

CLOSING THE GAP FOR ALUMINIUM EMISSIONS: TECHNOLOGIES TO ACCELERATE DEEP DECARBONIZATION OF DIRECT EMISSIONS

COMMUNITY PAPER

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EXECUTIVE SUMMARY

The aluminium sector must accelerate the scaling of decarbonization technologies to address direct emissions.

The aluminium industry is facing increasing pressure to decarbonize, underlining the need for technologies that will enable the industry to reach net zero by 2050. While indirect emissions due to electricity consumption represent the greatest opportunity to reduce its carbon footprint (~60% of sectoral emissions), the industry also needs to consider how to address its direct emissions (~30–35%).

There are two major sources of direct emissions in the aluminium sector: the consumption of carbon anodes during aluminium smelting and the generation of thermal energy for high-temperature processes. Unlike renewable electricity, which can be used to address indirect emissions, there is no ready solution to address direct emissions. Several technologies are available, though each faces its own challenges to achieve scale. This report explores the most promising technologies to address direct emissions in the aluminium industry, taking into consideration technology readiness level (TRL), cost, challenges and potential impact.

Inert anodes represent the best opportunity to mitigate carbon emissions from the smelting process; however, they are not yet commercially available. Carbon capture, utilization and storage (CCUS) could potentially be applied at sites close to geological storage reservoirs or other industrial sites where transportation and storage infrastructure can be shared, but it brings its own technical and economic challenges.

Green hydrogen presents the best opportunity to feed high-temperature processes at this time. While currently cost-prohibitive, hydrogen is expected to become financially

viable in the next decade. In the mid-term, CCUS could be a viable method of mitigating emissions for young assets with access to cheap fossil fuels.





Engineering improvements to existing processes can also provide cost savings and reduce emissions, although they cannot forge the way to net zero alone. While not covered in this report, additional efforts to improve recycling and sorting can reduce the overall demand for primary aluminium and reduce sector-wide emissions.

A favourable regulatory and investment environment will be integral to driving the development and scaling of these technologies. This includes a range of incentives to invest, such as the introduction of a carbon price, the availability of public and private funding mechanisms or government spending to build the required infrastructure to scale these technologies.

Decarbonization will take a coordinated effort across local, national and international governments, multilateral organizations, industry players and researchers/academia. The high-impact actions aluminium companies can take to move the needle on direct emissions include: collaborative research, design and development (RD&D), multilateral engagement and integration with/formation of industrial clusters.

As the recent 26th United Nations Climate Change Conference of the Parties (COP26) meeting in Glasgow increased attention on the role of heavy industries in tackling climate change, the time has never been better for the aluminium sector to take collaborative action to decarbonize.

Table 1 – Frontier technologies to address direct emissions in the aluminium value chain^{1,2}

Frontier technology	Value chain impact					Conditions where technology works best	Potential impact on direct emissions
	Mine	Refinery	Smelter	Casting	Recycling		
Inert anodes			✓			<ul style="list-style-type: none"> - Greenfield assets - Existing sites where electrolytic cells are ready for replacement 	
CCUS		✓	✓	✓	✓	<ul style="list-style-type: none"> - Areas with access to cheap fossil fuels and limited recourse for renewable alternatives - Proximity to CO₂ geological storage capacity - Proximity to other industrial sites to form a hub 	
Hydrogen	✓	✓		✓	✓	<ul style="list-style-type: none"> - Areas with access to affordable renewable electricity - Proximity to other industrial sites to form a hub 	
Mechanical vapour recompression		✓				<ul style="list-style-type: none"> - Greenfield assets - Areas with access to affordable renewable electricity 	

PART 1

INTRODUCTION

Climate action is a business imperative, and the aluminium sector must respond.

1.1 Why now?

The International Panel on Climate Change (IPCC) has projected that global warming will exceed 1.5°C this century without deep reductions in greenhouse gas (GHG) emissions, resulting in extreme weather events, sea level rise, acidification of the ocean and more.³ To mitigate these impacts, there is an urgent need for action.

The aluminium sector emits 1.1 billion tonnes of GHGs annually, around 2% of all global anthropogenic emissions.⁴ The International Aluminium Institute (IAI) predicts that if no action is taken, GHG emissions will reach 1.6 Gt CO₂e annually by 2050.⁵

Climate action is no longer optional; with recent discussions on the EU Carbon Border Adjustment Mechanism and commitments by investors through the Glasgow Financial Alliance for Net Zero, it is a business imperative.

Technologies that will enable the industry to mitigate direct emissions are already being developed; the greatest challenge now is scaling and deploying these technologies in a commercial operating environment. Collaborative action across the aluminium sector, other heavy industries, policy-makers and investors is critical to achieve industry-wide decarbonization.

1.2 Aluminium industry emissions

More than 60% of the emissions associated with aluminium production are indirect emissions attributed to electricity consumption.⁶ The greatest obstacle facing many aluminium players is how to transition from fossil fuel-based electricity to fossil-free electricity. Despite there being a significant disparity in starting points for aluminium players, renewables are now cost-competitive with fossil fuels in most parts of the world, even on an unsubsidized levelized-cost basis.⁷

Unlike renewable electricity, there is no ready solution to address direct emissions that arise directly from aluminium processing. Every pathway faces challenges to achieving scalable, affordable technology. The Aluminium for Climate initiative aims to bring aluminium players together to address this “final gap” for the industry to decarbonize.

This initiative was established in 2019 under the Mission Possible Partnership, a coalition committed to reducing heavy-industry GHG emissions driven by – among others – the World Economic Forum and the Energy Transitions Commission.⁸ The aim of the initiative is to support the sector’s collective efforts to address its major challenges, including: 1) accelerating the transition to renewable power; and 2) scaling technologies to address direct emissions.

This report explores the current landscape of decarbonization technologies with the potential to address direct emissions, their possible impact on the aluminium sector and how aluminium players can act now.



PART 2

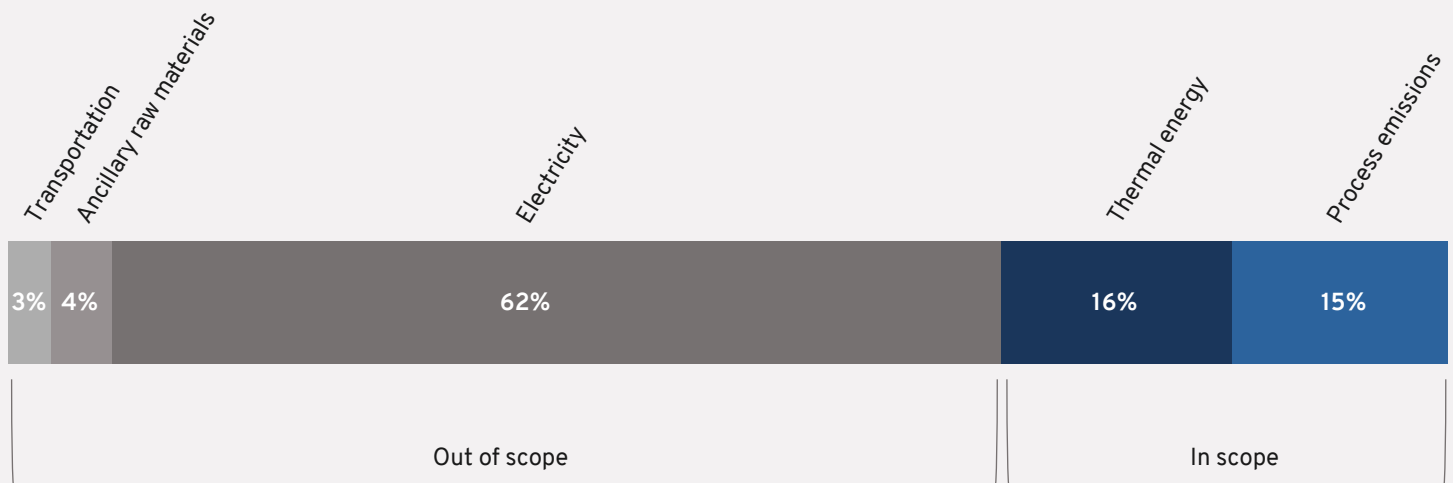
DECARBONIZATION TECHNOLOGIES

Addressing the aluminium sector's direct emissions requires the development and scaling of frontier technologies.

The aluminium industry has two primary sources of direct emissions: 1) the consumption of carbon anodes; and 2) the generation of thermal energy to produce industrial heat and steam.

Figure 1 – Emissions sources in the aluminium sector⁹

Around 30% of aluminium sector emissions are direct and will be addressed in this report.







A broad range of technologies are available that will decrease the carbon footprint of the aluminium industry – it will take a combination of these technologies to tackle direct emissions. This report focuses on carbon mitigation technologies to address direct emissions from primary aluminium production; removal or neutralization technologies (e.g. direct air capture) are not

in scope. The technologies explored in this report include: inert anodes; carbon capture, utilization and storage (CCUS); hydrogen; and mechanical vapour recompression. While not covered in this report, improving aluminium recycling and sorting will reduce the overall demand for primary material and sector-wide emissions.



Table 2 – A summary of decarbonization technologies to address direct emissions in the aluminium sector

There is a broad toolkit of potential decarbonization technologies that can be used to reduce direct emissions.

Emission sources	Process emissions		Thermal energy	
Potential technologies	Inert anodes	CCUS	Hydrogen	Mechanical vapour recompression
Technology readiness level in aluminium industry	4-5	3-4	1-2	5
Potential impact on sectoral direct emissions				
Cost	\$\$	\$\$\$	\$\$\$	\$\$
Benefits	<ul style="list-style-type: none"> - Best solution to address direct emissions from carbon anode consumption 	<ul style="list-style-type: none"> - Widely applicable to hard-to-abate emissions across many sectors - Ideal in areas with access to cheap fossil fuels 	<ul style="list-style-type: none"> - Widely applicable to hard-to-abate emissions across many sectors - Ideal in areas with access to cheap fossil fuels 	<ul style="list-style-type: none"> - Associated with energy and cost savings - Potential to decrease carbon footprint of sites that are not economical to decarbonize with other methods
Challenges	<ul style="list-style-type: none"> - Not yet commercially available 	<ul style="list-style-type: none"> - Highly expensive for gas streams with low CO₂ concentration - Not economically attractive without a carbon price or incentive 	<ul style="list-style-type: none"> - Green hydrogen is not yet cost-competitive - Lack of widespread infrastructure 	<ul style="list-style-type: none"> - Requires high levels of renewable electricity

2.1 Inert anodes

Inert anode basics

Inert anodes are an alternative to the carbon anodes that are consumed in electrolysis during aluminium smelting, the most carbon-intensive step in aluminium creation. More than 400 kg of carbon anode is consumed per tonne of aluminium, resulting in the formation of more carbon dioxide than aluminium (around 1,500 kg CO₂/tonne of aluminium).^{10,11} Inert anodes have little to no direct GHG emissions.

Currently, most research is focused on developing the correct anode material. Materials such as ceramics, metal alloys and cermet are all being explored as potential candidates.¹² Several companies, including Rio Tinto, Alcoa, RUSAL and Arctus Aluminium, are actively developing inert anode technology.

Inert anode benefits

Inert anodes are the best option to reduce direct emissions associated with carbon anode consumption – around 10-15% of sectoral emissions – assuming the use of renewable energy.

Several aluminium players are actively pursuing research and development of inert anodes; however, due to the competitive environment and proprietary nature of the technology, it is difficult to evaluate the expected benefits beyond carbon reduction.

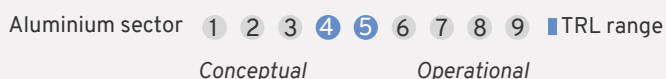
Technology readiness level (TRL)

Technology readiness levels¹³ are a way of indicating the maturity of technology based on a scale of 1-9, with 1 being conceptual and 9 operationally proven.

Inert anode technology has been a key focus of research by the aluminium sector for decades. Recent developments across the industry to pilot inert anodes in an industrial setting mark a turning point. While the technology is not yet operationally available, it has been demonstrated at more than one location at an industrial scale with an estimated TRL of 4-5.

Figure 2 – Technology readiness level of inert anodes

Inert anodes are still in development and not yet commercially available.



ELYSIS has announced that its inert anodes may become commercially available as soon as 2024.¹⁴ RUSAL has conducted an industrial pilot to produce a batch of low-carbon aluminium, but a larger-scale roll-out is not anticipated until 2030.¹⁵ Arctus Aluminium believes it will have a commercial-sized cell in operation in 2025 and will sell its technology, starting in 2030.¹⁶

Current and projected cost of inert anodes

The current and projected costs of inert anodes are unknown. The existing technology is proprietary, making it difficult to estimate the costs of anodes when they become commercially available, or how much retrofit will be required to existing facilities. To be competitive with carbon anodes, inert anodes will need to cost around \$110–\$120 per tonne of aluminium produced.¹⁷

Geographical or regional limitations

At this time, there are no known geographical or regional variables that would affect the ability to use inert anodes. However, there may be supply challenges depending on the materials needed to produce the anodes. The restriction of the supply of certain materials, such as ceramics, could pose a challenge. Due to the potential high energy needs to run inert anode electrolytic cells, the capacity for this technology to be truly carbon-free is dependent on the regional availability of affordable renewable power.

Challenges or barriers to industrial use

The path to decarbonization will be affected by the speed at which the broader aluminium industry can adopt inert anode technology. Retrofit of existing facilities may make financial sense only if the process elements (e.g. electrolytic cells) already need replacement, or if the regulatory environment makes the cost of retrofit preferable to creating a high-carbon product (e.g. through a carbon tax).¹⁸ Young aluminium smelters may need incentives or subsidies to make retrofitting financially viable.

In addition, the operational requirements of inert anodes are still unknown. Some research suggests that the use of inert anodes results in higher electricity demand, which would increase indirect emissions if the process is reliant on fossil fuel-based energy sources.¹⁹ End-of-life requirements for inert anodes also need to be understood. As they are not consumed by electrolysis, there will need to be adequate infrastructure to dispose of or recycle waste. Furthermore, while the operational carbon footprint of aluminium smelters will decrease, there will still be emissions tied to inert anode production and transportation.

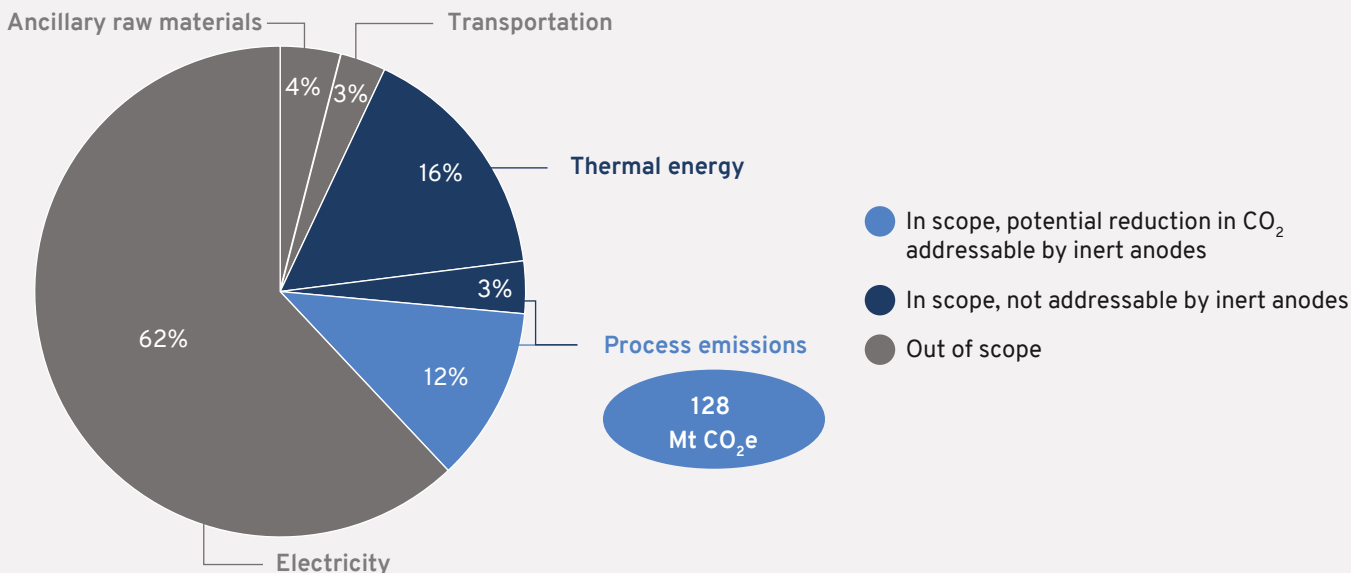
Potential level of impact on the aluminium industry's footprint

Although the speed of adoption of inert anodes is uncertain, they have the potential to mitigate all direct CO₂ generated by electrolytic and anode production processes – around 12% of sectoral emissions – assuming the use of non-fossil fuel-based electricity and 100% smelter uptake.²⁰

Figure 3 – Potential of inert anodes to reduce aluminium sectoral emissions²¹

Inert anodes could address around 12% of sectoral emissions.

Sectoral emissions = 1.1 Gt CO₂e



Use cases

ELYSIS

ELYSIS is a joint venture between Alcoa, Rio Tinto and Apple to create inert anodes to produce low-carbon aluminium. ELYSIS has begun construction of its first commercial-scale prototype at one of Rio Tinto's smelters in Canada. The companies hope to demonstrate the viability of the technology by 2024 and commercialize it for the rest of the aluminium sector.²²

RUSAL

RUSAL has produced more than 1,500 tonnes of the lowest-carbon aluminium ever (0.01 tonnes CO₂e/tonne aluminium in direct emissions) using inert anode technology and renewable electricity sources. Its new electrolytic cells not only decrease direct emissions but also reportedly produce oxygen equivalent to 70 hectares of forest.²³

Arctus Aluminium

Arctus Aluminium R&D team, in cooperation with the Innovation Centre Iceland, has produced high-purity (99.9%) low-carbon aluminium in a test cell with vertical inert anodes and wetted cathodes in a low temperature (800°C) electrolyte.²⁴

2.2 Carbon capture, utilization and storage

CCUS basics

Carbon capture, utilization and storage (CCUS) is the capture of direct CO₂ emissions from industrial processes that are then transported, used as an input to create another product or stored permanently underground.²⁵ Most existing CCUS applications are within the oil and gas industry for enhanced oil recovery (EOR), enabling companies to benefit from captured carbon. However, recent developments in the CCUS space are focused on abatement and storage of carbon to enable decarbonization of heavy industries.

CCUS is a promising solution for hard-to-abate sectors in which decarbonizing through renewable electricity alone is still financially or technically unfeasible. The International Energy Agency's (IEA) Net Zero by 2050 Scenario projects that the operating capacity of CCUS facilities must increase to 7.6 Gt CO₂ annually by 2050.²⁶ Current global capacity is approximately 40 Mt CO₂ annually, less than 1% of the capacity needed.²⁷

In recent years, the pipeline of CCUS projects has been growing, due to strengthening climate targets by governments and companies and the introduction of incentives that improve the investment opportunity for new facilities.²⁸ Plans for more than 30 new CCUS facilities have been announced since 2017; two-thirds are focused on capture and storage from direct emissions in heavy industries (e.g. coal-fired power plants, cement production) rather than usage for EOR, marking a shift in priority.²⁹ Around one-third of planned CCUS projects are tied to the development of industrial hubs that benefit from shared infrastructure, rather than point-source solutions.³⁰

CCUS benefits

CCUS is widely applicable and has the potential to reduce emissions in almost all parts of the global energy system.³¹ Several industries' decarbonization pathways incorporate CCUS, meaning there is an opportunity for cross-industry collaboration and shared investments.

In the aluminium industry, CCUS is potentially the most viable mid-term solution for facilities that have access to cheap fossil fuels, have no recourse to affordable renewables, are far from end-of-life and have access to affordable carbon transportation and storage infrastructure.

Technology readiness level (TRL)

Technologies to capture CO₂ from flue gas have been commercially available for decades.³²

Absorption-based CCUS technology could be used in primary aluminium production during the refining process to capture emissions from fossil fuel-based thermal energy generation and during the smelting process to capture CO₂ from carbon anode consumption (TRL 3–4).³³ This technology captures carbon emissions from flue gas by sending the gas through a solvent to absorb the CO₂.

Transporting CO₂ via pipeline, ship, rail and truck is mature (TRL 9) but not yet implemented at the scale required to meet future global needs.³⁴ Industry has extensive experience transporting pressurized gases, so technical feasibility should not be a barrier to scaling.³⁵

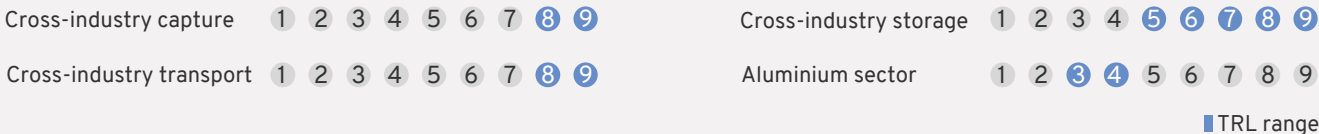


For storage, CO₂ is injected into a porous rock layer deep underground, which is covered by an impermeable layer that prevents leakage; this is most frequently done in deep saline formations or depleted oil and gas reservoirs.³⁶ Injection, storage

and monitoring of CO₂ is essentially the same process that is already used in the oil and gas sector; EOR and saline storage is widely used across the industry (TRL 9), while storage in depleted reservoirs is being piloted (TRL 5–8).³⁷

Figure 4 – Technology readiness level of CCUS

CCUS is mature in other sectors, but not yet implemented at scale in the aluminium industry.



Current and projected cost of CCUS

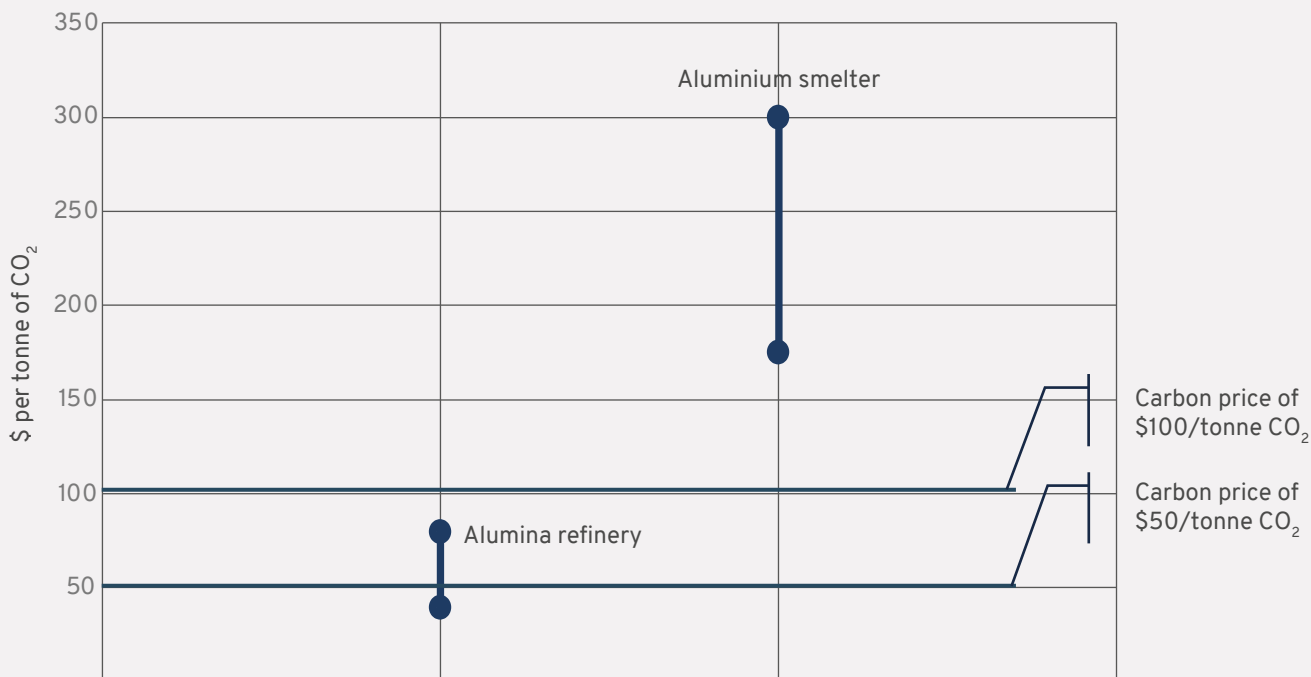
Although CCUS deployment has tripled in the past decade, it reached only 13% of the expected operational capacity projected by the IEA in 2009 of 300 Mt CO₂ per year by 2020.³⁸ One reason is the high capital cost associated with CCUS. Unless captured carbon is tied into a value chain that will generate revenue (e.g. fertilizers or EOR), the value case is reliant on incentives to invest or penalties for high emissions.

The cost of carbon capture varies greatly based on the concentration of CO₂ at the point source and the type of capture technology implemented, ranging from \$15/tonne CO₂ for high-concentration streams to more than \$100/tonne for lower-concentration sources.³⁹

Flue gas from aluminium smelters has a low concentration of CO₂, translating to a carbon capture cost of well over \$100/tonne of CO₂.⁴⁰ To reduce this cost, smelters would need to redesign electrolytic pots to eliminate fugitive carbon emissions and compress their flue gas prior to capture, which is technically possible but expensive.⁴¹

The application of carbon capture to an alumina refinery generally presents a better value case as the flue gas contains a higher concentration of CO₂, although it can vary greatly depending on the refinery. In these instances, the cost of CCUS could be as low as \$50–\$80/tonne of CO₂.

Figure 5 – Estimated cost of carbon capture for aluminium refining and smelting^{42,43}



The costs of transportation vary greatly depending on the transportation methods available (with pipeline being the cheapest) and the transport distance to the storage resource.⁴⁴

Overall, CCUS becomes more affordable when transportation and storage infrastructure can be shared through industrial hubs. Limited storage could double the cost of abatement.⁴⁵

Geographical or regional limitations

CCUS facilities are currently concentrated in the US, although the past decade has seen a rise in commissions in Australia, Brazil, Canada, China and the Gulf region.⁴⁶

The greatest geographical limitation of CCUS is proximity to a carbon storage resource to reduce transportation costs. This is dependent on the geology of the region; while some resources have been well-characterized with substantial data, many are not, and additional assessment is required to understand capacity.^{47,48}

Challenges or barriers to industrial use

The greatest barrier to scaling CCUS is the high capital cost for capture technology and the installation of the vast infrastructure needed for widespread use. This transportation and storage infrastructure requires comprehensive planning and development in the near term, as it can take years to approve and build. In the future, a lack of infrastructure could restrict the pace at which CCUS grows.⁴⁹

Furthermore, CCUS will not result in 100% CO₂ abatement; most applications are currently designed to capture 85–90% of point source emissions to optimize the cost per tonne of CO₂ captured. Higher capture rates are technically feasible but may result in additional operating costs.⁵⁰

The aluminium industry specifically could face challenges due to flue gas composition. Beyond the consideration of CO₂ concentration, some smelter flue gas streams may have too much oxygen or sulphur dioxide (SO₂) for a good capture rate.⁵¹

The right type of carbon capture technology will vary depending on the emissions source.

Another barrier is the perception of CCUS as a competitor to renewable energy or other innovations that will decrease reliance on fossil fuels.

Finally, there is concern about the availability of safe, secure and adequate storage capacity, leading to some degree of public resistance, particularly in Europe.^{52,53} To address these concerns, additional data needs to be gathered to assess geological storage worldwide. On an operational level, local communities must be engaged in the planning and development of sites.⁵⁴

Potential level of impact on the aluminium industry's footprint

CCUS has the potential to address both major sources of direct emissions in the aluminium industry: 1) the generation of thermal energy; and 2) direct process emissions due to the consumption of carbon anodes.

Overall, inert anodes present a better opportunity to decarbonize direct emissions from smelters due to the low concentration of CO₂ in flue gas. However, CCUS could be viable for smelters that are near other high-emissions industries and can exploit shared transportation and storage infrastructure via industrial clusters.

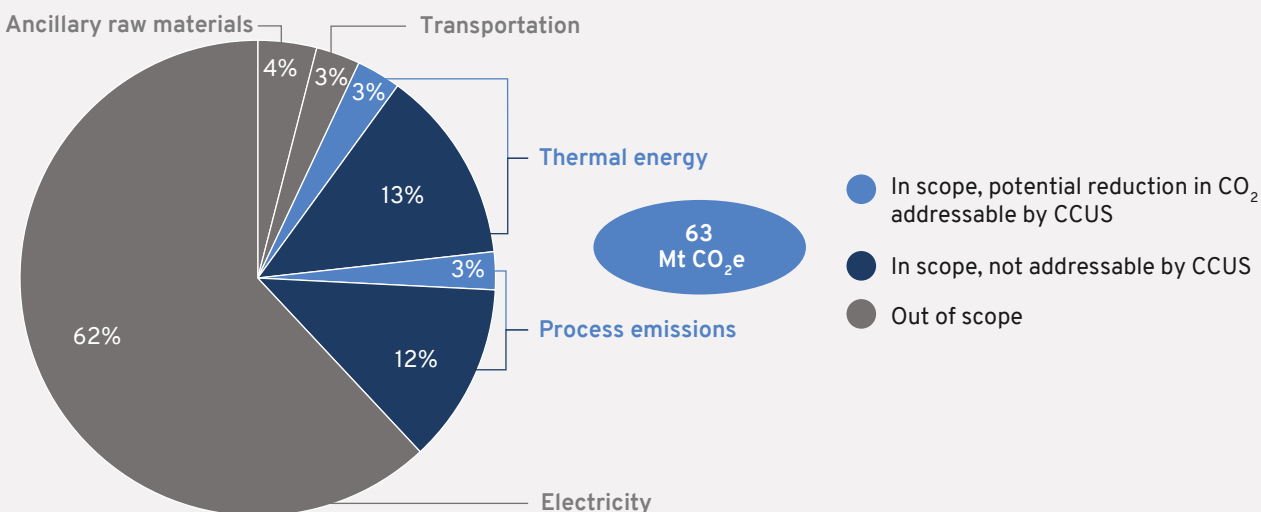
The application of CCUS to refineries to capture emissions from fossil fuel-based industrial heat and steam generation has the greatest potential, particularly in areas with cheap fossil fuels.

The proximity of a refinery or smelter to a geological storage site is integral to determining the viability of CCUS. Currently, around 30% of refining and 35% of smelting production is within the bounds of geological carbon storage formations, as identified by the Oil and Gas Climate Initiative's (OGCI) *CO₂ Storage Resource Catalogue*.⁵⁵ This is likely to evolve over the coming years as additional work is done to characterize global storage capacity.

Figure 6 – Potential of CCUS to reduce aluminium sectoral emissions⁵⁶

Assuming a 90% average capture rate, aluminium refineries and smelters within the bounds of geological storage formations could mitigate around 6% of sectoral emissions using CCUS.

Sectoral emissions = 1.1 Gt CO₂e



The use of bauxite residue for carbon sequestration

Alumina refineries produce a huge amount of bauxite waste, or red mud, which is left over from the refining process. Red mud is highly alkaline, making it mostly unusable to feed into other production streams (e.g. agriculture). This results in substantial costs for alumina refineries to manage and treat bauxite waste. Around 10 years ago, researchers began exploring the potential of CO₂ sequestration using bauxite residue. This not only has the potential to provide refineries with a way to sequester carbon emissions but also has the benefit of neutralizing the bauxite residue through reaction with CO₂, introducing new avenues for use or disposal. While preliminary research supports the technical feasibility of this process, the economics of industrial deployment are still unknown.⁵⁷ In May 2021, Alcoa announced the implementation of this process at its Kwinana alumina refinery in Western Australia with anticipated savings of 70,000 tonnes of CO₂ annually and plans to expand deployment to its refineries.⁵⁸

Use case

Alvance

Alvance is working in a consortium alongside Trimet, LRF (Rio Tinto's research centre) and the Fives Group to evaluate the most economical way to capture carbon in aluminium smelters. The initiative is looking at amine technology to determine the feasibility of capturing flue gases directly versus the need to concentrate the CO₂ for better capture. Alvance is framing a pilot to launch by 2024 in the hope of capturing up to 70% of emissions from the smelting process.⁵⁹

2.3 Hydrogen

Hydrogen basics

There are several methods used to generate hydrogen: 1) “grey hydrogen”, produced using fossil fuels by splitting natural gas into hydrogen and CO₂; 2) “blue hydrogen”, produced using the same process as grey hydrogen with the addition of CCUS to capture 90–95% of emissions; and 3) “green hydrogen”, which uses renewable energy-powered electrolyzers to produce hydrogen from water.⁶⁰ Grey hydrogen is by far the most commonly produced, although blue and green production are increasing due to more ambitious climate commitments and the potential for hydrogen to play a major role in a green economy.

Most net-zero scenarios foresee the rapid growth of hydrogen to address hard-to-abate emissions from industries such as steel, cement, shipping and aviation. By 2050, as much as 500–800 Mt of hydrogen will be needed annually.⁶¹

Hydrogen benefits

Hydrogen is considered the “Swiss army knife” of renewable energy solutions, as it can be used across many sectors, including electricity, fuel and thermal energy, for a broad range of purposes.

Hydrogen could provide a viable export opportunity for countries or regions with large resources of untapped renewable potential, such as Australia, Chile or the Middle East. It can also be used to capture and store excess renewable power, making it ideal to address the intermittency of other power sources (e.g. solar, wind) or supply areas that have limited access to renewable electricity, which is a challenge in the aluminium sector.⁶²

Several industries are also looking at the possibility of co-feeding hydrogen alongside natural gas for industrial heating.⁶³ Even if a full-scale green hydrogen transition is

not currently economical, operators could work with energy providers to reduce the amount of natural gas required per tonne of aluminium. To date, this has primarily been explored in the energy industry, although recent announcements in the cement industry show promise for use in furnaces similar to those used in alumina refineries.⁶⁴ Co-feeding hydrogen with natural gas is not yet being tested in aluminium operations.

Technology readiness level (TRL)

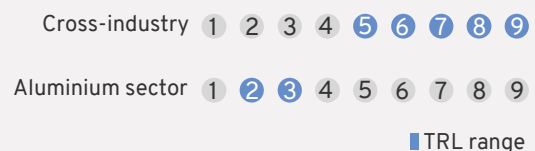
Grey, blue and green hydrogen have varying degrees of maturity.

Outside of the aluminium sector, grey hydrogen production technology is proven and used in the oil and gas and chemicals industries. Blue hydrogen employs the same foundational technology as grey, with the addition of CCUS capabilities. While technically feasible, it represents less than 2% of all hydrogen production annually.⁶⁵

Green hydrogen use is still limited at a commercial scale and represents just 1% of all hydrogen production annually, but electrolyzers themselves are a mature, established technology and the technical feasibility of green hydrogen is high (TRL 8–9).⁶⁶

Figure 7 – Technology readiness level of green hydrogen

While electrolyser technology is mature, hydrogen use in the aluminium sector is untested.



The use of hydrogen as a fuel source to produce high-temperature heat for industrial use, such as in alumina refining, is theoretically possible, although little hydrogen is used for this purpose today (TRL 2–3).⁶⁷ Even if it were proven at-scale for other industries, in the aluminium industry additional engineering will be required to adjust the fuel source without affecting the quality of the end product, although this should not present a major barrier.

Current and projected cost of hydrogen

Grey, blue and green hydrogen are all technically feasible; the greatest barrier to scalability is the cost. Grey hydrogen costs around \$1.50/kg H₂, blue hydrogen costs around \$2/kg H₂ and green hydrogen costs around \$3–\$5/kg H₂.⁶⁸

Low-carbon hydrogen (blue or green) is not yet cost-effective.⁶⁹ However, the costs for both blue and green hydrogen are anticipated to fall over the coming decade.⁷⁰ In the short to medium term, blue hydrogen is expected to remain more affordable than green, particularly in regions with access to cheap fossil fuels and affordable CO₂ transportation and storage infrastructure.⁷¹ Long-term, green hydrogen is expected to become the most affordable option due to the declining costs of renewables and electrolyzers. The Hydrogen Council anticipates that green hydrogen costs could decline as much as 30% by 2030 (\$1.40–\$2.30/kg H₂) and break even with grey hydrogen by 2028 in the best-suited regions, and by 2035 in average-rated regions.⁷²

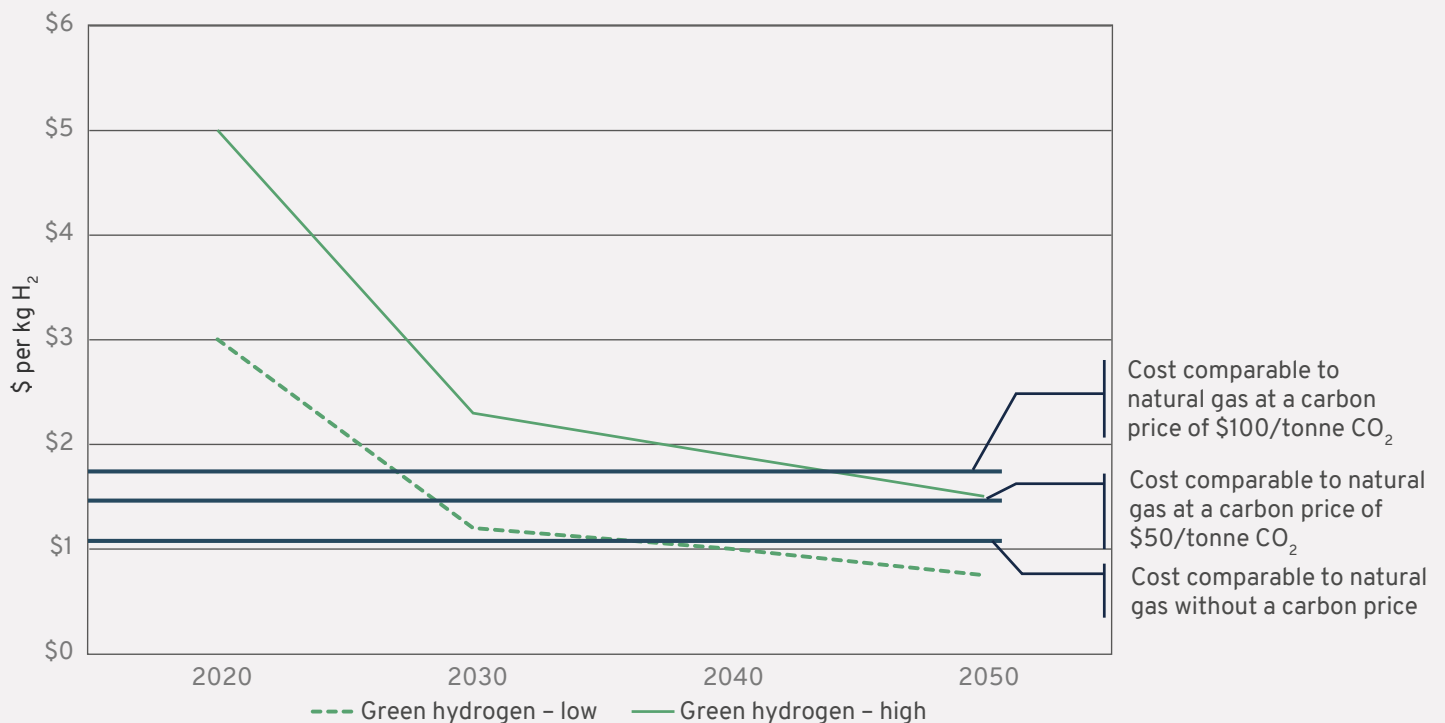
Conversely, blue hydrogen costs are expected to decrease by only around 5–10% by 2050.⁷³ Blue hydrogen may play a role in areas with limited access to renewable energy and access to cheap fossil fuels.

As the cost to produce hydrogen falls over the coming decade, the cost of transportation will become increasingly important. Trucking is currently the most cost-effective method (\$1/kg H₂), but by 2030 it is anticipated that hydrogen will be able to be shipped long distances for as low as \$2–\$3/kg H₂.⁷⁴ In the long term, a pipeline network is the best method for distribution; some of the existing infrastructure built for natural gas could be employed as a starting point.⁷⁵ As the anticipated cost of transportation could potentially more than double the cost of hydrogen, it is currently best used if generated in close proximity to off-takers, such as in an industrial hub.

Without a carbon price, subsidy or other incentive, blue hydrogen is unlikely to be cost-competitive with grey hydrogen due to the additional cost of CCUS. In the medium to long term, green hydrogen presents the most economic sense in most parts of the world due to the declining cost of renewables.⁷⁶

Only continued investment in technology improvement will drive down the cost of hydrogen. The Hydrogen Council estimates that 65 GW of electrolysis are needed for green hydrogen to become competitive with grey hydrogen, a funding gap of around \$50 billion.⁷⁷

Figure 8 – Projected cost of green hydrogen⁷⁸



Geographical or regional limitations

The production of green hydrogen is greatly affected by access to abundant affordable renewable energy sources; until long-distance transportation methods are established, users will be dependent on regional production. The declining cost of renewables is the primary driver to increase the viability of green hydrogen. Even in areas with access to cheap renewables, such as the Middle East, there is competition to use existing infrastructure (e.g. whether to use solar power for electrification or to produce hydrogen that could be sold as an export).

If hydrogen is being produced by intermittent renewables at an industrial scale, it can be stored similar to carbon storage. In these instances, the availability and proximity to underground storage capacity will influence the viability of the technology.

As with CCUS, the most competitive use cases for hydrogen are industrial hubs that co-locate hydrogen supply and demand across several industrial players that share infrastructure.

Challenges or barriers to industrial use

Many view blue hydrogen as a viable mid-term solution until green hydrogen becomes more economically viable. However, a recent study by Cornell and Stanford University researchers has shown that without robust methane-leakage monitoring, blue hydrogen production could be worse for the climate than burning natural gas (by as much as 20%).⁷⁹ Moving forward, aluminium players should evaluate the use of blue hydrogen from a life-cycle standpoint to ensure well-intentioned changes don't result in greater emissions.

The greatest barrier to the growth of green hydrogen is the high cost, which is significantly affected by access to low-cost renewable energy. In addition, the intermittency of some renewable sources may make a direct feed of green hydrogen impossible and increase reliance on local storage capacity.⁸⁰

Beyond production costs, hydrogen requires extensive infrastructure for transportation and storage, which needs local,

national and international collaboration between governments and industry.⁸¹ In the interim, aluminium companies could begin investigating how furnaces react to the use of hydrogen in preparation for increased supply.

For industrial heat generation, hydrogen is not a direct replacement for natural gas. Although some industries have explored co-feeding, the complete replacement of a fuel source will require engineering to convert process equipment to use hydrogen without sacrificing product quality.⁸²

As with the introduction of any new material to an operating environment, companies using hydrogen will need to establish clear, reliable safety systems and protocols to protect their assets and, most importantly, their employees. Workers will need comprehensive training and certification to be able to handle hydrogen on-site and mitigate the risk of incidents.

Finally, all end-use industries will need a standard certification to verify the hydrogen is truly green. Through trusted labelling, hydrogen companies will be able to charge a premium for green hydrogen and users of green hydrogen will be able to prove the low-carbon nature of their processes and avoid carbon taxes.

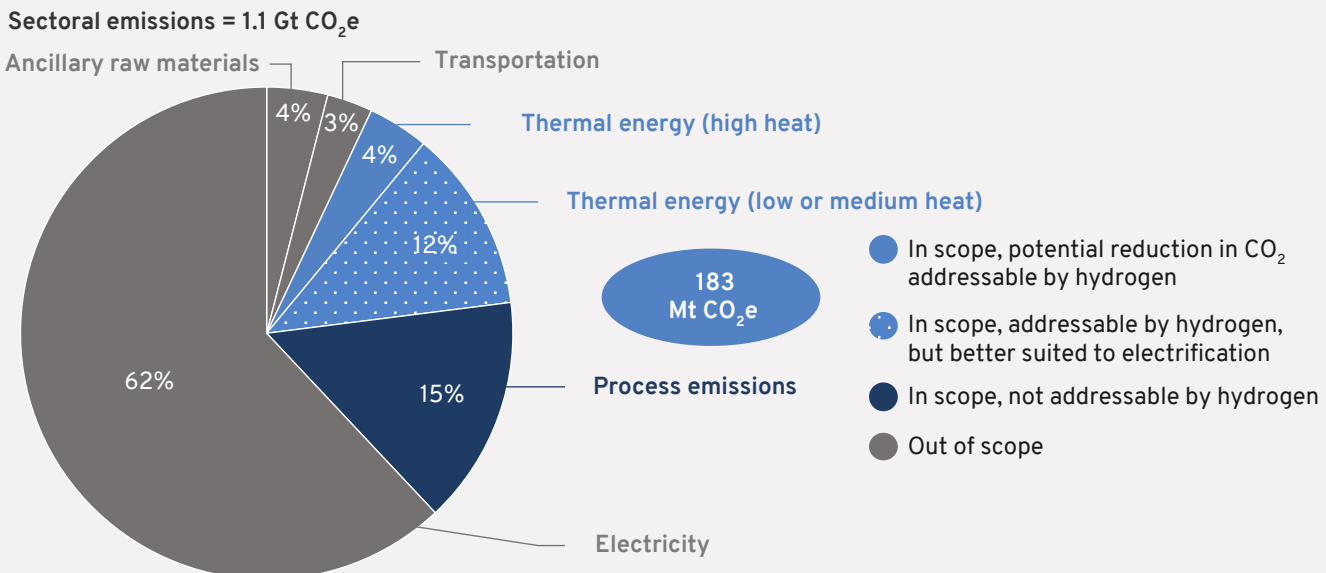
Potential level of impact on the aluminium industry's footprint

With regard to the aluminium industry's direct emissions, hydrogen has the potential to provide an alternative fuel for thermal energy generation.

While hydrogen could theoretically feed all thermal energy processes, electrification remains a more efficient solution for most low- and medium-heat processes as the conversion of electricity to hydrogen can experience as much as 20–40% conversion losses.⁸³ This means that, while the use of hydrogen could be used to reduce up to 183 Mt of CO₂e annually of direct emissions, electrification with renewable energy remains a more efficient option for low- and medium-heat thermal energy generation (e.g. bauxite digestion, casting, remelting).⁸⁴

Figure 9 – Potential of hydrogen to reduce aluminium sectoral emissions⁸⁵

Hydrogen could address the aluminium industry's emissions due to thermal energy, although electrification of low- and medium-heat processes may be more efficient.



Use cases

Rio Tinto

Rio Tinto has partnered with the Australian Renewable Energy Agency (ARENA) to evaluate whether hydrogen can be used as an alternative to natural gas in alumina refineries. This feasibility study will replace natural gas with green hydrogen during calcination at the Yarwun alumina refinery in Queensland.⁸⁶

Norsk Hydro

In April 2021, Norsk Hydro announced that it is exploring the potential to operate hydrogen facilities. It is using its expertise in renewable power to evaluate green hydrogen as an alternative to natural gas for its own operations, while exploring an additional revenue stream as hydrogen plays an increasing role in the green economy. This transition could reduce Hydro's CO₂ emissions by as much as 30% by 2030.⁸⁷

2.4 Mechanical vapour recompression

Mechanical vapour recompression basics

Mechanical vapour recompression (MVR) is used to recover waste heat from steam that would otherwise be discharged during processing. Instead, the steam is captured and redirected to a compressor that raises the pressure and temperature of the steam, which can then be reused and allows for significant energy savings.⁸⁸

Benefits of mechanical vapour recompression

MVR represents an opportunity to reduce the carbon footprint of existing operations, regardless of power source or geographic location. This can begin decreasing the footprint of the industry while less mature, more capital-intensive technologies (e.g. green hydrogen) become economical.

Furthermore, MVR can be applied to both brownfield and greenfield operations. If the technology proves to be cost-effective to retrofit, it could be one of the most financially viable opportunities to decrease emissions at existing facilities, particularly alumina refineries.

Beyond carbon savings, MVR can decrease operational costs through energy savings; in alumina refining, energy accounts for as much as 30–50% of the total production cost.⁸⁹

Technology readiness level (TRL)

Outside of the aluminium industry, MVR is a mature, established technology used in distillation plants, dairy processing plants and more (TRL 9).

The use of MVR in the aluminium industry is still in its early stages. While there are a few examples of MVR in operation, implementation at a broader scale is still to be determined (TRL 5).⁹⁰ Many unknowns remain, including the cost of retrofitting existing facilities, greenfield cost and the timeline to become commercially viable.

Current and projected cost

The capital costs to install MVR can be high. A greenfield application tends to present a more appealing business case than a retrofit scenario, especially to design and construct the infrastructure needed to capture waste heat from existing processes.

Challenges or barriers to industrial use

MVR alone will not allow any site or process to eliminate GHG emissions, although it will decrease the footprint of existing facilities that are currently not economical to decarbonize via other methods (e.g. CCUS, hydrogen).

MVR also requires a large amount of electricity. While the electricity demand to run MVR is one-third of that required for an electric boiler and one-quarter of that required for equivalent hydrogen generation, alumina refineries do not often have a high electricity demand as they rely on the combustion of natural gas or coal to produce thermal energy.⁹¹ The introduction of MVR would increase electricity needs by several times, meaning the site must have access to affordable renewable electricity. Furthermore, most grids lack the capacity to quickly and easily accommodate additional electricity demand at this scale.

Potential level of impact on the aluminium industry's footprint

The most promising application of MVR in the aluminium value chain is to recover waste heat during the refining process to reduce fossil fuel-based thermal energy production. Early estimates predict that MVR powered by renewable energy could reduce carbon emissions from alumina refineries by as much as 70%.⁹²

Further exploration could identify additional applications along the value chain (e.g. remelting).

Figure 10 – Technology readiness level of MVR

While MVR technology is mature in other sectors, it remains untested at scale in the aluminium industry.

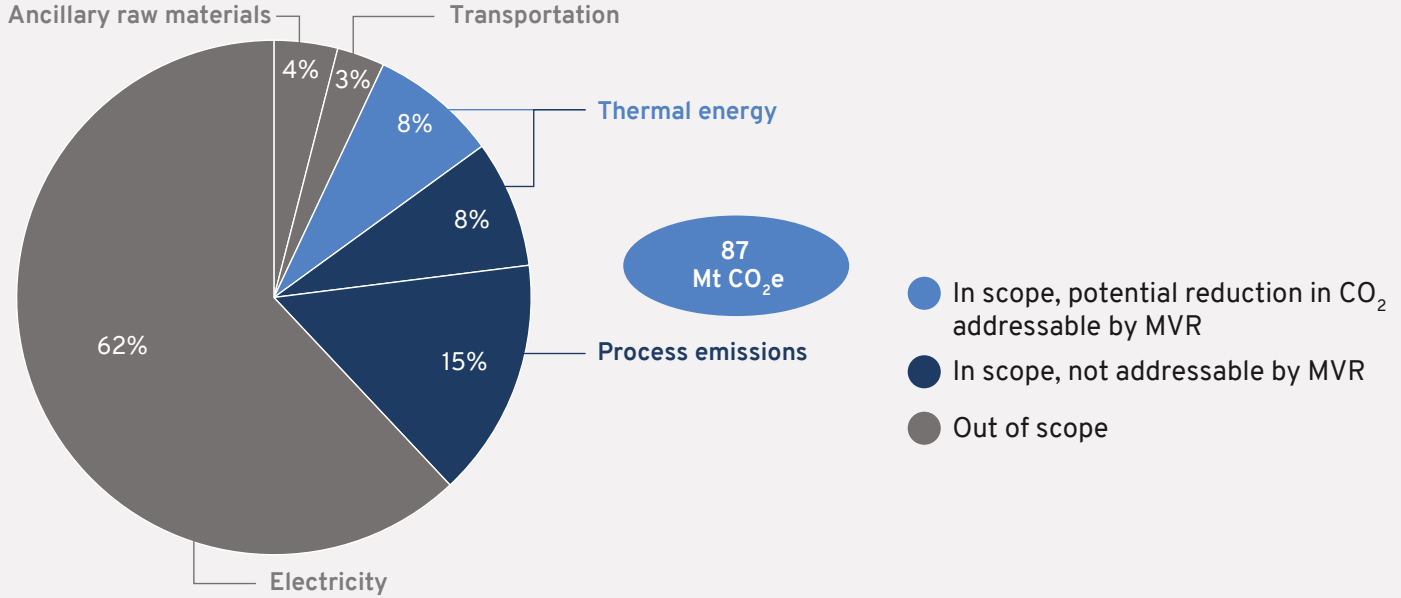
Cross-industry 1 2 3 4 5 6 7 8 9

Aluminium sector 1 2 3 4 5 6 7 8 9 ■ TRL range

Figure 11 – Potential of MVR to reduce aluminium sectoral emissions⁹³

MVR could address up to 70% of thermal energy emissions for alumina refining, equivalent to 87 Mt CO₂e annually.

Sectoral emissions = 1.1 Gt CO₂e



Use case

Alcoa

Alcoa is in the process of evaluating MVR powered by renewables by adapting existing technology to suit the alumina refining process. The Australian Renewable Energy Agency (ARENA) granted Alcoa (US) \$8.8 million to pilot this technology. If the feasibility studies are successful, Alcoa plans to install a 3 MW MVR module at the Wagerup refinery in Western Australia to test the technology at scale by 2023.⁹⁴



2.5 Engineering and process improvements

The technologies explored earlier in this report are considered breakthrough technologies that, if widely implemented, would result in a step-change reduction in carbon emissions. However, smaller-scale engineering and process improvements can provide opportunities for advancement that have less impact but are more affordable and easier to implement in the short term.

Most engineering and process improvements have a clear business case tied to energy savings, resulting in lower operating expenses. Table 3 shows an overview of some of the most impactful improvements aluminium players can make.

Table 3 – Engineering and process improvement technologies that result in emissions reductions

Technology	Description	Value chain impact	TRL
Electric boilers for low- and mid-heat processes	Transitioning from fossil fuel-powered to electric boilers is perhaps one of the easiest technologies to implement to reduce emissions. Theoretically, the technology is straightforward, although the capital costs remain restrictive. As with all electrification opportunities, access to affordable renewable power remains key.	Refining, remelting	4–5
Fluidized bed calciners	The use of fluidized bed calciners is technically feasible and mature; many aluminium players already use this technology. Fluidized bed calciners are more energy-efficient than rotary calciners and can result in both energy and cost savings (as much as 30–35%). ⁹⁵	Refining	9
Low-temperature digestion	Low-temperature digestion is technically feasible and already used at some alumina refineries, yet it relies on the quality of bauxite input into the process. Higher-quality bauxite can be processed at a lower temperature and yield lower emissions. This could have an impact on a site-by-site basis, but will likely have limited impact industry-wide, as it is unlikely that the supply of bauxite will significantly change.	Refining	9
Eco-Söderberg technology ⁹⁶	In 2009, RUSAL developed a new type of electrolytic cell using a more environmentally friendly process. RUSAL began transitioning its plants to Green Söderberg technology in 2016. These facilities have shown an average 14% reduction in pollutant emissions (including 32% reduction of fluoride) and achieved cost savings through decreased electricity consumption.	Smelting	9
Waste heat recovery	As much as 30–45% of heat produced during aluminium smelting is lost as waste heat and carried away by exhaust gas. ⁹⁷ There is an opportunity to implement waste heat recovery systems to reduce overall energy consumption. Several companies have technologies that are commercially available, including, but not limited to: energy modulation technology by EnPot, shell heat exchangers from REEL International and heat pipes by Cronus. ^{98,99,100}	Smelting	7–9



PART 3

TAKE ACTION

Although the best solution depends on each site’s operating environment, shared challenges pave the way for collaborative action.

Several decarbonization technologies are available and there is no one-size-fits-all approach to mitigating direct emissions in the aluminium industry. There is significant variation in the starting points for aluminium players; some producers have access to hydropower assets limiting the overall company’s carbon footprint while others have major investments in young fossil fuel infrastructure and are struggling with electricity decarbonization. The best-suited technologies change based on each player’s operational environment, including

policy, geography and role in the aluminium supply chain. All technologies explored should be evaluated from a life-cycle standpoint to ensure they do not result in greater emissions.

While companies are reliant on forces external to the aluminium industry to create a beneficial regulatory environment, they can take action now through collaborative research and development, multilateral engagement and the formation of industrial hubs.

3.1 Creating a favourable investment environment

The speed at which these technologies can evolve is greatly dependent on the regulatory and investment environment and will require a strong policy response with partnership across

governments, industries, investors and stakeholders.¹⁰¹ Table 4 presents several policy options to stimulate innovation and improve the value case for decarbonization technologies.

Table 4 – Policies that could promote investment in decarbonization technologies¹⁰²

Potential policies	Inert anodes	CCUS	Hydrogen	MVR	Engineering improvements
Incorporate innovative technologies into government’s decarbonization strategies	✓	✓	✓	✓	✓
Provide public and/or private funding to support innovative R&D efforts	✓	✓	✓	✓	✓
Incentivize the development of decarbonization technologies through subsidies, tax credits or grant funding ¹⁰³	✓	✓	✓	✓	✓
Ensure lower barriers that extend the timeline for project approval and funding		✓	✓		
Coordinate, fund and regulate the construction of new infrastructure for the energy system		✓	✓	✓	
Introduce a carbon tax to drive investment in low-carbon technology and infrastructure	✓	✓	✓	✓	✓
Introduce carbon border taxes with robust embedded carbon accounting frameworks to reduce the likelihood of carbon leakage	✓	✓	✓	✓	✓
Provide carbon contracts to minimize carbon price uncertainty and reduce investment risk	✓	✓	✓	✓	✓
Develop common international standards for the trade, transport and storage of new energy products		✓	✓		
Define a standard certification system for blue and green hydrogen			✓		
Introduce consistent traceability and labelling of low-carbon and secondary aluminium throughout the value chain and across borders	✓	✓	✓	✓	✓

International cooperation will become increasingly important in the short to medium term. Aluminium is a global industry and

uncoordinated efforts risk carbon leakage to parts of the world with less stringent carbon policies.

3.2 Collaborative research, design and development

Except for inert anodes, the technologies explored in this paper are not unique to the aluminium industry. Many of these technologies have been tested and are operational in other sectors. Delaying action until the costs are equivalent to existing processes might place aluminium producers behind the curve; it is important to understand the engineering requirements of these technologies as soon as possible so that aluminium players can quickly adopt new solutions as they become more affordable.

Where sector-specific collaboration is ideal, companies should identify ways to collaborate with peers across the industry. This eases the financial burden and risks associated with innovation and enables smaller players to contribute to research they would not be able to drive alone. It may be beneficial for neutral parties such as industry associations to facilitate collaborative R&D efforts between competitors (e.g. the European Aluminium Innovation Hub).

Recommended action by aluminium players

- Identify peers that share similar decarbonization challenges and technological needs
- Partner with start-ups or research institutions to provide avenues for pilot studies to demonstrate breakthrough technologies in an industrial context
- Partner with other industries that are invested in scaling up technologies such as CCUS or hydrogen to share information
- Explore the application of commercially available technologies within the aluminium industry
- Invest in continued engineering improvements to existing processes
- Identify opportunities that could provide additional revenue streams from decarbonization technologies (e.g. selling excess green hydrogen)

Low-Carbon Emitting Technologies (LCET) programme

In 2019, the World Economic Forum launched the Low-Carbon Emitting Technologies (LCET) initiative together with its Chemicals and Advanced Materials Industry Community.¹⁰⁴ This initiative aims to accelerate the development and scaling of low-carbon emitting technologies for chemical production and will be formalized into a stand-alone entity by the end of 2023.¹⁰⁵ To date, significant progress has been made, including:

- Building trust between participants and setting collaborative goals
- Understanding the landscape and readiness of technologies for the industry
- Identifying areas of collaboration to progress both early-stage and late-stage technologies
- Working closely with a third-party intellectual property lawyer
- Defining metrics to measure progress
- Collaborating with policy-makers around the world to inform policy decisions¹⁰⁶
- Exploring financing mechanisms for pilot projects to identify the lowest-risk financing model

By working collaboratively, industry partners can select the best locations to run pilots, using criteria such as access to renewable power, the regulatory environment and access to funding.

3.3 Multilateral engagement

Beyond RD&D efforts, aluminium companies can work to enable a supportive investing environment through engagement with stakeholders outside of heavy industry, including governments, standard-setters and investors.

Aluminium players should work with local and national governments and policy-makers to provide expertise on what it will take to drive change in the industry. Companies can help develop mechanisms that make decarbonization an attractive option for aluminium players and consider

the specific challenges the industry is facing. Furthermore, aluminium companies should seek public funding to finance capital-intensive initiatives.

Industry standards and certifications are critical to providing consistent, transparent definitions and metrics. The Aluminium Stewardship Initiative (ASI) is a multistakeholder initiative that defines global standards for sustainable production and sourcing across the aluminium value chain. In the revision of its Performance and Chain of Custody Standards, currently under



way, the ASI is seeking alignment with existing and emerging standards and methods for decarbonization.

Engagement with other decarbonization standard-setters (e.g. SASB, TCFD and CDP) would enable aluminium companies to support the creation of metrics they would be expected to report.¹⁰⁷ Working with these organizations enables the sector to be part of the solution to develop meaningful and transparent reporting frameworks, rather than being forced to respond to outside influence.

Finally, aluminium companies should engage with investors. The recent establishment of the Glasgow Financial Alliance for Net Zero and the launch of RMI's Center for Climate-Aligned Finance show how seriously investors are taking decarbonization; companies that fail to act are at risk of increased investment challenges or even divestment. While publicly available sustainability reports are a good start, more direct engagement with investors can allow for a better chance to ensure that

3.4 Industrial clusters

Heavy industry is responsible for as much as 30% of global carbon emissions.¹⁰⁹ Many decarbonization solutions, such as CCUS or hydrogen, are industry-agnostic and represent an opportunity for the hardest-to-abate sectors to work together.

Technologies that are not economically feasible to apply to a single point source become viable in the context of a broader industrial ecosystem. Industrial sites in close proximity can capitalize on economies of scale to decrease capital and operating costs and reduce investment risks. Co-locating supply and demand decreases transport costs, enables facilities to share expensive infrastructure and provides the ability to mix and match solutions that would not work in isolation. Furthermore, industrial hubs can be a way to share risk among companies and make proposals more attractive to public and private investors.

Industrial hubs are ideal for electrification using renewable energy, hydrogen production, CCUS or the formation of circular

sector-relevant pathways are considered in view of the market context (e.g. lack of market premiums for low-carbon products).

Recommended actions by aluminium players

- Work with governments to establish policies that will trigger investments in low-carbon technologies
- Partner with governments to access public funding for innovative RD&D
- Engage with standard-setters to establish a uniform reporting framework and transparently report progress
- Provide transparent and trustworthy data on the current state and progress towards goals
- Set up ESG Investor Days to communicate the company's decarbonization pathway¹⁰⁸

business models (e.g. locating a car manufacturer next to an aluminium plant). Each cluster's strategy could vary greatly based on geography, industry composition, tax structure and more.

Recommended actions by aluminium players

- Identify nearby Industrial sites that could contribute to an industrial hub (e.g. using OGCI's CCUS hub tool)¹¹⁰
- Assess the needs of each partner, align on shared goals and create a roadmap
- Define commercial models to share risk
- Work with government and industry organizations to establish regulatory structures or investments in cluster infrastructure¹¹¹

Net Zero Industrial Clusters

The World Economic Forum, in collaboration with Accenture and EPRI, launched the Net Zero Industrial Clusters¹¹² initiative at COP26 to accelerate the formation of industrial clusters to work towards net zero. Four global clusters have currently signed on, with a total emissions reduction commitment equivalent to the country of Denmark (30 Mt). The initiative aims to have 100 industrial clusters signed up by 2024.



PART 4

CONCLUSION

While there is no single solution to address primary aluminium's sectoral direct emissions, the time is right for cross-industry collaborative action.

There is no silver bullet to address carbon emissions; instead, aluminium companies must consider a suite of technological solutions to meet decarbonization targets. The best path forward for aluminium players will depend on their resource availability, energy access, regulatory environment and the speed and cost of technology development and scaling.¹¹³ Companies should focus on progress rather than perfection and identify areas to begin to take meaningful action, not just as individuals but also as an industry. As so many of these technologies and challenges are shared across industries, the aluminium sector should look for opportunities to collaborate with other heavy industries such as chemicals, steel, oil and gas, and shipping.

The COVID-19 pandemic, as devastating as it has been for the world, has shown the power of collaborative action as governments, private companies, research institutions, NGOs and the public work together to solve a common problem.

Similarly, society can be successful in reaching net zero only if there is endorsement and action from all stakeholders.

Cross-industry collaborative action is required to ensure: 1) an attractive proposition for technological solution providers; 2) pooling of funding to maximize investment opportunities; and 3) the sharing of methodologies to accelerate deployment, which is currently lacking.

The rapid progression of climate change makes urgent action more important than ever; the UN has called the 2020s the “decade to deliver” and set the path to reach a 1.5°C or 2°C scenario. We have 80% of that decade left. With the completion in November 2021 of COP26, which emphasized the role of industrial decarbonization, the environment for cross-industry and multistakeholder collaboration is more promising than ever before for sectors such as aluminium to act.



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ENDNOTES

1. Concentrating solar power also presents a viable alternative for thermal energy generation but is applicable only in regions of the world with high solar radiation (e.g. Australia, the Middle East), which at this time constitute less than 20% of global refining capacity and would address ~2% of global sectoral emissions.
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 - 2 Technology concept formulated
 - 3 Experimental proof of concept
 - 4 Technology validated in lab
 - 5 Technology validated in relevant environment
 - 6 Technology demonstrated in relevant environment
 - 7 System prototype demonstrated in operational environment
 - 8 System complete and qualified
 - 9 System proven in operational environment
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