MAKING NET-ZERO ALUMINIUM POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

ALUMINIUM TRANSITION STRATEGY / SEPTEMBER 2022

MISSION POSSIBLE PARTNERSHIP

Sponsored by

Energy Transitions Commission

RMI ENERGY. TRANSFORMED.

WE MEAN BUSINESS COALITION

WORLD ECONOMIC FORUM

In collaboration with the International Aluminium Institute

INTERNATIONAL ALUMINIUM

THE MISSION POSSIBLE PARTNERSHIP

At current emissions levels, staying within the global carbon budget for 1.5°C might slip out of reach in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: some of the biggest emitters of greenhouse gases into the atmosphere — transportation sectors like aviation, shipping and trucking, and heavy industries like steel, aluminium, cement/concrete, and chemicals manufacturing — are the hardest to abate. Transitioning these industries to climate-neutral energy sources requires complex, costly, and sometimes immature technologies, as well as direct collaboration across the whole value chain, including companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. Our objective is to propel a committed community of CEOs from carbon-intensive industries, together with their financiers, customers, and suppliers, to agree and, more importantly, to act on the essential decisions required for decarbonising heavy industry and transport. Led by the Energy Transitions Commission, the Rocky Mountain Institute, the We Mean Business Coalition, and the World Economic Forum, MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most hard-to-abate sectors: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals.

The foundation of MPP's approach: 7 Sector Transition Strategies

Transitioning heavy industry and transport to net-zero GHG emissions by 2050 — while complying with a target of limiting global warming to 1.5°C from preindustrial levels — will require significant changes in how those sectors operate. MPP facilitates this process by developing **Sector Transition Strategies** for all seven hard-to-abate sectors.

A Sector Transition Strategy

is a suite of user-friendly tools (including a report, an online explorer, and an open-source model) aiming to inform decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to deliver net zero within the sector by 2050 and to comply with a 1.5°C target.

In line with industry-specific replacement cycles of existing assets (like steel plants or aircraft) and the projected increase in demand, the market penetration of viable decarbonisation measures each sector can draw on is modelled.

The objectives of the MPP Sector Transition Strategies are:

1. **To demonstrate industry-backed, 1.5°C-compliant pathways to net zero,** focusing on in-sector decarbonisation and galvanising industry buy-in across the value chain.

2. **To be action-oriented with clear 2030 milestones:** By quantifying critical milestones for each sector in terms of its required final energy demand, upstream feedstock resources, and capital investments, MPP wants to lay the foundation for tangible, quantitative recommendations of ways to reach these milestones through collaboration among industry, policymakers, investors, and customers.

3. **To be transparent and open:** MPP's long-term goal is to fully lay open the internal machinery of the Sector Transition Strategies, that is, to make its Python models open source and all data inputs open access. In addition, MPP is developing online explorers that bring the Sector Transition Strategy reports to life: individual users will be able to explore the results of the reports and to customize model input assumptions, study the impact of individual levers, and dive deeper into regional insights.

4. **To break free from siloed thinking:** The transition of a sector to net zero cannot be planned in isolation since it involves interactions with the broader energy system, for instance, via competing demands for resources from multiple sectors. All MPP Sector Transition Strategies are based on similar assumptions about the availability and costs of technologies and resources like electricity, hydrogen, or sustainable biomass. By providing a harmonized, cross-sectoral perspective, we intend to inform decision makers with a fair, comparable assessment of transition strategies for all seven sectors.

On the basis of its Sector Transition Strategies, MPP intends to develop practical resources and toolkits to help operationalize industry commitments in line with a 1.5°C target. Among others, the quantitative results of the Sector Transition Strategies will inform the creation of standards, investment principles, policy recommendations, industry collaboration blueprints, and the monitoring of commitments. These will be developed to expedite innovation, investments, and policies to support the transition.

Goals of the MPP Aluminium Transition Strategy

In this report, we explore the potential to reduce emissions associated with the production of aluminium. This analysis has been conducted using the Aluminium Sector Transition Strategy Model and is informed by the valuable work conducted by the International Aluminium Institute for the "1.5 Degrees Scenario: A Model to Drive Emissions Reduction" and extensive engagement with the wider aluminium community and aluminium sector experts as part of the Aluminium for Climate initiative (initiated by the World Economic Forum in 2019). The approach here is shaped by four main objectives:

- Provide a first detailed open-sourced asset-based analysis of the approach that the aluminium sector can use to reach 1.5°C.

- Provide a detailed reference point for the changes that will be needed over the next 30 years to underpin corporate target setting, science-based targets, and financial-sector alignment methodologies.

- Inform priority actions, trade-offs, and decisions in the 2020s by stakeholders that will shape the aluminium markets, including industry leaders, governments, buyers of carbon-intensive materials, and financial institutions.

- Underpin a coherent set of commitments to action from stakeholders across the value chain, which together will unlock investment in zero-carbon solutions.

To promote transparency and collaboration, the model materials and analytics are open-access tools, such that the inputs and assumptions are available for enquiry, and future iterations may build on this effort. This open-access approach lends itself to periodic refinement as data and insights evolve. Critically, it also ensures that the industry can align behind a strategy it considers technically and economically feasible, subject to appropriate value-chain collaboration, finance, and policy support. The Archetype Explorer tool that accompanies this report enables users to adjust various parameters in the model to reflect the circumstances faced in a particular geography, supporting real-world decision-making.

Industry support for MPP's Aluminium Transition Strategy

This report constitutes a collective view of participating organisations in the Aluminium Sector Transition Strategy. Participants have generally validated the model inputs and architecture and endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. These companies agree on the importance of limiting global warming to 1.5°C and the importance of reaching net-zero GHG emissions in heavy industry and transport by mid-century, and they share a broad vision of how a 1.5°C-aligned transition scenario could be achieved. The companies recognize that actions to support this broad vision should be pursued expeditiously.

The fact that this agreement is possible among the industry leaders listed below should give decision makers around the world confidence that it is possible to simultaneously meet rising aluminium demand, reduce emissions from the sector to net zero by 2050, and comply with a 1.5°C target. It should also provide confidence that the critical actions required in the 2020s to set the sector on the right path are clear and should be pursued without delay, and that the industry is ready to collaborate with its value chain.

Unless otherwise stated, the report is based on publicly available, open-access input assumptions, and endorsers have not provided commercially sensitive information for technologies under development. Although assumptions have been developed through a consensus view of participants, there are significant risks and uncertainties, particularly related to cost, performance, and rate of implementation for technologies. Actual results may differ materially from those indicated by these forward-looking assumptions.

AUTHORS & ACKNOWLEDGEMENTS

This report was prepared by the Mission Possible Partnership aluminium team in collaboration with the International Aluminium Institute (IAI).

The coordination of the report, analysis, and stakeholder engagement was led by:

Marten Ford (Energy Transitions Commission, ETC)
Min Guan (ETC)
Jason Martins (ETC)

and supported by:

Pernelle Nunez (IAI)
Marlen Bertram (IAI)
Jörgen Sandström (World Economic Forum, WEF)

The model and analytics effort was led by **Min Guan** (ETC) and delivered by:

Jason Martins (ETC)
Luis Natera (ETC)
Hugo Stevens (ETC)
Abindra Soemali (ETC)
Aparajit Pandey (ETC)

Steering and guidance were provided by MPP leadership who oversee the development of all the MPP Sector Transition Strategies:

Faustine Delasalle (Executive Director, MPP)
Eveline Speelman (ETC)
Alasdair Graham (ETC)

We thank Andrea Bath, Henry Gilks, Andrew Isabirye, Laëtitia de Villepin, Maaike Witteveen, Ben Dixon, Adair Turner (all from ETC), Linlin Wu (IAI), Renée Van Heusden (WEF), Wen Zhang (WEF), aluminium sector experts as part of the Aluminium for Climate initiative (initiated by the World Economic Forum in 2019) and other collaborators for providing valuable contributions to this project. The report was edited and designed by M. Harris & Company.

PREPARED BY

Mission Possible Partnership (MPP)

Led by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-as-Usual scenario. MPP brings together the world's most influential leaders across finance, policy, industry, and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net-zero. **www.missionpossiblepartnership.org**

Energy Transitions Commission

Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our commissioners come from a range of organizations – energy producers, energy-intensive industries, technology providers, finance players, and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. **www.energy-transitions.org**

World Economic Forum

The World Economic Forum is the international organization for public–private cooperation. The Forum engages the foremost political, business, cultural, and other leaders of society to shape global, regional, and industry agendas. Learn more at **www.weforum.org**.

RMI

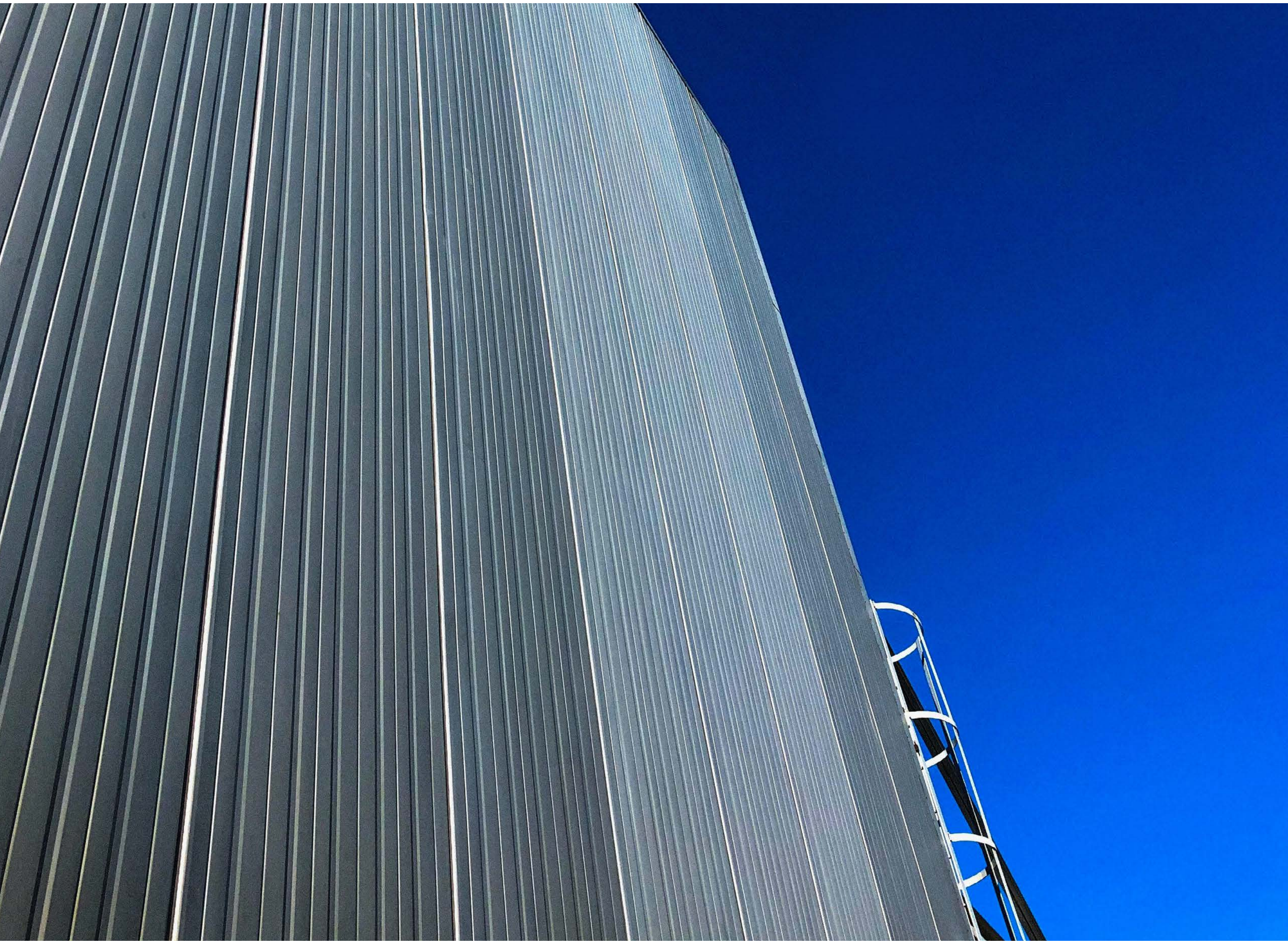
RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. **rmi.org**

International Aluminium Institute (IAI)

The International Aluminium Institute is the only body representing the global primary aluminium industry and was established in 1972. Current IAI membership includes global bauxite, alumina, and aluminium companies in all the major producing regions. Through the IAI, the aluminium industry aims to promote a wider understanding of its activities and to demonstrate both its responsibility in producing the metal and the potential benefits to be realised through its use in sustainable applications and recycling. **international-aluminium.org**

CONTENTS

TEN CRITICAL INSIGHTS ON THE PATH TO A NET-ZERO ALUMINIUM SECTOR



1. Bringing the aluminium sector on a path to net zero by 2050 is technically and economically possible. Achieving it will require a mix of levers within the primary aluminium sector, in the wider aluminium value chain, and in partnership with the power sector.

The aluminium sector is currently responsible for approximately 2% of global emissions, about 1 gigatonne of carbon dioxide equivalent (1 Gt CO_2e). Without efforts to curtail them, annual emissions could grow by as much as 90% by 2050 as a result of population growth and economic development (Exhibit A).

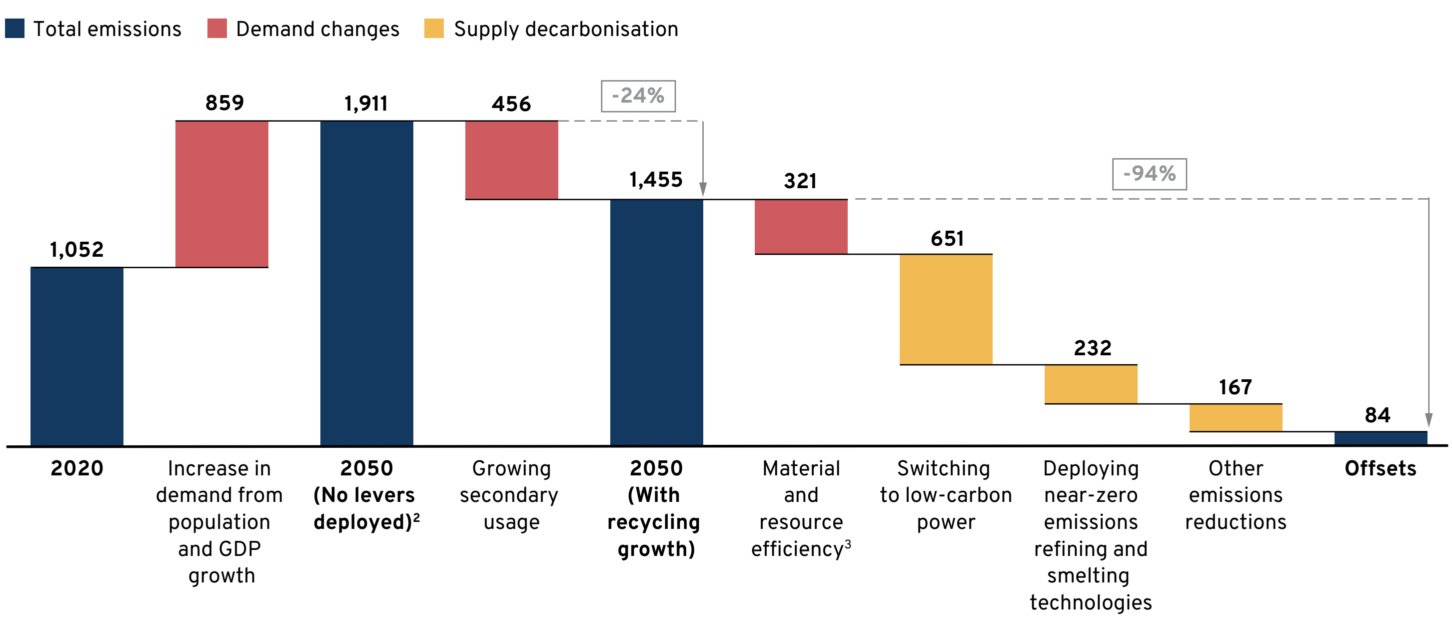
As Exhibit A shows, the aluminium sector can deliver a net-zero sector through four major levers, which are common across all scenarios developed to look at the sector's low-carbon transition:

- **Transitioning to low-carbon power (651 million tonnes [Mt] of CO_2e savings in 2050).** Aluminium is a heavily electricity-intensive industry, with almost 1,000 terawatt-hours (TWh) of electricity demand. Switching to low-carbon electricity is the biggest step the industry can take to deliver a sector compatible with net zero.
- **Maximising secondary aluminium production (456 Mt CO_2e in 2050).** Recycling aluminium (secondary production) has a significantly lower carbon footprint than new (primary) aluminium production (0.5 t CO_2e/t aluminium [Al] versus up to 16 t CO_2e/t Al).
- **Maximising resource efficiency (321 Mt CO_2e in 2050).** The industry should ensure that product design uses aluminium efficiently. Examples include extending the life of buildings in

EXHIBIT A

A low-carbon aluminium sector is possible by 2050

Emissions for the aluminium sector,[1] Mt CO_2e/y



[1] Includes all direct and indirect emissions along the value chain for primary and secondary aluminium production (i.e., mining, alumina refining, aluminium smelting, anode production, casting, fabrication, recycling, and transport).
[2] Based on the IAI's Reference scenario, except for primary/secondary production ratio, which is assumed constant between 2020 and 2050; 2020 carbon intensity of aluminium assumed constant.
[3] Based on demand projections from the IAI's 1.5°C scenario.

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

China, extending automotive lifetimes, and using mobility-as-a-service in order to reduce the number of vehicles needed to meet people's mobility needs.

- **Deploying new technology to deliver near-zero-emissions refineries and smelting facilities (232 Mt CO_2e in 2050).** New technology is required to decarbonise thermal energy in refineries, such as heat recovery and fuel switching, and low-carbon anodes in smelters. These technologies need to be commercialised and be widely available by 2030.

Particular uncertainties, such as material substitution (both from and to the aluminium sector), could also play a role in delivering these reductions in emissions.

To deliver these steps, the whole value chain will have to address key problems such as access to low-cost and low-carbon power, lack of availability of aluminium to recycle, and lack of a business case for low-carbon aluminium production.

2. Rapid action is required in order for the sector to adhere to a 1.5°C pathway. Power decarbonisation by 2035 is necessary but not sufficient, with almost half of cumulative emissions savings requiring additional levers.

A Business-as-Usual (BAU) scenario would be responsible for cumulative GHG emissions between 2020 and 2050 of 37 Gt CO_2e – an overshoot of more than 100% against a 1.5°C carbon budget for the aluminium sector of 15 Gt CO_2e.

In contrast to this BAU scenario, two net-zero scenarios combine different power decarbonisation pathways to reach net zero by 2050. The main difference between the 1.5°C scenario and the No CCS scenario is that the former focuses on using carbon capture and storage (CCS) for existing fossil fuel power assets, while No CCS focuses on new connections to low-carbon power grids.

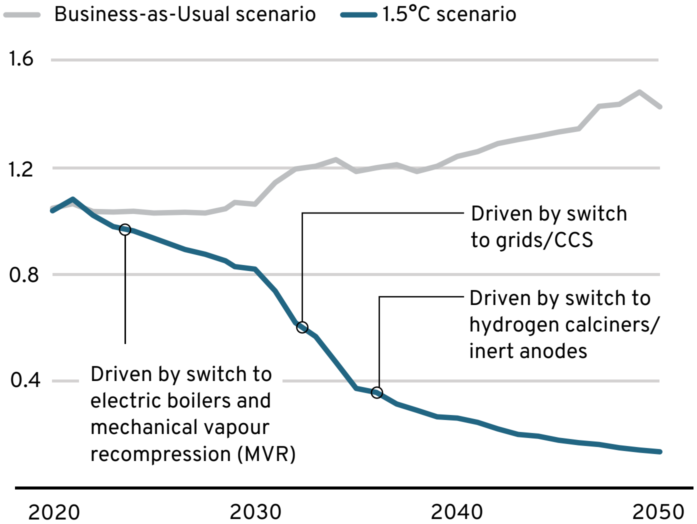
In the 1.5°C scenario, low-carbon power will deliver over half of these emissions reductions (12 Gt CO_2e), decarbonising the sector's power needs by 2035 through decarbonising power grids and deploying CCS, and, in the longer term, using small modular nuclear reactors (Exhibit B).

Power decarbonisation is necessary but not sufficient to adhere to a 1.5°C pathway. Solutions such as low-carbon heat in refineries must be deployed beginning in the late 2020s, low-carbon anodes in smelters need to start commercially deploying at scale by 2030, and material efficiency is critical. These technologies are generally at a lower readiness level than are power decarbonisation technologies and require not only further research and development, but also access across the industry.

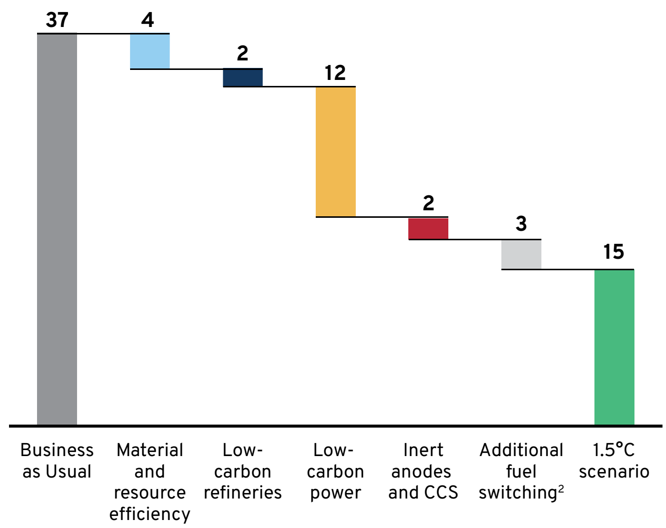
EXHIBIT B

Delivering 1.5°C requires rapid action across the aluminium value chain

Emissions[1] pathways, Gt CO_2e/y



Cumulative emissions, Gt CO_2e, 2020 to 2050



[1] Includes all Scope 1, Scope 2, and Scope 3 emissions associated with primary and secondary aluminium production.
[2] Includes additional value chain emissions reduction via low-carbon fuel switching and other decarbonising levers for mining, casting, fabrication, recycling, and transport.

Source: Aluminium Sector Transition Strategy Model (2022)

3. Power decarbonisation is the biggest decarbonisation lever, with 1,000 TWh of low-carbon electricity required by 2035, up from 250–300 TWh today.

Aluminium is a particularly electro-intensive industry, accounting for ~4% of global electricity demand in 2020. Approximately 250–300 TWh[i] is low carbon already through captive hydroelectric generation and connections to grids which are low carbon through a mix of hydro and nuclear. Decarbonising this power will require up to 1,000 TWh of low-carbon power by 2050. The falling costs of variable low-carbon power represent an opportunity; however, significant challenges remain, as aluminium smelters require constant power inputs. Greater development of other complementary power technologies such as batteries and hydrogen will be needed over the coming decades.

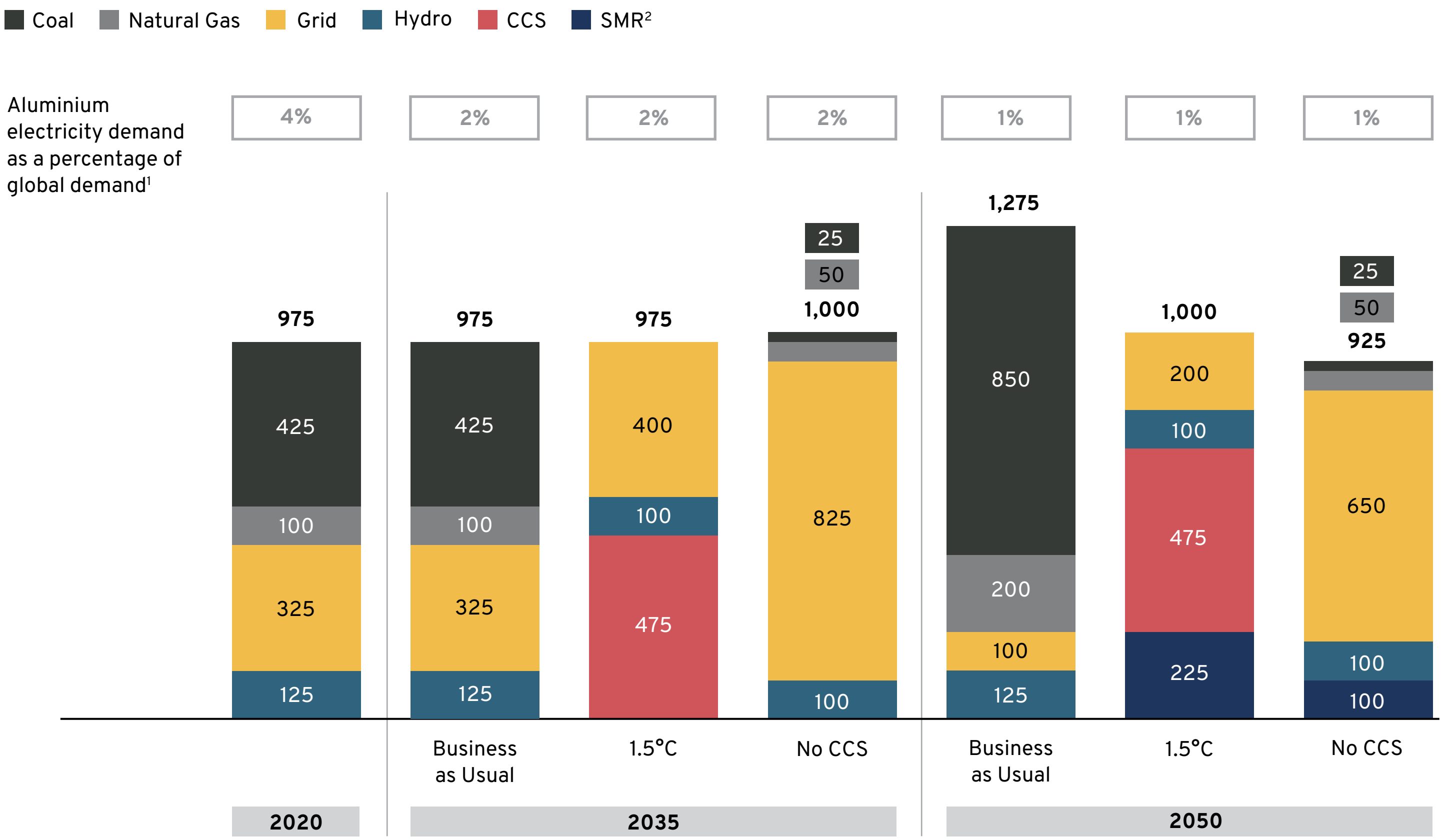
Aluminium's share of global power demand will shrink from 4% to ~1%–2% by 2050 as a result of the growing electrification of other sectors. This shift will, in the long term, weaken the aluminium sector's bargaining power for access to low-cost electricity.

To achieve a 1.5°C pathway, producers that currently use captive power production will face a choice, either producing low-carbon captive power through CCS, connecting to a low-carbon grid, or developing power purchase agreements (PPAs) with low-carbon power providers. Not every location will be able to use the grid or PPAs, because local grids do not decarbonise fast enough to keep the sector as a whole on track for 1.5°C. There are numerous combinations of power supply that can deliver power needs broadly in line with a 1.5°C trajectory (Exhibit C). The difference between the 1.5°C scenario and the No CCS scenario is that in the latter, no carbon capture is used for decarbonising smelters' power supplies.

i IAI 2020 data on primary production (hydro, other renewables, and nuclear).

Delivering a 1.5°C pathway requires a significant amount of power from CCS or from low-carbon grids

Smelter power demand mix across scenarios, TWh per year



[1] Global electricity demand in 2020, 2035, and 2050 is sourced from ETC, *Making Clean Electrification Possible*, 2021, www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Power-Report-.pdf.
[2] SMR = small modular reactor, up to 3,000 MW in capacity.

Source: Aluminium Sector Transition Strategy Model (2022)

4. Location matters for how smelters and refineries decarbonise. There is significant variation in availability of local low-carbon power and in how quickly the local grids can decarbonise.

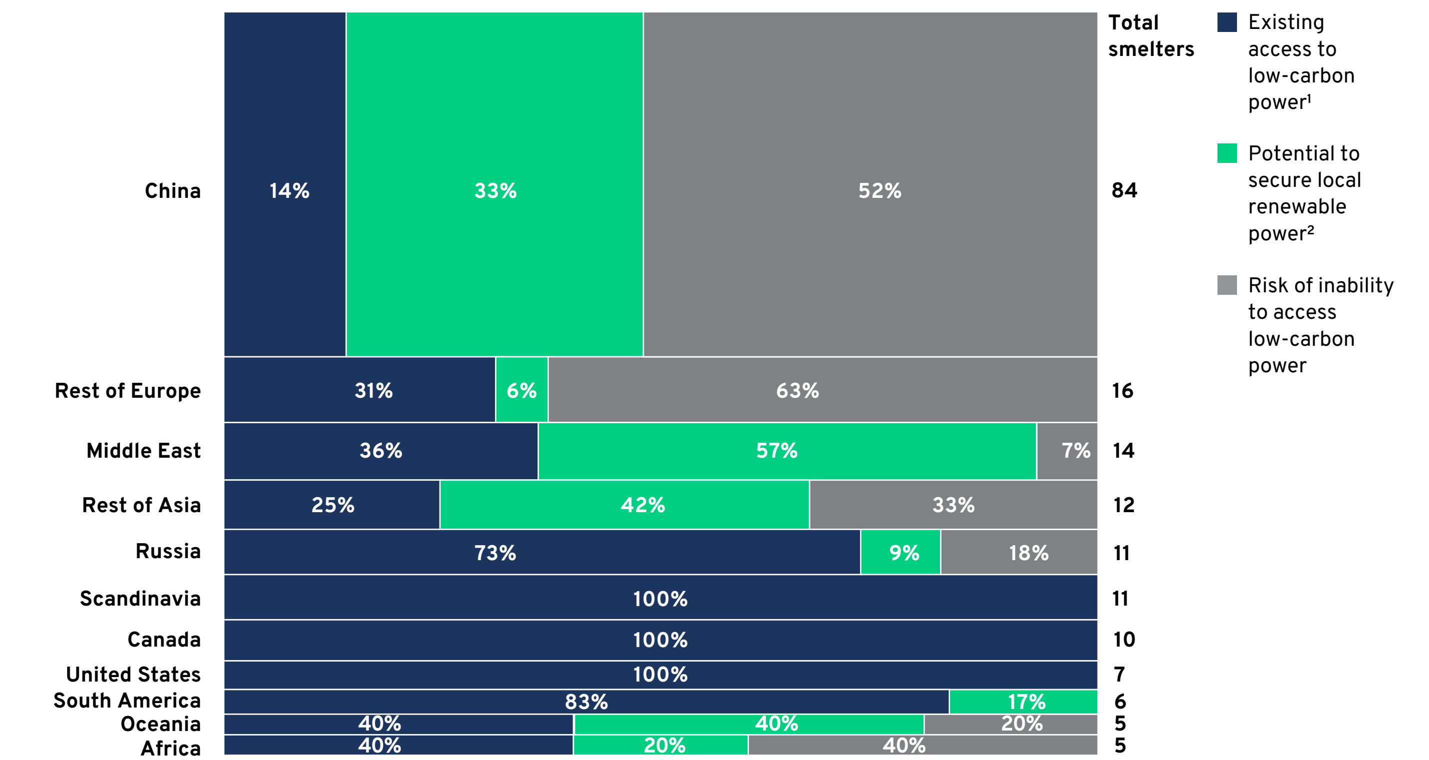
It is expected that about 65% of aluminium smelters (representing 60% of global production capacity) will be able to source PPAs or low-carbon grid power to reduce their average emissions intensity while still benefitting from the dependability of a grid connection. A significant exception for this is in China, where about 52% of smelters are unlikely to access local PPAs, as they are not located in areas with sufficiently high wind or solar generation capacity factors above 20% (Exhibit D).

In the absence of an affordable low-carbon energy source, it is expected that these smelters may be shut down and relocated, with potential implications for the shape of global aluminium production and trade. Alternatively, they could retrofit their direct power generation facilities to include CCS, employ novel low-carbon power solutions (for example, using portfolios of renewables), or use long-distance transmission connections to regions with greater low-carbon power availability. All of these alternative options carry significant extra complexity and challenges.

EXHIBIT D

Access to low-carbon power varies significantly by location, and some regions have particular challenges

Access to low-carbon power supply by smelter in 2020, % of regional smelters



[1] Includes captive hydropower, renewables, PPAs, and grids with carbon intensity currently less than 100 g CO_2/kWh.
[2] Defined by geolocational data for smelters with local capacity factors for solar PV or wind power greater than 20% or 30%, respectively.

Source: Aluminium Sector Transition Strategy Model (2022)

5. Secondary aluminium plays a critical role in the expanding aluminium market, increasing from 33% of total demand (33 Mt/y) in 2020 to 54% (81 Mt/y) in 2050.

Current post-consumer scrap collection rates vary widely across geographies and sectors; for example, the aluminium can collection rate is above 95% in Brazil but only approximately 50% in North America.[1] Globally, average scrap collection rates for all end-use sectors will need to move from about 70% today to more than 90% by 2050 to maximise circularity in the sector.[2] Achieving this shift will require greater emphasis on eco-design, whereby the design of products and buildings incorporates end-of-life planning as a critical element for increasing reuse and recycling rates.

In addition, alloy separation, sorting, and purification methods will all need to be developed to maximise the volumes of available post-consumer scrap. A particular challenge is presented by composite materials in which aluminium accounts for a low percentage of the overall product, making the metal difficult and expensive to recover and often leading to downcycling into lower value products. Avoiding downcycling will require close cooperation between the aluminium end-use sectors and policymakers in order to develop strategies for recycling alloy-contaminated products.

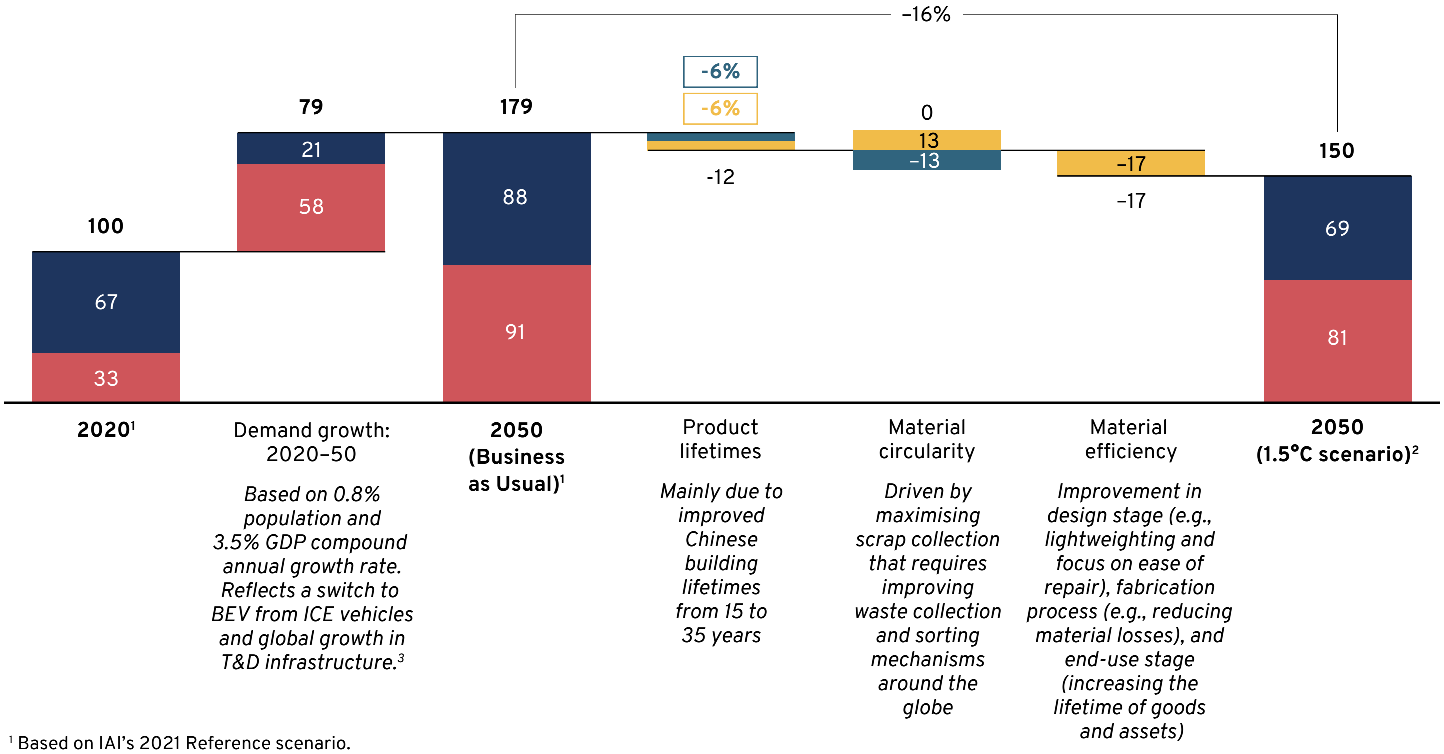
Taken together, the aforementioned measures allow the secondary sector to grow its supply of aluminium from 33 Mt in 2020 to 81 Mt by 2050 (Exhibit E). If this can be achieved, secondary aluminium production can address the expected demand growth over the coming 30 years, reducing the role for new carbon-intensive primary production.

The good news is that some levers in achieving this growth are already proven. For example, Germany has achieved high can collection rates (over 98%) through regulating and normalising scrap collection via a deposit return scheme. The challenge is how this success can be replicated in more complex situations, such as extracting scrap aluminium from buildings, where it is likely to be mixed with other material.

EXHIBIT E

Majority of aluminium demand by 2050 is expected to be met by secondary aluminium in a 1.5°C scenario

Demand for aluminium, Mt per year



[1] Based on IAI's 2021 Reference scenario.
[2] Based on IAI's 1.5°C scenario.
[3] BEV = battery electric vehicle, ICE = internal combustion engine, T&D = transmission and distribution.

Source: IAI Material Flow Model (2021)

6. Without any action, aluminium demand is expected to rise 80% by 2050. Material efficiency can play a critical role in ensuring that aluminium is used effectively, potentially reducing demand by 29 Mt and limiting growth to 50%.

Approximately 50% of global aluminium demand today comes from the transport and construction sectors (26% and 24%, respectively). Additional significant demand comes from electrical and machinery equipment (11% each), foil stock and packaging (8% each), and consumer durables (6%).[3]

Without deliberate action being taken, the underlying demand for aluminium is expected to increase by 80% between 2020 and 2050 (Exhibit E). Increased material and product efficiency from, for example, longer building lifetimes in China could reduce this to a 50% increase.

Measures across all end-use sectors will be required in order to limit demand growth. Such measures include reducing losses in product manufacturing processes; designing end-use products with greater durability, longevity, and lightweighting; shifting consumption patterns from single-use to multiuse packaging; and developing business models focused on repair and refurbishment at product end-of-life stages.

7. Cumulative investment of approximately US$1 trillion across the primary production value chain will be needed to deliver a net-zero sector, or a 1.5°C pathway. The majority of this investment will be needed in power supply and smelters.

The 1.5°C pathway will require four key categories of investment over the coming 30 years (Exhibit F):

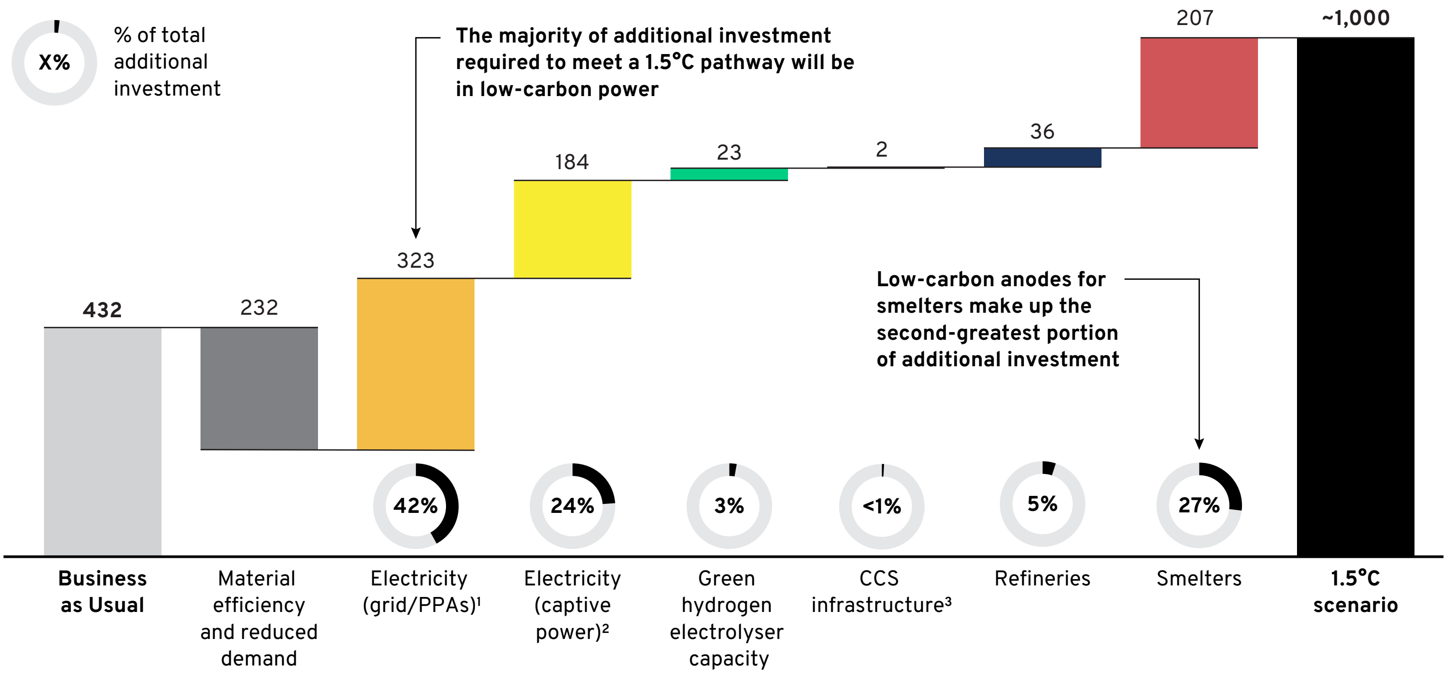
- Investments in low-carbon power both within and outside the aluminium industry (including renewable PPAs, grid decarbonisation, CCS retrofits to existing thermal captive power): requiring approximately $500 billion by 2050
- Investments by aluminium producers in smelters, primarily in low-carbon anode retrofits: approximately $200 billion by 2050 (different anode technologies will have different investment-operational cost trade-offs; given the stage of technology development, this is highly uncertain)
- Investments by aluminium producers in refineries covering the transition to low-carbon fuels at refineries: estimated to be $36 billion by 2050
- Investments in CO_2 transport and storage infrastructure as well as hydrogen production: estimated to be $26 billion by 2050

Delivering these significant investments in diverse and new types of projects will require significant partnership across the value chain, particularly in coordinating power investments with the aluminium sector needs.

EXHIBIT F

Total additional investment to deliver 1.5°C is mainly outside the primary aluminium industry in electricity generation

Cumulative investments required in the primary aluminium sector, billion $, 2020–50



[1] Uses an assumption that refineries will use 100% electricity from PPAs.
[2] Includes investments in captive power such as fossil CCS or nuclear SMR.
[3] Uses an estimate of \$5/t CO_2 capital expenditure for CO_2 transport and storage infrastructure.

Source: Aluminium Sector Transition Strategy Model (2022)

8. Low-carbon aluminium will cost up to $400/t more to produce than conventional aluminium on average by 2035. However, cost increases will vary significantly from producer to producer.

Delivering low-carbon aluminium will result in particularly high costs for retrofitting existing refineries and smelters. These additional costs in the initial roll-out will be driven by the higher capital expenditures associated with most technology changes, as well as higher running costs. Over a longer period of time as capital is amortised, this cost differential will be driven down.

These increases in costs will vary significantly depending on the current circumstances of individual refineries and smelters. They are also highly dependent on long-term energy prices. As illustrated in Exhibit G, global averages highlight two key trends:

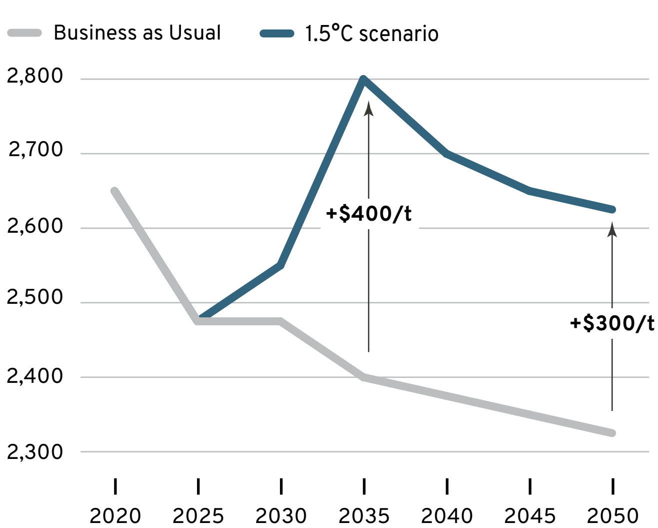
- **Refineries** could see increases of **$150/t Al** (30% above current levels) for converting to low-carbon means of production.
- **Smelters** could see significant variation, with cost increases of **$75/t–$600/t Al** depending on their current power arrangements.

Clear action is required to address this cost gap: (1) action to bring down costs of technologies through early stage R&D and continued power decarbonisation rollout; (2) policy action and action from buyers to facilitate a market for low-carbon aluminium (through a combination of carbon pricing, green premium, and removing support for high-carbon production); and (3) the mobilisation of green and sustainable financing across the entire value chain.

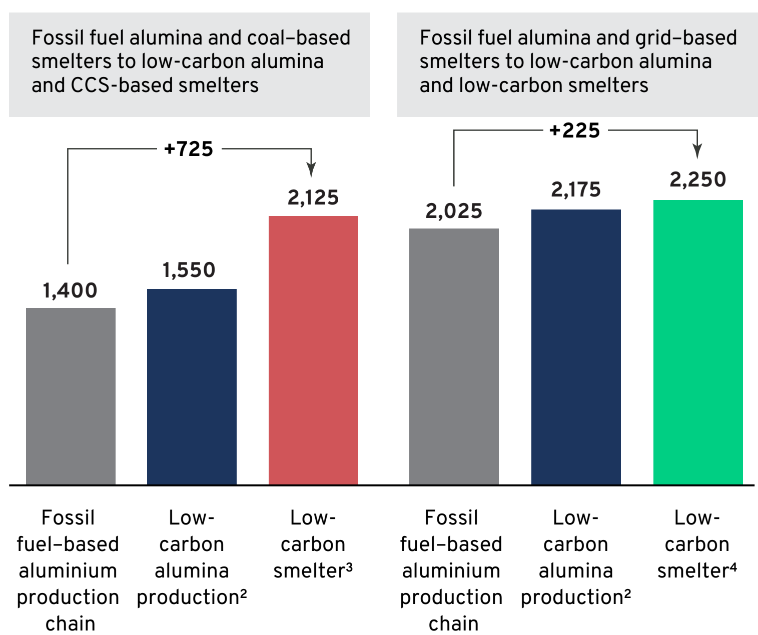
EXHIBIT G

Individual asset transitions will vary by situation, but the overall transition could increase the average cost of aluminium production by $400/t by 2035

Aggregate levelised cost of aluminium, $ per tonne



2035 marginal cost of aluminium by technology,[1] $ per tonne



[1] These case studies are examples of the costs of retrofit (so do not include existing capital expenditures associated with the existing asset, unlike aggregate levelised cost); they represent only some transition paths for the industry, and the entire transition will not be complete by 2035.
[2] Switch from coal– and gas–based refineries to MVR– and hydrogen–based refineries.
[3] Switch from a captive coal and carbon anode smelter to coal-CCS and inert anode smelter.
[4] Switch from a typical grid-connected and carbon anode smelter to grid and inert anode smelter.

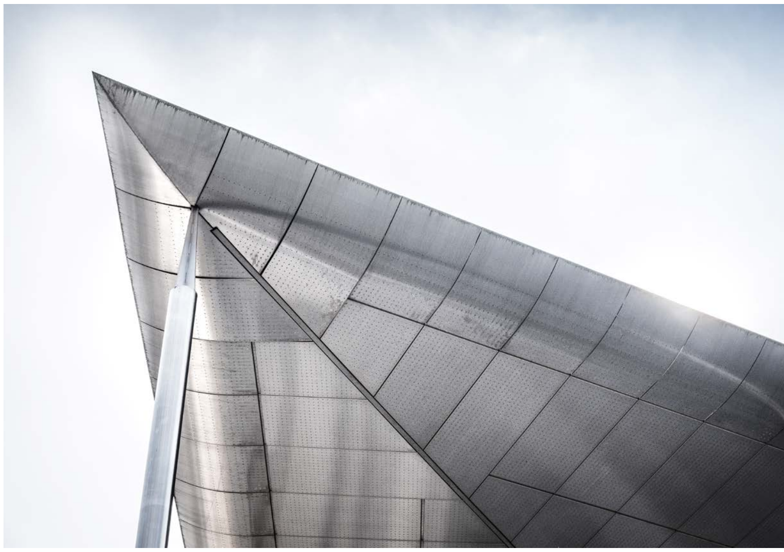
Source: Aluminium Sector Transition Strategy Model (2022)

9. The aluminium sector can reduce emissions by 2050 by up to 95%. Therefore, further breakthrough technologies or a limited number of offsets will be needed to deliver a net-zero sector.

Low-carbon power, low carbon anodes, and fuel switching in refineries can reduce emissions from the production of aluminium by 95%. Residual emissions in 2050, totalling approximately 84 Mt CO_2e/y, are largely derived from the role CCS might play in power provision (assuming a CO_2 capture rate of 90%) and from remaining carbon anodes and fossil-fuelled calciners.

Those residual emissions will need to be mitigated by carbon dioxide removal (CDR) solutions, including, for example, natural climate solutions (NCS); hybrid solutions such as bioenergy with carbon capture and storage (BECCS); and engineered solutions such as direct air carbon capture and storage (DACCS). Offsetting the residual emissions would cost an additional $10.5 billion in 2050 alone at an average abatement cost of $125/t CO_2.

CDR solutions are required in addition to, and not instead of, deep and rapid in-sector decarbonisation.



10. Delivering net zero will require different forms of coordination across the value chain and with policymakers and regulators across the energy system.

Delivering a low-carbon aluminium sector will require a step change in engagement and coordination along every link of the value chain. Four areas of focus are particularly key:

Technology dissemination: Dissemination is critical as key new technologies such as low-carbon anodes and new calcination methods will be required by all sites. Strategies involving low- or zero-cost licencing and building supply chains will be helpful in this process.

Secondary aluminium: The users of aluminium, the waste sector, and the wider value chain will have to work together and with policymakers to maximise scrap recycling rates in order to enable the significant expansion of the secondary sector. In addition, the secondary sector will have to decarbonise its recycling processes.

Electricity markets: Close collaboration between the aluminium sector and the electricity market is vital. It will be needed to make sure long-term investment plans are aligned, so that aluminium smelters can access low-carbon electricity at the right price and so that the benefits a long-term secure buyer can offer can be included.

CCS: Finally, where CCS is required, collaboration with other potential local users of CO_2 transport and storage networks and local project developers and policymakers will be necessary to generate the economies of scale to make it affordable. A stable underlying regulatory framework will be required as well.

CONCLUSION

Transforming the aluminium sector to a 1.5°C-aligned sector is possible. It will require a substantial investment and change in how the whole value chain coordinates, particularly with the power sector and recycling sector, to deliver technical change, and with users of aluminium, finance institutions, and policymakers to deliver the market to enable low-carbon aluminium to flourish.

Early action during this decade through planning and delivering power decarbonisation is a vital first step. This action must be complemented with action to build the secondary aluminium market, commercialise new technologies, and build a business case that can bridge the cost gap between fossil fuel and low-carbon aluminium production.

A joint effort by actors along the entire value chain can make this mission possible.

MAIN REPORT

MAKING NET-ZERO ALUMINIUM POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

PART I

DECARBONISING ALUMINIUM: CHALLENGES AND SOLUTIONS

1.1 Aluminium today: Demand, supply, and climate impact

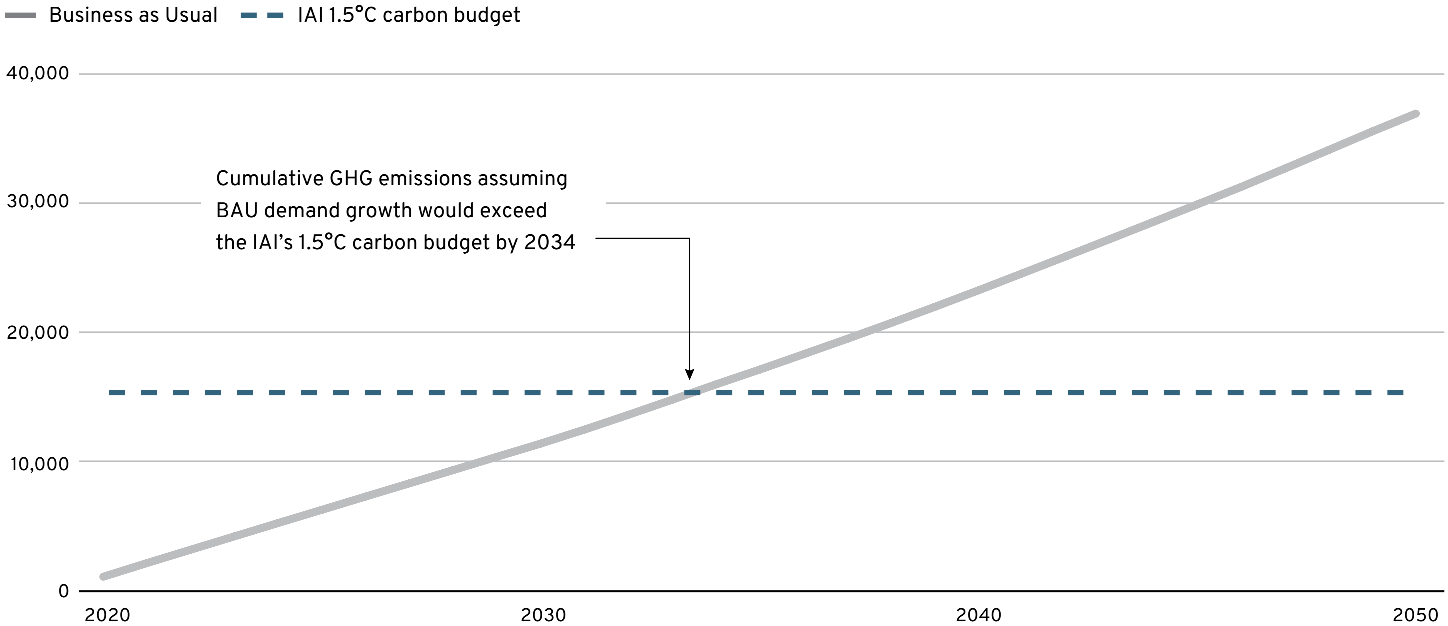
1.1.1 Aluminium, an essential but carbon-heavy material of modern life

Aluminium is a lightweight, malleable, and corrosion-resistant material with excellent electrical and thermal conductivity and the potential to be recycled infinitely. Thanks to its favourable properties, it has become part of people's everyday lives and embedded in the fabric of modern applications, from the foil they use in their kitchens to the bodies of the vehicles they travel in and the structures of the buildings they live in. It also serves as a key material in the energy transition and can, for example, be found in solar photovoltaic panel frames, wind turbine towers, and power transmission cables. Furthermore, it is an essential driver of economic activity around the world, contributing billions to local GDP levels ($73 billion in direct economic output in the United States alone[4]) and providing 7.5 million direct and indirect jobs globally.[5]

EXHIBIT 1.1

Projected cumulative GHG emissions from primary aluminium production in a Business-as-Usual demand scenario would exceed the IAI's 1.5°C-compliant carbon budget by the early 2030s

Cumulative GHG emissions in a BAU scenario, Mt CO_2e, 2020–50



Source: IAI 1.5 Degree Scenario (2021), Aluminium Sector Transition Strategy Model (2022)

The 160% increase in global demand for aluminium ingots between 2000 and 2020 illustrates the material's growing place in our societies.[6] Business-as-Usual (BAU) projections from the International Aluminium Institute (IAI) suggest this trend is set to continue, with global demand expected to reach 179 million tonnes (Mt) per year by 2050 (a 79% increase over 2020 demand, or 2% per year).[7] Such an increase is expected to be primarily driven by GDP and population growth, notably in the Global South (i.e., Africa, Asia, Latin America).

Given societies' reliance on aluminium, its high carbon intensity poses a serious challenge to climate change mitigation efforts. In 2018, total GHG emissions from aluminium at the global level amounted to 1.1 Gt CO_2e (around 2.2% of global GHG emissions), a 92% increase from 2005 levels.[ii,8] Sectoral emissions can be broken down into Scope 1 (direct process), Scope 2 (electricity related), and Scope 3 (other) emissions, which respectively account for 29%, 64%, and 7% of total emissions. If the carbon footprint of a tonne of primary aluminium were to remain constant, the BAU growth in global demand for primary aluminium would result in cumulative CO_2e emissions of around 37 Gt by 2050, a 300% overshoot from the IAI's 1.5°C-compliant carbon budget (Exhibit 1.1).

1.1.2 Aluminium supply and its climate impact

Aluminium is supplied through both primary and secondary production, which, respectively, accounted for 66% and 34% of the total global production in 2020 of 98 Mt.[9] Primary aluminium production follows a process that has been in place since the late 19th century. Its technology process consists of four steps (as shown in Exhibit 1.2):

1. **Bauxite mining:** Bauxite ore is excavated by open-cut mining and then treated through crushing, washing (which may not be required, depending on the concentration of aluminium in the ore), and drying before being transported to refineries.

2. **Alumina refining:** Following the Bayer process, the alumina compound of bauxite is first dissolved in a caustic soda and lime mix heated at temperatures ranging from 100°C to 320°C (depending on the bauxite quality). The resulting solution, aluminium hydroxide, is then filtered, precipitated, and ultimately calcinated at temperatures ranging from 1,000°C to 1,300°C (depending on the calcination technology) to produce alumina.

ii Total GHG cradle-to-gate emissions generated in bauxite mining, alumina refining, anode production, electrolysis, casting, recycling, semis production, and internal scrap remelting; includes process, thermal energy, electricity, and ancillary materials emissions; global average.

3. **Aluminium smelting:** Using the Hall-Héroult process, alumina is fed into a cell where a high-intensity electrical current (approximately 400–450 kiloamperes [kA] with the best available technology) creates an electrolysis reaction that reduces the alumina into liquid aluminium. This reaction requires the presence of anodes, which today are produced, sometimes on site, from carbon materials (e.g., coal tar pitch, petroleum coke).

4. **Casting:** Aluminium ingots are formed by pouring molten aluminium into moulds in the shape of the desired final product.

Primary production emits about 16 t CO_2e per tonne of aluminium (Al) (2018 global average), whereas secondary production emits only about 0.5 t CO_2e/t Al.[iii,10] As shown in Exhibit 1.3, primary aluminium's carbon footprint can be broken down into power-related emissions, direct emissions from thermal energy and process CO_2/other GHGs, upstream emissions from the production of ancillary raw materials, and transport emissions, which, respectively, account for 67%, 26%, 4%, and 3% of total emissions per tonne.[11]

The 160% increase in global demand for aluminium ingots between 2000 and 2020 illustrates the material's growing place in our societies. Business-as-Usual projections from the International Aluminium Institute suggest this trend is set to continue, with global demand expected to reach 179 million tonnes per year by 2050 (a 79% increase over 2020 demand, or 2% per year).

EXHIBIT 1.2

Primary aluminium production is significantly more energy and emissions intensive than secondary production

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

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

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

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

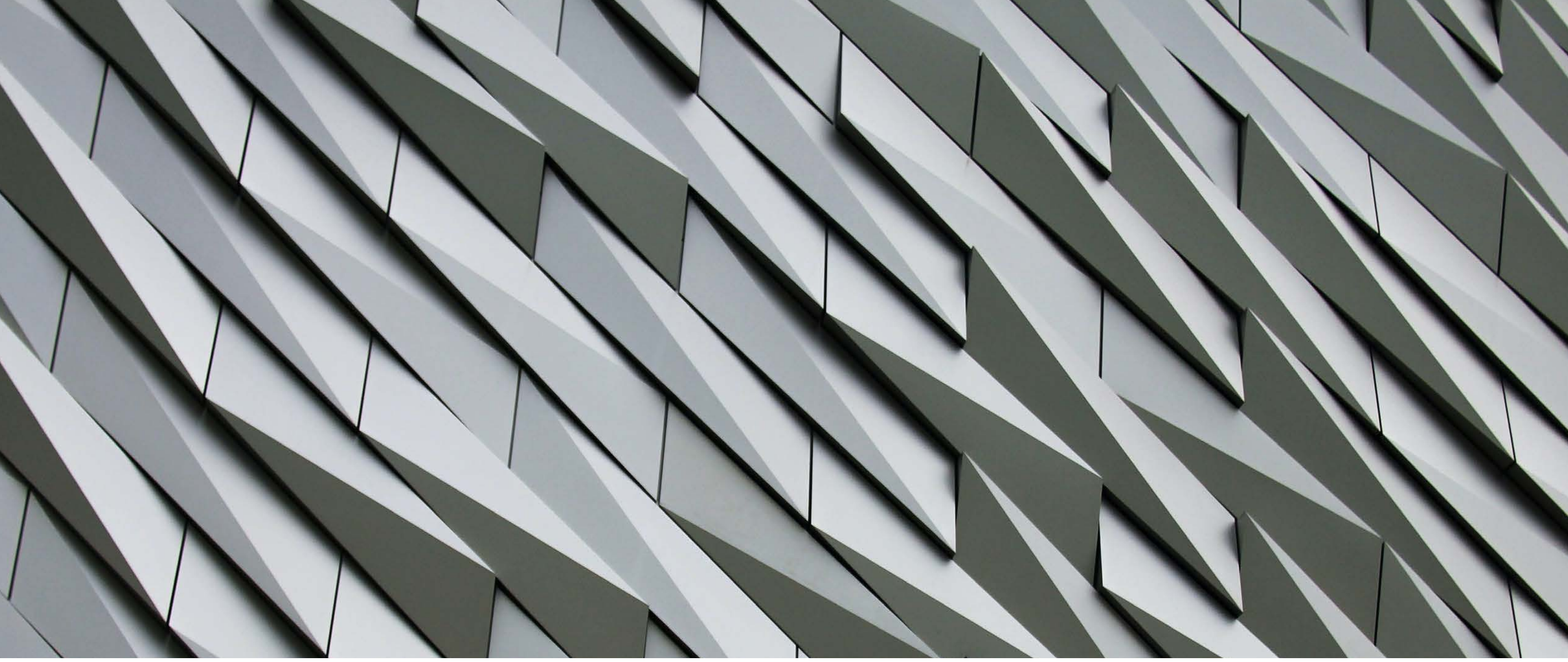
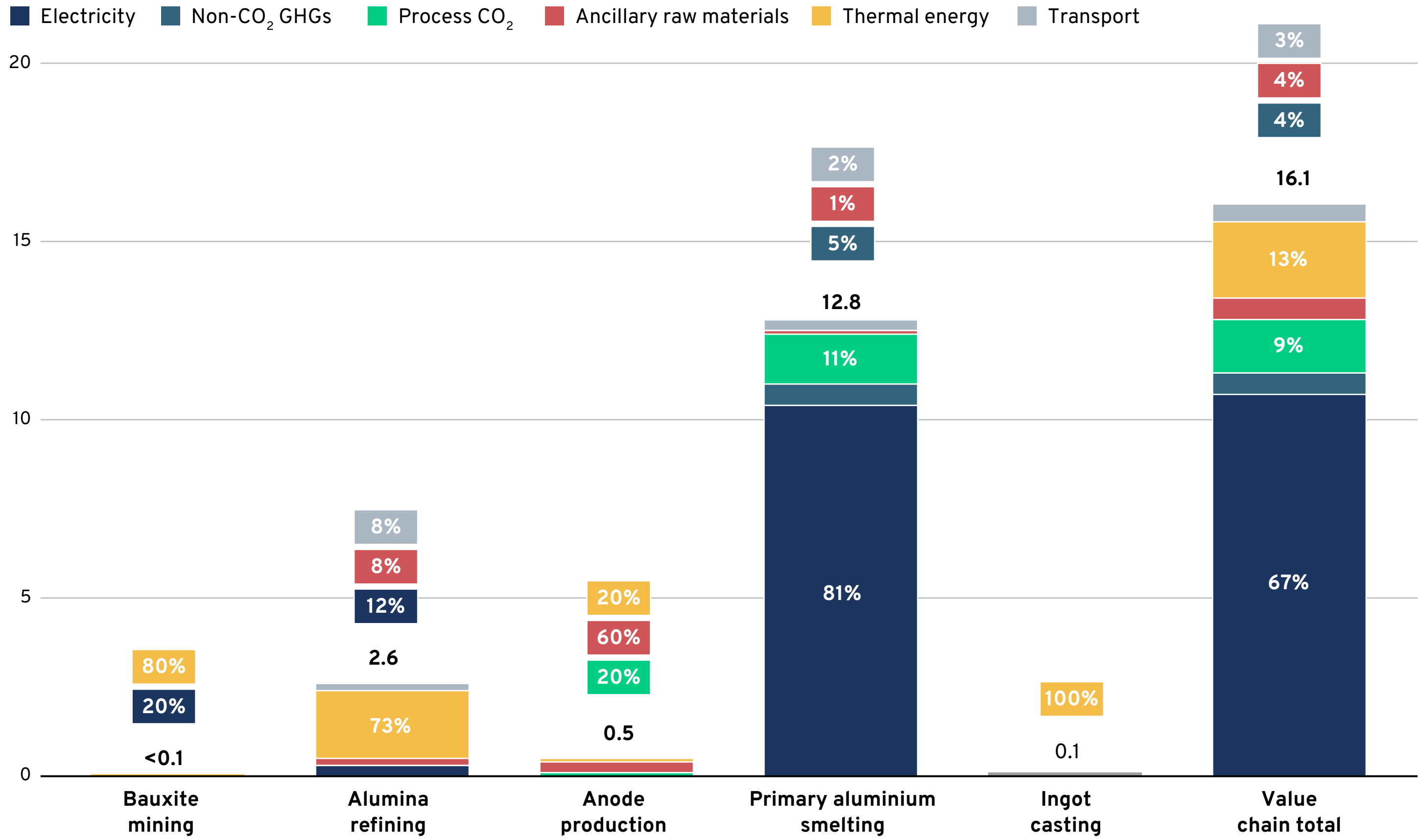


EXHIBIT 1.3

Breakdown of the emissions generated by the production of a tonne of primary aluminium

GHG emissions per primary ingot by process step and type of emissions, t CO_2e/t Al



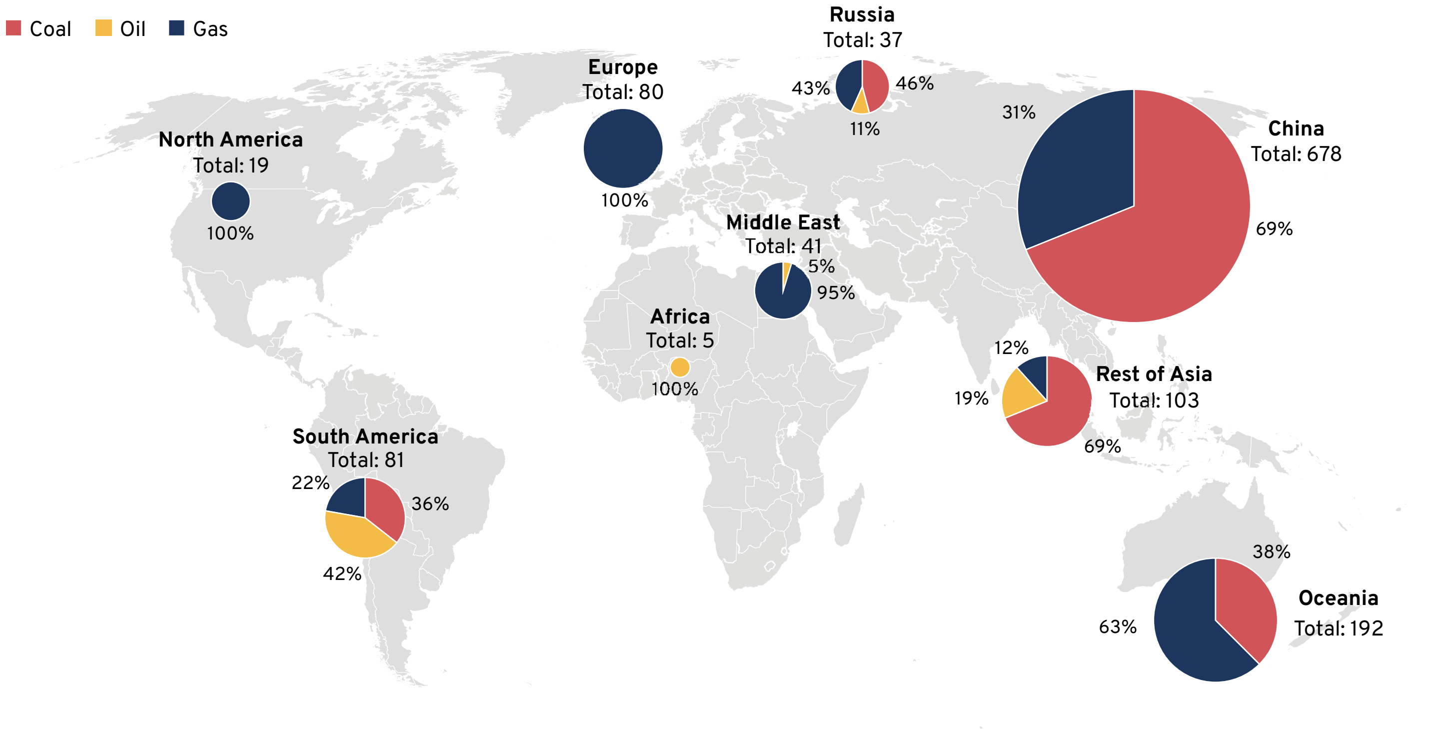
Note: All values are based on IAI 2018 global average values.

Source: International Aluminium Institute (accessed June 2022)

Map of 2020 energy consumption for alumina refining by region

EXHIBIT 1.4

Refining energy consumption by region, total and percentage, petajoules, 2020



Source: Mission Possible Partnership (MPP) analysis of public data, 2022

Direct emissions consist mainly of:

- **Smelting process emissions:** CO_2 and perfluorocarbons (PFCs) are emitted when, respectively, oxygen freed from the alumina reacts with the carbon anode and when anode effects occur.[iv] These process emissions amount to, on average, 2 t CO_2e/t Al (about 12% of total emissions; 2018 global IAI average).

- **Refining thermal energy emissions:** Refining a tonne of alumina on average requires 9.8 gigajoules (GJ) of thermal energy (2020 IAI global average), 69% for digestion, and 31% for calcination.[12] In 2020, coal was still the dominant fuel used, making up 53% of the global thermal energy fuel mix, ahead of natural gas (42%) and oil (5%). As shown in Exhibit 1.4, significant regional disparities exist: China and India rely heavily on coal, while Europe, the Middle East, and North America mainly use natural gas. Emissions from fuel combustion on average amount to 1.9 t CO_2e/t Al (about 12% of total emissions; IAI 2018 global average).

Power-related emissions make up the bulk of primary aluminium's total emissions. This is because:

- **Smelters need large amounts of consistent high load power:** An average smelter with a 500 kilo-tonnes per year capacity consuming 14 megawatt-hours (MWh) per tonne of aluminium (IAI 2018 global average) and running at 100% capacity has a power requirement above 800 megawatts (MW).

- **Smelters' power mix is still heavily dependent on fossil fuels, notably coal:** At a global level, 66% of power supplied to smelters is generated from fossil fuels (55% coal, 10% natural gas, 1% others), and zero-emissions electricity sources make up the remaining 34% (30% hydropower, 3% renewables, 1% nuclear).[13]

The type of power source greatly affects a smelter's emissions profile. Smelters running on power from coal emit approximately four times the GHGs emitted by smelters running 100% on hydropower (15–20 t CO_2e/t Al versus 4 t CO_2e/t Al).

iv Anode effects are rapid voltage increases that occur when the alumina content in the electrolytic bath decreases below required levels. These voltage increases cause carbon from the anode to react with the fluorine found in the molten cryolite bath, which generates PFCs.

As shown in Exhibit 1.5, significant geographical differences exist in the type of power supply fuel used today. China, India, and Australia are heavily dependent on coal, whereas Europe, North America, and South America rely mainly on hydropower.

Secondary aluminium can offer the same quality as primary aluminium, but producing secondary aluminium is a significantly less energy-intensive process (requiring about 3.3 GJ/t for secondary aluminium versus about 66 GJ/t for primary aluminium). This is because the secondary aluminium production process involves only two major energy-consuming steps: melting scrap (pre- or post-consumer) and casting the resulting liquid aluminium.

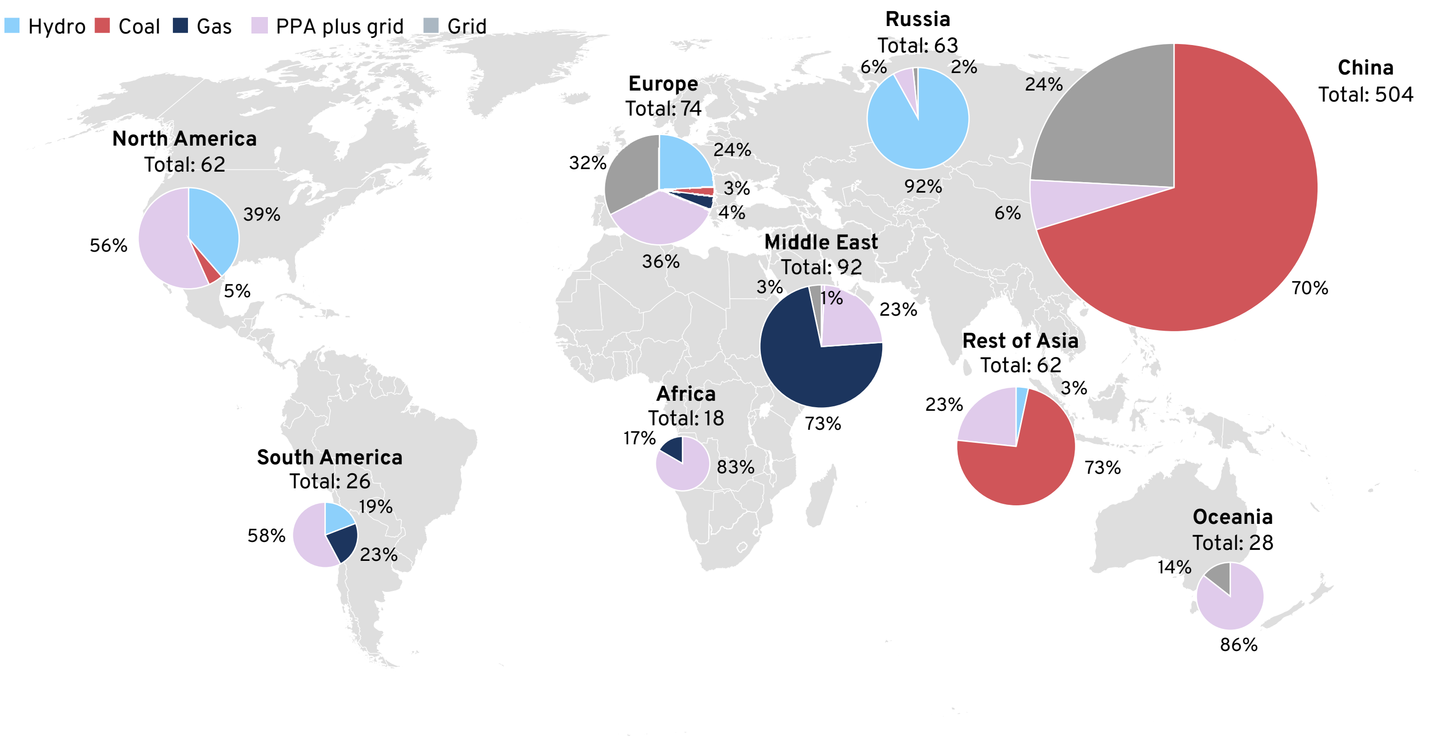
Secondary production capacity is dependent on scrap collection rates, which, as shown in Exhibit 1.6, vary by region and end-use sector. In 2020, the global average cross-sectoral scrap collection rate stood at 70%, an increase of 10 percentage points since 2000.[14] Regions leading in scrap collection include China (2020 average collection rate 79%), Europe (77%), and Latin America (77%). End-use sectors with the largest collection rates are automotive (89%), construction (85%), and can packaging (84%).[15]

However, overall collection volumes will be dependent on overall demand in each end-use sector. Because approximately 50% of global aluminium demand today comes from the transport and construction end-use sectors (26% and 24%, respectively), continuing to increase collection rates will drive greater volumes of secondary production, in comparison with the packaging end-use sector, which makes up only 8% of global demand.[16]

EXHIBIT 1.5

Map of 2020 electricity consumption for aluminium smelting by region and power source

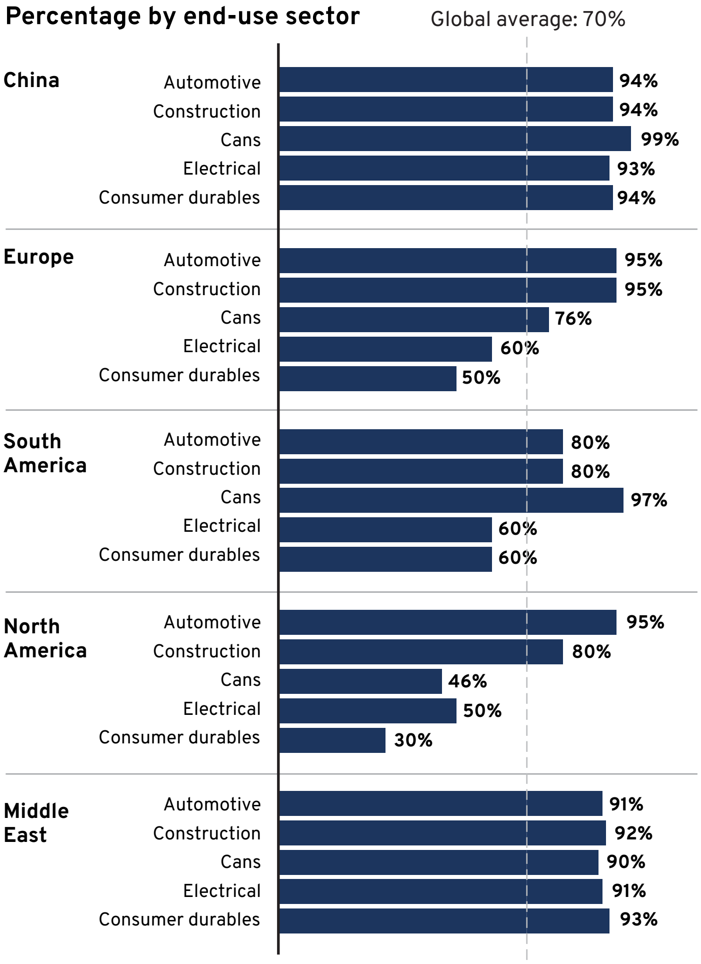
Smelting electricity consumption by region, total and percentage, TWh, 2020



Source: Mission Possible Partnership (MPP) analysis of public data (2022); IAI Material Flow Model (2021)

EXHIBIT 1.6

2020 post-consumer scrap collection rates by geography



Source: IAI Material Flow Model (2021)

1.1.3 Why aluminium is hard to decarbonise

Aluminium is a sector often labelled as “hard to abate” for two main reasons. First, the sector has been dependent on fossil fuels to generate the consistent high load power needed by smelters for electrolysis and to achieve the high temperatures necessary for alumina refining. Second, process emissions are inherent to the smelting of aluminium, which relies on carbon anodes to conduct the electricity needed for the reduction process.

For aluminium to reach net-zero emissions by 2050, five main challenges must be addressed:

1. **Securing access to low-carbon power:** Decarbonising smelters’ power supply is fundamental to reaching net-zero emissions. However, renewable power is variable and not able to meet 100% of demand without backup storage or grid connections. Additionally, securing renewable PPAs is difficult because demand typically outweighs supply, and many geographies have yet to mature a merchant power market.

2. **Deploying critical technologies:** Abating direct emissions requires the deployment of certain technologies that have yet to achieve commercial readiness in an aluminium-specific context. These essential technologies, such as low-carbon anode technologies (including inert anodes, carbon anodes with CCS, and chloride-based technologies) and electric or hydrogen calcination, are not expected to be ready for large-scale deployment before 2030. Even then, rollout is likely to face two challenges: (1) ensuring industry-wide access to these technologies, which are currently developed by a handful of firms; and (2) finding sufficient supplies of low-carbon power and green hydrogen.

3. **Securing the business case for low-carbon aluminium:** The financial performance of aluminium producers is very sensitive to variations in operating costs, which can account for more than 80% of costs. By 2035, the average cost of delivering low-carbon aluminium could increase production costs by $400/t. To incentivise primary producers to invest in the decarbonisation of their operations, bridging that gap will be essential, and it will rely on the introduction of equalising levers, such as a carbon cost or a price premium for low-carbon aluminium.

4. **Increasing scrap for secondary production:** Maximising the recycling of pre- and post-consumer scrap is one of the most cost-effective actions aimed at decarbonising the sector, given recycling’s low-carbon footprint. To unlock the benefits, increasing collection rates, redesigning products, and further developing the technology in order to improve the cost-effectiveness of recycling will be needed across all geographies. However, even if these levers for secondary production are maximised, the limited scrap availability means supply will be insufficient to meet demand, which will require primary production to continue playing a significant role into 2050.

5. **Ensuring a level playing field globally:** Given that aluminium is a globally traded commodity, discrepancies in compliance-related increases in the cost of manufacturing aluminium are likely to incentivise the transfer of market share and investments to more favourable geographies, which could result in “carbon leakage” from one country to another.

1.2 Levers for decarbonising the aluminium sector

To achieve full decarbonisation, the sector needs to employ four main levers: (1) material and resource efficiency, (2) maximising secondary production, (3) switching to low-carbon power, and (4) deploying near-zero-emissions refining and smelting technologies (Exhibit 1.7).

Each lever's potential to abate emissions is different. The scale-up in secondary production is associated with a 25% reduction in annual emissions by 2050. Likewise, holding the scale-up in secondary production almost constant, the demand reduction in the 1.5°C scenario would reduce BAU emissions by another 17%.

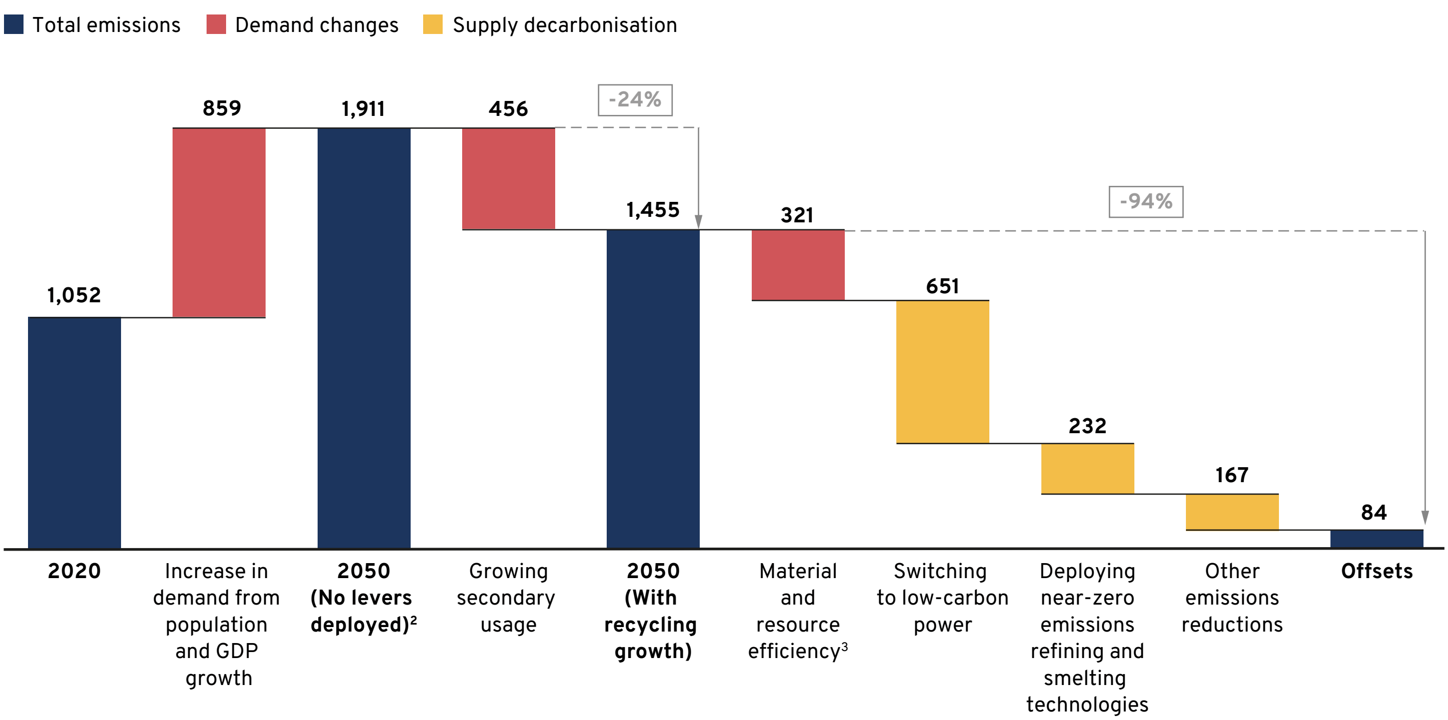
Even with these two levers fully deployed, primary aluminium demand volume is expected to remain constant from 2020 to 2050 in the 1.5°C scenario. Consequently, a net-zero ambition for the aluminium sector is realistic only if primary production is decarbonised at pace, which would require smelters to switch to low-carbon power and near-zero-emissions refining and smelting technologies to be deployed at scale. These two levers have the potential to abate 38% and 15%, respectively, of the remaining 2050 BAU emissions.

Exhibit 1.8 dives deeper into each of these four levers, highlighting their applicability across the aluminium value chain, technology readiness level (TRL),[v] and market availability for technological interventions, and the main barriers to their adoption or deployment.

EXHIBIT 1.7

Overview of emissions reduction potential by decarbonisation lever

Emissions for the aluminium sector,[1] Mt CO_2e/y



[1] Includes all direct and indirect emissions along the value chain for primary and secondary aluminium production (i.e., mining, alumina refining, aluminium smelting, anode production, casting, fabrication, recycling, and transport).
[2] Based on the IAI's Reference scenario, except for primary/secondary production ratio, which is assumed constant between 2020 and 2050; 2020 carbon intensity of aluminium assumed constant.
[3] Based on demand projections from the IAI's 1.5°C scenario.

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

v Technology readiness levels are a measure of the development of a technology or process from 1, an initial concept, to 9, commercialisation.

EXHIBIT 1.8

Possible solutions in decarbonising the aluminium sector

Readiness level High | Medium | Low

		Applicability at scale (i.e., potential impact)	TRL	Market availability at scale to date	Main barriers
1) Material and resource efficiency • Circular product design • Fabrication loss reduction • Increased product lifetimes • End-of-life repair, reuse, or recycling		High, but strong dependence on behaviour of downstream customers.	Various	Various	Demand growth due to population and GDP increases; substitution of lower-performance materials with aluminium.
2) Maximising secondary production		High potential impact owing to low-carbon footprint of secondary aluminium; strong dependence on downstream customers and waste management sector.	9	High	Cross-sectoral collection rate increases; scrap downcycling.
3) Switching to low-carbon power	Carbon capture and storage (CCS)	High: technology retrofittable in all fossil fuel power plants.	9 (coal) 8 (gas)	Medium	Global and regional carbon storage capacity.
	Grid (plus renewables PPA)	High, assuming plant is within distance from local grid. PPAs are also location dependent, but possible if pursued.	9	High	Feasibility of adding PPA renewables to grid-powered plants depends on regional capacity factor of renewables.
	Nuclear small modular reactors (SMRs)	High, dependent on modular nuclear technology being used in first-user sectors.	4–5	Low	Regional regulatory stance on nuclear (e.g., disaster risk and nuclear waste).
4) Deploying near-zero-emissions refining and smelting technologies	Electric boilers	High: technology retrofittable in any plant.	9	High	Availability of low-carbon power.
	Hydrogen boilers	High: technology retrofittable in any plant.	8	High	Availability of green hydrogen.
	Concentrated solar thermal (CST)	Low: minimum level of continuous solar irradiation needed.	7	Low	Solar irradiation potential; space.
	Mechanical vapour recompression	High: technology retrofittable in any plant.	7	Low	Availability of low-carbon power.
	Hydrogen calcination	High: technology retrofittable in any plant.	4–5	Low	Availability of green hydrogen.
	Electric calcination	High: technology retrofittable in any plant.	4–5	Low	Availability of low-carbon power.
	Inert anodes	High: technology retrofittable in any plant.	7	Low	Market-wide access to technology; high upfront capital expenditure; scale of retrofit.
	CCS (smelting)	High: technology retrofittable in any plant.	3–4	Low	Low CO_2 concentration in smelting flue gases; availability of transport and storage infrastructure for captured CO_2.

Source: MPP analysis (2022); building off of previous work: "Closing the Gap for Aluminium Emissions: Technologies to Accelerate Deep Decarbonization of Direct Emissions (MPP, 2021)

BOX 1

Decarbonising aluminium is gaining traction

The aluminium sector's transition to net-zero emissions is gaining traction. Primary producers are adopting ambitious climate goals. Renewable PPAs have been secured for several smelters (e.g., Alumar in Brazil). Biomass and electric boilers have been or are being rolled out in several refineries. Inert anode prototype cells have reached commercial scale, and pilot projects on electric and hydrogen calcination are under way. Demand signals for low-carbon aluminium are gaining in intensity, notably with aluminium recently having been added to the scope of the First Movers Coalition.

Climate goals of selected aluminium producers

Aluminium producer	Share of global production (2021)	Interim goal	Long-term goal
Hongqiao	8%	GHG targets not yet announced	
Chinalco	6%	Reduce emissions by 40% by 2035	
En+Group	6%	Reduce GHG emissions intensity (Scope 1 and Scope 2) by 50% by 2030 from a 2015 baseline	Achieve net zero (Scope 1 and Scope 2) by 2050
Rio Tinto	5%	Reduce emissions (Scope 1 and Scope 2) by 15% by 2025 and by 50% by 2030	Achieve net zero by 2050
Alcoa	4%	Reduce GHG emissions intensity (Scope 1 and Scope 2) by 30% by 2025 and 50% by 2030 from a 2015 baseline	Achieve net zero (Scope 1 and Scope 2) by 2050
Hydro	3%	Reduce GHG emissions by 30% by 2030	Achieve net zero (Scope 1 and Scope 2) by 2050
EGA	2%	Reduce GHG emissions intensity (Scope 1 and Scope 2) by 7% by 2023 from a 2020 baseline	
Alba	2%		Achieve net zero by 2060
South32	1%	Reduce emissions (Scope 1 and Scope 2) by 50% by 2035	Achieve net zero by 2050
CBA	0.4%	Reduce emissions by 40% by 2030 from a 2019 baseline (mining to casting)	Commit to a target approved by the Science Based Targets initiative in line with sectoral trajectory that is well below 2 degrees

Source: MPP analysis, corporate announcements

The global body for the primary aluminium industry, the IAI, has developed GHG pathways and demand forecasts that inform its members' efforts to meet global climate goals. This includes two scenarios that model projections of global aluminium demand to 2050:

1. A Reference scenario, which assumes an 80% increase in global aluminium demand and a scale-up in secondary production (to about 50% of total production) by 2050.
2. A 1.5°C scenario, which assumes a reduced growth in demand (50% growth) from increased circularity and a similar scale-up in secondary production.

The IAI has been the primary data and analytical collaborator for the Sector Transition Strategy (STS). Collaboration between MPP and the IAI has entailed utilising the IAI's core modelling work as key inputs to the STS. The IAI's analyses have also supplied a robust starting point that the STS modelling could leverage and build upon.

1.2.1 Material and resource efficiency

In a future circular economy aligned on a 1.5°C pathway, most sectors and the broader society will need to make a fundamental change in consumption patterns. Throughout the value chain, new and best-practice measures are likely to lead to reduced demand for common metals such as aluminium.

Minimising aluminium demand, and therefore the need for primary production, is the first lever to pull in reducing total sectoral emissions. It can be achieved by implementing material efficiency strategies at every stage of aluminium's life cycle, such as:

- At the design stage: Lightweighting can reduce the amount of aluminium needed to supply a given service; robust designs incorporating ease of repair can increase product lifetimes; designs that facilitate end-of-life recycling can help maximise secondary production.
- At the fabrication stage: Reducing material losses in manufacturing, which are significant in the aluminium sector (approximately 15% of the global production output is "new" scrap[17]), can increase the efficiency of production.
- At the use stage: Increasing the lifetime of goods and assets containing aluminium, for example through repair and refurbishments, can reduce the need for new aluminium.
- At the end-of-life stage: Repurposing and reuse can help alleviate the demand for new aluminium in other applications of the material.

The implementation of these strategies will be particularly challenging and require close collaboration among players operating in the different stages outlined above.

1.2.2 Maximising secondary production

Aluminium can be remelted and cast infinitely without compromising quality and with minimal loss. This is true for both pre- and post-consumer scrap, though the latter requires treatment to remove impurities and alloy-specific methods to safeguard quality. Substituting secondary for primary aluminium is a cost-efficient solution in abating sectoral emissions. On average, producing a tonne of secondary aluminium generates only about 3% of the emissions associated with a tonne of primary aluminium while costing significantly less, thanks to lower energy consumption (about 5% of the energy consumed for primary production[18]).

Maximising secondary production will require an increase in volumes of pre- and post-consumer scrap available for recycling. This can be achieved only if industry leaders, policymakers, and the waste management sector take collective action on product design and end-of-life collection and dismantling. The scale-up of secondary production is likely to face two barriers. First, around 25%–30% of aluminium is lost in each use cycle because of post-consumer scrap collection leakage and pre-consumer scrap processing loss.[19] Second, producers of secondary aluminium currently tend to avoid combining alloy-specific scrap batches, which results in a downcycling of scrap that undermines the establishment of closed-loop systems. Both barriers will need to be addressed for secondary aluminium to fully take up its role in the sector's decarbonisation.

Growth of secondary production is also facing important regional dynamics that may become even more significant over the coming years. For instance, regional scrap export bans may lead to a dearth of scrap on the global market. This could end up limiting the potential of some regions to significantly scale up secondary production.

1.2.3 Switching to low-carbon power

Given the weight of power-related emissions in primary aluminium's carbon footprint, the main avenue for decarbonisation is switching smelters' power supply away from fossil fuels and towards low-carbon power supply. Several viable options exist to do so:

- **Carbon capture and storage (CCS):** Retrofitting CCS capabilities to smelters' fossil fuel–based captive power plants can reduce power emissions by up to 90%.[20] However, the rollout of CCS depends on the availability of captured CO_2 transport and storage infrastructure and the residual emissions from coal and gas extraction and use.
- **Switching to the grid:** Smelters based in locations with possible connections to the grid may find switching to it favourable if it is decarbonised or if renewable PPAs are available. Under this option, grid connection costs would need to be incurred at the outset.
- **Nuclear small modular reactors (SMRs):** SMRs have the potential to offer smelters with consistent high-load, low-carbon power. While still needing significant R&D (the current TRL is just 4–5), the technology is expected to become commercially available in the aluminium industry beginning in 2035 and could become cost competitive around 2040.

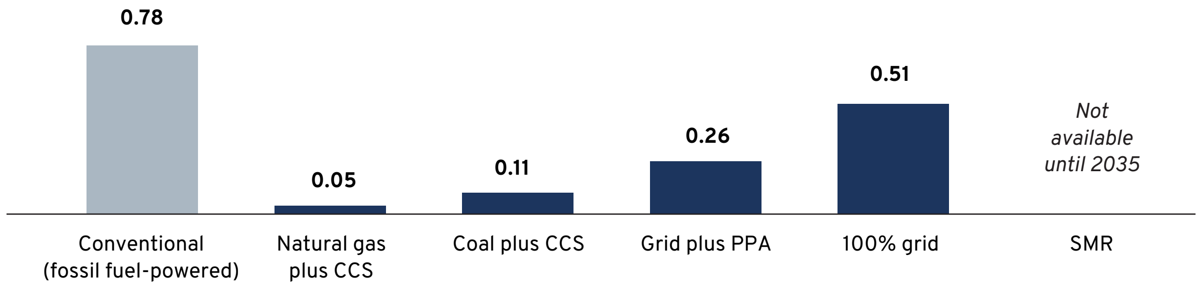
The suitability of these options varies greatly depending on local availability, electricity systems, and prices. CCS is preferable in locations without access to a grid or where grid emissions intensity is high without a clear path to decarbonisation. Switching to the grid is a good option when (1) low-carbon power sources already make up, or are expected to make up, a significant share of the electricity mix, or (2) a mature power market exists for renewable PPAs. Finally, SMRs' scale and longevity can make the technology economically attractive even when the other two options are available (Exhibit 1.9).

Today, 34% of the power mix provided to smelters consists of zero-emissions electricity, the bulk of it (30% of the total power mix) generated by hydropower plants.[21] Although adding new hydropower capacity is theoretically possible, there is limited appetite to do so in reality because of a lack of suitable locations, social and environmental concerns, and risks of climate change–induced reductions in precipitation.

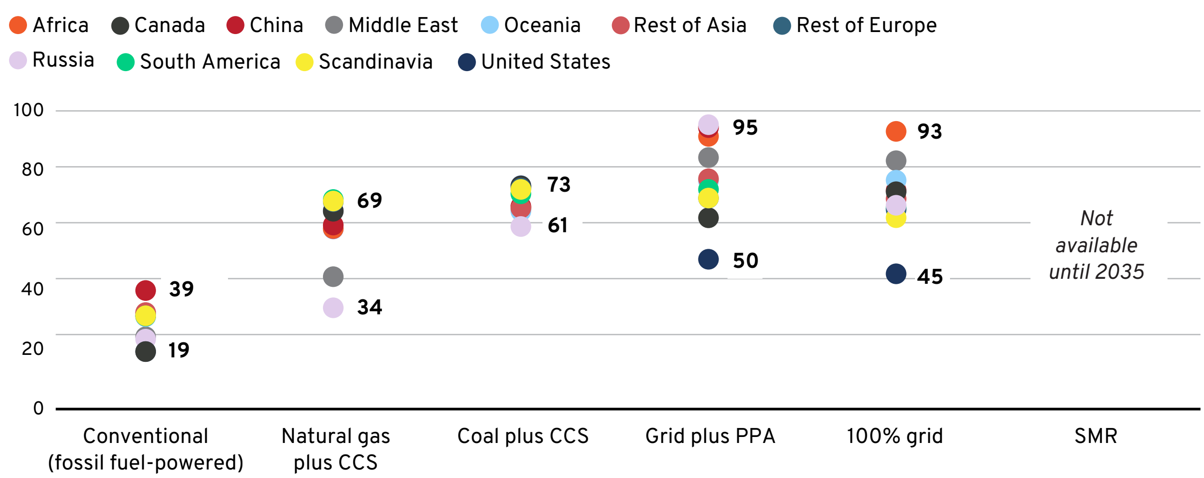
EXHIBIT 1.9

Comparison of conventional and near-zero-emissions smelter power supply technologies

Direct emissions 2030,[1] t CO_2e/MWh



2030 levelised cost per MWh of electricity, in $



	Conventional (fossil fuel-powered)	Natural gas plus CCS	Coal plus CCS	Grid plus PPA	100% grid	SMR
Commercial readiness year	–	2027	2020	2020	2020	2035
Technology readiness level (TRL)	9	8	9	9	9	4–5

[1] Grid emissions shown here are a global average.

Source: MPP analysis; industry engagement

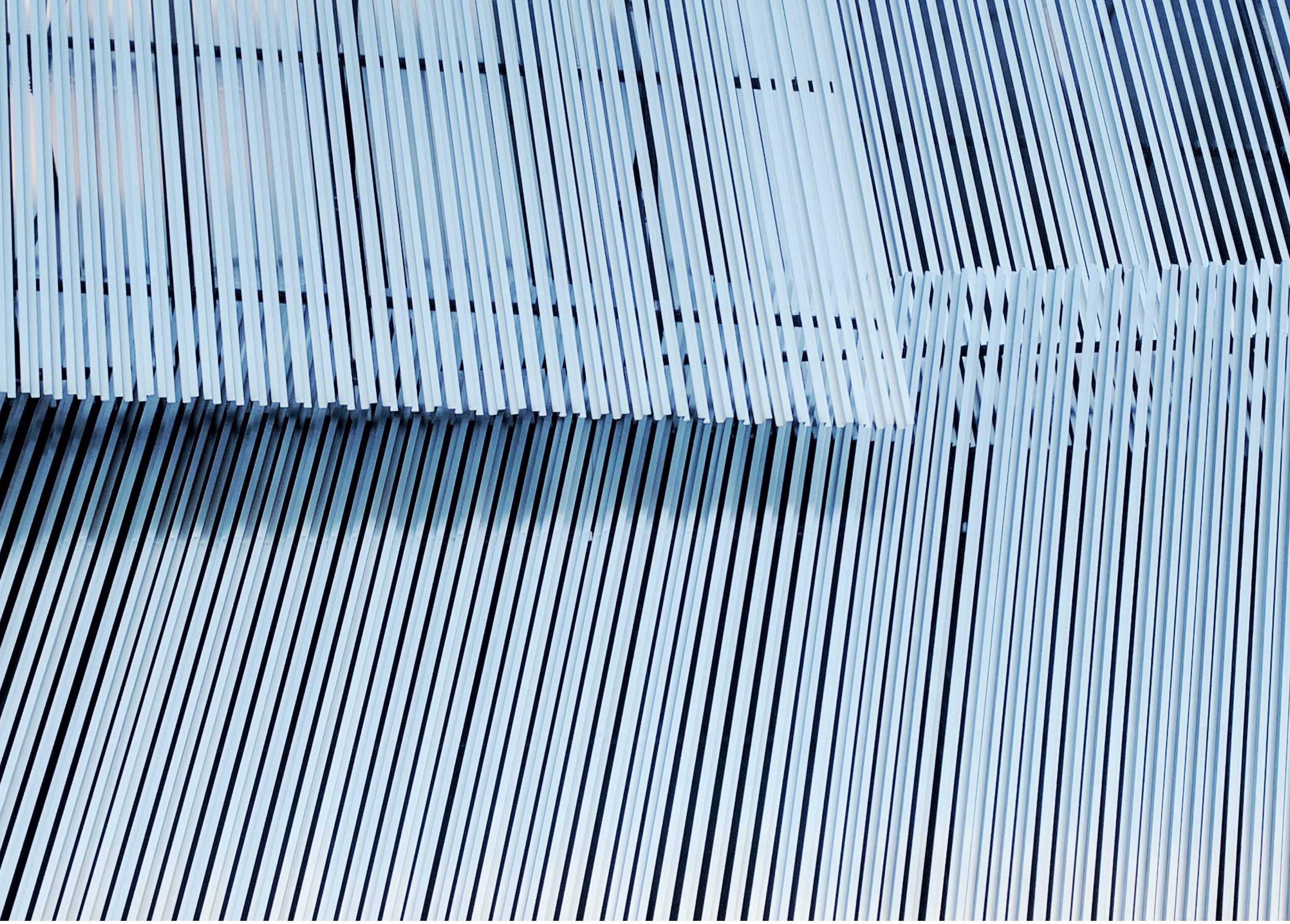
1.2.4 Deploying near-zero-emissions refining and smelting technologies

To succeed, a net-zero ambition for the aluminium sector requires direct emissions from refining and smelting, which currently make up 26% of primary aluminium cradle-to-gate emissions, to be abated. This fourth lever can be used only if near-zero-emissions technologies are deployed widely at the three energy-intensive steps of the primary aluminium value chain: bauxite digestion, aluminium hydroxide calcination, and aluminium smelting. A range of solutions in decarbonising digestion will likely become commercially available in the late 2020s, whereas fewer and (up to now) less-mature options are expected from 2030 onwards for calcination and smelting.

Digestion

Steam requirements for digestion are currently met by low-temperature coal, gas, or oil boilers. Near-zero-emissions alternatives include:

- **Fuel switching:** Electric and hydrogen boilers both have the potential to abate 100% of direct emissions. They benefit from high levels of technological maturity (their respective TRLs are 9 and 8) and existing applications in other sectors. To maximise their emissions reduction potential, their deployment in alumina refineries needs to be coupled with the use of low-carbon electricity and hydrogen.



- **Mechanical vapour recompression (MVR):** An MVR system captures process waste heat, which it recompresses using electricity to increase the temperature to the level needed at process entry. By turning waste vapour into new process steam, the technology can replace fossil fuel boilers. Thanks to their coefficient of performance (COP) of 3, MVR systems require far less electricity than the fossil fuel energy they eliminate.[vi] By replacing a significant majority of the steam produced from conventional fossil fuel boilers for digestion, MVR technology is expected to enable up to a 95% reduction in fossil fuel consumption and emissions compared with using conventional boilers.[vii, 22] Although it is already used in other sectors, MVR requires further R&D efforts to be adapted to refining before it can be deployed at scale, which is expected to be possible from 2027 onwards.
- **Concentrated solar thermal (CST):** CST has the potential to meet around 75% of a refinery's digestion energy requirement, with the rest provided by backup boilers.[viii, 23] The technology requires high levels of consistent solar irradiation, which is why it is suitable only in specific locations. CST applications already exist in power generation, but the technology has yet to be deployed in an alumina context, which is not expected before 2027.

In summary, fuel switching, MVR, and CST each have the potential to drastically cut thermal energy emissions from alumina refining. Their suitability depends on local conditions (Exhibit 1.10).

vi Coefficient of performance (COP) is defined as kWh steam substituted/kWh electricity used. For instance, a COP of 3 assumes that for 1 kWh of electricity used, 3 kWh of steam (heat) is substituted.

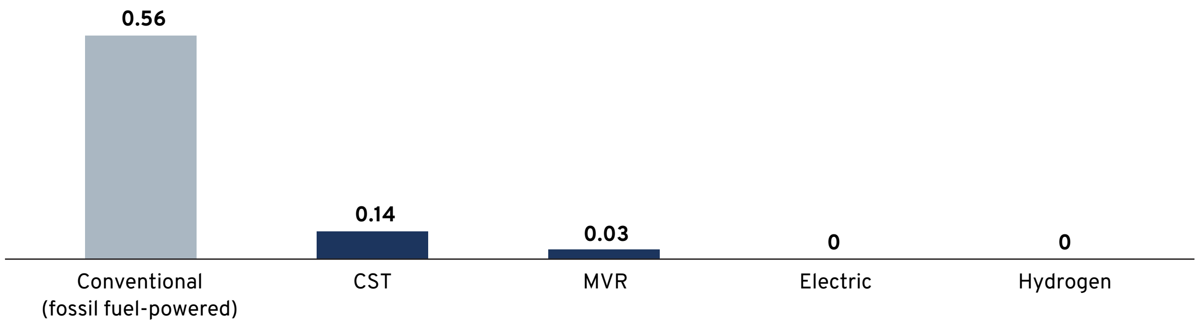
vii ARENA and Alcoa expect MVR could reduce by up to 70% an alumina refinery's carbon footprint and thus fossil fuel consumption, which corresponds to a reduction of up to 95% of fossil energy in digestion (assuming digestion takes up about 70% of total refinery energy).

viii A CST unit's capacity factor varies by the type of CST technology used and the unit's thermal energy storage (TES) potential. The 75% value mentioned is based on CST tower technology coupled with 14 hours of TES.

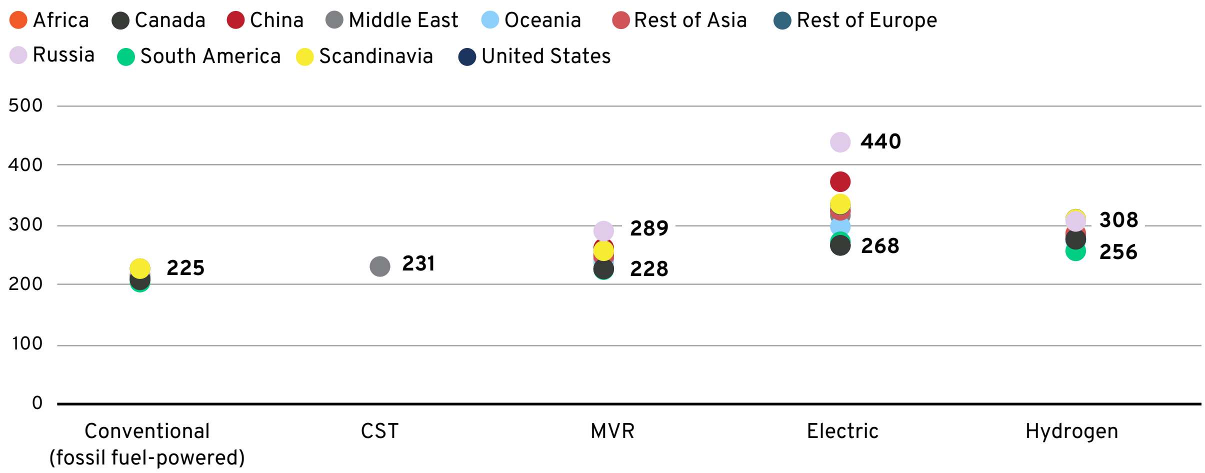
EXHIBIT 1.10

Comparison of conventional and near-zero-emissions digestion technologies

Direct emissions 2030, t CO_2e/t alumina



2035 levelised cost per tonne of alumina, in $



	Conventional (fossil fuel-powered)	CST	MVR	Electric	Hydrogen
Commercial readiness year	–	2027	2027	2020	2027
Technology readiness level	9	7	7	9	8

Source: MPP analysis; industry engagement

Calcination

Calcination is a direct-firing process with temperature requirements of 1,000°C–1,300°C that are currently met by natural gas or heavy fuel oil combustion. Fuel switching, either to electricity or to hydrogen, is the only option currently researched by the industry to decarbonise calcination. Like electric and hydrogen boilers, electric and hydrogen calciners have the potential to drastically reduce emissions from refining so long as they are coupled with low-carbon electricity and hydrogen, making the effectiveness of their rollout dependent on the parallel deployment of renewable energy. These calciners are still at initial stages of development (TRL 4–5) and will require an increase in R&D efforts to achieve commercial readiness by 2030 (Exhibit 1.11).

Smelting

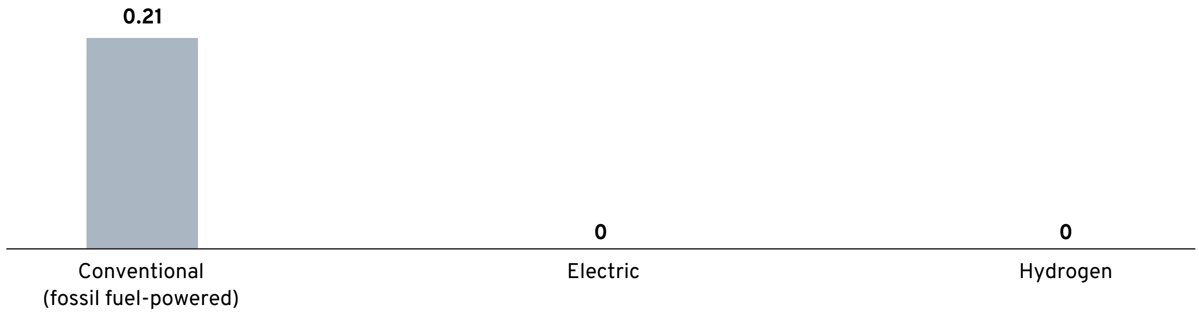
Process emissions consisting of both CO_2 and PFCs are generated during the smelting of aluminium. The most promising avenues to reduce these emissions are (Exhibit 1.12):

- **Substituting carbon anodes for inert anodes:** Thanks to their chemically inert nature, these anodes have the potential to eliminate 100% of CO_2 and PFC emissions. The technology's promising emissions reduction profile has generated interest in the industry, and several companies are spearheading R&D efforts. Despite a current TRL level of 7, however, inert anodes are not expected to achieve commercial deployment readiness before 2030. In addition, retrofitting the technology to existing pot rooms would imply a significant redesign resulting in large upfront

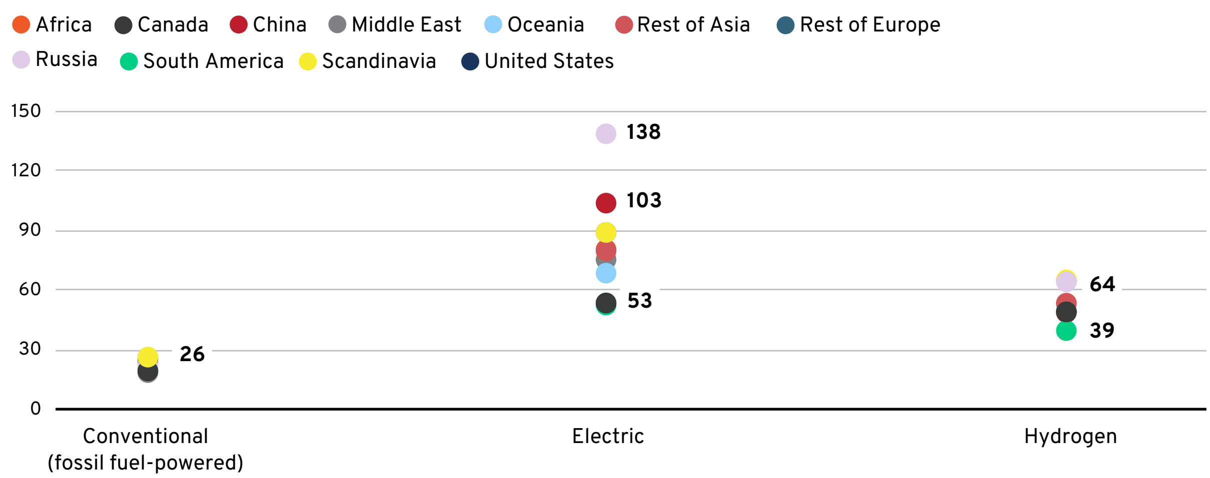
EXHIBIT 1.11

Comparison of conventional and near-zero-emissions calcination technologies

Direct emissions 2030, t CO_2e/t alumina



2035 levelised cost per tonne of alumina, in $



	Conventional (fossil fuel-powered)	Electric	Hydrogen
Commercial readiness year	–	2030	2030
Technology readiness level	9	4–5	4–5

Source: MPP analysis; industry engagement

capital expenditures. However, inert anodes' estimated longer lifetime (about one year versus one month for carbon anodes) has the potential to unlock operating expenditure savings of about 10%, making the technology financially attractive over a smelter's lifetime.[ix]

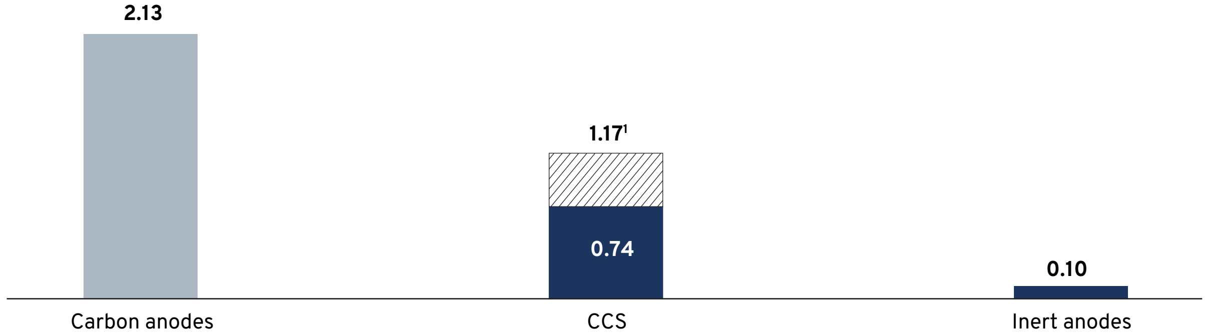
- **Retrofitting smelters with CCS facilities:** CCS technology is expected to be capable of reducing CO_2 emissions in smelter flue gases by 90%, but not reducing PFC emissions.[24] Its emissions reduction potential can be increased if the emissions from fuel combustion in the CCS plant are recycled into the absorber, and if the CCS system is designed to include emissions from the carbon anode production facilities for smelters with on-site production. From a cost perspective, deploying CCS in aluminium is likely to be more expensive than in other sectors because of the low CO_2 concentration in smelters' flue gases (approximately 1%). Cell redesign to increase CO_2 concentration is technically possible, but would require substantial upfront investment.

ix Inert anode cost and performance assumptions have been developed through publicly available literature and expert review—they should not be taken as the endorsed cost and performance of any inert anode developer, which at this stage are both commercially sensitive and unavailable from an open-sourced report.

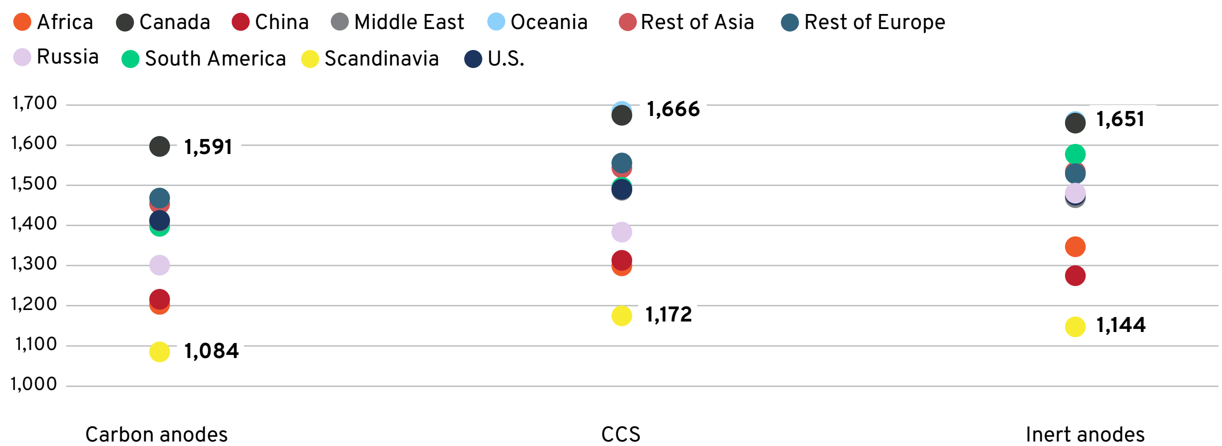
EXHIBIT 1.12

Comparison of conventional and near-zero-emissions smelting technologies

Direct emissions 2030, t CO_2e/t alumina



2035 levelised cost per tonne of alumina, in $



	Carbon anodes	CCS	Inert anodes
Commercial readiness year	–	2030	2030
Technology readiness level	9	3-4	7

[1] Upper emissions range assumes CO2 capture plant requires natural gas for thermal energy requirements; however, CCS can achieve the lower range if thermal energy is supplied by zero-carbon sources (e.g. hydrogen) or CO2 capture plant flue gas is re-captured in the CCS plant.

Source: MPP analysis; industry engagement

ACHIEVING NET ZERO: POSSIBLE TRAJECTORIES

A range of possible scenarios can deliver a 1.5°C pathway in the aluminium sector. There are, however, significant milestones that must be attained for the sector to reach net zero and a 1.5°C pathway. We use a core 1.5°C-aligned scenario to illustrate these core milestones and then look at alternative scenarios that show the robustness of the general conclusions, but also illustrate how they can change the investment, policy, and business decision-making needs over the coming 30 years.

The scenario and the sensitivities show that although there may be uncertainties in the technology combinations that can be used to deliver significant carbon savings, focusing on the outcomes creates a strong set of milestones for the industry to deliver. For example, across all scenarios considered, delivering low-carbon power by 2035 is an essential step, but how that is achieved will depend on a number of factors that are not yet determined. Uncertainty also exists for technology development in refining decarbonisation, but the choice of technology will depend on the evolution of local electricity and hydrogen markets.

2.1 Scenario definition

The scenarios considered in the Sector Transition Strategy (STS) aim to minimise the total cost of ownership (TCO) for the aluminium sector within a given set of constraints, including technology market entry and ramp-up, wider power sector decarbonisation, and how often a plant will consider upgrading its facility.

To look at the real-world impacts, we consider a BAU scenario and a core 1.5°C-aligned scenario, along with several alternative scenarios to illustrate key features of the sector decarbonisation pathway (Exhibit 2.1).

- **BAU scenario:** In the BAU scenario, the aluminium industry seeks the lowest TCO for refineries and smelters needed to meet the growing demand for aluminium.
- **1.5°C scenario:** The 1.5°C scenario describes a trajectory that is near zero emissions by 2050. This is spurred by the availability and deployment of low-carbon power networks, greater resource and material efficiency, and advanced development of fuel switching and anode technologies.
- **No CCS scenario:** Aligned to the 1.5°C scenario, this scenario assumes that carbon capture will not be available for power decarbonisation of existing assets.

In addition, this section illustrates the impacts of (1) faster growth in aluminium demand (High Substitution), (2) more rapid availability of low-carbon power (Rapid Grid Decarbonisation), (3) impacts of an increasing carbon price (Carbon Cost), and (4) a fastest-possible abatement scenario (Fastest Abatement). These are designed to illustrate some of the key uncertainties faced by the sector.

The approach is not a full model of the aluminium value chain and market (for example, it does not include trade flows or non-energy decision-making factors). The conclusions instead focus on the key actions the sector must take to reach a 1.5°C-aligned pathway, which must be borne in mind by decision makers in industry, policy, and finance.

The aluminium STS model is flexible by design to help users examine how different assumptions regarding technology economics and availability, demand, and commodity pricing trends affect the pace and nature of the transition. As shown in Exhibit 2.2, it is based on a bottom-up, asset-by-asset approach that assesses the business case for switches to low-carbon technologies with the constraint of achieving net zero by 2050. The model also assesses input sensitivities to illuminate how changes in prices will affect the dominant technologies in a net-zero world.

The modelling focuses on technologies and strategies to reduce emissions from the smelting and refining processes. There are other emissions associated with recycling, mining, and associated parts of the wider aluminium value chain; for these, the analysis presented uses the IAI's 1.5°C scenario pathway.[x]

x Full details can be found in the *Technical Appendix.*

EXHIBIT 2.1

Summary of scenarios modelled and their associated sensitivity runs

	BUSINESS-AS-USUAL SCENARIO	1.5°C-ALIGNED SCENARIO	ALTERNATIVE SCENARIOS
Primary Aluminium Demand,[1] % increase in demand, 2020–50	**High growth:** Aligned with IAI Reference scenario – 32%	**Moderate growth:** Aligned with IAI 1.5°C scenario – 4%	**High Substitution:** Aligned with IAI High Substitution scenario – 57%
Recycling, % increase, 2020–50	275% growth in secondary production	245% growth in secondary production	
Resource and material efficiency	No further efficiency gains	Resource and material efficiency limiting growth in total aluminium demand to 50%	
Power grid, variation between regions	Electricity price in 2035: \$35–\$125/MWh Carbon intensity in 2035: 5–550 g/kWh	Electricity price in 2035: \$35–\$90/MWh Carbon intensity in 2035: 2–380 g/kWh	**Rapid Grid Decarbonisation:** Low-carbon power available through the grid by 2035
Decision making	Selection of lowest-cost technology to meet demand	Selection of lowest-cost technology to meet the 1.5°C budget	**Fastest Abatement:** Firms can choose only low-carbon options
Remaining emissions, Mt CO_2e emissions in 2050	Aligned with IAI Reference scenario (250 Mt CO_2e)	Aligned closely to IAI 1.5°C scenario (84 Mt CO_2e)	
Other key assumptions			**Carbon Cost:** Adds an increasing carbon cost to TCO decision making **No CCS:** CCS is unavailable for meeting smelter power needs

[1] Total aluminium demand growth (primary and secondary aluminium) in each scenario: BAU (81%), 1.5°C scenario (50%), and High Substitution (94%).

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

EXHIBIT 2.2

The aluminium STS model is a bottom-up simulation of net-zero pathways

A: Model inputs

Calculation inputs

- Supply and demand
- Average age, production volumes, and technology of current plants
- Commodity prices
- Costs and commodity consumption of production technologies
- Carbon budget

Optimisation constraints

- 1.5°C IAI carbon budget and emissions pathway
- Technology years of availability
- Technology ramp-up rates
- Minimum regional production
- Possible technology switches

B: Model calculations

Metrics for every technology switch

- Levelised cost of production (LCOX)
- Marginal cost of production (MC)
- Emissions in Scope 1 and Scope 2 for CO_2, N_2O, CH_4, and PFCs

Year-by-year optimisation of plant investment decisions

- Capacity utilisation of plants is adjusted based on demand
- Plants can be decommissioned, retrofit, rebuilt, and newly built

Yearly granularity of asset-level decision-making from 2020 to 2050 for 15 different regions[1]

C: Model outputs

Net-zero pathway for the primary aluminium industry

- Production volumes and production cost by supply technology
- Annual and total investments required
- Emissions trajectory
- Demand for energy carriers and feedstocks

(Not exhaustive)

[1] The 15 regions are: Africa, United States, Canada, South America, Scandinavia, Rest of Europe, Russia, Oceania, Middle East, five regions of China (Central, East, North, Northwest, South), and Rest of Asia.

Source: MPP analysis

2.2 What will it take to achieve a net-zero aluminium sector?

If it is to achieve net zero, by 2035, the sector will have to decrease emissions by two-thirds; by 2050, it will need to reduce emissions by almost 95%. This effort will also enable the aluminium sector to reduce cumulative emissions to 15 Gt CO_2e between 2020 and 2050, consistent with a 1.5°C pathway. A comparison between the BAU and 1.5°C scenario pathways and cumulative emissions is shown in Exhibit 2.3.

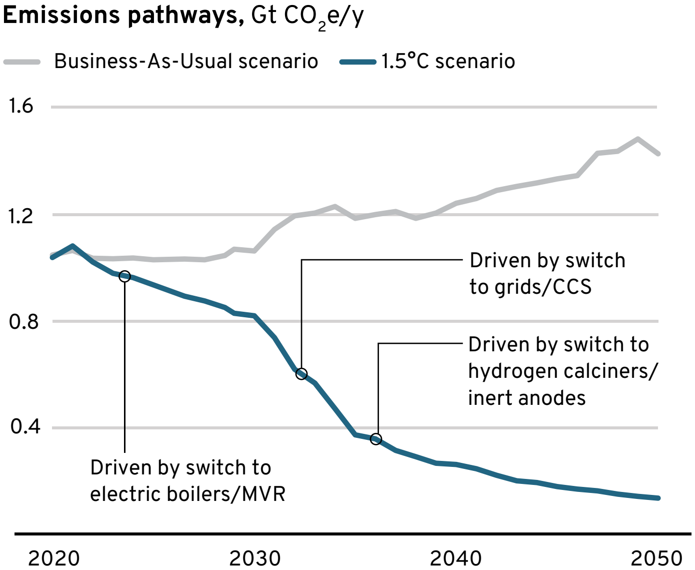
The 1.5°C scenario suggests the following important milestones:

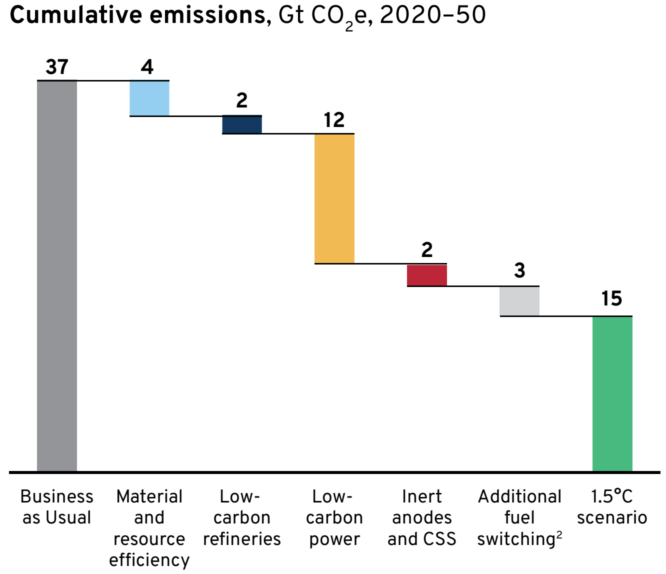
- **Over the period 2025–35,** all power supplied to aluminium smelters must switch to grids or other low-carbon captive power technology in which the carbon intensity is less than 100 g CO_2/kWh. This is a critical milestone, as power emissions represent approximately two-thirds of aluminium value chain emissions, and in order for the industry to be on a 1.5°C pathway, significant progress is required over the coming decade.
- **By 2030,** new technology such as low-carbon anodes, low-carbon digestion, and new calcination technology will need to begin deploying at scale.
- **By 2050,** the aluminium sector should reduce its GHG emissions by approximately 95% through power decarbonisation, new technology to address direct emissions from smelters and refineries, and increased recycling rates and material efficiency.
- **By 2050,** there is likely to be some small role for CDR solutions, given the role of carbon capture and other residual emissions in the value chain.
- **Gradual increases in aluminium product collection rates from 70% to more than 90% by 2050,** along with improved product design, are critical to achieving a trebling of secondary production growth.

Early action is key to delivering a pathway consistent with a 1.5°C-aligned carbon budget of 15 Gt CO_2e. Without the deployment of any decarbonisation or circularity levers, cumulative emissions to 2050 would total 37 Gt CO_2e. However, the industry members that have endorsed the aluminium STS broadly agree that the 1.5°C scenario can be delivered by reaching the milestones outlined above. Particularly important is the rapid decarbonisation of the power sector, which makes up 50% of cumulative emissions savings to 2050.

EXHIBIT 2.3

Delivering 1.5°C requires rapid action across the aluminium value chain[1]





[1] Includes all Scope 1, Scope 2, and Scope 3 emissions associated with primary and secondary aluminium production.
[2] Includes additional value chain emissions reduction via low-carbon fuel switching and other decarbonising levers for mining, casting, fabrication, recycling, and transport.

Source: Aluminium Sector Transition Strategy Model (2022)

2.2.1 Delivering a 1.5°C aluminium sector will require action across the value chain

Delivering the 1.5°C scenario will require deploying a significant scale of new power assets, emerging technologies, and innovative ways of handling and processing scrap aluminium, across multiple segments of the value chain. What may sound daunting to stakeholders is an achievable pathway for the sector: these actions are all based on known and emerging technologies, and can be accomplished with the right combination of coordination, incentives, and development of the business case for low-carbon aluminium. The impacts of various technologies on cumulative emissions savings are shown in Exhibit 2.4.

The rest of this section explores the combination of technologies in the 1.5°C scenario and what might drive them. For comparison, technology deployment in the BAU scenario is also shown in Box 3.

2.2.2 Smelter decarbonisation

To decarbonise aluminium smelters' Scope 1 and Scope 2 emissions, new anode technology and low-carbon electricity supply will need to be developed and deployed. Exhibit 2.5 shows the technology deployment curves to 2050 for both electricity supply and anode technology in the 1.5°C scenario.

These actions are all based on known and emerging technologies, and can be accomplished with the right combination of coordination, incentives, and development of the business case for low-carbon aluminium.

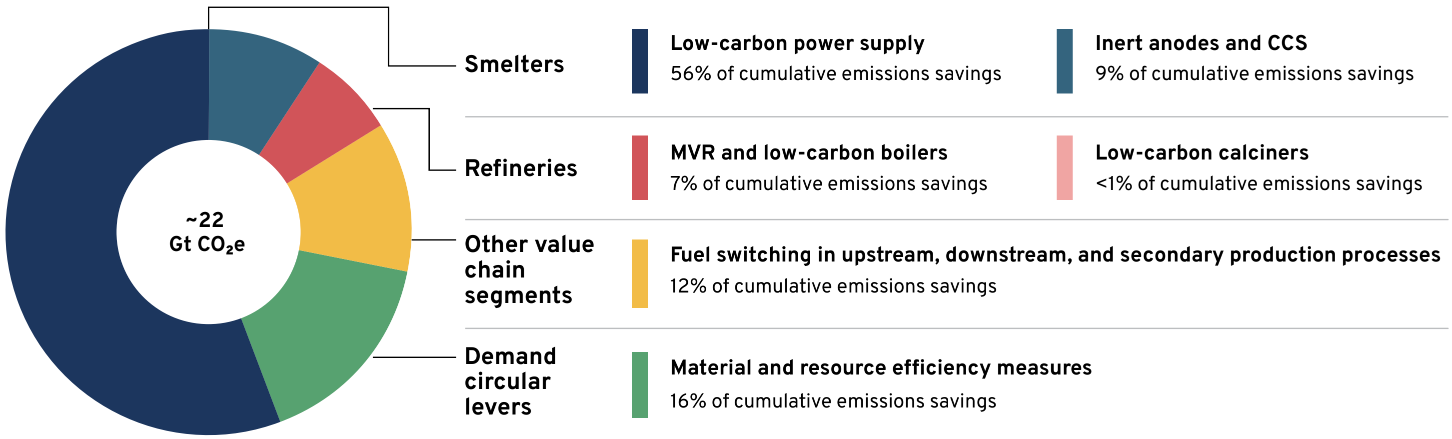
Power decarbonisation

Electricity supplied to the aluminium sector needs to be constant and reliable to enable smelters to run effectively. This need presents a challenge for smelters and their power suppliers. There are two key considerations for a smelter deciding on electricity supply:

- **Technology solution:** The three overarching solutions are likely to be renewables with low-carbon firming capacity (likely requiring backup grid connections), CCS retrofits to

EXHIBIT 2.4

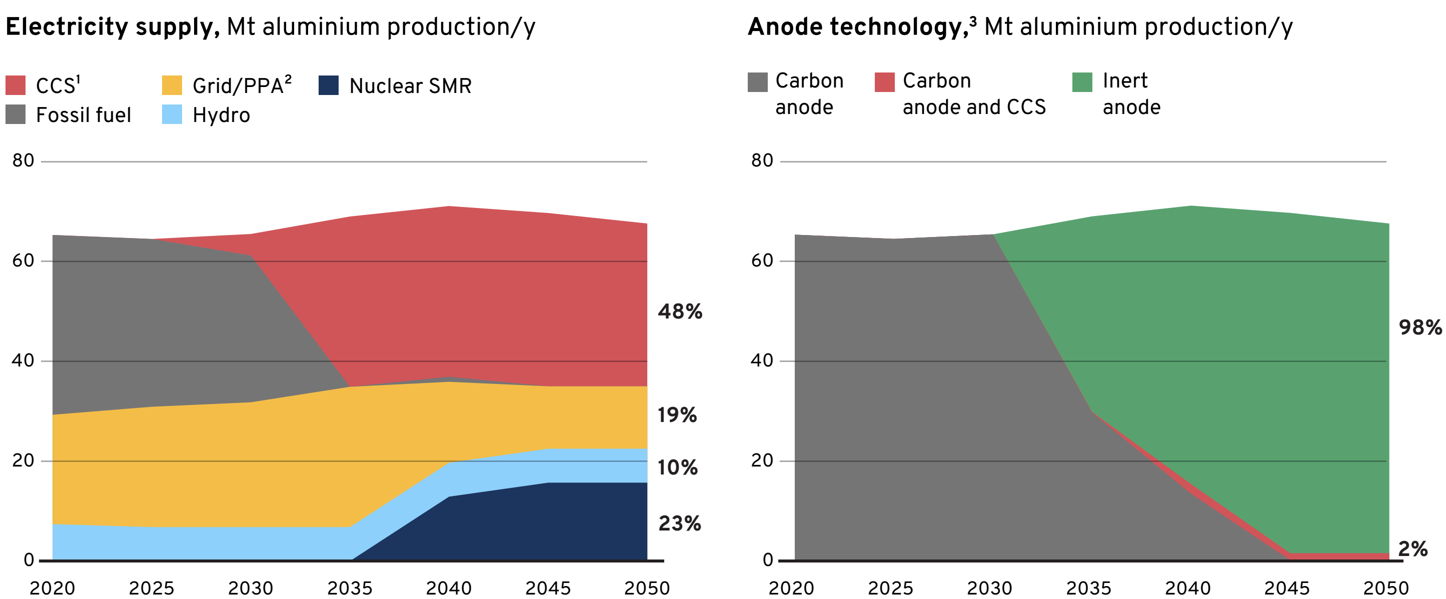
Role of technologies in delivering the ~22 Gt CO_2e of cumulative emissions (2020-2050) reduction in the 1.5°C scenario, compared with the Business-as-Usual scenario



Source: Aluminium Sector Transition Strategy Model (2022)

EXHIBIT 2.5

Smelter power decarbonisation is likely to be driven by a mix of grid and low-carbon captive technologies; low-carbon anodes roll out over the period 2030–45



[1] Includes CCS applied to gas and coal power plants.
[2] Includes smelters with grid-supplied power or a mixture of renewable PPAs and grid-supplied power.
[3] Anode technology is at an early stage of development, and although at this stage inert anodes are assessed to be more cost-effective than other technologies, there is a high range of uncertainty around their cost and performance. New evidence through the technology development process will emerge and could change this view significantly.

Source: Aluminium Sector Transition Strategy Model (2022)

fossil-fuelled captive power, and nuclear SMRs to provide baseload low-carbon power.

- **Business model for supply of power:** Once smelters have decided on a technology solution, they must consider how best to set up their commercial arrangements. Today, some companies look to obtain their power through captive power, some establish PPAs with specific electricity generators, and some rely on contracting with the grid itself.

In the 1.5°C scenario, CCS plays a prominent role because significant smelter capacity is located in regions where electricity grids will not reach a sufficient level of decarbonisation until the 2040s, even taking their current efforts into account. In addition, many smelters are in areas with insufficient local renewables potential. Post-2035, nuclear SMRs can play a role in meeting this demand in these locations. If CCS cannot play a large role for technical, policy, or strategic reasons, then connections to grids can deliver the carbon abatement required (though with a slightly higher level of cumulative emissions) for a 1.5°C pathway (see Box 2 for details).

There are a number of additional options that smelters could use to decarbonise their power requirements, but they are highly site specific and this analysis does not capture them. These include long-distance private wire arrangements to areas of higher renewables concentration (possibly combined with batteries or other storage arrangements) and wholesale moving of smelters to areas with greater low-carbon electricity potential.

Anode decarbonisation

Technology to decarbonise anodes in smelters is at an early stage of development. Some inert anode technologies (e.g., Elysis or Arctus) are planned to supply small amounts of low-carbon aluminium over the coming years. By 2030, this technology and other options such as CCS or chloride-based electrolysis (such as Hydro's HalZero process) should be widely available, and this transition can begin across the whole smelter asset base.

Given the different stages of technology development for low-carbon anode technologies, comparisons or strict future market share analysis is challenging at this stage, and different technologies may better suit different companies and/or individual asset circumstances.

Although in this analysis inert anodes represent the greatest carbon-reducing and cost effective solution – this should be interpreted as based on the evidence available at this time. It would be expected that as each class of technology (inert anodes, CCS, and chloride-based technologies) develops, the financial and business cases will evolve.

Given the uncertainties involved in emerging technologies and in comparing technologies at different stages of development, it is useful to consider the characteristics that any technology will have to demonstrate:

- It must reduce emissions by at least 50% compared with current anode production and use, with a strong preference for elimination of emissions where possible.

- It must be viable to be deployed at scale across multiple companies and smelters from 2030.

2.2.3 Refinery decarbonisation

To decarbonise alumina refineries' Scope 1 emissions, new low-carbon digestion and calcination technology will be required. Exhibit 2.6 shows the technology deployment curves to 2050 for both digester and calciner technologies in the 1.5°C scenario.

BOX 2

Non-availability of power CCS

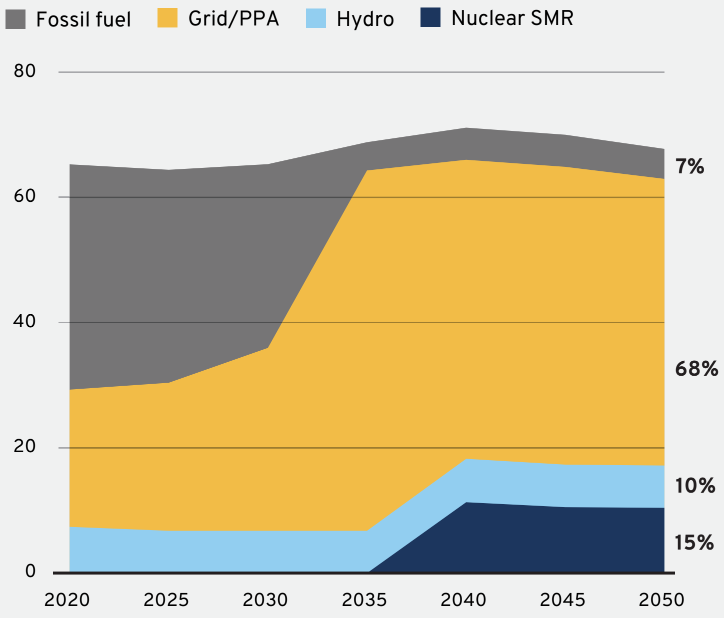
The 1.5°C scenario relies heavily on CCS for decarbonising captive coal plants, particularly those in China. This approach presents significant regulatory, policy, and technical challenges. It would also involve the aluminium sector being a first-mover adopter of power CCS. Continued coal use even with CCS might be unviable in a net-zero world by 2050.

If CCS is not available for power decarbonisation, then:

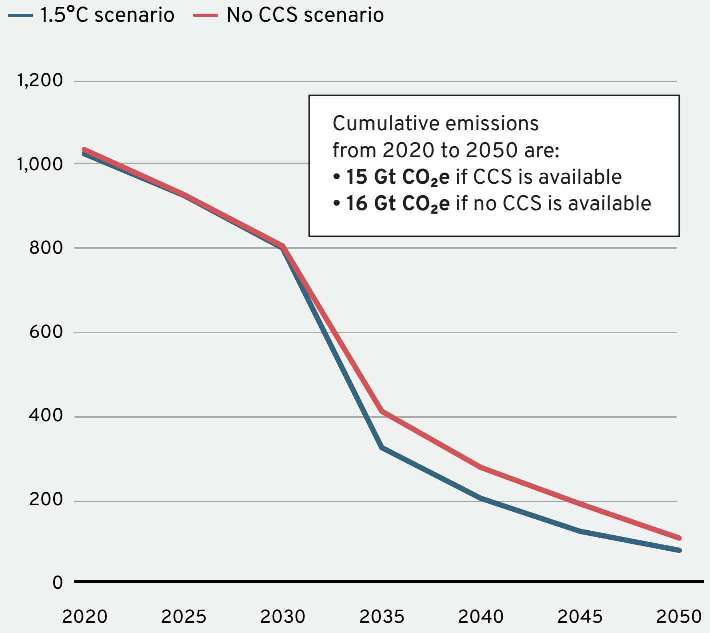
- **Power decarbonisation can still be achieved through connecting to local grids,** minimising emissions through the use of renewables PPAs, and employing a greater rollout of nuclear SMRs from 2035 onwards.
- **Cumulative sectoral emissions would increase slightly, from 15.2 Gt CO_2e to 16.2 Gt CO_2e,** because of a greater contribution from grid emissions in the 2030s and unabated captive fossil fuel power in the 2040s.
- **More rapid adoption of low-carbon anodes** would be needed to offset some of the increased emissions from captive thermal power (see exhibit below).

Other options for achieving further power decarbonisation were outside the scope of the STS modelling. The most influential could be moving smelter capacity to locations with lower-carbon grids and greater access to renewables – for example, moving capacity from northern China to southern China.

Electricity supply, Mt aluminium production/y



2020–50 direct and indirect emissions, Gt CO_2e/y



Source: Aluminium Sector Transition Strategy Model (2022)

In addition, there are opportunities to decarbonise other parts of the aluminium value chain more rapidly, for example, reducing emissions faster from fossil fuels and electricity use in secondary production. This approach would require new secondary production facilities to be low carbon by default, as well as requiring more rapid retrofitting of facilities with new hydrogen and electrification technologies. Further work would be needed to look at this in detail and quantify the impacts of an accelerated decarbonisation effort in secondary aluminium production.

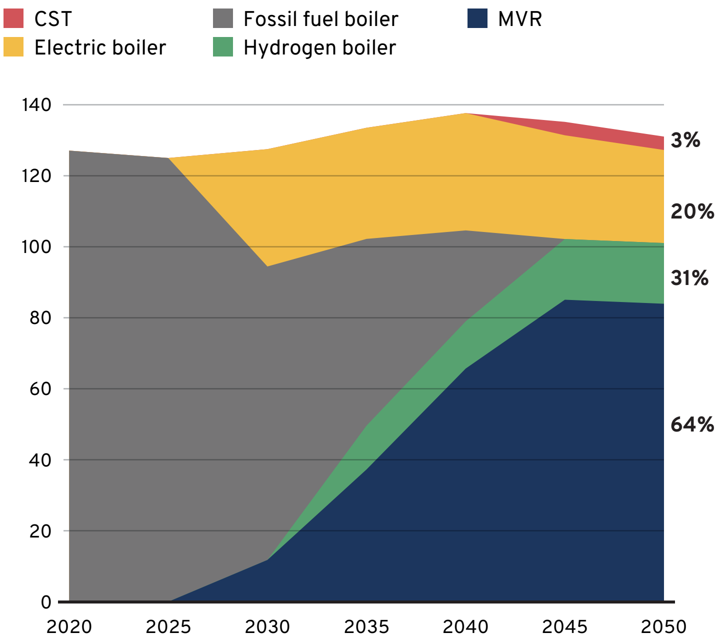
This analysis reveals a number of technology pathways for decarbonising the power system. Although CCS can play a significant role, other pathways can deliver broadly equivalent outcomes that may be within reach of a 1.5°C carbon budget.

EXHIBIT 2.6

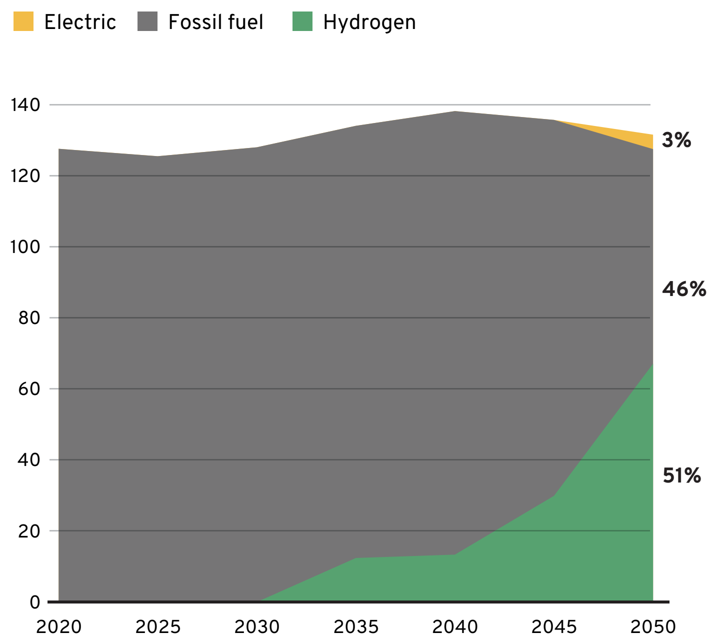
Refinery decarbonisation is likely to be driven by electric technologies in the digestion process (MVR and electric boilers)

2020–50 refinery technology deployment in the 1.5°C scenario

Digester technology, Mt alumina production/y



Calciner technology, Mt alumina production/y



Source: Aluminium Sector Transition Strategy Model (2022)

Digestion decarbonisation

The majority of emissions in refineries (approximately 70%) come from the digestion process, with MVR systems playing a dominant role in the 1.5°C scenario. MVR can extract waste heat from the process, enabling a high-efficiency, relatively low-cost decarbonisation method. However, although MVR systems have been deployed widely in other sectors, the technology has seen limited piloting in the aluminium sector to date. This leaves some technology risk, as MVR is required to begin deploying at alumina refineries in the late 2020s. It would be expected that a mix of technologies would come forwards, depending on the local availability and price of electricity and hydrogen.

Calcination decarbonisation

The calcination process makes a much smaller contribution towards overall aluminium sector emissions. Low-carbon calciners supplied by hydrogen or electricity are expected to be relatively expensive compared with other decarbonisation technologies and only begin deploying in 2030.

There may be potential to deliver further carbon savings through faster deployment of low-carbon calcination technology. However, this would have a relatively minor impact overall on cumulative emissions savings in the sector. As with digestion decarbonisation, the mix of technology solutions will depend greatly on local factors, most notably electricity price and hydrogen price and availability.

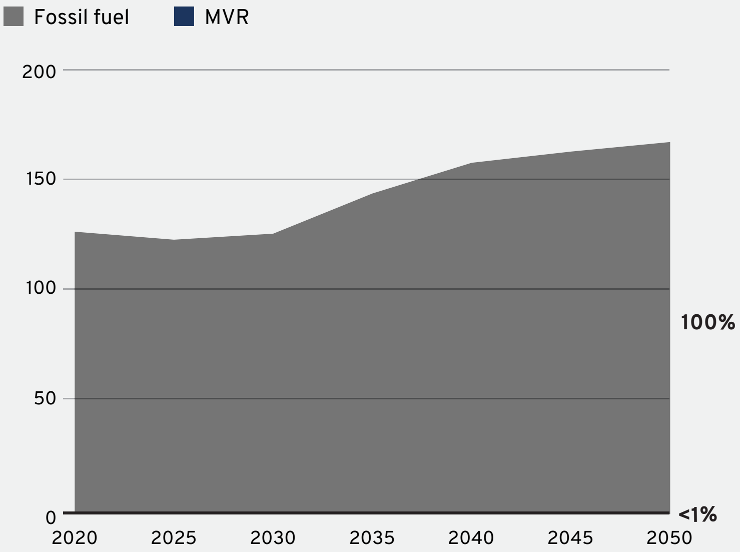
BOX 3

BAU technology deployment

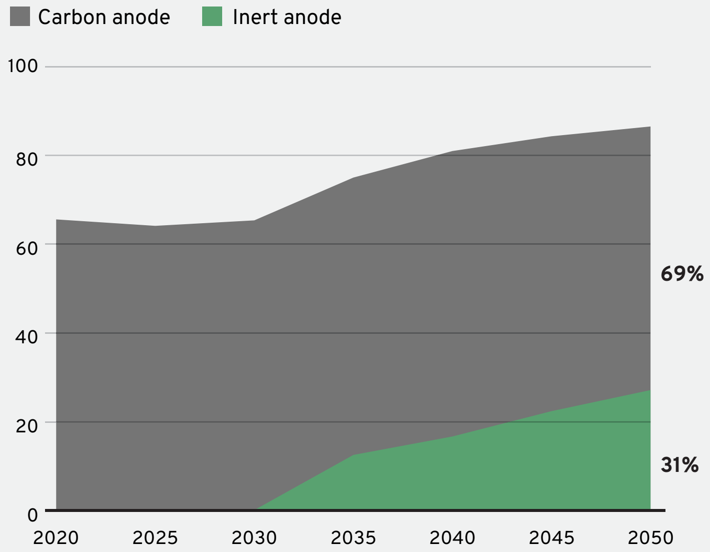
The BAU scenario does not see significant deployment of low-carbon technologies, given the higher levelised costs of low-carbon alumina and aluminium production. The only low-carbon technology to be deployed is inert anodes, which are deployed in new capacity built to meet expanding aluminium demand. For these newly built smelters, the expected running cost savings from inert anodes outweigh the investment costs.

2020–50 technology deployment in the Business-as-Usual scenario

Refineries – digestion, Mt alumina production/y



Smelters – anode technology, Mt aluminium production/y



Source: Aluminium Sector Transition Strategy Model (2022)

2.2.4 Material circularity and other emissions savings

Material circularity and efficiency offers the opportunity to use aluminium more efficiently, through improved recycling and production measures. This approach can be undertaken through a number of avenues (see Box 4 for a deep dive):

- **Product lifetimes:** Extending the lifetime of products can mean that aluminium is used more effectively. For example, it is possible to expand the lifetime of buildings in China from 15 to 35 years.[25]
- **Material circularity and increasing secondary aluminium production:** On average, only about 0.5 t CO_2e is emitted per tonne of secondary aluminium, in contrast to about 16 t CO_2e per tonne of primary aluminium. From a cost perspective, the numbers are not so different: secondary aluminium trades at about 85% of primary aluminium traded prices.
- **Material efficiency:** Improvements in the design stage (e.g., lightweighting and a focus on ease of repair), the fabrication process stage (e.g., reducing material losses), and the end-use stage (e.g., increasing the lifetime of goods and assets) can all contribute.

Emissions from other parts of the value chain, such as additional electricity use in refineries, bauxite mines, or secondary smelters, as well as fossil fuels used to supply thermal energy in the anode production, casting, recycling, or fabrication processes, must be significantly reduced to deliver the 1.5°C scenario. These processes will require decarbonisation in two main ways:

- **Grid decarbonisation:** Some of these processes are electricity based and will decarbonise alongside the local electricity grid. It might be possible to deliver more rapid decarbonisation through PPAs or other contractual arrangements.
- **Fuel switching:** Many of the sector's upstream and downstream processes involve using thermal energy from gas or coal for heating. These processes can be decarbonised by using hydrogen or electricity instead.

Deep dive on improving material circularity

Today, about 75% of all primary aluminium produced is still in circulation, and scrap collection rates range from 10% to 90% across regions and products. High-value end-use sectors, such as the automotive and construction sectors, and middle-income countries lead collection rates thanks to the attractiveness of employment in the post-consumer scrap collection sector.

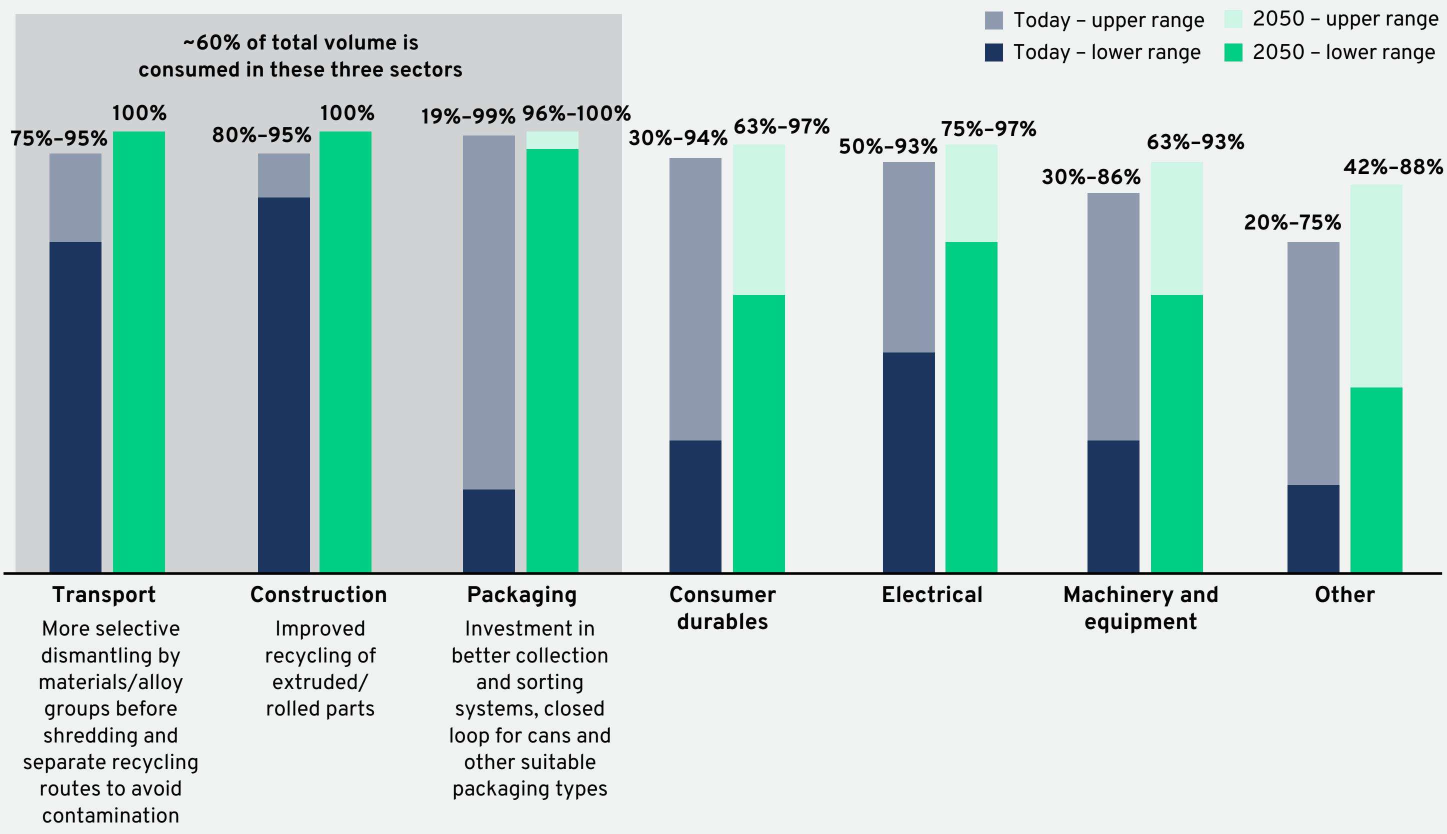
The aluminium sector will need to work together with the waste management sector and governments to implement the scrap collection levers needed. This is not a theoretical exercise – there are already regional case studies of how to maximise collection rates (for example, average European packaging collection rates are at 75%, and Brazil achieves rates of more than 95%). The exhibit below shows the change in scrap collection rates in each end-use sector that will be required by 2050 in the 1.5°C scenario.

The European Aluminium Association report on circular aluminium recommends separating the different aluminium alloys at collection to enable products to be recycled to meet the same purpose and to avoid downgrading of aluminium as it becomes mixed with steel and copper at its end of life.

Packaging could be the end sector in which it is most difficult to maximise collection rates owing to its relatively low value; maximisation in this area will likely depend on smart regulatory intervention in combination with new technology and collaboration along the value chain. Key levers for packaging include deposit return schemes, improved sorting, and enhanced collection infrastructure before aluminium reaches the landfill.

The growth of secondary aluminium production presents an opportunity, namely, an added-value case for investment in the waste collection sector. This investment is likely required regardless of its impact outside the aluminium sector (e.g., to minimise plastic waste leakage).

Aluminium collection rate range across sectors, % of total available



Note: 2%–10% loss is difficult to eliminate due to remelting losses in the recycling process.

Sources: IAI, European Aluminium Association

2.2.5 The evolution of the energy sector and aluminium demand is highly uncertain; this creates challenges and opportunities for decarbonisation

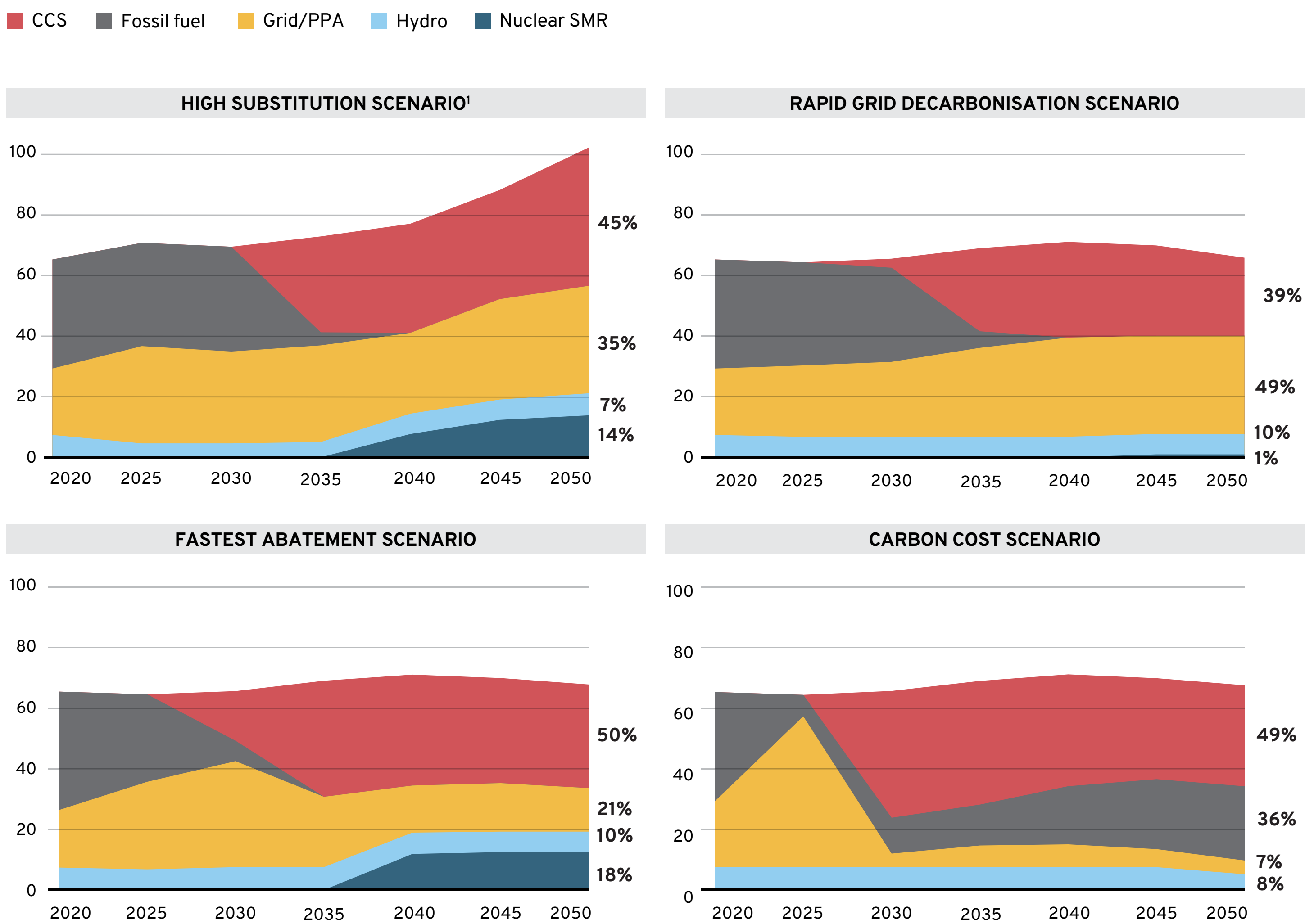
There is significant uncertainty around much of the future path of the energy system as well as demand for metals. These could offer opportunities or challenges for the aluminium sector in delivering on a 1.5°C-aligned pathway. To illustrate, four alternative scenarios are shown in Exhibit 2.7 (High Substitution, Rapid Grid Decarbonisation, Fastest Abatement, and Carbon Cost).

The first two alternative scenarios highlight the challenge of greater primary aluminium demand and the opportunity of more rapid decarbonisation of the electricity grid. In both scenarios, the aluminium sector is able to meet the 1.5°C carbon budget, but the two scenarios use significantly different combinations of power technologies to reach this goal. The two other scenarios reflect the change in technology deployment when, in one case, selection is limited to technologies that achieve the greatest abatement and, in the other case, when decision-making is driven by an increasing cost of carbon.

EXHIBIT 2.7

Alternative scenarios highlight the uncertainty in future technology mixes

2020–50 smelter power supply technology deployment, Mt aluminium production/y



[1] Based on demand projections from IAI's High Substitution scenario. All other scenarios use the IAI's 1.5°C scenario. Sums exceed 100% due to rounding.

Source: Aluminium Sector Transition Strategy Model (2022)

High Substitution scenario

If the demand for aluminium increases further as it replaces other metals in the global economy (for example, replacing steel in the automotive sector), primary aluminium demand will increase significantly. To meet this increased demand, significant new capacity would be needed beyond 2040. Much of the extra demand can be met in geographies that have a high availability of low-carbon power and low costs; however, siting new assets will depend on a combination of demand locations, supply chains, and underlying energy prices.

By 2040, new aluminium capacity will be able to be built with a very low carbon impact, without significant impact on the sector's carbon emissions. In contrast to the 1.5°C scenario, this scenario demonstrates the importance of new capacity beyond 2030 being built for low carbon emissions by default.

Rapid Grid Decarbonisation scenario

In this scenario, all regional grids achieve net-zero emissions by 2035. If lower-carbon-intensity power is available earlier, either through more rapid decarbonisation of grids or through local PPA projects, grids could play a greater role in delivering progress. Thus, if the grid were to decarbonise fully by 2035, grids would take about 50% of 2050 low-emissions smelter technology in the 1.5°C-compliant scenario, as opposed to about 25%.

Fastest Abatement scenario

The Fastest Abatement scenario has a mechanism to switch to the lowest-emissions technology available in any given year, regardless of cost. Although this is not realistic for the current global economic environment, it serves to illustrate the extreme of what is possible technologically. This assumes that from 2030, only low-carbon decisions are made by refineries and smelters, and by 2040, refineries and smelters implement only near-zero-carbon technology choices.

This scenario could materialise in different forms of implementation, some possible examples being government-mandated environmental standards for new plants, conditional access to financing, and industry initiatives that encourage the phaseout of high-emissions investments.

The Fastest Abatement scenario switches power supply much faster to a lower-emissions source, which means it replaces coal generation with gas generation despite the high cost and marginal emissions savings. For smelters, the model is forced to implement two technological switches to maximise the decrease in annual emissions. Smelters currently supplied by direct coal power generation switch to grid and captive gas before 2030, and then to captive gas with CCS by 2040.

Carbon Cost scenario

The Carbon Cost scenario models the adoption of lower-emissions technologies if a consistent global carbon cost is applied. The model prioritises technologies with the lowest TCO after the carbon cost per year is applied. For the sake of simplicity, this scenario uses a global linear cost curve, with the purpose of illustrating the impact of carbon costs on the BAU pathway.

Achieving a global carbon price is complex in practice, but this scenario serves as an illustration of the technology changes needed for a minimal cost pathway to net zero by 2050. This scenario is driven by increased operating cost depending on the technology emissions, incorporating a cost per tonne of carbon emitted that rises from $30 to $100 for smelters between 2025 and 2050, and $50 to $300 for refineries.

In the Carbon Cost scenario, there is little deviation from the BAU pathway prior to 2030, as lower-emissions grid/PPA power is unavailable for the approximately 30% of smelters found in north and central China and the carbon price is not high enough to drive decarbonisation of power supply. Post-2030, as the carbon price rises above $70/t and low-carbon refinery options mature, we see both retrofitting of refinery boilers and switching of smelter power supply to captive coal with CCS and grid. After 2040, a much higher carbon price, about $250–$300, is required for calciners to switch to decarbonised technology, because the relative delta of emissions is low compared with that of boilers (for example, a gas-to-hydrogen calciner switch saves approximately 0.15 t CO_2e/t alumina [Aa] compared with a gas-boiler-to-MVR switch savings of approximately 0.4 t CO_2e/t Aa).

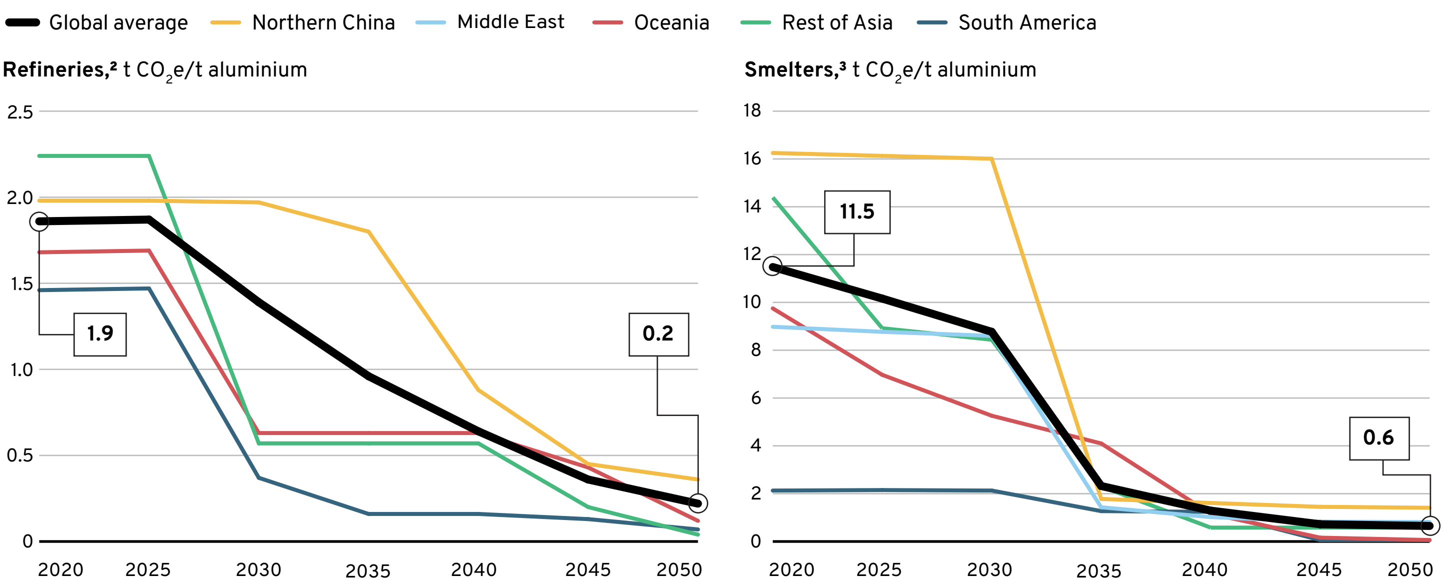
2.2.6 Regional distribution of emissions intensity

Regional disparities in production carbon intensities exist today, but should converge and follow similar pathways after 2035 (Exhibit 2.8). The existing combination of technologies used at a refinery or smelter will play a significant role in deciding the action needed between now and 2050. Regions where coal is commonly used in smelters, such as northern China, will have to rapidly reduce emissions using low-carbon power (less than 100 g CO_2e/kWh). In regions where hydropower is more common, such as Scandinavia or Canada, the action needed is focused on delivering low-carbon anodes

EXHIBIT 2.8

Emissions intensity varies greatly among regions, particularly for smelters, depending on the upstream emissions associated with power generation

2020–50 emissions intensity[1] in the 1.5°C scenario



[1] Scope 1 and Scope 2 emissions.
[2] Emissions associated with digestion and calcination.
[3] Emissions associated with electrolysis for smelters and excludes emissions embedded in alumina.

Source: Aluminium Sector Transition Strategy Model (2022)

from 2030 onwards. By 2035, electricity input is broadly decarbonised, and the differences in carbon intensity between regions and smelters are significantly less.

This distribution in emissions intensity is present in refineries too, though to a lesser extent than in smelting facilities. The speed of decarbonisation across regions is driven primarily by the cost of electricity; in regions where lower-cost electricity is available, decarbonisation can occur more rapidly.

These differential regional pathways to a global low-carbon aluminium sector show the importance of a structured transition that enables the sector to decarbonise, without carbon leakage to higher-carbon-intensity regions. However, this analysis also stresses the importance of providing support to higher-carbon regions where greater technological interventions are needed to achieve a fully decarbonised aluminium supply chain.

2.2.7 Investment needs for the transition to low-carbon primary aluminium

A significant investment, approximately $1 trillion, is required to deliver the transition to a low-carbon primary aluminium sector (Exhibit 2.9); however, the majority of the investment will not be in deploying new technologies at smelters or refineries. Instead, the investment is required mainly in the electricity sector to supply low-carbon electricity via the grid.

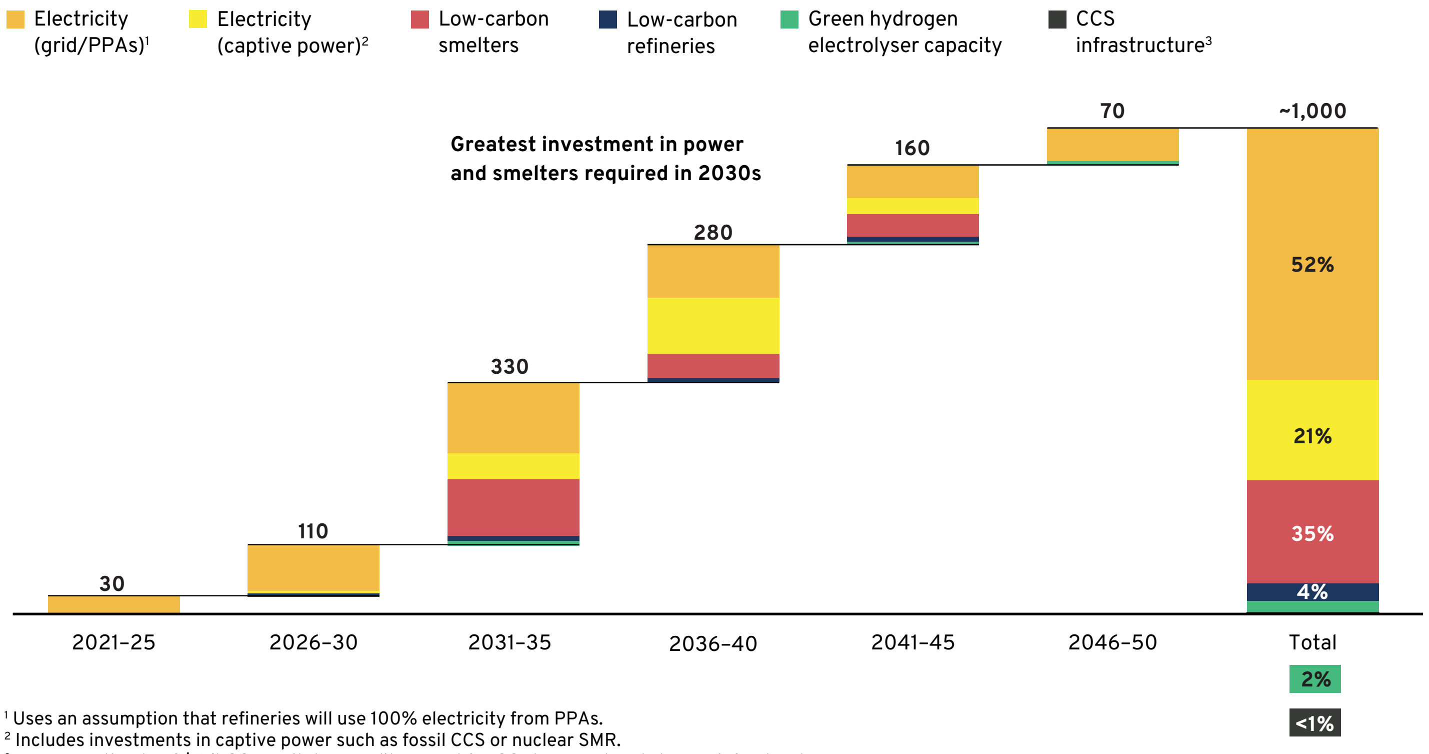
Investment will peak in the early 2030s when the peak low-carbon electricity transition occurs. Planning for this level of investment will need to start in the mid-2020s, given the lead times and build times of these assets.

The single biggest investment in smelters and refineries will be inert anodes, which are highly capital intensive. They also have a large degree of uncertainty with respect to the return that might be provided, given the relatively early stage of inert anode technology development.

EXHIBIT 2.9

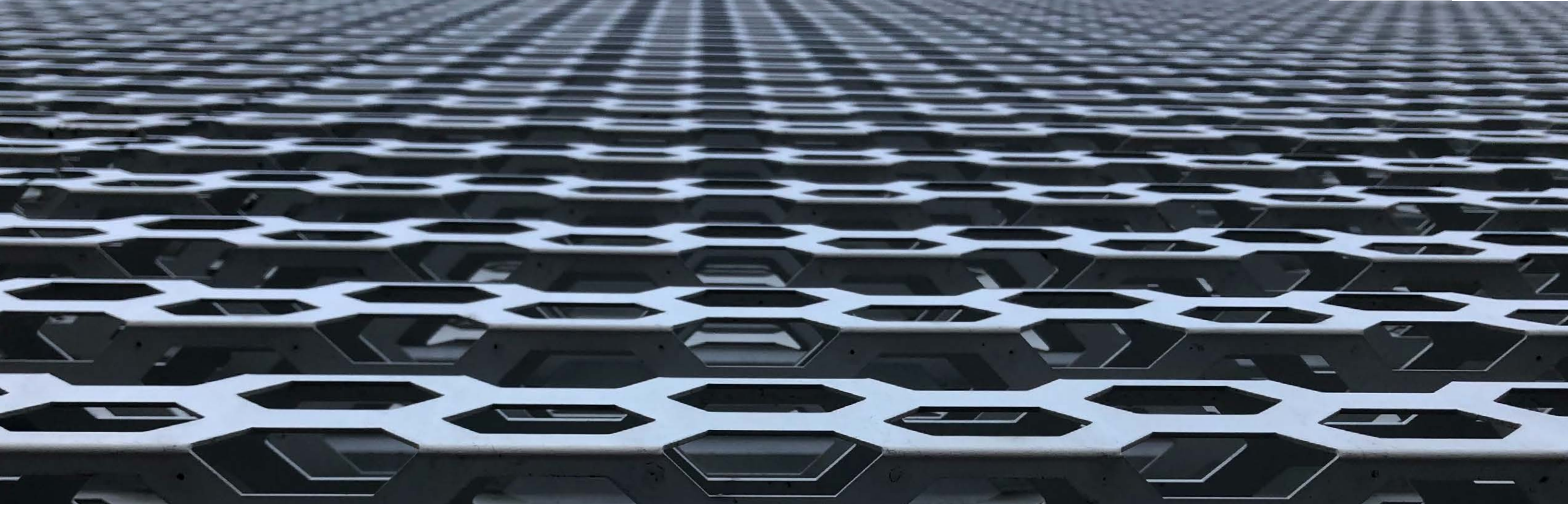
The majority of cumulative investment in the aluminium sector will be needed in the electricity system

Five-year investments for the primary aluminium sector – 1.5°C scenario, billion $



[1] Uses an assumption that refineries will use 100% electricity from PPAs.
[2] Includes investments in captive power such as fossil CCS or nuclear SMR.
[3] Uses an estimate of $5/t CO_2 capital expenditure cost for CO_2 transport and storage infrastructure.

Source: Aluminium Sector Transition Strategy Model (2022)



Different anode technologies will have different capital and operational cost profiles; for example, carbon anodes with CCS would tend to have lower investment requirements than inert anodes, but higher operating costs.

Additional investment, not quantified here, would be needed to deliver this transition, including:

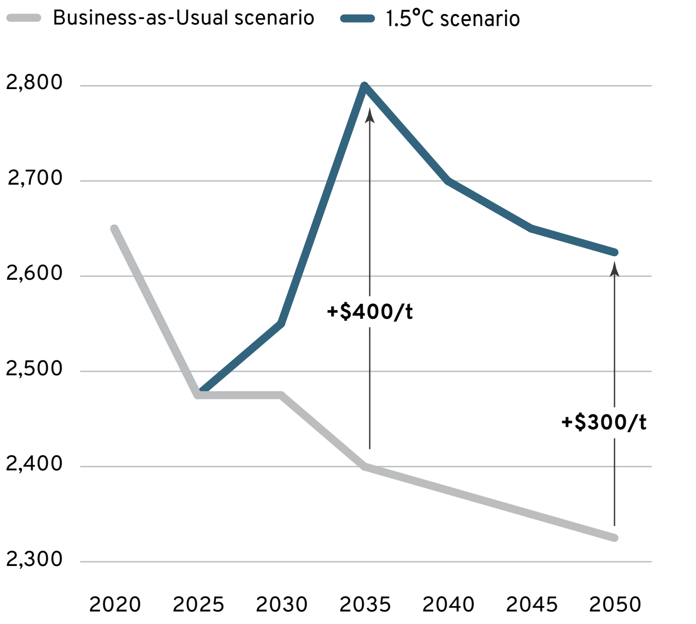
- **Power grid investment:** Transmission and distribution systems will need expanding and upgrading, particularly if connecting to renewables and to smelters. Globally, this infrastructure is estimated by the Energy Transitions Commission (ETC) to cost a cumulative $36 trillion between 2020 and 2050, but it is important to note that this number is not an additional cost on top of the BAU scenario.
- **Secondary aluminium collection:** New processing and production facilities will have to deliver the significant expansion of secondary aluminium, much of which is also required in a BAU world. Additional investment may also be needed to unlock greater collection rates, but this may also rely on behavioural change and education on the consumer front rather than requiring major technology investments for post-collection processing.

The level of investment will be highly sensitive to the combination of CCS and grid renewables deployed. The costs of CCS, while material in upfront capital, are more intensive in operating costs (the cost of coal or gas), whereas renewables are more capital intensive.

EXHIBIT 2.10

Aggregate levelised costs of production peak in 2035 in the 1.5°C scenario

Aggregate levelised cost, $/tonne aluminium



Source: MPP analysis

2.2.8 The business case for low-carbon aluminium

At an aggregate level, the transition towards a low-carbon aluminium sector will increase the average levelised cost of aluminium by approximately $300/t by 2050 (Exhibit 2.10). This cost will peak in 2035 as the power supply to smelters is decarbonised, but then fall as additional low-cost power technology such as SMRs becomes available. New-build inert anodes will also bring down average costs.

The aggregate levelised cost of alumina would increase by $60/t (equivalent to an approximate increase in the aluminium price of $120/t). This increase is driven by higher operational and fuel costs associated with low-carbon refining technologies as well as higher levels of investment needed.

By 2050, the aggregate levelised cost of producing aluminium would increase by $180/t (excluding the costs of low-carbon alumina). This is attributable to higher power costs from delivering low-carbon power, which varies significantly depending on the power sources.

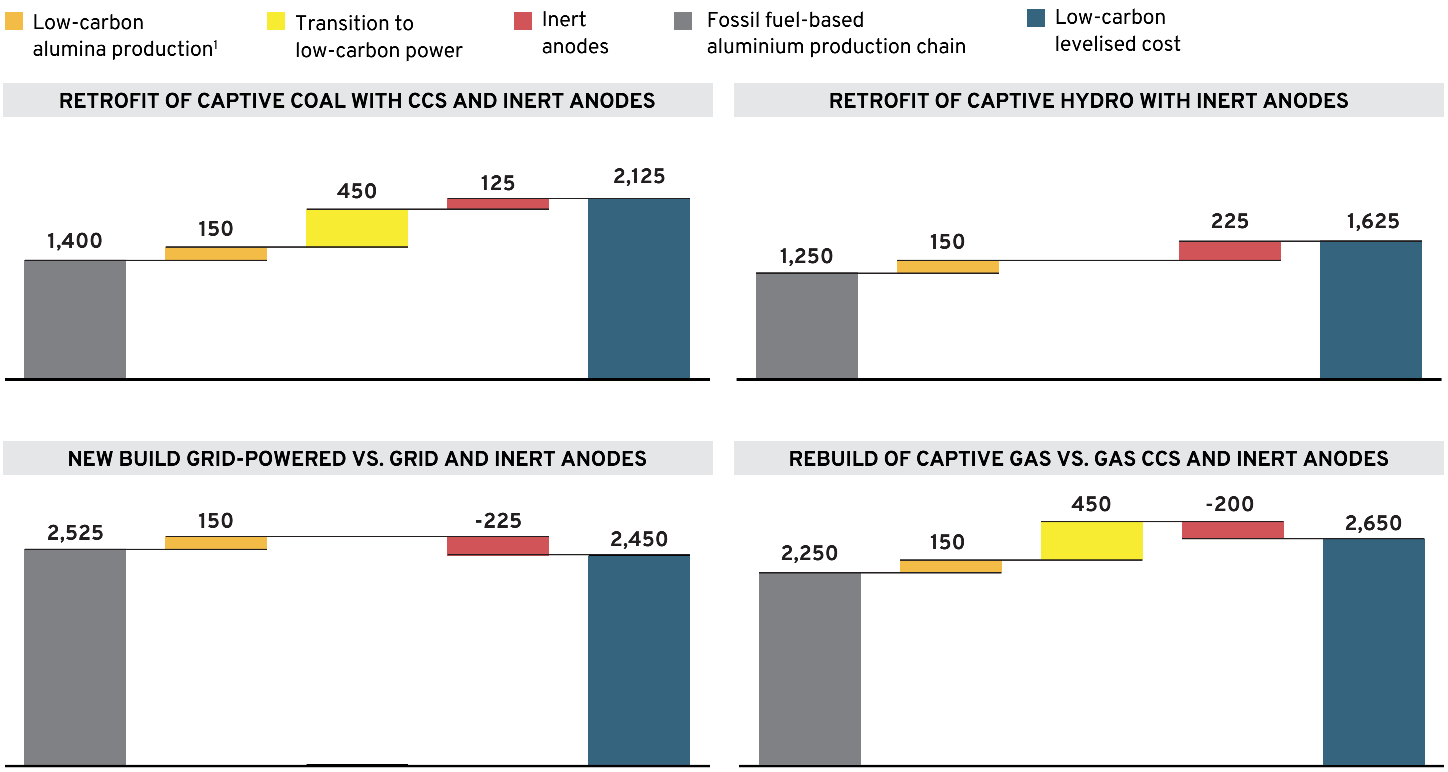
These averages mask significant global variation, depending both on the region and on the technology combinations delivered. Exhibit 2.11 shows the difference in levelised cost for a variety of case studies. There are several key conclusions:

- **Low-carbon alumina adds about $150–$200/t** to the levelised costs of low-carbon aluminium (based on MVR and hydrogen calciners).
- **Power decarbonisation at smelters has significant variability in costs** (from incurring zero costs to, in some extreme cases, increasing costs by more than $500/t), and decarbonisation costs will be highest for those with captive fossil fuel plants. Such plants will have to invest in CCS, grid connections, or other low-carbon captive power sources.
- **Sites with current access to captive (or contracted) low-carbon power** (such as hydropower) will not face power decarbonisation costs, though they could face increased competition for these power sources.
- **Grid-connected smelters could face relatively low additional costs** for power decarbonisation; however, this will depend on two critical electricity system decisions:
  - How transition costs (including paying for new generation capacity as well as transmission and storage costs) are shared among electricity system users.
  - The extent to which smelters can still achieve significant discounts in power prices in a more variable system (see Box 6 for more details about system interactions).
- **Only for new-build smelters are inert anodes likely to help reduce costs**, because of the high costs of retrofit relative to new build. New build reduces levelised costs by up to $200/t Al, whereas retrofits increase costs by a comparable amount.

EXHIBIT 2.11

Case studies of levelised cost of aluminium production

Marginal cost changes for selected smelter case studies in 2035, $/tonne aluminium



[1] Reflective of global weighted average increase in cost between fossil-based alumina production (coal boiler and gas calciner) and low-carbon alumina production (MVR and hydrogen calciner).

Source: Aluminium Sector Transition Strategy Model (2022)

Combined, these factors mean that the costs faced by individual smelters or refineries (or new build entrants) will be highly variable and extremely context dependent, creating significant challenges for a smooth transition.

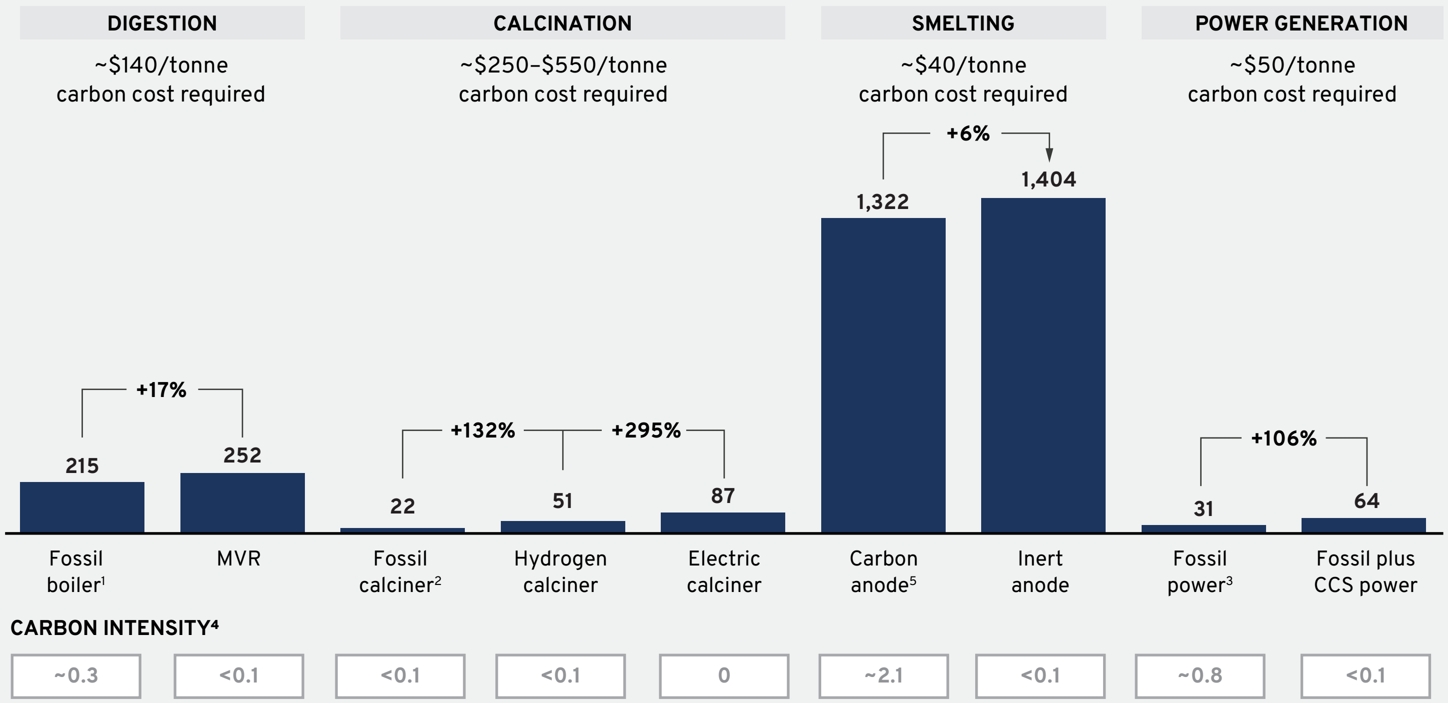
These different costs faced by various parts of the aluminium value chain and differences in investment cycles for assets, access to resources, and ambition levels across the aluminium value chain will mean that low-carbon technologies will, in the absence of intervention, have to compete alongside incumbent technologies in the wholesale aluminium markets. Therefore, measures will be required to bridge the "green premium" — the cost differential between high-carbon and low-carbon aluminium — during the transition. One such possibility, implementing a cost of carbon, is shown in Box 5.

BOX 5

Using a cost of carbon to address cost gaps

Placing a cost on carbon offers one way to address the challenge of supporting the development of low-carbon aluminium production solutions. When a cost is applied to emissions, the cost of high-carbon aluminium production increases compared with the cost of low-carbon alternatives, enabling low-cost producers to compete in the market. As shown in the exhibit below, different carbon cost levels would unlock different actions across the aluminium sector.

Average LCOX in 2035 of existing and cheapest low-carbon technology, $/tonne product or $/MWh — brownfield retrofit



[1] Fossil boilers include coal, gas, and oil boilers.
[2] Fossil calciners include gas and oil calciners.
[3] Fossil power includes gas-powered and coal-powered plants.
[4] Units for carbon intensity for refining and smelting technologies are given in t CO_2e/t Al and for power technologies are given in t CO_2e/MWh.
[5] Carbon anode smelter LCOX does not include any refurbishment capital costs.

Source: MPP analysis

2.2.9 The aluminium sector has significant interactions with the rest of the energy system

The transition to a low-carbon aluminium sector will require significant resources from the rest of the energy system, particularly low-carbon electricity. An overview of these demands is shown in Exhibit 2.12, which provides the following insights:

- **Low-carbon electricity:** Although the total electricity demand stays relatively constant at 900–1,000 TWh until 2050, by 2035, almost all of this electricity demand needs to be met by low-carbon electricity sources.
- **Hydrogen** plays a small role in the aluminium system, mainly in calciners, with some role in digestion at refineries depending on the location and local hydrogen prices, relative to electricity prices.
- **Coal demand** will likely fall between today and 2050, as some smelters switch to grid electricity use and refineries decarbonise. If coal CCS is available (as in the 1.5°C scenario), demand could decrease by about 50% by 2050. On the other hand, if coal CCS is not deployed (as in the No CCS scenario), then coal demand would decrease by 95% by 2050.
- **CO_2 storage capacity:** The aluminium industry does not take up a significant portion of available CCS. It stores about a cumulative 8–12 Gt CO_2 from 2020 to 2050, which is less than 0.1% of the International Energy Agency's lower estimate of available carbon storage globally (8,000–55,000 Gt CO_2).

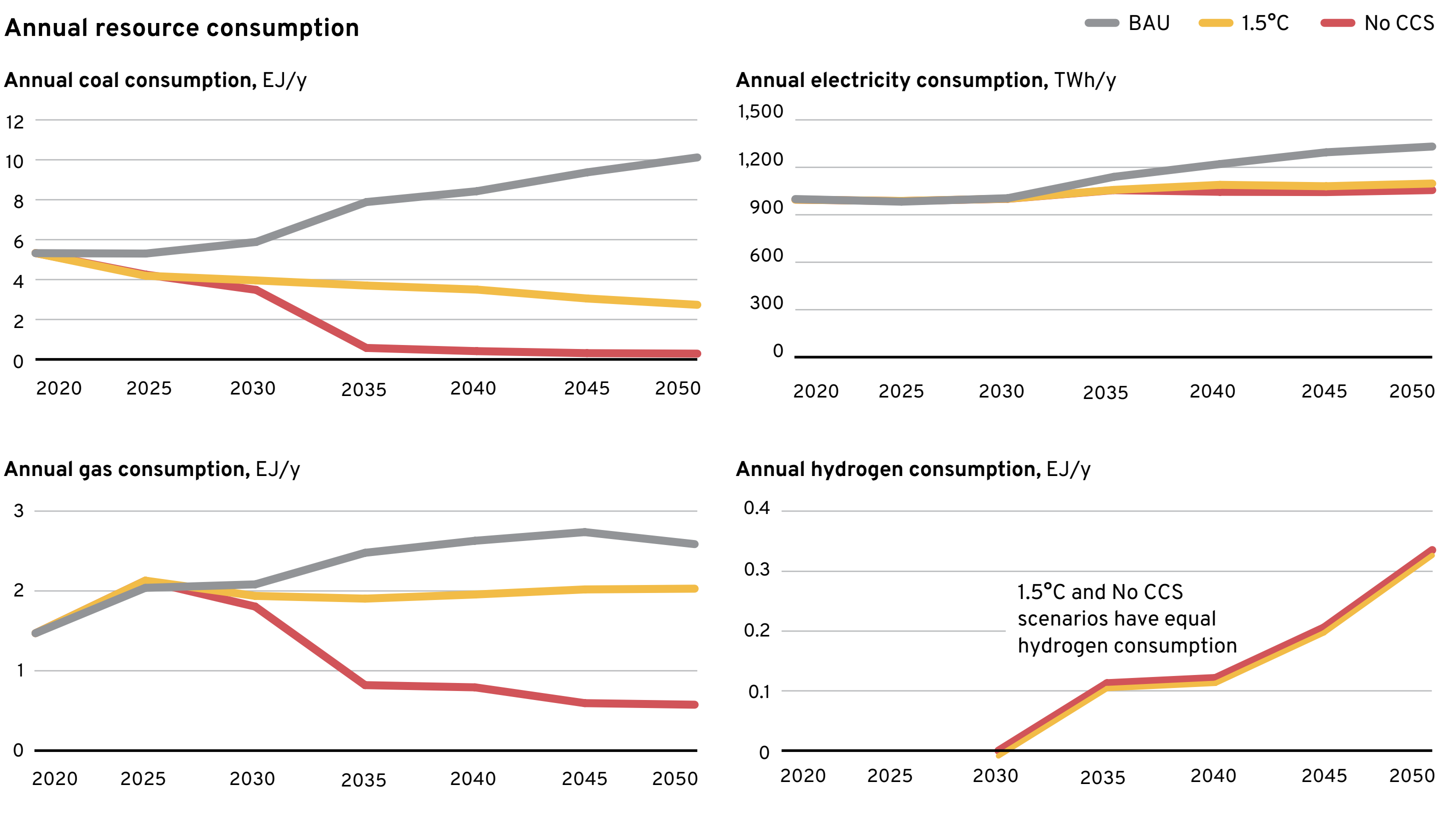
Interactions with the electricity system

Aluminium serves as a major consumer of baseload power, accounting for 4% of global power consumption in 2019. However, this is expected to decrease to 1% by 2050 in a net-zero world as other industries increase power demand because of electrification.

Given that aluminium is such a significant consumer of dependable power, it has a significant role to play in defining future low-carbon power systems. This is critical from an economic perspective, because grid supply is often the most

EXHIBIT 2.12

Resource consumption in the aluminium sector by scenario

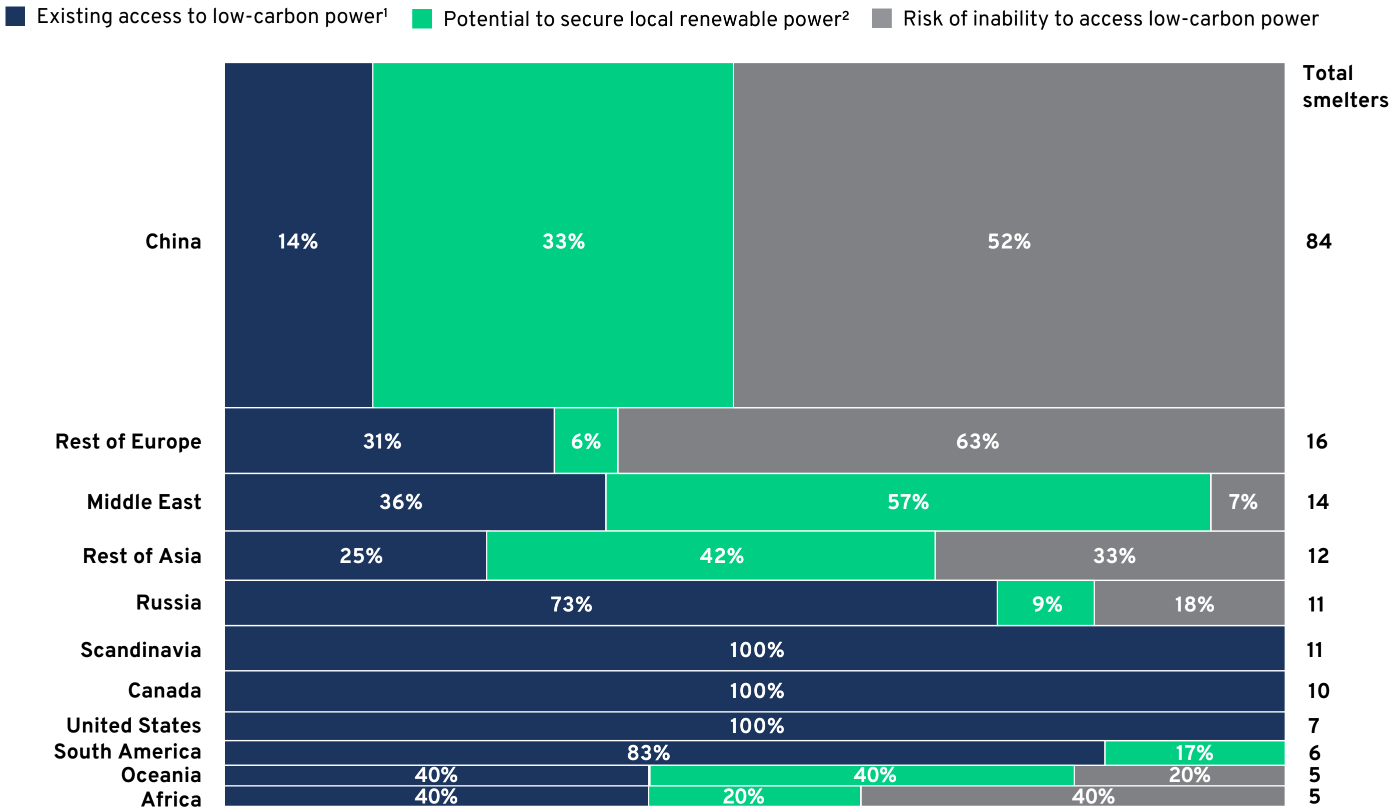


Source: Aluminium Sector Transition Strategy Model (2022)

EXHIBIT 2.13

Access to low-carbon power varies significantly by location, and some regions have particular challenges

Access to low-carbon power supply by smelter in 2020, % of regional smelters



[1] Includes captive hydropower, renewables, PPAs, and grids with carbon intensity currently less than 100 g CO_2/kWh.
[2] Defined by geolocational data for smelters with local capacity factors for solar PV or wind power greater than 20% or 30%, respectively.

Source: Aluminium Sector Transition Strategy Model (2022)

cost-effective of all the power options, but also from a swift decarbonisation perspective, because in order to achieve decarbonisation of power supply, smelters will need to start exploring low-carbon power supplies by 2025 (see Exhibit 2.13).

It is expected that about 70% of aluminium smelters will be able to source PPAs or low-carbon grid power to reduce their average emissions intensity while still benefitting from the dependability of a grid connection. A significant exception to this is China, where approximately 52% of smelters are unlikely to access local PPAs because they are not located in areas with sufficiently high wind or solar generation capacity factors. In the absence of an affordable low-carbon energy source, it is expected that these smelters may be shut down and relocated, or will have to retrofit their direct power generation facilities to include CCS, as demonstrated in the 1.5°C scenario (and in the alternative scenarios).

The aluminium industry can help drive the decarbonisation of the power system. As high-intensity off-takers, smelters can help secure renewables investment in riskier geographies with high solar and wind potential, as well as push to develop bilateral PPA markets. This would not only serve to drive towards a net-zero 2050 but also bring equality to regions in the Global South through access to technology and energy supplies.

Over the longer term, smelters can play a key role in being more flexible users of power to help alleviate the stress of balancing a decarbonised variable generation grid system. To date, there have been some successful demand-side response trials in Australia, such as the Tomago aluminium smelter, which is able to ramp potlines down by 50 MW (about 17% of power consumption) or shut down up to two potlines if it has more than an hour's notice. Ramping up this flexibility capability will be more critical as the world moves towards a decarbonised grid system that has a large share of variable renewable generation.

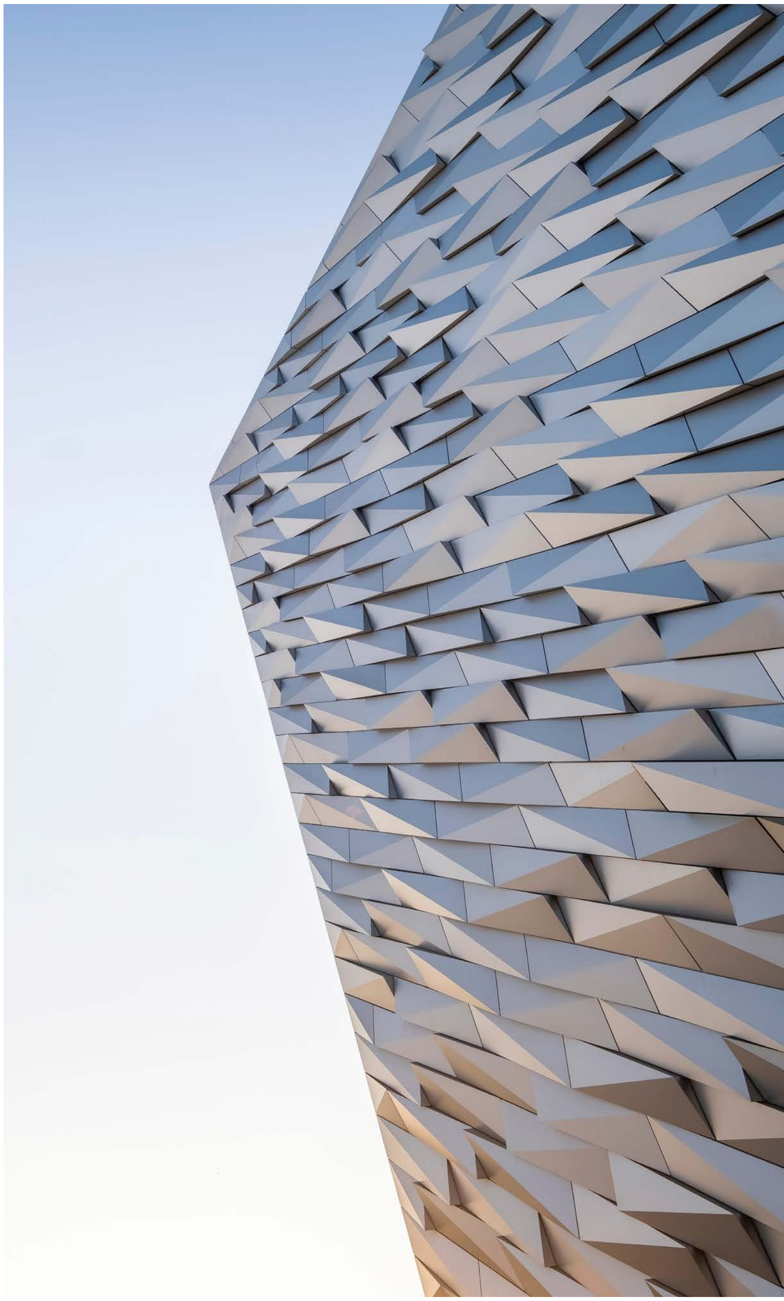
CONCLUSION: FROM STRATEGIC THINKING TO ACTION IN THIS DECADE

Aluminium can play a significant role in delivering net zero and staying within a 1.5°C carbon budget. However, it faces some key challenges that will require collaboration, not just among industry, policymakers, and finance providers, but also critically within the power sector and waste sector. This section highlights the milestones needed for the industry to be on track for a net-zero sector and the key actions these various communities need to deliver those milestones.

3.1 Key milestones until 2030 and 2035

The 2020s represent a critical decade for the decarbonisation of the aluminium sector, with four key milestones for the aluminium value chain to ensure that it can keep within the 1.5°C carbon budget (technical milestones outlined in Exhibit 3.1).

- **Transition to using low-carbon power for smelters**
    - Each smelter should have an investable plan in place for how it will source low-carbon power by the late 2020s, which identifies the enabling infrastructure needed to deliver the power and appropriate agreements with those infrastructure providers.
    - By 2035 all primary aluminium will need to be produced with low-carbon power (<100 g/kWh or grid-connected with a rapidly decarbonising grid).
- **Commercialise new technology for smelters and refineries by 2030**
    - Over a third of alumina should be produced using low-carbon steam production by 2030.
    - Low-carbon anodes must be commercially deployed at scale from 2030, with deployment at small scale by the mid- to late 2020s.



- Low-carbon calcination technology must be tested at scale by 2030, with a view to mass deployment from the mid-2030s.

- **Establish a market for low-carbon aluminium**
  - A clear route to market for low-carbon aluminium running at scale should be established by 2030 to give the right signals for a diverse set of production technologies for primary aluminium (due to greater variation in marginal costs for low-carbon technologies).
  - The market should include demand-side commitments and carbon costs, with some support from policymakers for emerging technologies.

- **Expand secondary production significantly and widely**
  - Secondary aluminium production should be increased from 33% (of total aluminium demand) in 2020 to 42% in 2030, facilitated by global collection rates improving from 70% to more than 80% by 2030.

EXHIBIT 3.1

Timeline for transition across the aluminium sector

		EARLY 2020s	LATE 2020s	EARLY 2030s	LATE 2030s
SMELTER TRANSITION	*Low-carbon power*	Plan for final investment decision	Power transition		
	Anodes	R&D	Small-scale deployment	Mass deployment	
REFINING TRANSITION	*Digester*	Small-scale deployment	Mass deployment		
	Calciner	R&D	Small-scale deployment	Mass deployment	
SECONDARY PRODUCTION	*Collection*	Improvements in collection rates (policy and sorting technology)			
	Capacity	Expansion of secondary production capacity			

Source: Aluminium Sector Transition Strategy Model (2022)

3.2 Policy, industry, and finance action to achieve 2030 milestones

Policymakers, industry leaders, and financial institutions have the power to enable the transition of global aluminium to net zero. Indeed, participation is necessary for the sector to successfully address five major challenges in this decade:

- Insufficient infrastructure, access to low-carbon power, and setup of merchant markets
- The slow commercialisation of critical technology
- Lack of a positive business case for low-carbon aluminium
- Lack of scrap for secondary production
- Fossil fuel subsidies preventing a level playing field

These key challenges are more difficult to address in the aluminium sector because of its linkages to other parts of the economy, including links to the power sector, the waste and recycling sector, and the CO_2 transportation and storage sectors. These interactions mean that overcoming any one of these challenges often entails cross-sector collaboration.

Although these challenges are significant, the solutions do not have to come from the aluminium industry alone. Critical action is required from the power sector (offering effective low-carbon power options), policymakers (helping to enable the positive business case and wider infrastructure development), and financial institutions (financing the transition and moving away from financing fossil fuel–based options) to help the whole sector transition effectively.

This action and planning must be led by producers in collaboration with customers, with support from policymakers, the power sector, and finance providers. It's also critical for action to begin immediately — although there are many actions required to deliver a low-carbon aluminium industry, many of these actions must be delivered in parallel, given the urgency of reducing emissions (Exhibit 3.2).

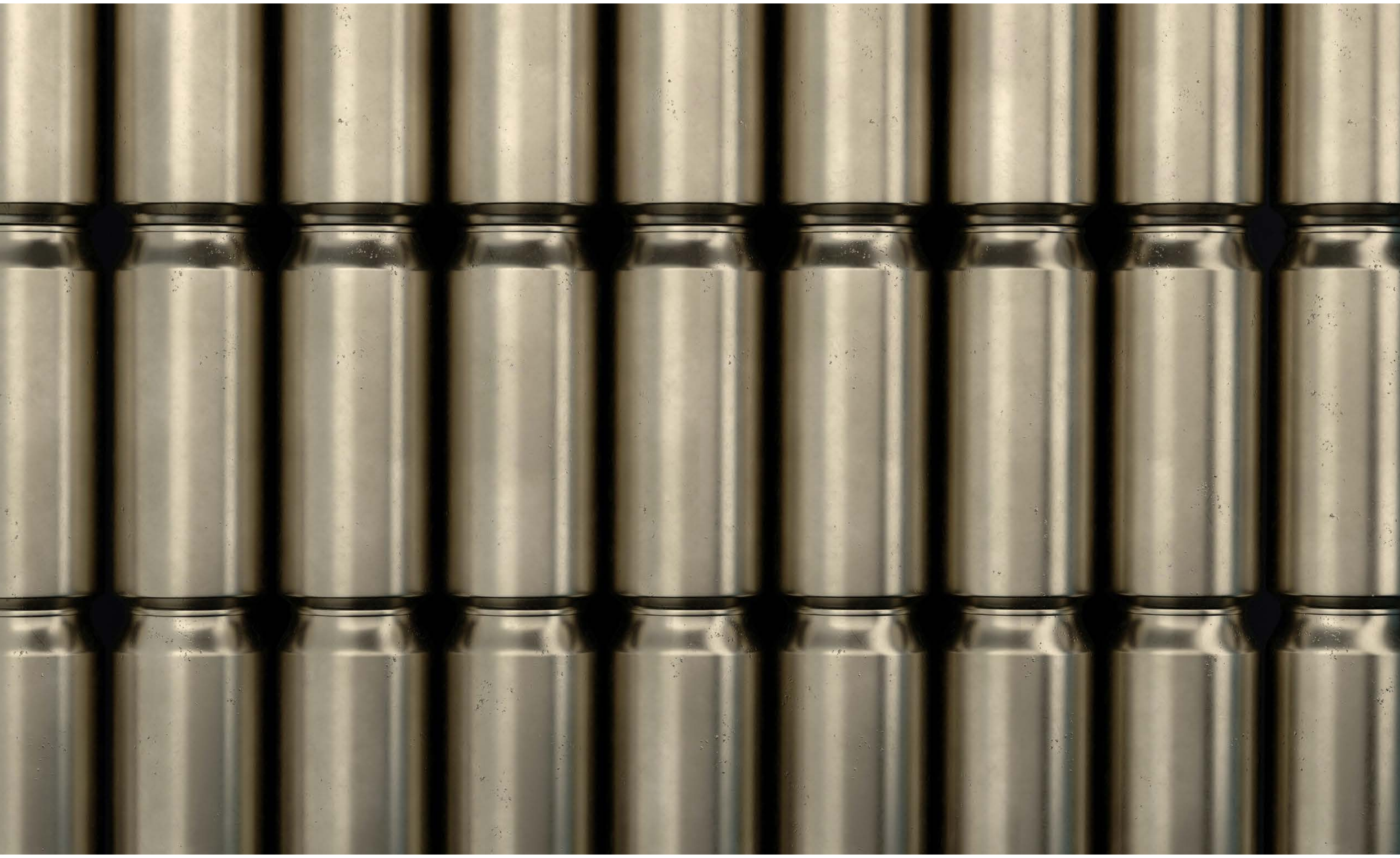


EXHIBIT 3.2

Example solutions to address barriers to decarbonisation in the aluminium sector

Problem	Problem statement	Potential solutions	Examples
Access to low-carbon power	Smelters do not have access to low-carbon power	Long-term planning for policy transition Shared infrastructure provision including low-carbon power networks, CCS networks, and hydrogen provision	EGA and GE Power decarbonisation roadmap
Pre-commer-cialisation of critical technology	Near-zero-emissions smelting and refining technology are not commercialised	R&D support Industry consortia to share risk and spread learning – consider embedding licensing in development model from day one	Elysis Project, with smelters and policymakers jointly funding new technology
Business case for low-carbon aluminium	Near-zero-emissions primary aluminium cannot be produced without a green premium	Carbon pricing Buying signals for low-carbon aluminium (from government and wider market) Climate-aligned finance standards pushing investment towards low-carbon projects Data standards, with clear and consistent data about emissions intensity of aluminium	First Movers Coalition Climate Aligned Finance project
Lack of scrap for secondary production	Not all scrap aluminium is easy for secondary producers to access	Increased collection rates Development of more product-to-product recycling to maximise recycling Further development of purification technology to maximise aluminium recovery	Deposit schemes for specific products
Level playing field	Fossil fuel use can receive explicit and implicit support, which makes it more challenging to deliver low-carbon projects	Business support and energy subsidies designed not to favour fossil fuel investments and use	

Source: MPP analysis

3.2.1 Key policy actions in this decade

Policy action is critical to unlocking low-carbon aluminium production. This action can take several forms, such as providing support for making the business case for low-carbon aluminium investable; ensuring networks such as CCS, low-carbon electricity, and hydrogen are set up in time and can be accessed in a stable regulatory framework; and enabling greater levels of aluminium recycling.

Policymakers' role in the business case for low-carbon aluminium

Policymakers can play a key role in ensuring that the business case for low-carbon aluminium incentivises businesses to invest in low-carbon production. The levelised cost of low-carbon aluminium is greater than the fossil fuel status quo, so policymakers can consider a number of levers to close the financing gap:

- **Adding a carbon cost** can help significantly in closing the cost gap between fossil fuel–based aluminium production and low-carbon production. This signal needs to be sufficiently strong, global, and predictable if it is to unlock the long-term investments required for the aluminium sector. The EU Emissions Trading System, with its proposed Carbon Border Adjustment Mechanism, is an example of such a scheme and illustrates the need for careful design in thinking about how carbon pricing operates for globally competitive products.

- **Developing demand signals from buyers** is also critical. Government can be effective here through purchasing decisions. Public and private procurement can help in delivering demand signals to producers to invest in low-carbon production methods. The recently launched First Movers Coalition[26] is an example of how demand signals can be used to potentially drive action across the value chain.

- **Providing direct support** can also play a critical role, particularly for pilot and early deployment of new technologies, as other incentives such as carbon pricing and demand-side mechanisms mature and become investable signals. However, this support cannot just be capital support; to be effective, it needs to cover additional operating costs. Support can be provided through research and development, as with the support the Canadian government and the Quebec government have given through Investissement Quebec to the Elysis project[27] or the Mechanical Vapour Recompression for Low-Carbon Alumina Refining project supported by the Australian Renewable Energy Agency.[28]

These three levers are unlikely to be effective on their own. For example, in the long term, continuous direct support will not be sustainable or fiscally viable, carbon costs would likely not cover the whole gap in costs, and demand levers are too early in development to serve as investable signals. Therefore, policymakers should employ a mixed approach, depending on their local conditions.

Policy action can take several forms, such as providing support for making the business case for low-carbon aluminium investable; ensuring networks such as CCS, low-carbon electricity, and hydrogen are set up in time and can be accessed in a stable regulatory framework; and enabling greater levels of aluminium recycling.

Policymakers' role in levelling the playing field

Policymakers should also be ensuring that their support for industries does not implicitly support fossil fuel use and should instead allow low-carbon aluminium production to compete on a level playing field.

Policymakers' role in secondary production

Policymakers can also play a critical part in encouraging recycling and reuse of aluminium to enable the secondary market to grow significantly. This can come in the form of incentives, mandates, or other policy tools, but the objective should be to ensure that once a product reaches the end of its life, the aluminium can be accessed and recycled. For example, this would include looking at how to support more product-to-product loops to maximise reuse through deposit return schemes.

Policymakers' role in infrastructure delivery

Policymakers can take a variety of actions in delivering low-carbon power and enabling infrastructure to unlock decarbonisation of the aluminium sector:

- **Policy certainty:** Delivering solutions such as low-carbon power, CCS, and hydrogen requires clear, transparent, and stable regulatory systems for complex energy and climate systems. With clear frameworks for these networks, businesses can confidently develop plans for investment.
- **Market design:** Aluminium smelters require substantial amounts of constant power — in all systems, this means that some firming power will be required in order to deliver constant power for smelter needs. This new low-carbon power market, with low-marginal-cost variable supply as well as higher marginal cost firming supply, will pose a challenge for industries such as aluminium. Policymakers and regulatory designers will have to carefully consider how new market designs can balance the needs of all users.
- **Support of rapid deployment of low-carbon technology:** Effective policy supporting the rapid deployment of low-carbon generation is key for the aluminium sector, from permitting to market design and planning to deal with variability.

3.2.2 Key industry actions in this decade

Propelling a sector towards a 1.5°C carbon budget will require significant actions from the aluminium industry, but also from other associated industries. Each of these industries will be required to make changes to deliver a sector that is low carbon (Exhibit 3.3).

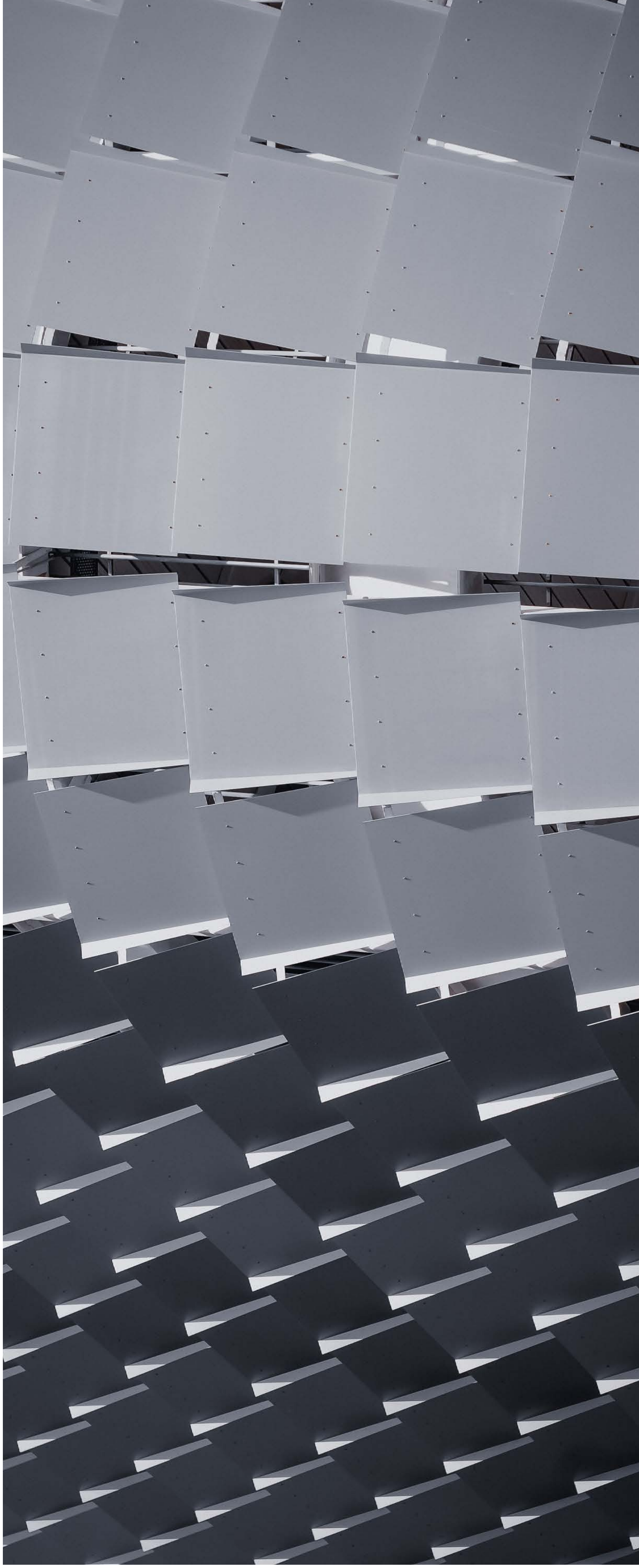


EXHIBIT 3.3

Actions in this decade by part of the aluminium value chain

Industry player		Key actions to 2030	Examples
Primary producers	Smelters	Develop plans for the decarbonisation of their own power requirements, identifying the best solution for their local situation by the middle of the 2020s Deliver the low-carbon-power projects or contracts for PPAs, with all projects coming online by 2035 Increase research and development for inert anode or CCS for carbon anodes to commercialise by 2030, with a commitment to equitable access to critical technologies Develop low-carbon alumina offtake agreements with refineries	EGA and GE Power decarbonisation roadmap R&D: Elysis Project, led by Alcoa and Rio Tinto
Primary producers	Refineries	Develop plans to develop and deploy potentially cost-effective technology where possible, such as MVR and electric boilers Work collaboratively with equipment manufacturers to bring low-carbon calciners and new boiler technology to market, commercialising by 2030	Ma'aden solar facility R&D: Alcoa and ARENA MVR development
Primary producers	Equipment manufacturers	Work with refineries to bring low-carbon calciners and new boiler technology to market, commercialising by 2030	
Power and infrastructure developers		Work with aluminium and alumina producers to find power solutions that meet their power generation needs, including transmission and distribution providers and CCS developers	Hydro and Macquarie wind and solar project for Alunorte
Secondary producers and recycling industry		Maximise collection rates in partnership with policymakers and other parts of the aluminium value chain Develop new products and capabilities to maximise the use of scrap; for example, new purification technology or product-to-product recycling Build capacity to process scrap for new products	New Novelis recycling plant in Bay Minette
Aluminium users		Develop low-carbon aluminium offtake agreements between users and producers Design products to maximise the use of secondary aluminium and find efficiencies in design and use where possible	First Movers Coalition including Ford, Volvo, Apple, Ball, Novelis, and Trafigura

Source: Emirates Global Aluminium; GE; Elysis; Ma'aden; ARENA; Hydro; Novelis; First Movers Coalition

These actions need to combine to deliver new investments in refineries, smelters, and additional secondary production. These actions must be coordinated and led by producers so they can combine their own planning with clear articulations of what is needed from power and infrastructure providers. Box 6 outlines some of the coordination challenges for grid integration, and illustrates how different players within the energy system must work together to deliver a low-carbon sector.

BOX 6

Integrating aluminium smelters into a low-carbon grid

Smelters currently require constant power to smelt aluminium. For many smelters today, this power is delivered through captive coal plants, hydropower assets, or grid connections.

In a low-carbon world, power will have a significant variable component. It will be driven by low-marginal-cost wind and solar, with firming power supplied through, for example, batteries, hydrogen, or other storage assets, as well as demand-side response technologies and processes.

This change poses a significant challenge for the integration of aluminium into the grid, because today's smelters would have limited options to mitigate either price or carbon intensity spikes.

The solution will require a combination of effort from:

- **Electricity market design development (policymakers, power developers, and smelters):** In a variable system, market design for pricing is critical to ensure that the right incentives are available for all players in the energy system. This can support the business case for delivering these assets and provide the business case for developing demand-side solutions.
- **Research and development (power developers, smelters, and equipment manufacturers):** Further smelter research and development is likely to be required to unlock potential demand-side response, as well as further development of firming power options.
- **On-site asset development (smelters and power developers):** It may be cost-effective for smelters to design and develop their own systems to meet their needs, for example, on-site batteries or other firming assets.

The aluminium industry will not be the only sector to have these integration challenges. Many other electro-intensive industries, emerging hydrogen demand, and other parts of the wider energy system will face similar system integration challenges. This has two significant implications for the aluminium industry. First, learning from others is possible. Second, solutions will be optimised for the whole energy system, rather than specifically for the aluminium sector; aluminium's share of global power demand falling from 4% in 2020 to 1% in 2050 will reduce its market power, and flexible demand will be more highly sought after.

3.2.3 Key finance actions in this decade

Finance provision for the aluminium sector will play a key role in helping decarbonise the aluminium sector. Delivering the transition outlined in the aluminium Sector Transition Strategy will require a significant amount of capital investment in new power assets as well as new and retrofitted smelters and refineries. In addition, finance provision for fossil fuel–based assets will have to decrease over this decade, and no new fossil-based finance should be provided by 2030.

This finance provision can build on the success achieved in financing low-carbon power generation over the past decade, given the significant proportion of investment in the power provision for smelters.

Key milestones for the finance community will be:

- **Mobilising large amounts of capital for low-carbon power** for aluminium by the mid- to late 2020s, enabling all primary producers to have access to finance should they require it to decarbonise their power supply by the early 2030s.
- **Mobilising smaller amounts of capital for the replacement of current fossil fuel boilers** with low-carbon alternatives, throughout the 2020s.

- **Developing finance propositions and blueprints for innovative technologies** to support the wide-scale rollout of critical technologies post-2030.

- **No funding of new fossil fuel–based projects at refineries and smelters by 2030,** when the complete set of decarbonisation technologies needed for a low-carbon sector should be available. In addition, finance for fossil fuel–based power should be phased out by the mid-2020s.

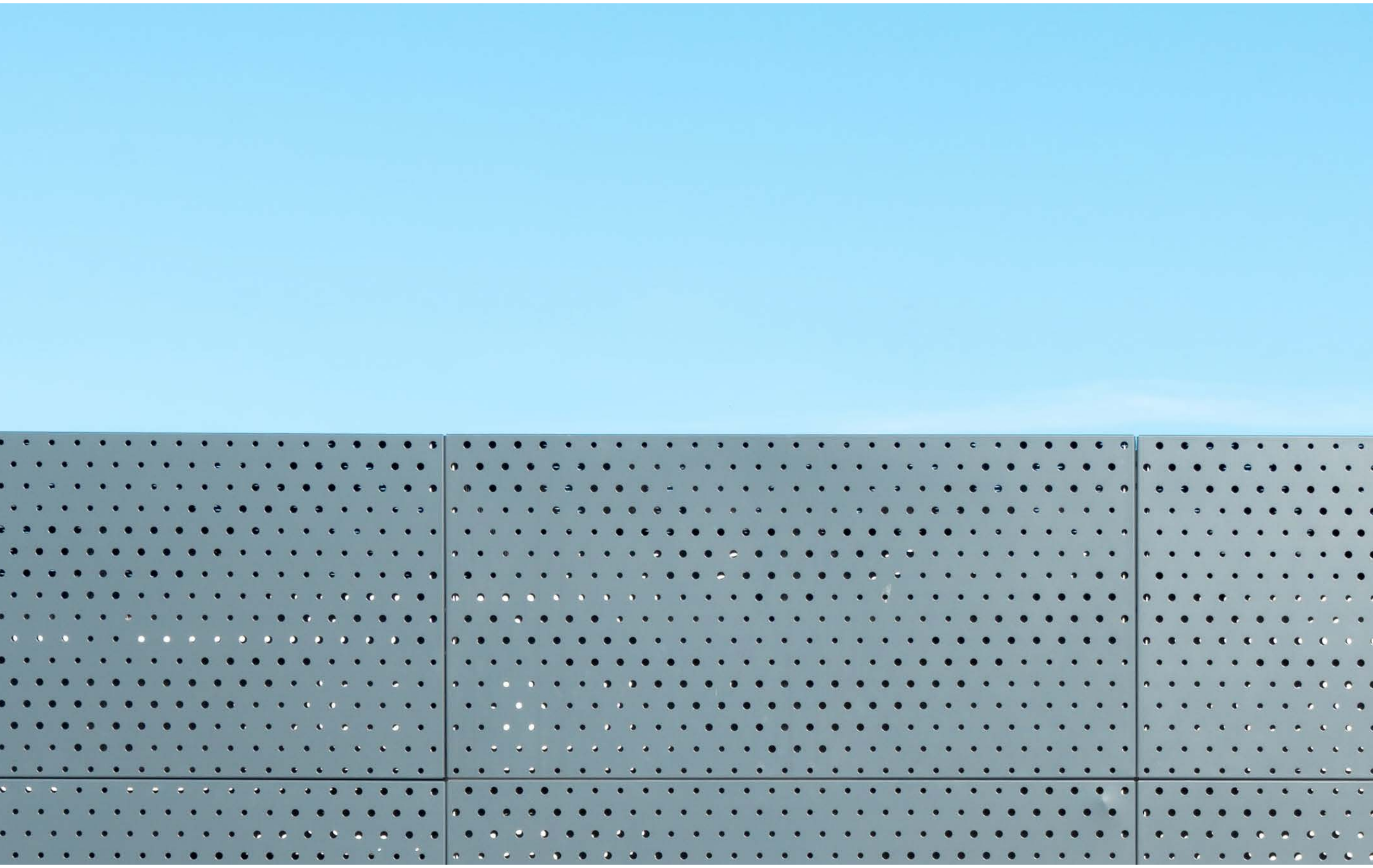
- **Early adaptation of commodity trading systems** in the mid-2020s to include transparent low-carbon standards for metals, such as aluminium, to support greater volumes of green premium purchases.

In order to deliver these milestones, the finance community needs to take several key actions:

- **Climate-aligned investment:** Capital providers (banks, institutional investors, public-sector banks) invest in ambitious companies and infrastructure projects. Climate-aligned investment principles similar to the Poseidon Principles[29] in the shipping sector can create clarity and transparency as to which companies and projects are investable and which are not, in line with net-zero and 1.5°C targets.

- **Cross-sector investment collaboration:** Those developing investments for low-carbon aluminium production will have to learn from how such investments have been developed in the power sector and other materials sectors. In addition, because of the overlap with the power sector, investment coordination will be key to achieving decarbonisation goals. Much of the early decarbonisation activity for the sector is reliant on power decarbonisation, where there is a long track record of low-carbon investment.

- **Coordination efforts:** Efforts made by the aluminium value chain and policymakers to close the cost gap between low-carbon aluminium and fossil fuel–based aluminium will rely on a mix of effort and interventions, for example, buying signals and carbon pricing, which have different combinations of risks and certainties. The finance community can provide a key coordination role in ensuring this combination is bankable for new investments.



THE WAY FORWARD

The aluminium industry can play a critical role in limiting warming to 1.5°C, and now is the time to deliver on this ambition. Given the rapidly falling costs of low-carbon power and commitments from all countries to deliver low-carbon power systems, aluminium producers have a significant opportunity to make substantial early strides in meeting this ambition. New technologies provide the opportunity to decarbonise beyond the power sector and reach a fully net-zero-consistent position. This opportunity is reflected in the commitment producers are making in terms of corporate targets, but also in terms of research, development, and deployment of low-carbon projects.

Transforming these ambitions into targets, and then into whole-sector action, will require the entire value chain to push to this goal, whether that be buyers, secondary producers, primary producers, or power systems. But it is vital to start immediately. The first critical step for all primary producers is to plan the best way to reach a fully decarbonised power supply by 2035. Alongside this, the full value chain must commit to delivering the new technology for refineries and anodes and start the rollout process in the coming decade. Aluminium customers, the finance community, and policymakers also play critical roles in making these plans investable and deliverable.

There is also significant work to do to further illuminate the detailed transition and costs for recycling and downstream parts of the value chain and how they can be implemented in practice.

Finance initiatives such as the RMI Center for Climate-Aligned Finance, demand programmes through the First Movers Coalition, and standards guidance through the Aluminium Stewardship Initiative offer opportunities to give the sector the tools needed to make significant investments and progress towards a 1.5°C pathway.

There are still significant challenges, some financial — such as the cost gap between fossil fuel–based aluminium and low-carbon aluminium — and some technical, such as integrating aluminium producers into a low-carbon power grid.

The Aluminium for Climate (AFC) initiative and the wider aluminium community will contribute towards mobilising the value chain to enhance the environment for investment. AFC stands ready to support financial institutions in designing interventions that will help put the global aluminium sector, and its wider ecosystem, on a path to reach net-zero emissions. Together, these partners can propel this committed community of stakeholders to act on the essential decisions needed to deliver a sustainable future for this industry and the planet.

GLOSSARY

AFC	Aluminium for Climate
BAU	Business as Usual
CCS	carbon capture and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CST	concentrated solar thermal
EJ	exajoule
ETC	Energy Transitions Commission
GDP	gross domestic product
GHG	greenhouse gas (expressed in CO_2e)
Gt	gigatonne
IAI	International Aluminium Institute
LCOE	levelised cost of electricity
LCOX	levelised cost of production (of product 'X')
MPP	Mission Possible Partnership
Mt	million tonnes
MVR	mechanical vapour recompression
MWh	megawatt-hour
PPA	power purchase agreement
R&D	research and development
SMR	small modular reactor (nuclear)
STS	sector transition strategy
TCO	total cost of ownership
TRL	technology readiness level
TWh	terawatt-hour

ENDNOTES

1 Associacao Brasileira Do Aluminio, "Aluminium Beverage Can Recycling Index 2009-2021", accessed June 2022, **http://abal.org.br/en/statistical-information/aluminum-cans-2009-2021/**.

2 International Aluminium Institute (IAI), "Material Flow Model", accessed January 2022, **https://alucycle.international-aluminium.org/**.

3 World Economic Forum and Accenture, "Aluminium for Climate: Exploring Pathways to Decarbonize the Aluminium Industry", **https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf**.

4 The Aluminum Association, "U.S. Aluminum's Economic Impact", accessed June 2022, **https://www.aluminum.org/economy#:~:text=Today%2C%20the%20U.S.%20aluminum%20industry,%24103%20billion%20in%20economic%20output**.

5 IAI, "Employment in the Global Aluminium Industry", accessed April 2022, **https://international-aluminium.org/wp-content/uploads/2021/06/Employment-in-Aluminium-Industry-Report-2021.pdf**.

6 IAI, "Material Flow Model", accessed January 2022, **https://alucycle.international-aluminium.org/**.

7 Ibid.

8 Our World in Data, "Total Greenhouse Gas Emissions", accessed June 2022, **https://ourworldindata.org/explorers/co2?facet=none&country=CHN~USA~IND~GBR~OWID_WRL&Gas=All+GHGs+%28CO%E2%82%82eq%29&Accounting=Production-based&Fuel=Total&Count=Per+country**; IAI, "Greenhouse Gas Emissions – Aluminium Sector", accessed January 2022, **https://international-aluminium.org/statistics/greenhouse-gas-emissions aluminium-sector/**.

9 IAI, "Material Flow Model", accessed January 2022, **https://alucycle.international-aluminium.org/**.

10 International Aluminium Institute (IAI), "Greenhouse Gas Emissions – Primary Aluminium", accessed January 2022, **https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/**; Climate Action, "Carbon Footprint of Recycled Aluminium", accessed April 2022, **https://www.climateaction.org/news/carbon-footprint-of-recycled-aluminium**.

11 IAI, "Greenhouse Gas Emissions – Primary Aluminium", accessed January 2022, **https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/**.

12 IAI, "Metallurgical Alumina Refining Energy Intensity", accessed January 2022, **https://international-aluminium.org/statistics/metallurgical-alumina-refining-energy-intensity/**.

13 IAI, "Primary Aluminium Smelting Power Consumption", accessed January 2022, **https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/**.

14 IAI, "Material Flow Model", accessed January 2022, **https://alucycle.international-aluminium.org/**.

15 Ibid.

16 Ibid.

17 Ibid.

18 R. V. Heusden et al., "The Answer to the Aluminium Industry's Emissions Issue? Aluminium's Infinite Recyclability", accessed June 2022, **https://www.weforum.org/agenda/2021/12/aluminium-emissions-recycling-circular-economy/**.

19 Material Economics, *The Circular Economy – a Powerful Force for Climate Mitigation*, 2018, **https://materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1**.

20 International Energy Agency (IEA), *IEA Energy Technology Perspectives 2020: Special Report on Carbon Capture Utilisation and Storage CCS in Clean Energy Transition*, 2020, **https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCS_in_clean_energy_transitions.pdf**.

21 IAI, "Primary Aluminium Smelting Power Consumption", accessed January 2022, **https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/**.

22 Australian Renewable Energy Agency (ARENA), "Arena Insights Spotlight: Mechanical Vapour Recompression for Low-Carbon Alumina Refining," accessed April 2022, **https://arena.gov.au/assets/2021/10/insights-mechanical-vapour-recompression-for-low-carbon-alumina-refining.pdf**.

23 R. Bader et al., *Feasibility Study of CST Technologies for the Low Temperature Requirements of the Bayer Alumina Process*, accessed April 2022, **https://itpthermal.files.wordpress.com/2020/12/itp-alumina-report-public-30112020.pdf**.

24 O. Lassagne et al., "Techno-economic Study of CO_2 Capture for Aluminium Primary Production for Different Electrolytic Cell Ventilation Rates", *Chemical Engineering Journal* 230, 338–350 (2013).

25 Estimate from IAI, "Material Flow Model", accessed January 2022, **https://alucycle.international-aluminium.org/**.

26 First Movers Coalition, accessed June 2022, **https://www.weforum.org/first-movers-coalition**.

27 Elysis, accessed June 2022, **https://elysis.com/en**.

28 ARENA, "Arena Insights Spotlight: Mechanical Vapour Recompression for Low-Carbon Alumina Refining", accessed April 2022, **https://arena.gov.au/assets/2021/10/insights-mechanical-vapour-recompression-for-low-carbon-alumina-refining.pdf**.

29 Poseidon Principles, accessed June 2022, **https://www.poseidonprinciples.org/finance/#home**.

MISSION POSSIBLE PARTNERSHIP

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.