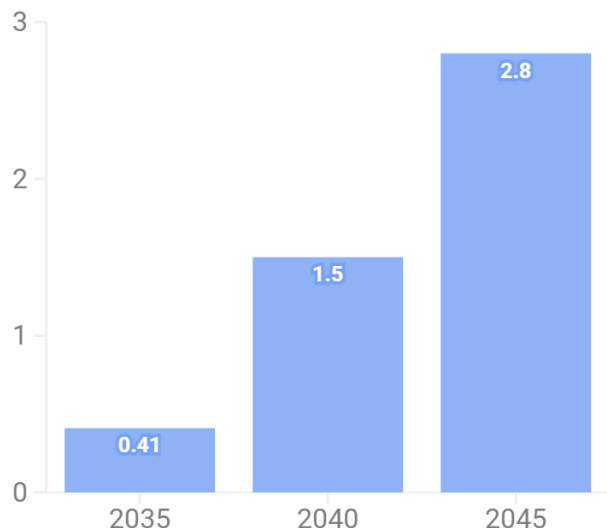
The results depict substantial cumulative emissions savings from the baseline decarbonisation scenario relative to the BAU scenario. The chart below depicts the emissions savings by 2040 which are estimated to be the equivalent of removing 900k ICEs off the road or 335 Mt CO₂e avoided. This increases to one and a half million ICE car equivalents off the road if technologies to reduce direct emissions in smelting are adopted for the same year.

Decarbonising aluminium in cars can lead to the equivalent of taking 3 million ICE's off the road in 2050

■ With process emissions reduction technology ■ No process emissions reduction technology

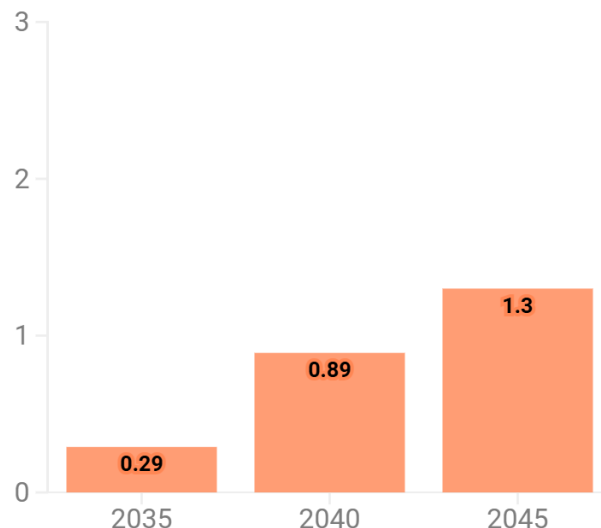
With process emissions reduction technology

Number of cars taken off the road (millions)



No process emissions reduction technology

Number of cars taken off the road (millions)



Amounts are relative to our BAU scenario



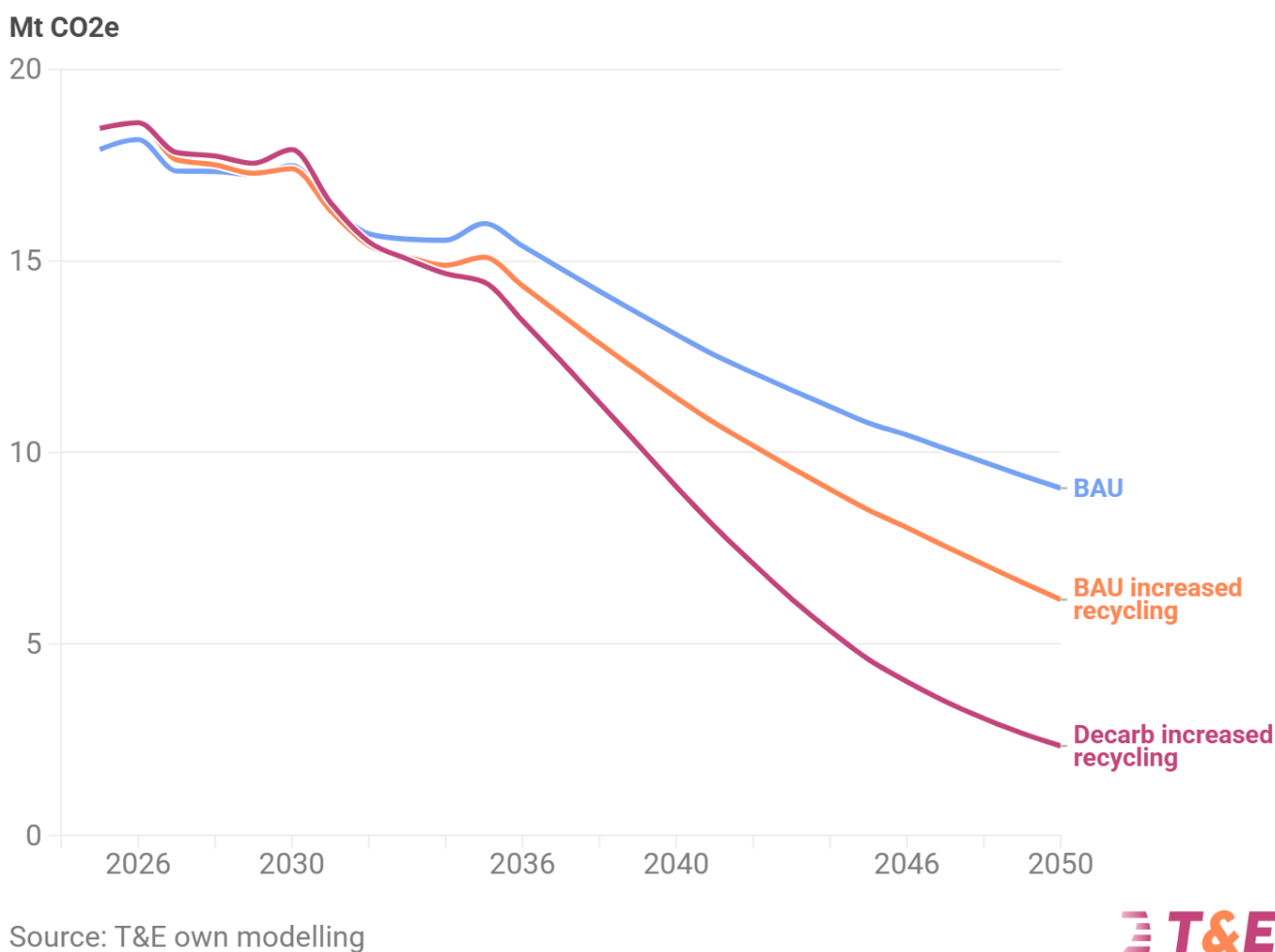
3.2 Recycling: high recycling scenarios and impacts on emissions

Recycling aluminum can also lead to significant emissions savings. Our analysis compared our previous BAU scenario with two more high-recycling scenarios. The first was a BAU recycling scenario, in which everything was assumed BAU except the share of the demand met by recycling. This share would increase to meet 80% of automotive demand by 2050. The final scenario entailed market wide decarbonisation (as depicted in the analysis in 3.1) but also with this switch to a high recycling uptake rate. In order for these recycling rates to be attained, Europe would need to avoid the cast surplus situation outlined earlier. This exercise serves as a carbon savings argument for a switch to a high recycling system within the European automotive industry, while also acknowledging the other co-benefits of security of supply and reducing primary extraction.

The high recycling decarbonisation scenario depicted below, as the maroon line, results in a gradually increasing emissions savings versus the BAU scenario. By 2035, the emissions savings is equal to taking 750,000 ICE cars off the road with this rising to over 2 million by 2040 before finally equating to over 3.5 million ICE cars off the road by 2050.

Improving scrap sorting and dismantling will be vital to decarbonise

Ambitious recycling can have substantial sectoral emissions savings

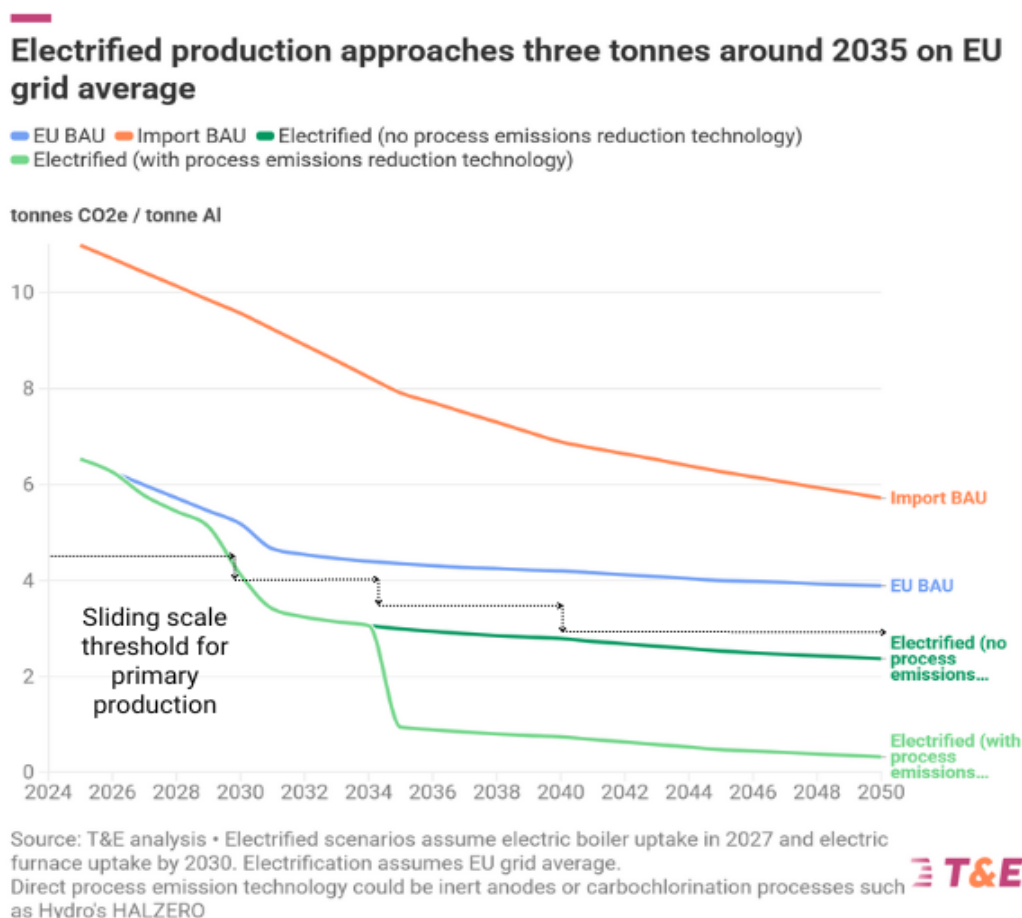


3.3 When can primary aluminium achieve “green” status in Europe?

Narrowing in on the unit level of primary aluminium, we modelled the per tonne level of aluminium and its associated emissions. The chart below depicts how the per tonne emissions of aluminium develop over time depending on the region and the technology adoption. What’s more, we developed “green only” aluminium which assumes a 100 percent decarbonisation technology uptake as soon as projected TRL is reached. This allows us to hypothesize when primary aluminium can reach green status on a smaller aggregate scale compared to our average tonne projection which is averaged across an entire region.

An electrified plant with an EU average grid intensity will reach the three tonnes CO₂e / tonne Al, below the threshold for “Green Aluminium”, by 2035. It would be more challenging for imports to comply due to their dirtier grids, providing a competitive advantage to EU production. A three tonnes green threshold provides a policy lever to rebuild and onshore primary

aluminium. European industry would benefit from the increased demand for clean aluminium within the transition to lightweight BEVs.



Section 4

4. Green aluminium: at what cost?

This section explores the cost impact of switching to green aluminium in cars. Will green aluminium be cost competitive with conventional aluminium and if so, when?

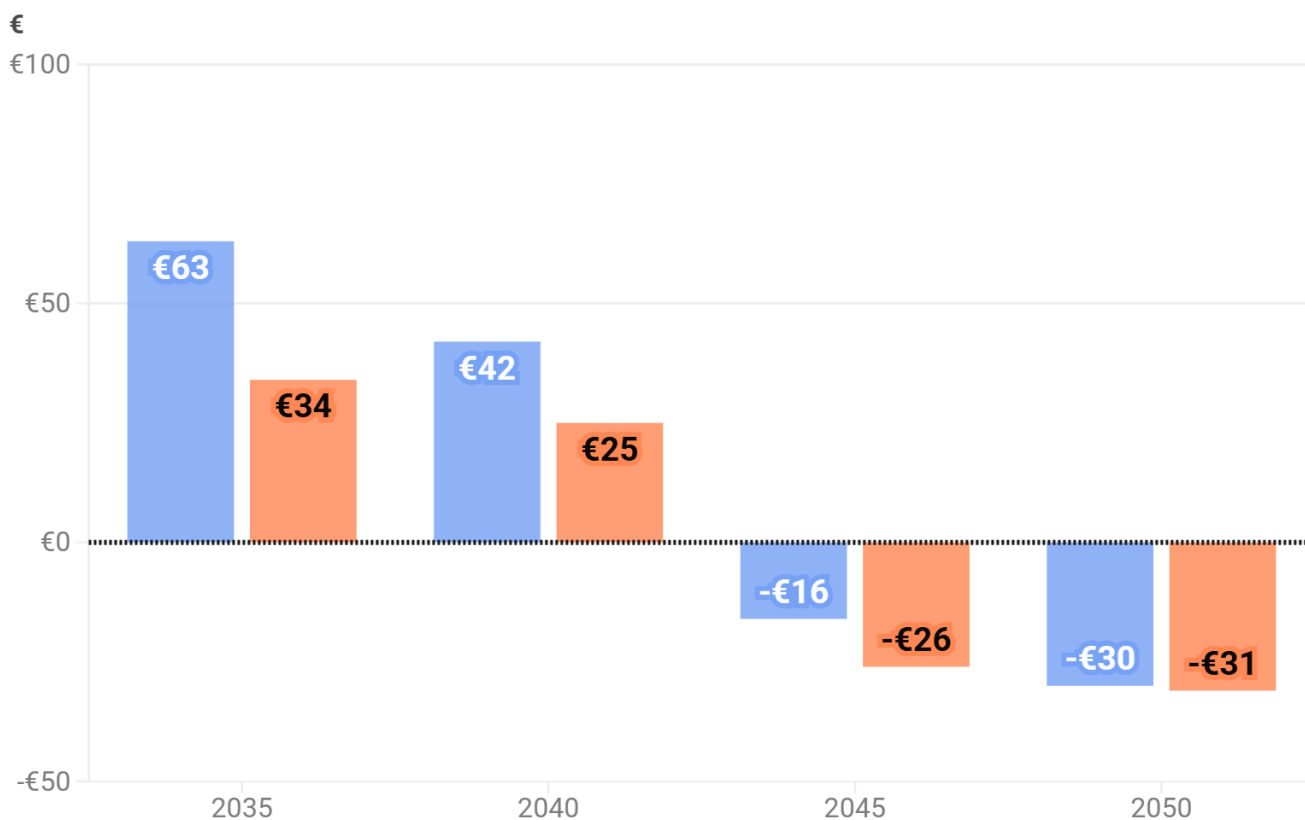
4.1 How much would green aluminium cost vs conventional aluminium?

Using green aluminium will cost carmakers more initially, before becoming cheaper in 2045. We modelled the cost difference between a business as usual conventional tonne of aluminium and our green aluminium, shown in the graph below. Beginning in 2035, when our estimates project aluminium can achieve “green” status we see the price gap peak at a difference of €60 and then become a cost savings of €26 by 2045 and finally a €30 savings by 2050.

Green aluminium projected to become cost competitive by 2040

Differences between cost of Green vs Conventional Aluminium

■ With process emission reduction technology ■ No process emission reduction technology



Source: Opex and Capex estimates from Mission Possible Partnership. Carbon price projections from IEA



It is projected that our green aluminium scenario will deliver a cost saving for cars post 2040 as the cost assumptions and input for green aluminium reduce. One of the key drivers of this is the increasing carbon cost burden for the conventional scenario. As the green aluminium process emissions move towards zero post 2035, the carbon cost of conventional aluminium increases from €578 in 2035 to €741 in 2050 per tonne. What's more, this increase is tied to the middle of the road carbon price set by the IEA. Applying the net zero scenarios to the carbon price, we see an even larger increase. Additionally, we would expect the price of key feedstocks such as electricity from renewables to decrease, favouring the green alternative. The cost breakdowns for both green and conventional are depicted below. It is worth noting the capex costs associated with green aluminium. Targeted CapEx support would be key to scaling green aluminium.

5. Conclusion

As carmakers make the transition to selling only electric cars, reducing tailpipe emissions to zero, the climate impact of the materials used to make a car are becoming increasingly important. With a vehicle's embedded, or production, emissions accounting for 60% of an electric car's total lifecycle emissions, and aluminium making up an important share of that, it is key to turn our attention to driving green aluminium production.

T&E's analysis shows that decarbonising aluminium in cars can lead to the equivalent of taking 900k ICEs off the road in 2040 in our baseline scenario. The technology to clean up aluminium is available, and now is the time to create the conditions to scale clean aluminium production, including low carbon primary production and increased recycling.

On top of this, Europe is currently heavily dependent on primary aluminium imports, However Europe can have a significant competitive advantage when it comes to green aluminium production, thanks to Europe's comparatively cleaner grid, coupled with the high electricity-intensity of aluminium production.

Taking into account the significant emissions reduction potential and the timeframes for innovation and aluminium plant investment cycles, now is the time to ensure robust and reliable policies to drive the transition to green aluminium and reduce the overall car carbon footprint. Policy and regulatory measures will be key to ensure timely uptake of clean aluminium in cars.

Recommendations

1

The EU should set minimum green (incl. recycling) aluminium quotas for new cars, via the upcoming Industrial Accelerator Act. Carmakers should be required to use a minimum of 60% green aluminium in new cars from 2035, increasing to 85% in 2040 and 95% in 2045, until all aluminium used in cars is required to be green by 2050. Green aluminum should be required to be made in the EU.

2

Recycled, local content targets should be introduced via a delegated act in the end-of-life vehicles (ELV) regulation, as part of the upcoming Circular Economy Act. Only post-consumer scrap should qualify to meet these targets.

3

The upcoming Circular Economy Act should include measures, including via improved waste codes, to significantly limit shipments of scrap aluminium outside of the EU.

4

The End-of-Life Vehicles Regulation (ELVR) should alleviate barriers to high quality recycling of aluminium, via dismantling requirements for certain parts and components and requirements to sort aluminium into cast and wrought alloys.

5

The Industrial Accelerator Act and Industrial Decarbonisation Bank should create strong conditions to invest into scaling green aluminium production in the EU, including via strengthened lead markets. The IAA should introduce a carbon product label for aluminium. These labels - which should be mandatory for all aluminium used in cars - should be based on aluminium carbon intensity. Similarly to steel labels, there should be carbon intensity thresholds (in tCO₂/t) divided into tiered classes in order to reward cleaner production with a better grade, which would incentivise investments in cleaner production pathways. Once a carbon label has been established, the lowest class and best performing can be defined as near-zero or green emission aluminium.

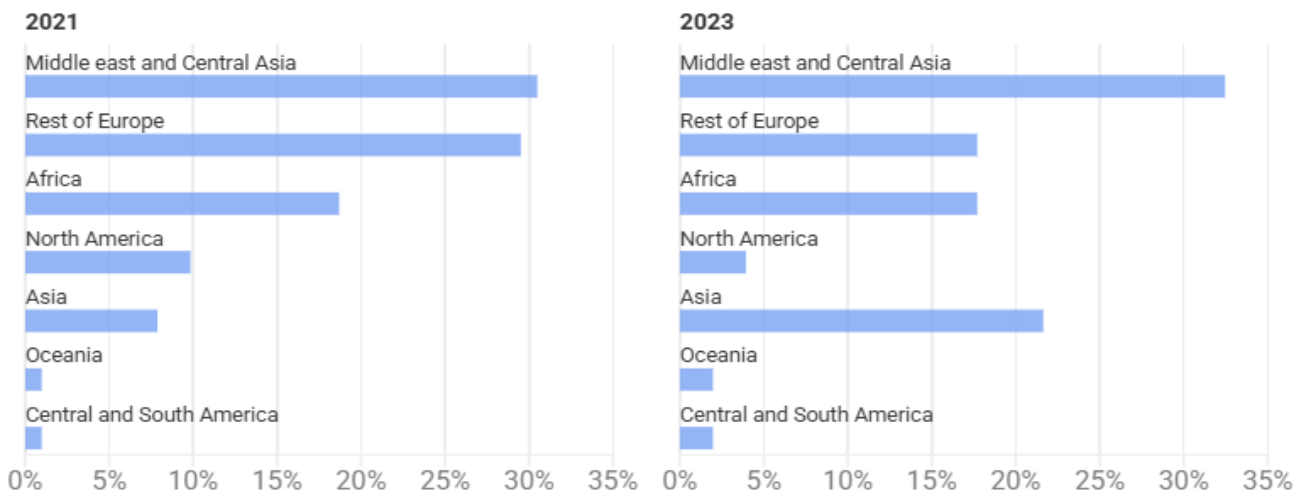
6

Under the revision of the EU car labelling directive, the EU should establish a vehicle carbon footprint label which would reward BEVs meeting both Made in EU and low carbon criteria. The label should focus on aluminum as well as other key vehicle emission hotspots (battery and steel).

Annexes

Primary aluminium imports became more carbon intensive in 2023

This was partly due to a drop in Russian imports, compensated by a rise in Asia and Middle eastern imports



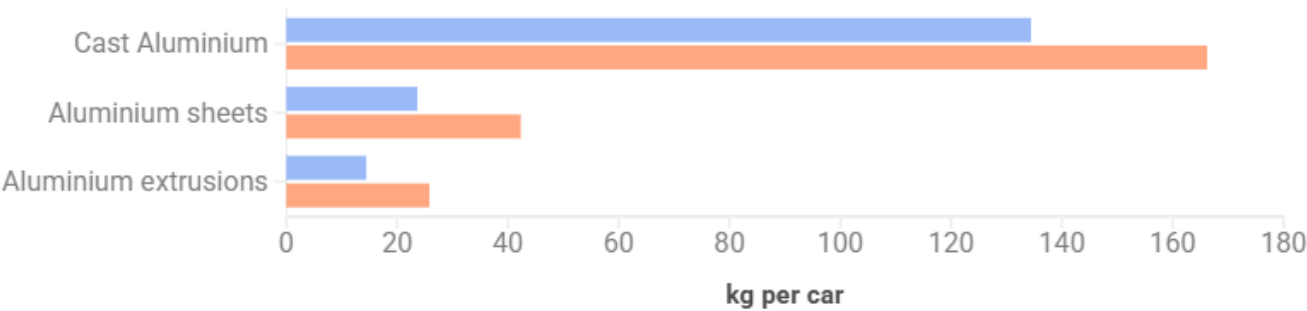
Source: European Aluminium



Annex 1.

Lightweighting of BEVs will lead to increases in Aluminium content

Conventional BEV Lightweight BEV



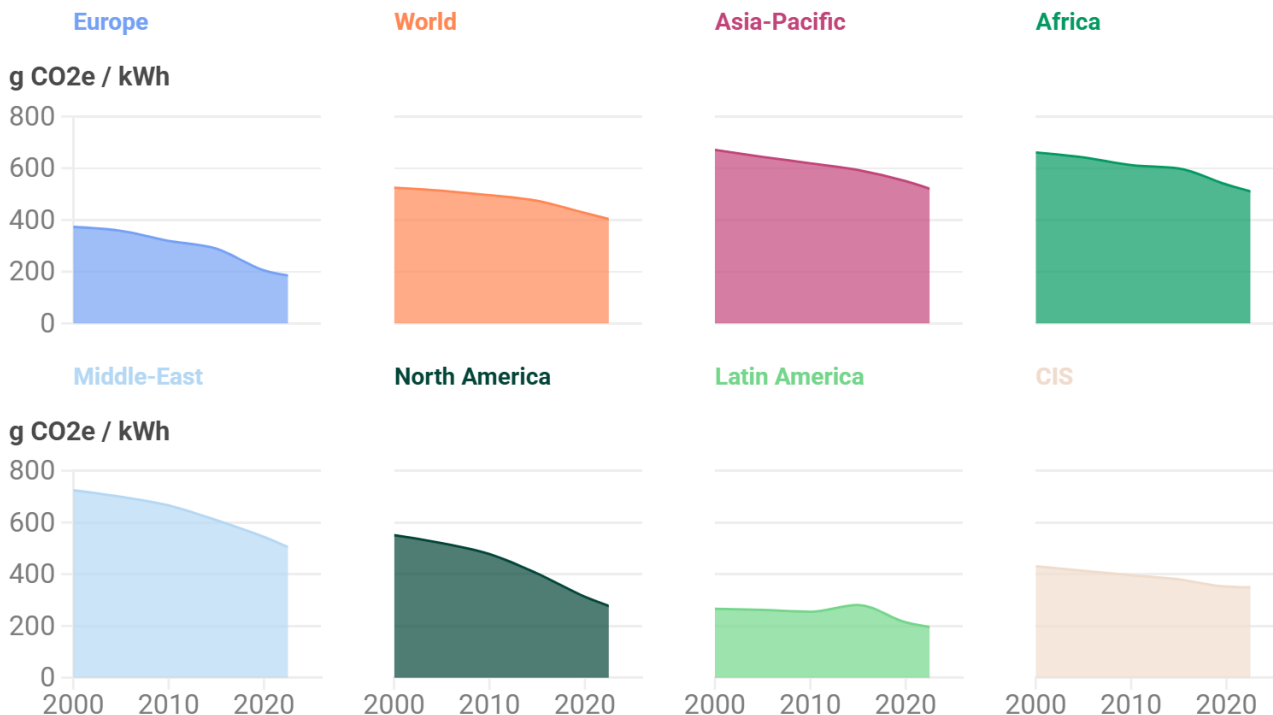
Source: Argonne National Laboratory



Annex 2.

Electricity grid intensities by region vary dramatically

This can have disparate effects on smelting emissions



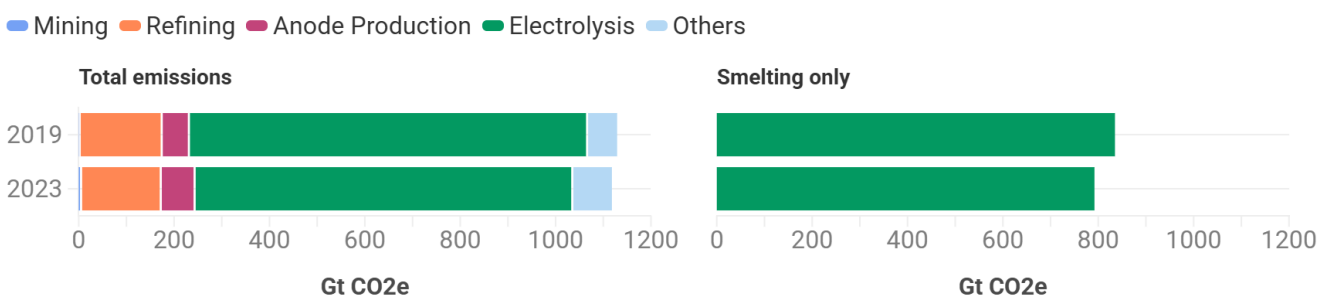
Source: Enerdata



Annex 3.

Smelting emissions are decreasing slowly with grid decarbonisation

Process still dominates total industry emissions however



Source: IAA



Annex 4.

1. Aluminium Demand model and emissions pathways

1. We used internal T&E forecasts for projected car sales by powertrain in Europe from 2025 to 2050. These projections assumed a 100% shift to BEVs from 2035 onwards (passenger cars only). Battery chemistry shares were also included to estimate aluminium mass per kWh.
2. Aluminium content per vehicle (CPV) was sourced from Ducker Carlisle. We extrapolated powertrain-specific CPV data to 2035 and assumed a fixed value for BEVs from 2035 to 2050.
3. Grid projections (2025–2050) were taken from Enerdata. We combined these with IEA regional smelter intensity figures to estimate indirect emissions from smelting.
4. Industry-level breakdowns including import splits by region and primary and recycling breakdowns were taken from European Aluminium. Additional scenarios were built using scenarios and assumptions such as that in Vision50 by European Aluminium as well as high recycling scenarios.
5. Emission factors along the supply chain were primarily taken from European Aluminium's decarbonisation report, cross-checked against GREET2, MPP, and the ACT initiative.
6. Material mass shares and emissions data were sourced from GREET2, including scrap content for wrought and cast products.
7. Embedded emissions were calculated using the material mix per powertrain and their associated emission factors.

Note: pre-consumer and post-consumer scrap are treated as recycling inline with current standards (however we recommend these standards change to exclude pre-consumer).

2. Cost Model

We developed a bottom-up cost model using input data from the MPP Aluminium model, including material costs, CAPEX/OPEX, labour, and energy use. Electricity prices were applied to both import and European production scenarios:

- Import case: IEA global proxy estimate
- European case: SKYpower EFuel model projections (Norway PPA estimates to 2050)

We included sensitivity analysis using data from the EU Commission's Reference Scenario and France's environmental ministry. Carbon price projections were based on IEA Net Zero scenarios.

3. Technology Adoption Pathways

We modelled S-curve adoption for key decarbonisation technologies:

- **Electric boilers:** Uptake begins ~2028, reaching near-full adoption by 2040 (medium pathway).
- **Electric furnaces:** Begin ~2030, achieving ~99% adoption by 2050.
- **Direct process emission reduction technology:** Gradual uptake from ~2035, reflecting higher technical barriers.

4. Green-Only Scenario

This scenario assumed immediate, full-scale adoption of all available decarbonisation technologies from the start of the modelling period.