ALUMINUM DECARBONIZATION AT A COST THAT MAKES SENSE

To reach an emissions pathway consistent with 1.5°C of global warming, the aluminum industry needs to reinvent itself and its production processes.

MISSION POSSIBLE PARTNERSHIP

Sponsored by Energy Transitions Commission

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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 (MPP) is an alliance of climate leaders focused on supercharging the decarbonization of seven global industries representing 30 percent of emissions: aluminum, aviation, cement and concrete, chemicals, shipping, steel, and trucking. 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 emissions. Learn more at **missionpossiblepartnership.com.**

Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by middle of the 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 nongovernmental organizations—that 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. Learn more at **energy-transitions.org.**

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PART I

INTRODUCTION

Infinitely recyclable, immensely strong, lightweight, and malleable: aluminum is the metal that makes modern economies tick. With uses ranging from beverage cans to cars, airplanes, and solar panels, it is also extremely versatile. There is only one real problem: while the metal itself is sustainable, its production usually is not. In fact, the aluminum industry accounts for about 2 percent of global greenhouse-gas (GHG) emissions. Mostly due to its high energy use, the aluminum industry emits around 1.1 billion metric tons (t) of GHGs a year.[1]

The aluminum industry as outlined in Mission Possible Pathway's (MPP) Sector Transition strategy and the International Aluminium Institute's (IAI) 1.5° work together can deliver a 1.5° pathway–aligned net-zero sector. One of the core challenges to achieving this, however, is that transforming the aluminum sector to a low-carbon sector will require upgrading refining and smelting assets and making significant investments in low-carbon power.

The investment case for decarbonizing each individual refinery or smelter will be determined by local circumstances, and local power availability and local policy arrangements will be critical.

This report and open-sourced investment model outlines the levers that could close the finance gap. Users can generate their own investment case using the underlying analysis from MPP's Sector Transition strategy with analytical support from McKinsey's Sustainability and Basic Materials Practices to understand what additional levers from financers, customers, and policy makers may be essential for each investment case.

How stakeholders can help

One of the challenges to aluminum decarbonization is that best currently available fossil-fuel-based technologies have a net present value greater than green alternatives. Overcoming these economic obstacles and risks will require collaborative action among stakeholders. Banks, investors, policy makers, and end customers will each have an important role to play.

The finance sector. Decarbonization won't be cheap. Cumulative investment of approximately $1 trillion across the primary production value chain will be needed to deliver a net-zero sector or a 1.5° pathway. The majority of this investment will be needed in power supply and smelters.[2] Aluminum producers will need to retire fossil-fuel-based production and make new investments in low-carbon alternatives, even though these are likely to have a lower return on capital and contain some technology and implementation risks. Financial institutions have the capability to mitigate some of these risks and shift cash flows toward green investments. Given the generally high levels of debt in the aluminum industry, improved interest rates for low-carbon investments and new products such as green loans or bonds used exclusively for climate-friendly projects could be key enablers. Additionally, banks could incorporate climate considerations into their lending decisions, such as those developed by the Center for Climate-Aligned Finance (CAF). Financial partnerships designed to support sustainable investment already exist, such as the Net-Zero Banking Alliance (NZBA), which brings together banks which represent 40 percent of global banking assets.

Governments and policy makers. Governments play a critical role in aluminum decarbonization not only because the government is a relevant end customer of particular aluminum products but also because aluminum is a strategic metal for the energy transition, raising governments as strategic investors in aluminum production and aluminum decarbonization. Governments have several tools to provide incentives for aluminum decarbonization. Government grants to aluminum producers can help offset some of the costs of green investment, while carbon contracts for difference (CCfDs) bring the operational costs of decarbonized operations in line with those of fossil-fuel-based technology. However, our analysis shows that the greatest impact to the economics of decarbonization could come from carbon pricing, whether through trading schemes or carbon taxes. This could spur investment in green aluminum and enable the economics of the industry's net-zero transition.

Customers. Aluminum users will likely have an important role to play in creating demand and helping shift the industry toward decarbonization. This could including paying what we estimate to be a 5 to 10 percent premium for green aluminum or by making firm advance commitments to purchase it. Such offtake agreements could be negotiated before a factory is constructed or begins operations, or before major retrofits are undertaken, significantly cutting investment risk. For manufacturers that have set decarbonization goals for their sourcing and supply chains, such premiums may be worth paying. Apple, for instance, has announced that its new iPhone SE will use zero-carbon aluminum produced from hydropower in Quebec.[3]

Rising demand for low-carbon products is pushing the aluminum industry away from the carbon-intensive processes that have dominated production for the past 135 years. At the same time, the dynamics of a warming planet are evidence that change needs to happen as fast as possible. To make the green transition a reality, players throughout the aluminum value chain need to seize the moment, work together to support a purposeful transition, and recreate the industry for the demands of the coming decades.

PART II

LEVERS TO ACCELERATE DECARBONIZATION

The intensity of GHG emissions associated with alumina refining and aluminum smelting leaves the industry with little choice but to seek out the most efficient way to decarbonize. However, while players across the value chain have been taking steps to align with a 1.5° pathway, more planning and investment are required to significantly reduce emissions associated with aluminum production.

To explore the potential for change, Mission Possible Partnership's Aluminium for Climate team, with analytical support from McKinsey's Basic Materials Insights and Sustainability Practices, has developed an open-access, open-source investment model for alumina and aluminum plant archetypes. The user-friendly model creates a twin lens on costs and decarbonization options for Scopes 1, 2, and 3 emissions. The model is structured to allow alumina refineries, aluminum producers, OEMs, upstream players, finance players, policy makers, and end-industry users to input their assumptions about decarbonizing alumina refineries and aluminum smelting, and to compare investment scenarios with best available technologies (BAT). Users can select a series of inputs for investment scenarios and run multiple levers to reduce the net-present-value (NPV) gap versus ongoing or BAT operations. The model aims to provide the latest thinking related to the key technologies and processes, evaluate the different options, and inspire decision makers on the options and prerequisites of deploying these technologies in the real world.

2.1 Investment risks

The significant investment required to decarbonize the aluminum industry could expose companies and stakeholders to a range of risks. These include market risks, specifically threats to market capitalizations, as well as credit and liquidity risks. There could also be risks associated with executing decarbonization projects and the impacts of policy and regulation (see sidebar "Potential risks associated with aluminum decarbonization"). The industry will need to manage all of these risks to successfully accelerate the decarbonization agenda.

A basic element of risk mitigation strategies will be dedicated to long-term planning, based on an understanding of all available and economically reasonable decarbonization pathways. In addition, there are various financial, policy, and demand levers that may create a more favorable environment for investment (see sidebar "Finance and policy levers to likely derisk investments").

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Potential risks associated with aluminum decarbonization

Market risk

An aluminum producer's shareholder value deteriorates due to a decarbonization investment that carries a lower return on capital compared with business-as-usual investments.

Credit risk

An aluminum producer contracts significant debt to undergo decarbonization investments with high uncertainty on future cash flows and potential for credit downgrading.

Liquidity risk

An aluminum producer has a perceived or actual inability to meet its liabilities due to a cash flow drain from investments in decarbonization efforts, threatening its financial position or even existence.

Technical and execution risk

An aluminum producer invests in a technology or project design that is unproven or that lacks internal tools, systems, processes, and people to successfully develop it, turning investment into stranded asset.

Political and regulatory risk

Trade barriers recently installed in the European Union, such as the carbon border adjustment mechanism, have dramatically changed the prospects of high-CO_2e investment exports.

Finance and policy levers to likely derisk investments

The decarbonization of the aluminum value chain needs to be a concerted effort between financial institutions, political institutions, producers, buyers, intermediaries and equipment providers. To successfully meet a 1.5°C scenario, a set of levers could help to stimulate investment in ultra-low-carbon aluminum production.

Finance levers

- Financial institutions will likely be part of the decarbonization of the aluminum value chain to reduce their financed emissions and at the same time mitigate climate risk by **decreasing interest rates, increasing loan duration**, or **increasing loan to value** of loans for players' decarbonization efforts through issuing:
    - **green loans**
    - **green bonds**
    - **transition bonds**
    - **sustainability-linked loans or bonds**[1]

Policy levers

- **Setting up carbon prices or taxes.** These can take multiple forms, such as locally regulated taxes, exchange-traded emissions systems like those currently installed in several parts of the world, and fees on imports, such as the cross-border adjustment mechanism that will be implemented in the European Union.
- **Offering government grants.** For example, a CA $1.8 billion grant (US $1.4 billion) from the Canadian government is making possible an ArcelorMittal investment in the steel industry to convert a blast furnace to an electric-arc furnace, resulting in a CO_2e emissions reduction of three million metric tons (or 60 percent emissions reduction). The Canadian government has also provided some support to Alcoa and Rio Tinto for development of the ELYSIS technology.
- **Developing carbon contracts for difference (CCfD).** For example, Germany is currently considering providing €43 billion funding for CCfD for use in heavy industry (for example, steel, cement, and chemicals). This will be a ten-year agreement resulting in an offset in CO_2e emissions of 20 million metric tons per year. A similar CCfD scheme has been implemented in the United Kingdom to accelerate the renewable-energy transition and has already supported 16 GW of low-carbon electricity.

Demand levers

- **Reaching offtake agreements.** Offtake agreements often help secure funds for decarbonization, reducing the investment risk. Buyers and sellers can reach an agreement to purchase a defined quantity of low-carbon-footprint product at a predefined price or at the cost of the production price.
- **Accepting green premiums.** Due to a lack of balance between supply and demand for low-carbon footprint products, a time-bound green premium can emerge, allowing for supply-side flexibility and coverage of the decarbonization cost.

[1] See, for example, "Hydro Alunorte signs USD 200 million sustainability-linked loan to finance fuel switch project," Hydro, April 1, 2022.

All of the levers—on the financial, policy, and demand side—are routes to mitigating and reducing the risks associated with investment. Ideally, they would be combined in various ways so that they are mutually reinforcing. A hybrid approach is likely to be optimal, because no single intervention will be sufficient to unlock sectorwide investment.

Here we consider each category of lever in detail and outline steps that leading players are already taking.

2.1.1 Financial levers

A significant element of the industry's transition will be a committed program of investment. This reflects the wider reality that the net-zero transition will demand average annual spending of $9.2 trillion across industries by 2050.

Decarbonization of the aluminum industry will require investment in the industry's operations as well as in the power and recycling sectors. In parallel, investment in fossil-fuel-based production will need to decline rapidly. To facilitate this process, the finance sector will need to play a critical role, supported by three key levers:

- improvement in terms for low-carbon investments, through interest rates, debt tenure, or other conditions
- bringing new finance products to market and tailoring finance to the particular combination of risks inherent in low-carbon products
- aligning the climate objectives of finance providers and alumina and aluminum producers through principles of credit provision associated with pathways to 1.5ºC

Finance providers can also make strategic contributions, leveraging investment expertise across the value chain to take a holistic approach to system change. They can apply lessons learned in other sectors and identify how different projects can be effectively integrated.

Improved terms. The terms for investment in low-carbon aluminum will be shaped by the mix of investment risks. As capital providers better understand decarbonization levers and project risk profiles, and as offtake commitments are made, more capital is likely to flow to green and brown-to-green investments. Capital providers that proactively work to make a product relevant to a low-emission future will lower their transition risk relative to their peers.

A range of financial instruments. Low-carbon aluminum projects present a different mix of risks than traditional aluminum projects, so tools that have been specifically designed for the green-finance market are likely to be most useful:

- **Green loans** are any type of loan instrument exclusively applied to finance or refinance new or existing eligible green projects, in whole or in part.
- **Green bonds** are bonds whose raised funds are applied exclusively to projects and activities that promote climate or other environmental sustainability purposes. According to the Climate Bonds Initiative, nearly $2 trillion in green bonds have been issued since market inception in 2007.[4]
- **Transition bonds** are bonds whose funds are applied exclusively to new and existing projects that support corporate climate strategies.
- **Sustainability-linked loans and bonds** embed "sustainability performance targets" and trigger a reduction in the cost of debt if certain KPIs are achieved. Unlike green or sustainable bonds, funds raised with this instrument are not tagged to a specific use but are for general corporate purposes.

The Loan Syndications & Trading Association (LSTA) has defined parameters associated with sustainability-linked lending to support sustainable economic activity.[5] Its framework consists of five components: selection of KPIs to assess sustainability and core business strategy; calibration of sustainability performance targets (SPTs), representing an improvement over industry standard operations; loan characteristics, dependent on the borrower meeting SPTs and KPIs; reporting at least annually to allow monitoring of performance of SPTs and KPIs; and verification of performance against SPTs and KPIs, at least annually. A limited number of institutions have explored sustainability-linked lending, but this tool can also support decarbonization.

"Low-carbon aluminum projects present a different mix of risks than traditional aluminum projects, so tools that have been specifically designed for the green-finance market are likely to be most useful."

Aligning climate objectives of finance providers and alumina and aluminum producers. Lending practices will likely evolve to meet the investment demands of the 1.5°C goal. This will mean boosting investment in low-carbon aluminum but also reducing investment in high-carbon projects. This kind of approach is encapsulated in the Poseidon Principles, a global framework for responsible ship finance that integrates climate considerations in lending decisions.[6] In aluminum, the Center for Climate-Aligned Finance (CAF) is working with three banking leads, leading aluminum producers, and partner organizations focused on sustainable finance to ensure that the objectives of firms in the aluminum sector and their financial partners are aligned and actionable.[7]

Bringing the community together. To meet net-zero targets, financial institutions need to work together to provide capital to both greenfield and retrofit projects. These kinds of partnerships are already developing. For example, the Net-Zero Banking Alliance, which brings together banks that are committed to aligning their lending and investments with net-zero emissions by 2050, currently represents 40 percent of global banking assets. The Glasgow Financial Alliance for Net Zero (GFANZ) has more than 450 members, representing $130 trillion of assets. GFANZ members will use science-based guidelines to reach net-zero emissions across all emissions scopes by 2050, as well as 2030 interim targets. GFANZ members report on their progress annually, including disclosures in line with the guidelines drafted by the Task Force for Climate-related Financial Disclosures (TCFD).

2.1.2 Policy levers

Governments have a key role to play in facilitating investment in decarbonization solutions as well as in promoting innovation. Mechanisms such as carbon pricing (through trading schemes or carbon taxes) show that policy can have a significant impact on corporate behaviors, while trade-based initiatives such as the European Union's Carbon Border Adjustment Mechanism use import duties to encourage both domestic and overseas producers to switch to cleaner technologies. Policy instruments such as carbon contracts for difference can create stable access to competitively priced clean electricity.

Government grants could offset some of the cost of investment. In the steel industry, CA $1.8 billion (US $1.3 billion)[8] in federal and provincial grants and loans enabled ArcelorMittal to convert a blast furnace to an electric arc furnace.[9] The conversion will lead to three million metric tons (or 60 percent) of emissions reduction.[10] The Canadian government has also provided support to Alcoa and Rio Tinto for research and development—for example, in relation to ELYSIS inert-anode technology, which promises to eliminate all direct GHGs from the traditional smelting process.[11] In Australia, Alcoa received support to test electric calcination, with AU $8.6 million (US $6.4 million) from the Australian Renewable Energy Agency (ARENA) and AU $1.7 million (US $1.3 million) from Western Australia's Clean Energy Future Fund (CEFF).[12]

Carbon contracts for difference (CCfDs) are a policy lever to help bring the operational costs of decarbonized operations in line with those of conventional technology (Exhibit 1). CCfDs typically offset the difference between the market price for emissions allowances (carbon price) and the cost of operating decarbonized technology. A price is selected for the decarbonized technology to level operational costs with those of conventional technology. When the operational costs exceed this level, the state pays the difference. Conversely, if the operational cost is lower than the agreed cost, the decarbonized facility pays the difference.

While no entity in the aluminum industry has yet used CCfDs, Germany is considering providing €43 billion to support their application in heavy industry. The vision is a ten-year agreement that will result in an offset of 20 million metric tons of CO_2e emissions per year.[13] A similar scheme has been implemented in the United Kingdom, supporting 16 GW of low-carbon electricity (enough to power 15 million homes).[14]

2.1.3 Demand levers

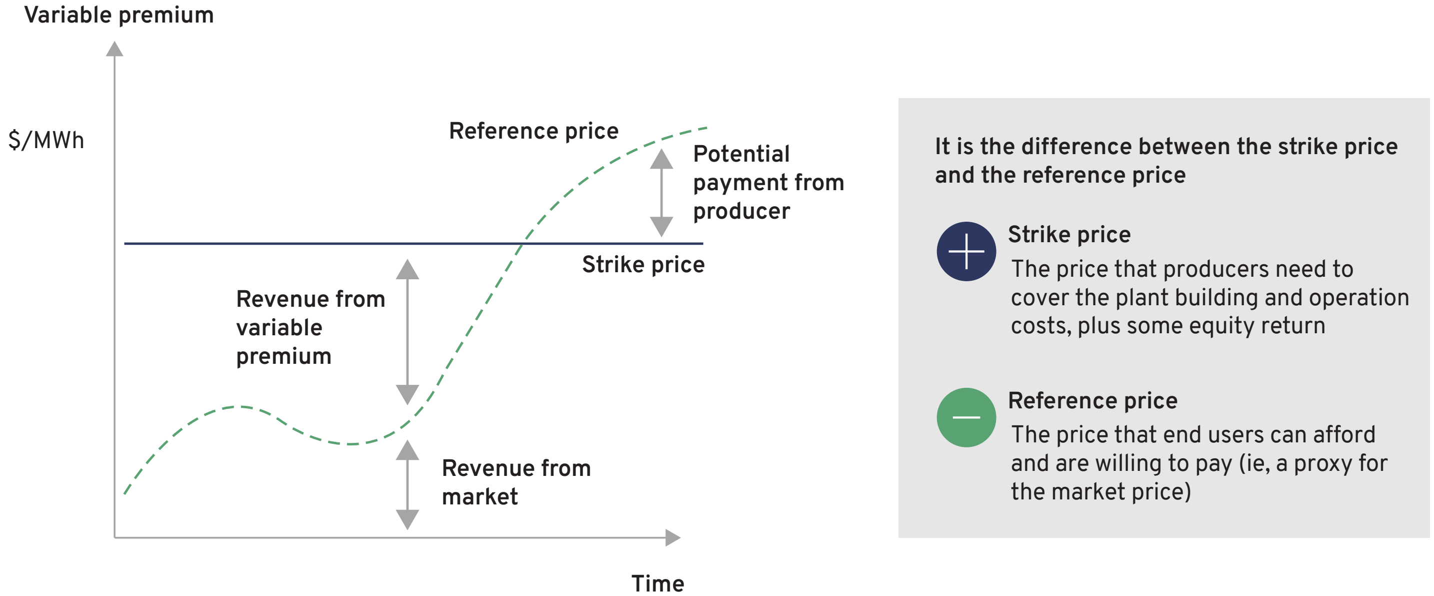
End users can play a role in supporting green investments by paying more or making firm commitments to purchase. In the former case, private- or public-sector buyers can pay a green premium when carbon emissions are below a certain threshold, such as less than 0.1 tCO_2e/t of alumina or below 4.0 tCO_2e/t of aluminum. According to Fastmarkets, a cross-commodity price reporting agency, green premiums have reached about 1 percent of the London Metal Exchange (LME) price, but they could climb to 5 to 10 percent.[15]

> ***"One of the challenges to decarbonization is that the current best available technology often has an NPV that is greater than the green-investment scenario."***

EXHIBIT 1

A variable premium in the carbon contracts for difference model is the difference between the reference price and strike price.

The variable premium is the $/MWh of hydrogen subsidized above the market value of low-carbon hydrogen by the UK government



Source: *Low carbon hydrogen business model: Consultation on a business model for low carbon hydrogen*, Section 4.1, UK Department for Business, Energy & Industrial Strategy, 2021.

Offtake agreements are arrangements between buyers and sellers to purchase a quantity of product at a defined price. They may be negotiated before a factory is constructed or begins operating, as well as for major retrofits, significantly cutting investment risk.

Many companies are working hard to decarbonize their aluminum supply chains. Apple, for example, is targeting net-zero climate impact across all business functions by 2030[16] and has announced that its new iPhone SE will use net-zero aluminum produced by ELYSIS.[17]

2.2 Combining levers: Five scenarios

One of the challenges to decarbonization is that the current best available technology often has an NPV that is greater than that of the green-investment scenario. Moreover, no single lever will be sufficient to support aluminum industry decarbonization on its own. The most likely scenario is that companies will adopt a mix of levers that facilitate either green investment or demand-side drivers. By combining levers, stakeholders can close the NPV gap for low-carbon investments (achieving a green premium) and secure cash flows. In general, finance will play a relatively minor role in bridging the NPV gap, particularly in cases with less capital expenditure, but it will play a more significant role where capital investment is more dominant—for example, in inert-anode retrofits.[18]

To model some likely combinations of levers and technology, this paper presents five scenarios that would either create a green premium or support demand.[19] These combinations of levers are illustrative; the user can explore the benefits of these scenarios through the supporting tool.

> *“Inert-anode technology can have similar electricity intensity as the Hall-Héroult process or as much as 20 percent higher, so smelters that rely on green electricity are suitable to retrofit with inert-anode technology.”*

2.2.1 Scenario 1: Retrofit of smelter in captive plant in the Middle East

Smelting operations in the Middle East have seven million metric tons of aluminum capacity, while electricity is mostly derived from natural-gas combined-cycle (NGCC) plants. NGCC is an advanced technology that improves the efficiency of natural gas. The scenario considers retrofitting the smelter and natural-gas facility with CCS.

- Best available technology: existing smelter with captive gas
- Green investment: retrofit CCS on smelter and NG power plant

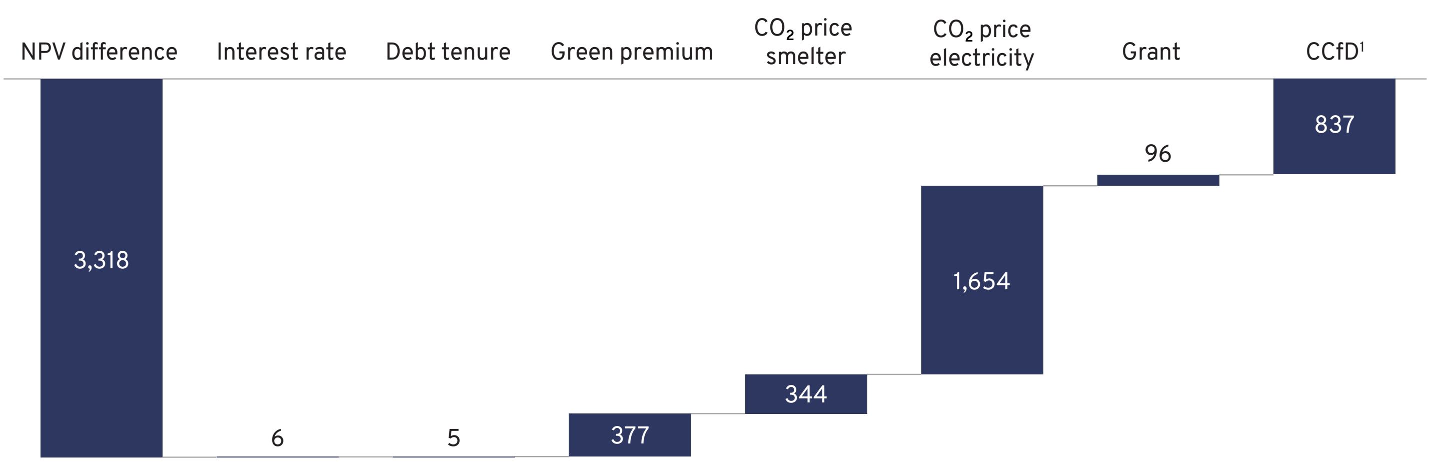
Retrofitting a smelter in the Middle East with CCS would produce a negative NPV of about $3.3 billion (Exhibit 2). Setting up a carbon price for both smelter and electricity generation (about $60 per tCO_2e as a starting price) and a CCfD for ten years (worth $150 million a year) could improve the investment NPV to offset the increasing operating costs of CCS. Since green-investment operating expenditure is higher than BAT, finance levers would have a smaller impact than demand and policy levers, which would attenuate the increased operating expenditure from CCS.

In this specific illustrative combination of levers, the finance levers make a relatively small contribution to reducing the NPV difference. This is for two reasons. First, significant CCS capital expenditures are required to retrofit the smelter and the natural-gas power plant. Second, there are increased operating expenditures for running the CCS plants, as compared with ongoing operations, where a reduction of interest rate and increase of loan duration are not enough to bridge the NPV difference.

EXHIBIT 2

Policy levers could improve the investment case for retrofitting a smelter in a captive power plant in the Middle East.

Net present value (NPV), based on 2022, $ millions



	Interest rate	Debt tenure	Green premium	CO_2 price smelter	CO_2 price electricity	Grant	CCfD[1]
Impact	0%	0%	11%	10%	50%	3%	25%
NPV of green investment vs base case	Interest rate decrease by 1 p.p.[2] (from 5.1% to 4.1%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $100 per ton aluminum (5% of LME[3]) for 30 years	Carbon price of $60 per ton CO_2 emitted for smelter for 30 years	Carbon price of $60 per ton CO_2 emitted in captive electricity emissions for 30 years	$100 million grant	Remainder of delta NPV covered by CCfD,[1] $150 million annually for 10 years

Note: Assuming green premium on aluminum will last 30 years; assuming carbon price applicable for 30 years and growing 0.5% per year; assuming carbon contracts for difference (CCfD) will last 10 years.
[1] Carbon contracts for difference.
[2] Percentage point.
[3] London Metal Exchange.
Source: McKinsey analysis

2.2.2 Scenario 2: Retrofit inert anode on smelter in Europe

Europe's customers are likely the most advanced globally in pursuing decarbonization targets, which is encouraging smelters to further decarbonize.[20]

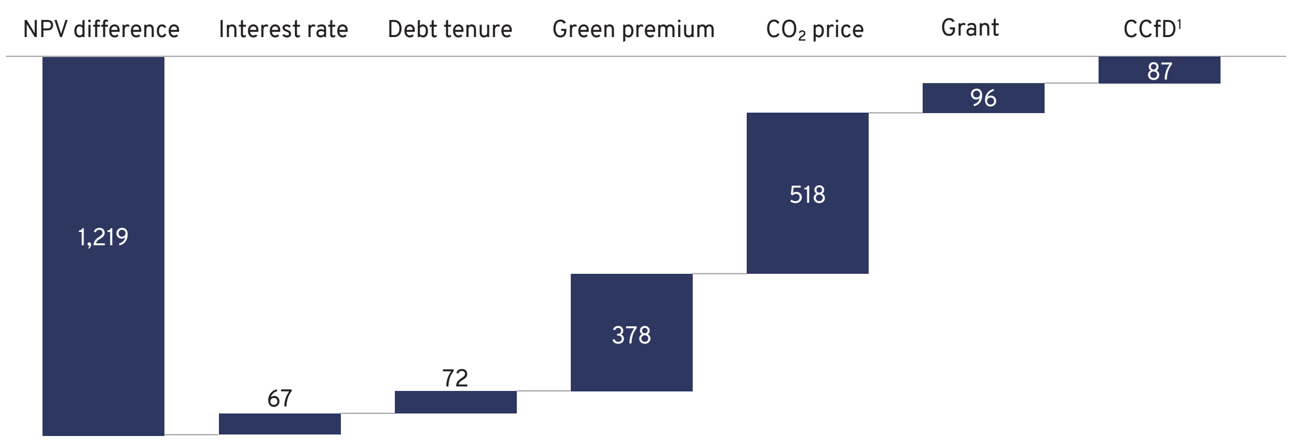
- Best available technology: existing smelter with captive hydro
- Green investment: retrofit inert anode

Inert-anode technology can have similar electricity intensity as the Hall-Héroult process or as much as 20 percent higher, so smelters that rely on green electricity are suitable to retrofit with inert-anode technology. Because there is uncertainty around the exact electricity intensity of this solution, we have expanded the analysis to two scenarios: a 15 percent increase over the current average (16 MWh/t of aluminum), and with equivalent consumption to current Hall-Héroult (13.8 MWh/t of aluminum). Retrofitting a smelter in Europe with inert anodes would have a negative NPV of about $1.2 billion when assuming electricity intensity of 16 MWh/t of aluminum (Exhibit 3). Under the second scenario (Hall Héroult–equivalent consumption), a combination of lower electricity intensity, a green premium, and the carbon price would be sufficient to make investment in inert-anode technology NPV neutral (Exhibit 4).

EXHIBIT 3

Green premiums and CO_2 prices may be required for inert-anode retrofit to have equal net present value in the European Union.

Net present value (NPV), based on 2022, $ millions



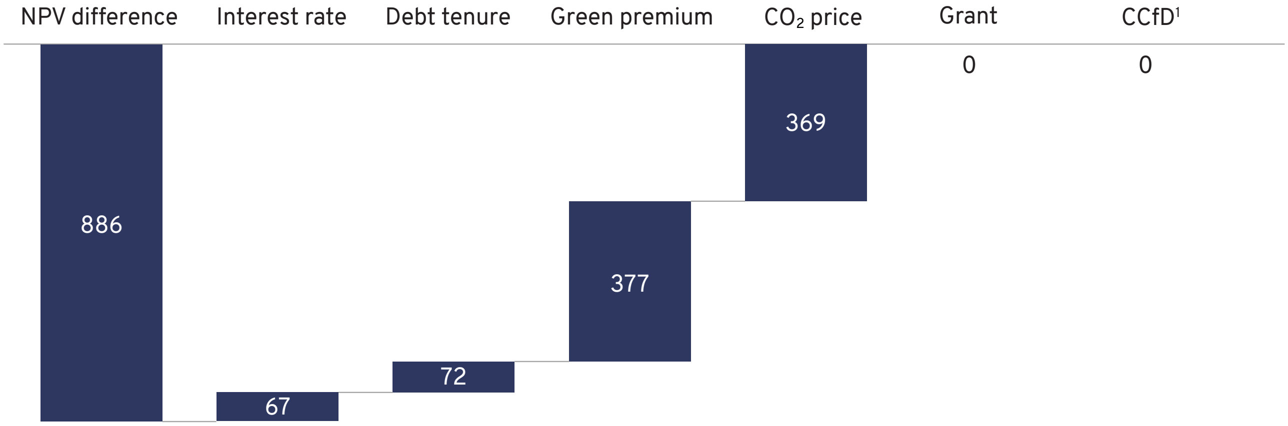
Impact	**6%**	**6%**	**31%**	**43%**	**8%**	**7%**
NPV of green investment vs base case	Interest rate decrease by 1 p.p.[2] (from 3% to 2%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $100/t aluminum	Carbon price of $60 per ton CO_2 emitted for smelter process emissions only	$100 million grant	Remainder of delta NPV covered by CCfD,[1] $15 million annually for 10 years

Note: Assuming electricity intensity of 16 MWh/t of aluminum.
[1] Carbon contracts for difference.
[2] Percentage point.
Source: Mission Possible Partnership

EXHIBIT 4

Green premiums and CO_2 prices may likely be required for inert-anode (with electricity intensity of 13.8 MWh/t) retrofit investment to have equal net present value in the European Union.

Net present value (NPV), based on 2022, $ millions



	Interest rate	Debt tenure	Green premium	CO_2 price	Grant	CCfD[1]
Impact	8%	8%	43%	42%	0%	0%
NPV of green investment vs base case	Interest rate decrease by 1 p.p.[2] (from 3% to 2%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $100/t aluminum	Carbon price of $43 per ton CO_2 emitted for smelter process emissions only	N/A	N/A

Note: Assuming electricity intensity of 13.8 MWh/t of aluminum.
[1] Carbon contracts for difference.
[2] Percentage point.
Source: Mission Possible Partnership

2.2.3 Scenario 3: Retrofit inert anode on smelter in China

China has the largest aluminum smelting capacity and one of the largest aluminum CO_2e footprints, and it is deploying the most solar, off-shore wind, and nuclear energy capacity.[21] Our analysis thus focuses on inert anodes powered by a green grid. Given the uncertainty around the electricity intensity of inert-anode technology, we use two scenarios.

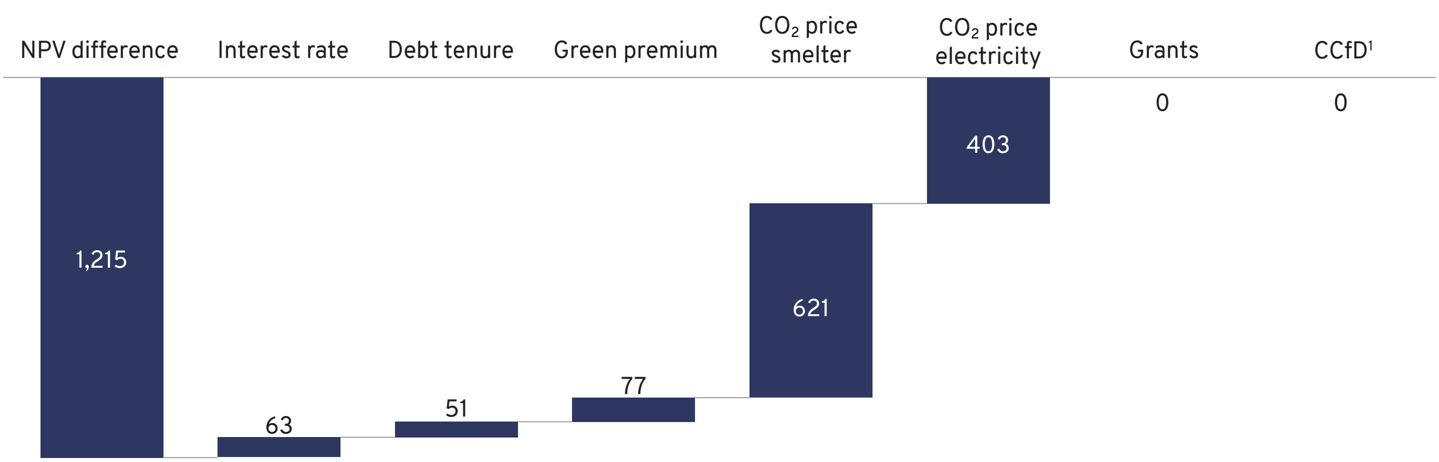
- Best available technology: existing smelter with captive coal
- Green investment: retrofit inert anode plus grid

Retrofitting a smelter in China with inert-anode technology and connecting it to the grid would have a negative NPV of $1.2 billion when assuming inert-anode electricity intensity of 16 MWh/t of aluminum (Exhibit 5). If similar intensity to Hall-Héroult is assumed, the negative NPV would be about $400 million (Exhibit 6). Since the base case is a coal-fired smelter, policy levers applied to electricity generation could have a significant impact.

EXHIBIT 5

Policy levers such as CO_2 pricing are needed to enable investments in inert anodes (electricity intensity of 16 Mwh/t) in China.

Net present value (NPV), based on 2022, $ millions



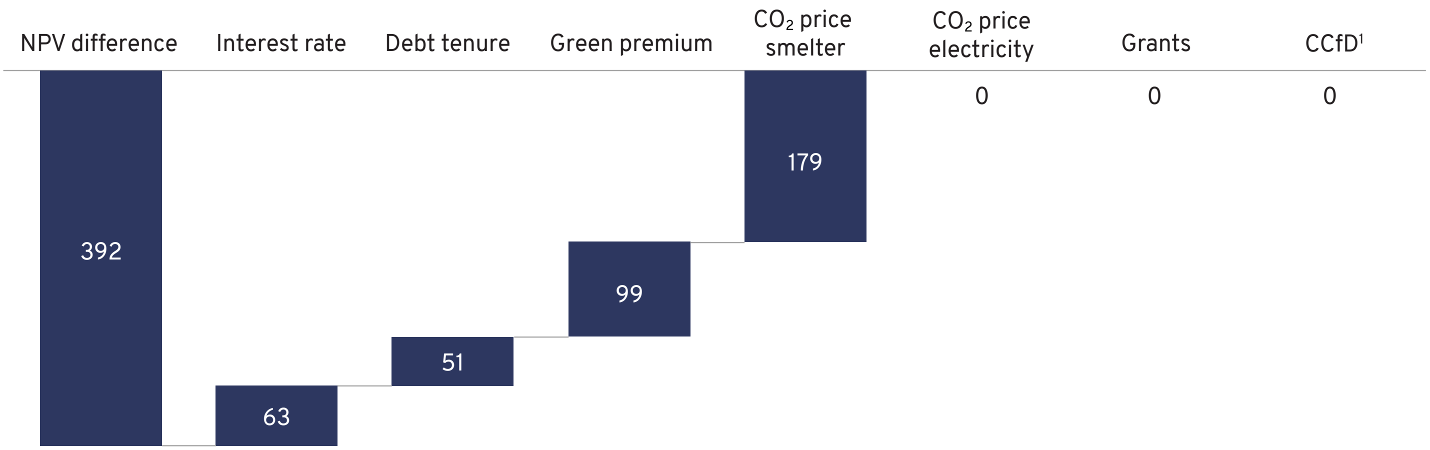
	Interest rate	Debt tenure	Green premium	CO_2 price smelter	CO_2 price electricity	Grants	CCfD[1]
Impact	5%	4%	3%	27%	60%	0%	0%
NPV of green investment vs base case	Interest rate decrease by 1 p.p.[2] (from 5.1% to 4.1%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $100 per ton Al (5% of LME) for 30 years	Carbon price of $60 per ton CO_2 emitted for smelter for 30 years	Carbon price of $7 per ton CO_2 emitted captive electricity emissions for 30 years	N/A	N/A

Note: Assuming electricity intensity of 16 MWh/t of aluminum; assuming green premium on aluminum to last 30 years; assuming carbon price applicable for 30 years and growing 0.5% per year; assuming carbon contracts for difference to last 10 years.
[1] Carbon contracts for difference.
[2] Percentage point.
Source: Mission Possible Partnership

Policy levers such as CO_2 pricing are needed to enable investments in inert anodes (electricity intensity of 13.8 MWh/t) in China.

EXHIBIT 6

Net present value (NPV), based on 2022, $ millions



	Interest rate	Debt tenure	Green premium	CO_2 price smelter	CO_2 price electricity	Grants	CCfD[1]
Impact	16%	13%	25%	46%	0%	0%	0%
NPV of green investment vs base case	Interest rate decrease by 1 p.p.[2] (from 5.1% to 4.1%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $100 per ton Al (5% of LME[3]) for 30 years	Carbon price of $21 per ton CO_2 emitted for smelter for 30 years	Carbon price of $60 per ton CO_2 emitted captive electricity emissions for 30 years	N/A	N/A

Note: Assuming electricity intensity of 13.8 MWh/t of aluminum; assuming green premium on aluminum will last 30 years; assuming carbon price applicable for 30 years and growing 0.5% per year; assuming carbon contracts for difference will last 10 years.
[1] Carbon contracts for difference.
[2] Percentage point.
[3] London Metal Exchange.
Source: Mission Possible Partnership

2.2.4 Scenario 4: Retrofit refinery in Oceania with MVR

Oceania is the second-largest producer of alumina, and the Australian Renewable Energy Agency (ARENA) has deployed a number of projects focused on decarbonizing alumina refineries. This has supported the development of MVR retrofit in digestion and hydrogen-calciner development. The scenario envisages retrofitting an Oceania refinery with MVR for digestion steam and hydrogen-fired calciner.

- Best available technology: existing refinery utilizing gas
- Green investment: retrofit MVR and hydrogen (H_2) calcination

Retrofitting a refinery in Oceania with MVR and green-hydrogen calciner would have a negative NPV of $1 billion (Exhibit 7).

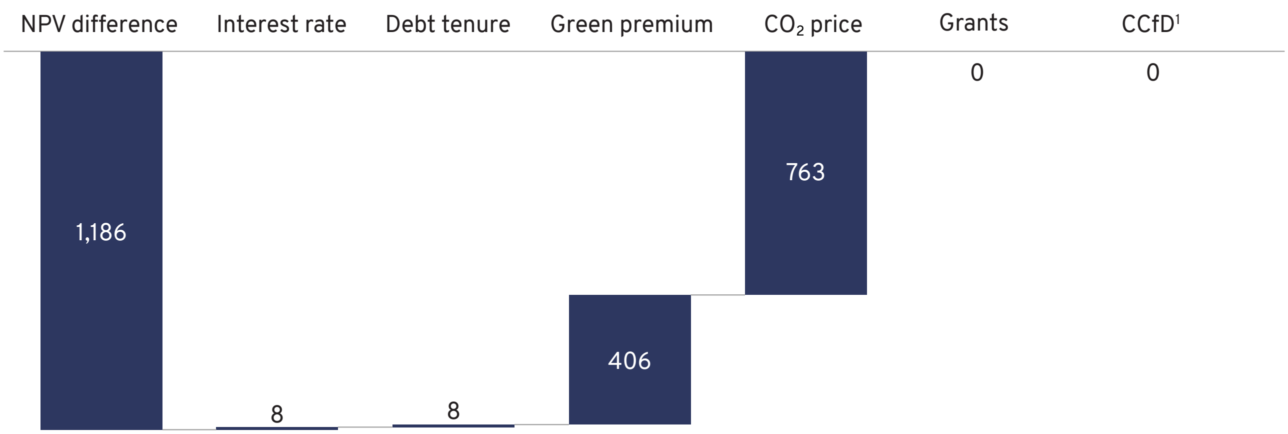
Since the base case is an NG-based calciner, policy levers applied to heavy emitters could have a significant impact.

Oceania is the second-largest producer of alumina, and the Australian Renewable Energy Agency (ARENA) has deployed a number of projects focused on decarbonizing alumina refineries.

EXHIBIT 7

Policy levers such as CO_2 pricing are needed to enable investment in mechanical vapor recompression and H_2 calciner in Oceania.

Net present value (NPV), based on 2022, $ millions



	NPV difference	Interest rate	Debt tenure	Green premium	CO_2 price	Grants	CCfD[1]
Impact		< 0.5%	< 0.5%	34%	64%	0%	0%
NPV of green investment vs base case		Interest rate decrease by 1 p.p.[2] (from 5% to 4%)	Debt tenure increase by 5 years (from 20 to 25)	Green premium of $30 per ton of alumina (9% premium) for 30 years	Carbon price of $60 per ton CO_2 emitted for 30 years	N/A	N/A

Note: Assuming electricity intensity of 12 gigajoules/t; assuming green premium on aluminum will last 30 years; assuming carbon price applicable for 30 years and growing 0.5% per year.
[1] Carbon contracts for difference.
[2] Percentage point.
Source: Mission Possible Partnership

2.2.5 Scenario 5. Retrofit South America refinery with electric boiler for digestion steam and H_2-fired calciner

South America is an important alumina producer with a relatively decarbonized grid. It would be feasible to retrofit refineries with electric boilers supplied with low-carbon electricity and green-hydrogen calciners.

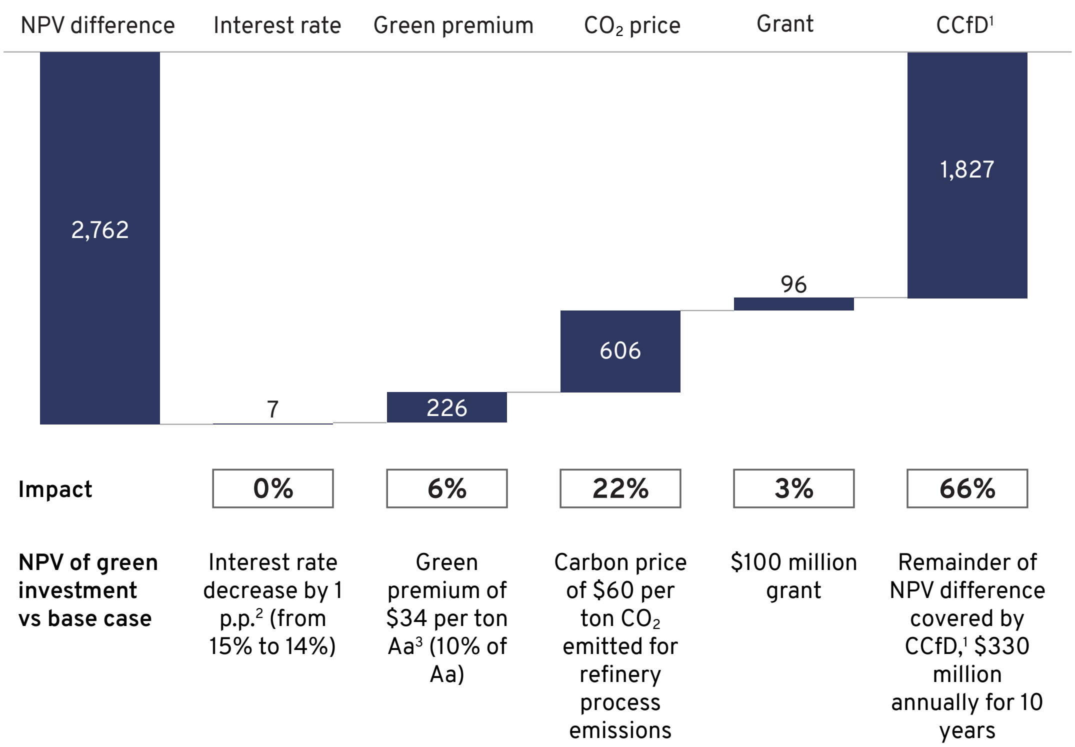
- Best available technology: existing refinery using gas
- Green investment: retrofit with electric boilers and H_2 calcination

Retrofitting a refinery in South America with electric boilers and H_2 calciner, replacing current natural-gas-based technologies, would have a negative NPV of about $2.8 billion. Setting up a carbon price (approximately $60 per tCO_2e) and a CCfD for ten years (worth $330 million per year) could improve the investment NPV and offset prices for green hydrogen and green electricity (Exhibit 8). The electric boiler carries a larger negative NPV than MVR, which is more efficient from a thermal-energy perspective.

EXHIBIT 8

Policy levers such as carbon contracts for difference may likely be required for green refinery investment to be economical.

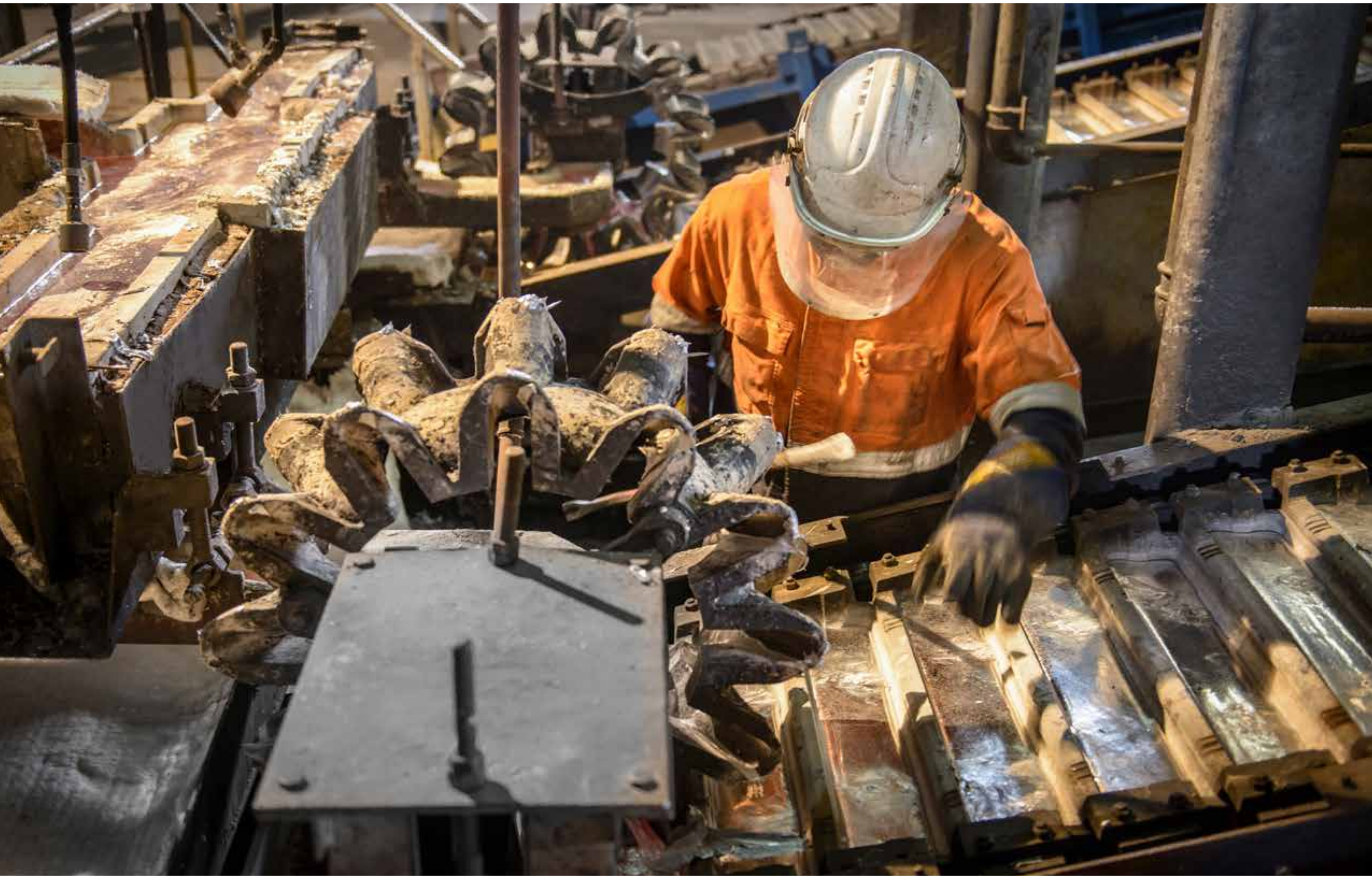
Net present value (NPV), based on 2022, $ millions



Note: Assuming green premium on alumina will last 5 years; assuming carbon price applicable for 30 years and growing 0.5% per year; assuming CCfD will last 10 years.
[1] Carbon contracts for difference.
[2] Percentage point.
[3] Alumina.
Source: Mission Possible Partnership

PART III

ROLES FOR STAKEHOLDERS



Whichever route is taken to decarbonization, it will require an effort from all players in the aluminum value chain. That said, individual approaches will vary—businesses will adopt decarbonization technologies that reflect local conditions, policy measures, and financial arrangements. For smelters relying on carbon-intensive electricity sources, for example, a carbon-pricing scheme that includes power emissions would better enable green investment. Where the operating expenditure gap to BAT is more relevant than the capital expenditure gap, demand and policy levers would play a more important role.

3.1 End users

The analysis shows that end users would need to pay a green premium to offset a negative NPV in all five scenarios. It assumes a 5 percent premium on the LME commodity price ($100/t aluminum) in smelter cases and a 10 percent premium ($34/t) on alumina for the refinery cases. These would both improve the NPV of the green-investment option.

Many aluminum consumers have decarbonization goals for their supply chains, so paying a premium could still be attractive.

Indeed, increased demand for green products would help shift the aluminum industry further toward decarbonization. Still, some end users are unlikely to see a substantial increase in final product prices after incorporating green-aluminum premiums into production costs. For example, at a green premium of $100/t aluminum, the final cost of a new car would increase by just 0.01 percent.[22] Even if the green premium covered the total additional cost of fully decarbonized aluminum production (estimated to be about $400/t in 2035[23]) and the aluminum in cars rose to 200 kilograms (kg) as projected, the final cost would increase by just 0.2 percent.

Furthermore, many aluminum consumers have decarbonization goals for their sourcing and supply chains, so purchasing a green aluminum product with a premium could likely be acceptable to consumers. In short, rising end user demand for green products will help shift the aluminum industry toward decarbonization.

3.2 Governments

The analysis shows that the greatest NPV impact comes from from carbon-pricing measures. This could shift the NPV balance in favor of decarbonized investment because emissions are covered by a carbon price. On that basis, the traditional smelter is substantially more expensive. In all scenarios, the analysis considers the impact of a starting carbon price of $60/tCO_2e$, growing 0.5 percent per year.

There is, however, an additional gap that needs to be covered. Grants and CCfDs could offset the capital and operating costs associated with decarbonized investment, even though the impact would be relatively low compared with that of carbon price mechanisms.

3.3 Financial institutions

Financial institutions also have the capability to shift cash flows and allocate significant funds to green investments. Due to generally high levels of debt as a share of total capital for investments in the aluminum industry (typically 50 to 75 percent), the bond and loan markets would be key enablers. Financial institutions could use green loans, green bonds, transition bonds, and sustainability-linked loans and bonds to meet their decarbonization targets. If these instruments offered players a lower interest rate or a longer tenure compared with financial products directed at carbon-intensive activities, they would further support decarbonization.

Rising demand for low-carbon products is pushing the aluminium industry away from the carbon-emitting processes that have dominated production for the past 136 years. These positive steps are predicated on a more significant role for frontier technologies that could reduce or completely abate the GHG emissions in refineries and smelters.

However, the analysis in this paper shows that financial institutions, end users, and government will need to work together to turn frontier technologies into net-positive projects that players can scale. No player in the value chain can decarbonize the sector alone. Indeed, end users could pay a green premium to cover the decarbonization cost, likely including a higher premium to encourage the large-scale investment required to reach committed emission targets. In addition, governments and financial institutions will play a key role covering the remaining decarbonization cost and accelerating investment decisions to quickly deploy frontier technologies.

Aluminum smelting direct-process and raw-material emissions

The average global direct emissions from aluminum smelting, including carbon anode manufacturing, is 2.5 tCO_2e per metric ton of aluminum.[24]

The majority of emissions—1.5 tCO_2e/t of aluminum[25]—are process CO_2 emissions generated during carbon anode production. This is part of electrolytic reduction where aluminum is deposited in liquid form on the cathode and oxygen is deposited on the anode. Oxygen reacts with the anode to form CO_2 gas while the aluminum is tapped in batches from the cell.[26]

In addition to CO_2 emissions, the electrolysis process generates perfluorocarbon compounds (PFCs) in what is known as the anode effect. The anode effect occurs when the alumina dissolved in the cryolite melt falls to a concentration level too low to support the current flow at the nominal voltage for aluminum production. During these periods, which typically occur during 0.03–0.50 percent of the total electrolysis time, the voltage rises to a level where reactions are initiated that produce the PFCs.[27] The average global emissions of PFCs are 0.5 tCO_2e/t of aluminum and can be reduced to 0.02 tCO_2e/t of aluminum by implementing best practices.[28]

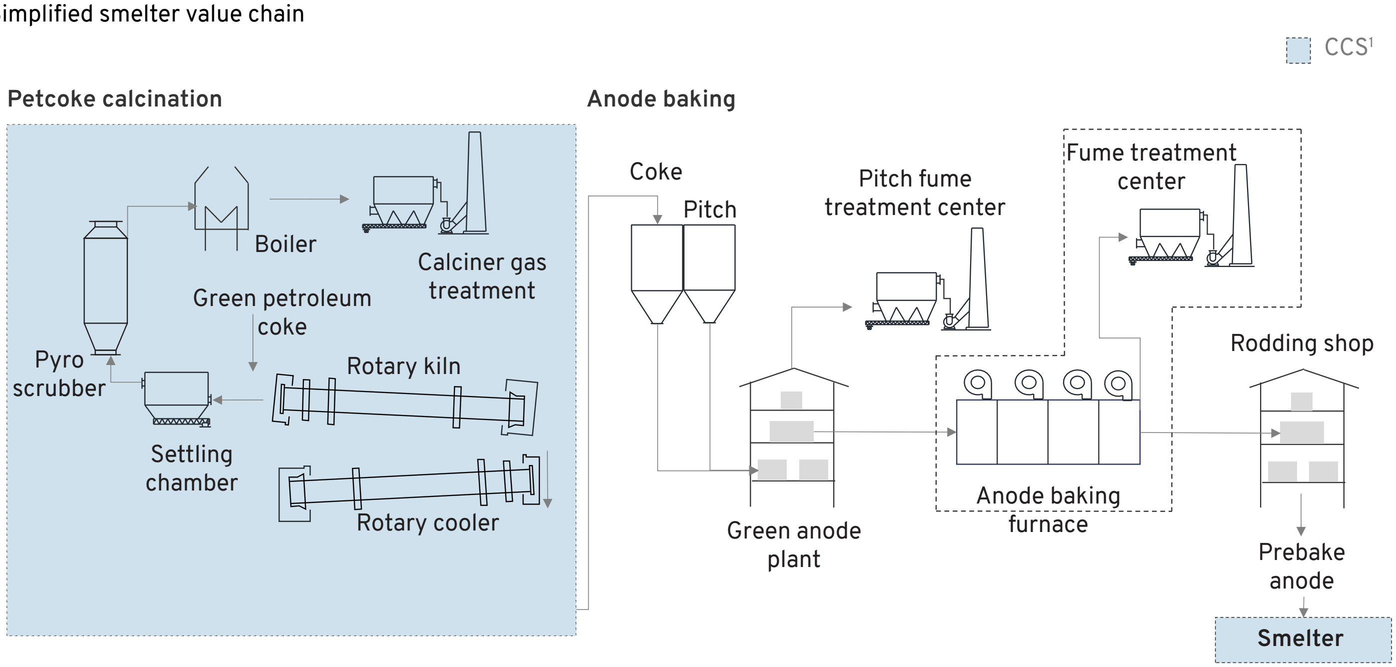
The remaining 0.5 tCO_2e/t of aluminum are associated with carbon anode manufacturing (Exhibit 9). This process requires the use of two main raw materials: calcined petroleum coke (CPC) and coal tar pitch (CTP). In the process, leftovers from dismantled anodes, called anode butts, are also recycled to reduce the use of raw material.

CPC is produced by processing raw "green" petroleum coke—a by-product of petroleum refining—into rotary kilns, where it is heated to temperatures between 1,200°C and 1,350°C. These high temperatures remove excess moisture, extract all remaining volatile hydrocarbons, and modify the crystalline structure of the coke, resulting in a denser, more electrically conductive product. CPC can be generated on-site or sourced from third-party companies. This process typically generates 0.3 tCO_2e/t of aluminum emissions.

EXHIBIT 9

Carbon capture and storage is applicable in different steps of the aluminum value chain.

Simplified smelter value chain



[1] Carbon capture and storage.
Source: Fives Group; Mission Possible Partnership; McKinsey analysis

The CPC is then processed to achieve a specific particle size distribution using a crushing and grinding circuit with particle classifiers. Once the required particle size distribution is reached, the processed petroleum coke is combined with CTP, a thick dark liquid, which is a distilled by-product of the production of coke and coal gas from coke ovens.

This mixture is molded to the required anode shape (denominated green anode) and then is thermally treated using an anode baking furnace. In this furnace, the green anodes are stacked between refractory walls separated by a flue channel in which hot gases flow. The overall baking cycle could last 10 to 14 days. For each metric ton of aluminum, about 0.4 t of anode is expected to be consumed. Because of the presence of volatile hydrocarbons, this process generates 0.1 t of CO_2e/t of aluminum from anode baking furnace direct thermal energy and 0.1 t of CO_2e/t aluminum from volatile-matter combustion.

The largest technical challenge to improving the energy efficiency of electrolysis is the development of a non-consumable inert anode.

Aluminum smelting direct-emission decarbonization levers

Most of the technical challenges associated with direct smelting emissions relate to CO_2 generation due to anode fabrication and anode consumption in the electrolysis process. For decades, the aluminum industry has been investigating the implementation of a non-consumable anode that could potentially abate most of the CO_2 generation during electrolysis and generate oxygen instead (inert anode). Carbon capture and storage (CCS) is also being explored as a way to retrofit existing operating smelters' facilities.

There are only three alternatives for aluminum smelters to decarbonize their direct smelting emissions, none of which is proven today (Exhibit 10):

- inert anode
- CCS
- carbochlorination with CO_2 regeneration

Inert anode: The potential aluminum game changer

Inert-anode technology has been seen as the main alternative to carbon anodes in the Hall-Héroult process. This technology requires use of an alternative, non-consumable material such as metal (for example, iron-nickel base alloy) or ceramic (including cermet) to replace the carbon anodes. Implementing this technology could increase the life span of the anodes by two to three years and generate oxygen as a by-product.

Wetted cathode is an alternative solution to improve system efficiency. This technology uses titanium diboride (TiB_2) to wet the cathode surface. By creating a cathode surface that is inert and wettable on the molten aluminum pad, the anode-cathode distance can be reduced by 50 percent or more, reducing the voltage drop and leading to substantial energy savings.

Inert-anode technology, coupled with wetted cathodes, offers the greatest opportunity to reduce GHG emissions with high efficiency. It eliminates the CO_2 and PFCs (particularly carbon tetrafluoride) associated with the consumption of the carbon anodes, as well as the need to manufacture a carbon anode in the first place.[29] However, direct-process and raw-material emissions from inert anodes could be 0.25 t of CO_2/t of aluminum, mostly linked to the production of ceramic-base inert anodes.[30] The electricity intensity of inert anodes is still uncertain, but could be as much as 20 percent more than in the Hall-Héroult process.[31]

There is currently no industrial-scale inert anode–based technology for aluminum smelting, though multiple companies are exploring the idea, and a commercial-scale plant is expected to be developed by 2030. ELYSIS (a joint venture among Alcoa, Apple, Rio Tinto, and the Canadian government) is running industrial trials at the Alma smelter in Canada. Apart from these two examples, there is very little public information on inert-anode operational performance, and estimates on when this will be adopted on an industrial scale vary vastly.

Retrofit Hall-Héroult and raw-material process with CCS

Deployment of CCS in the industry and transformation sector (cement, chemicals, fuel, and steel) shows promise for this approach to CO_2 abatement. These sectors accounted for 30 commercial CCS facilities in operation in 2021, with many more planned, including in the steel industry.[32]

Implementation in the aluminum industry is possible but presents challenges relating to low CO_2 concentration in the off-gas stream (Exhibit 11). This low concentration, specifically on the smelter process, is associated with the entrainment of fresh air required to manage the process heat balance. As a consequence, overall CO_2 concentration is reduced to about 1 volume percent. One alternative is to redesign the

EXHIBIT 10

Several smelter technologies have the potential for a low-CO_2 footprint.

■ Process CO_2 ■ Anode production ◔ Low ● High

	Hall-Héroult (HH)	HH + carbon capture and storage (CCS)	HH with CCS and electric anode baking with CCS	Inert anode
Approach	Global average smelter using 100% green electricity	Typical smelter using 100% green electricity with CCS	Typical smelter using 100% green electricity with CCS, electric anode baking with CCS, and petcoke calcination with CCS	Retrofit current HH, reusing potrooms holes, though cell needs to be redesigned
Emerging example	En+ Group, Hydro, Rio Tinto	Alvance, Hydro, Rio Tinto	N/A	Alcoa and Rio Tinto (ELYSIS), En+ Group
Aluminum smelter emissions, tCO_2 per t aluminum[1]	2.0 (Process CO_2 1.5; Anode production 0.5)	1.0 (Process CO_2 0.5; Anode production 0.5)	0.7 (Process CO_2 0.5; Anode production 0.2)	0.3
Logic or limitation	Multiple players including Chalco, Emirates Global Aluminium (EGA), and Hongqiao are exploring renewable-energy sources to fossil-fuel generation sources	Technology is still in its infancy Assuming 70% CCS efficiency, no PFC[2] capture and no reduction in carbon anode production emissions	Technology is still in its infancy Assuming 70% CCS efficiency, no PFC capture and green electricity for electric anode	Technology developments in the past 10 years
Maturity	●	◔	◔	◑ ELYSIS commercial demonstration by 2026

Note: Figures may not sum, because of rounding; excluding transport and raw material input; assuming perfluorocarbon control with best available technology (BAT).
[1] Metric tons of carbon dioxide per metric ton of aluminum across Scopes 1 and 2, including process CO_2 emissions, process non-CO_2 emissions, and anode fabrication emissions including raw materials (0.5).
[2] Perfluorocarbon. Assuming BAT marginal emissions of 0.02 t of CO_2e/t of aluminum.
Source: "Modular primary aluminium plant based on beck cells with multiple vertical inert anodes and wettable inert cathodes," Arctus Metals, April 5, 2017; Asbjørn Solheim, "Inert anodes—the blind alley to environmental friendliness?," *Light Metals*, 2018; Bjarte Øye, "Carbochlorination routes in production of Al," HighEFF, 2018; Efthymios Balomenos et al., "Carbothermic reduction of alumina: A review of developed processes and novel concepts," *Proceedings of the European Metallurgical Conference*, 2011; International Aluminium Institute; Mazin Obaidat et al., "Energy and exergy analyses of different aluminum reduction technologies," *Sustainability*, 2018, Volume 10, Number 4; Alcoa; EGA; Hydro; Rio Tinto

aluminum-smelter pots to avoid air leakage and increase the CO_2 concentration by 4–10 volume percent so the CCS process becomes economically viable.[33]

The anode production value chain could also benefit from implementing CCS. Although this portion of the value chain still has low CO_2 concentration (less than 10 volume percent), evolution in CCS technology applied to the cement industry could likely be retrofitted to the petcoke calcination process (similar usage of rotary kiln). The process of CO_2 concentration could also be boosted by oxyfuel firing and retrofitting existing operations with heat recovery units (such as boilers). This would avoid the use of bleed air to reduce gas temperature.[34]

The last portion of the anode value chain that could benefit from CCS implementation is the anode baking furnace. This technology could reduce CO_2 emissions from both direct energy input and volatile-matter combustion. Alternatively, considering that about 50 percent of energy for anode baking is related to direct energy input (mostly from natural gas or oil firing), the process could be reengineered to implement electric heating (with access to renewable energy) and to combine direct or air capture to reduce the remaining 0.1 t of CO_2e/t aluminum.

Among all CCS use cases, aluminum smelting, petcoke calcination, and anode baking furnace have a relatively low CO_2 concentration compared with natural-gas processing,

EXHIBIT 11

Typical aluminum value chain CO_2 concentrations are low compared with other industries.

Integrated aluminum CO_2 point sources and concentration

Integrated-route CO_2 point sources	CO_2e emissions across value chain, t CO_2e/t aluminum	Typical CO_2 concentration, %
Refinery (digestion)	0.9	3–5%
Refinery (calcination)	0.4	4–6%[2]
Petcoke calcination	0.3	4–8%
Anode baking	0.1; 0.1	3–5%
Smelter	1.6[1]	~1%

Industrial plant CO_2 concentration, %

Ethanol; ammonia; natural-gas (NG) processing; ethylene oxide; CTL[3]; GTL[4]	90+
Oxyfuel power generation	80
Refinery hydrogen	45
Cement	22
Coal power plant	14
NG combined cycle	5

[1] Including CO_2 and perfluorocarbons and assuming 1.5 t CO_2/t aluminum (Al) and 0.05 t CO_2/t Al, respectively.
[2] Based on natural-gas firing.
[3] Coal to liquid.
[4] Gas to liquid.
Source: "Cost of capturing CO_2 from industrial sources," US Department of Energy and NETL, January 10, 2014; Anna Carpenter, "CO_2 abatement in the iron and steel industry," IEA Clean Coal Center, January 2012; Henk Kortes and Ton van Dril, "Decarbonisation options for the Dutch aluminium industry," IPCC; NRCAN; PBL Netherlands Environmental Assessment Agency, June 4, 2019

cement rotary kilns, or coal-fired power plants. However, CCS is likely to be viable on smaller emissions sources only if sites can combine carbon capture on-site with smelter process CCS. Since many smelters do not have on-site anode production, this is a key barrier. Therefore, for first-of-a-kind projects, the CO_2e avoided capture rate would likely be below 90 percent. Assuming a 70 percent efficiency factor, the implementation of CCS in the smelter and raw-material process could reduce the CO_2e emissions from 2.0 t of CO_2e /t aluminum to 0.7 t of CO_2e/t aluminum (Exhibit 12).

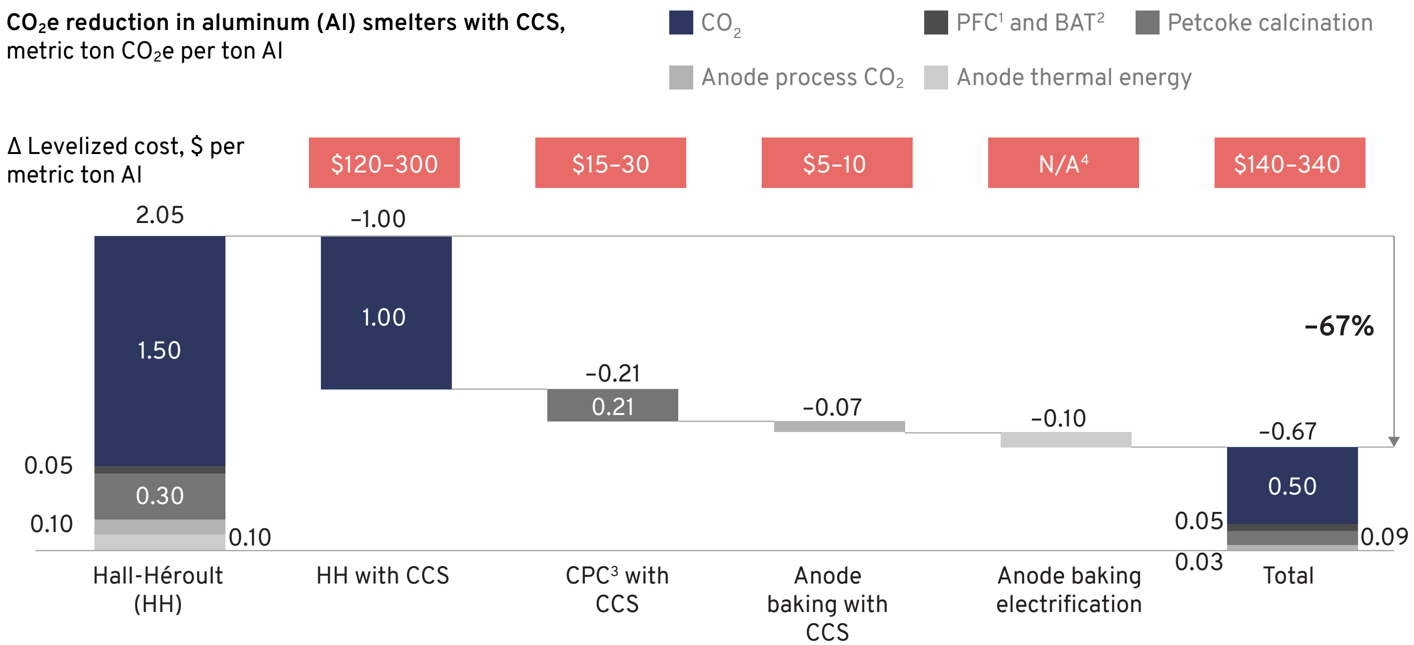
Carbochlorination with CO_2 regeneration

Carbochlorination with CO_2 regeneration is an alternative to the current aluminum smelting process.[35] Alcoa developed this process as a proposed alternative to the Hall-Héroult process. One of the initial benefits was a significant reduction in specific energy consumption (about eight MWh/t of Al), and the electrolysis could be carried out in a lower electrolyte temperature (about 720°C).

As proposed by Alcoa, the process includes the chlorination of aluminum oxide (alumina) obtained in the Bayer process, using CO as a reducing agent and chlorine gas (Cl_2) as a chlorination agent. The resulting aluminum chloride ($AlCl_3$) is then electrolyzed using a bipolar cell. The advantage of this process over the conventional Hall-Héroult process is that the aluminum chloride electrolysis produces a pure stream of Cl_2 that can be recycled back into the chlorination process, while the chlorination process produces a pure stream of CO_2 that could potentially be combined with CCS. The industry is also exploring the alternative of CO regeneration, which could reduce the use of CO (mostly generated by conventional sub-stoichiometry combustion). This would be through a closed-loop circuit that would electrolyze the generated CO_2 and

EXHIBIT 12

Implementation of carbon capture and storage technology could reduce smelter CO_2 emissions by more than 60 percent.



Note: Carbon capture and storage (CCS) efficiency considered at 70%; anode baking electrification CO_2 reduction based on fuel energy savings and utilization of green energy.
[1] Perfluorocarbon.
[2] Best available technology.
[3] Calcined petroleum coke.
[4] Data not available; technology is still in the conceptual phase and being formulated for this application (technology readiness level [TRL] = 2).
Source: "Electrification in primary aluminum," Kanthal, October 27, 2020; Felix Keller et al., "Specific energy consumption in anode baking furnaces," *Light Metals*, 2010; Olivier Lassagne et al., "Techno-economic study of CO_2 capture for aluminum primary production for different electrolytic cell ventilation rates," *Chemical Engineering Journal*, 2013, Volume 230

convert it back into CO. The process could add extra energy consumption of five MWh/t Al.

Although this process has been studied for a long time, project development is stalled because of difficulties associated with production and handling of pure aluminum trichloride. Aluminum players are still considering the benefits, with potential deployment of pilot operations by 2030 and an industrial-scale plant in the midterm.

Decarbonization capital expenditures

Capital expenditures for the Hall-Héroult process range from $2,100/t Al capacity (mostly in China) to $6,000/t Al capacity (mostly in Canada and Norway).[36] Approximately 50 percent of this cost is associated with the area where the pots are installed, pot technology, and the anode production facility (Exhibit 13).

Retrofitting existing Hall-Héroult smelters with CCS technology, taking into account a CO_2 concentration of 1 volume percent, could potentially add about 5 percent of the initial capital cost of the project.

The implementation of inert-anode technology could come at a similar capital cost to conventional smelter technology. Compared with Hall-Héroult technology, inert-anode projects have higher potroom costs, mostly associated with technology differences. Inert anodes would be produced in a centralized facility owned by the technology provider. Therefore, facilities will not require on-site anode production, and smelters will need to purchase the inert anodes to replace anodes that are near the end of life (two to three years). Given that the technology provider will own the technology and the intellectual property, capital expenditures will not vary significantly across regions.

Decarbonization operating expenditures

In 2021, the average operating cost of aluminum smelters worldwide was calculated to be between $1,654 and $1,750 per metric ton of aluminum,[37] with more than 88 percent of the cost associated with raw materials (44 percent), electricity[38] (30 percent), and anode production and consumption (14 percent) (Exhibit 14).

The implementation of CCS in existing smelter facilities could potentially lift overall operating costs by 6 percent, with most of the share (about 5.6 percent) associated with CCS operating costs and the balance with CCS energy consumption over Hall-Héroult cost.

Inert-anode technology, on the other hand, shows an operating cost reduction of 3–10 percent. Although energy consumption could be 20 percent higher than with Hall-Héroult, the longer life of the anode or cathode has a cost benefit. This wide range is associated with the implementation of the technology and the respective technology learning curve, with the first years of operation having the lowest cost benefit compared with existing smelting technology. This would rapidly increase during the first years of operation while the industry implements commercial improvements and best practices. This learning curve is expected to be rapid (one to two years) because of extensive pilot testing in the past decade. In order to be cheaper than existing Hall-Héroult technology, inert anodes will likely need to have a life span or two years or more, and cathodes will likely need to work for four years or more.

Refining: The Bayer process

The Bayer process can be separated into two main carbon intensive processes: digestion and calcination.

Digestion operating expenditures and capital expenditures

Decarbonization levels in refinery digestion plays an important role but requires extra investment for retrofitting of existing facilities. In this comparison, a natural-gas boiler was utilized as the baseline "best available technology." The natural-gas boiler assumes overall capital expenditures of $50 per metric ton of alumina (Aa) and operating expenditure cost of $63/t Aa, mostly associated with fuel costs (Exhibit 15).

An electric boiler could incur an additional capital-project cost of 10 percent, while operating costs associated with electricity sourcing could rise by 35 percent (assuming an electricity price of $37/MWh). Hydrogen-fired boiler prices could incur a similar capital expenditure as natural-gas boilers, but operating costs would be highly dependent on hydrogen prices and increase fuel cost about 4.3 times over existing natural-gas operations.[39]

Implementation of MVR technology shows the most reduction in operating costs—approximately 40 percent. This is mostly associated with heat loss recovery from the process. Despite the reduction in operating costs, the technology incurs higher capital expenditures with an increment of about 50 percent compared with natural-gas boilers.

Calcination operating expenditure and capital expenditure

The implementation of a green-hydrogen-based calciner could have the best decarbonization potential for calcination under a gas suspension technology baseline, considering that existing installed technologies could be quickly retrofitted for hydrogen firing.

Carbon capture could be an alternative solution when sourcing green hydrogen is difficult (for example, due to a remote location with no access to renewable energy). This technology could require an additional $42/t Aa of capital investment and would increase operating expenditures by $50/t Aa (Exhibit 16).

EXHIBIT 13

Inert-anode technology can be retrofitted, but it still demands a significant retrofit cost.

Capital expenditure, $ / t Al	Hall-Héroult (HH)	HH with carbon capture and storage	Inert anode	Delta versus HH explained
Potrooms	2,500		3,000	Use vertical inert-anode cells configuration
Anode rodding	500		-	No need; inert-anode to be purchased on the market
Casthouse	225		225	Equal to HH
Material handling	200		213	Equal to HH
Utility and SVC system	700		700	Equal to HH
Nonprocess facilities	200		200	Equal to HH
Site construction	450		438	~Equal to HH
Indirect cost	650		650	Equal to HH
Contingency	575		575	Equal to HH
CCS plant	-	277	-	N/A
Chlorination plant with CO_2 regeneration electrolysis	-		-	N/A
Greenfield	**6,000**		**6,000[1]**	**Similar to HH**
Retrofit cell		**277**	**3,000[2]**	**New potrooms, only leveraging pothole**

[1] *Path to net zero report 2021*, En+ Group.
[2] Starting from AP30 smelter technology.
Source: "Modular primary aluminium plant based on beck cells with multiple vertical inert anodes and wettable inert cathodes," Arctus Metals, April 5, 2017; Asbjørn Solheim, "Carbochlorination routes in production of Al," HighEFF, February 28, 2018; Asbjørn Solheim, "Inert anodes—the blind alley to environmental friendliness?," *Light Metals*, 2018; Efthymios Balomenos et al., "Carbothermic reduction of alumina: A review of developed processes and novel concepts," *Proceedings of the European Metallurgical Conference*, 2011; International Aluminium Institute; Jeff Keniry, "The economics of inert anodes and wettable cathodes for aluminium reduction cells," *Journal of the Minerals, Metals & Materials Society*, 2001, Volume 53; Mazin Obaidat et al., "Energy and exergy analyses of different aluminum reduction technologies," *Sustainability*, 2018, Volume 10, Number 4; Olivier Lassagne et al., "Techno-economic study of CO_2 capture for aluminum primary production for different electrolytic cell ventilation rates," *Chemical Engineering Journal*, 2013, Volume 230; Vetchinkina Tatiana Nikolaevna, Balmaev Boris Grigorievich, and Tuzhilin Aleksey Sergeevich, "Prospects of chlorine method of aluminium production in modern conditions," *KnE Materials Science*, 2020, Volume 6, Number 1

The operating expenses of smelting technologies depend on electricity prices.

EXHIBIT 14

Operating expenses	Unit	Hall-Héroult (HH)	HH with carbon capture and storage	Inert anode	Delta inert anode vs HH
Raw material	$ / t Al	756	756	756	Equal to HH
Electricity ($37/MWh)	$ / t Al	456–594[1]	456–594[1]	519–615	Up to 20% increase[2]
Carbochlorination	$ / t Al	-	-	-	
Anode	$ / t Al	240	240	96	Longer duration (36–48 months versus 1 month), 14x cost[3]
Aluminum fluoride	$ / t Al	23	23	23	Equal to HH
Labor	$ / t Al	78	78	66	15% savings due to longer life of anodes (2 years vs 1 month)
Cell rebuild	$ / t Al	28	28	28	Equal to HH
Maintenance	$ / t Al	35	35	35	Equal to HH
Other	$ / t Al	38	38	38	Equal to HH
CO_2-handling operating expenditures	$ / t Al	-	96	-	
CO_2-handling electricity	$ / t Al	-	8	-	
Total operating expenses	**$ / t Al**	**1,654–1,792**	**1,815 +6% of HH[2]**	**1,562–1,657**	**–3% to –10% of HH[2]**
Electricity operating expenses share	%	**28–33%**	**29%**	**33–37%**	

[1] Considers a range between 12.3 and 16 kWh/kg Al, according to McKinsey database.
[2] Compared against industry average HH specific energy consumption of 13.8 kWh/kg Al, resulting in an overall operating expense of $1,710/t Al.
[3] Based on ceramic inert anode and includes cathode price; cost = 96 x 3 years x 12 months / 240.
Source: "Modular primary aluminium plant based on beck cells with multiple vertical inert anodes and wettable inert cathodes," Arctus Metals, April 5, 2017; Asbjørn Solheim, "Carbochlorination routes in production of Al," HighEFF, February 28, 2018; Asbjørn Solheim, "Inert anodes—the blind alley to environmental friendliness?," *Light Metals*, 2018; Efthymios Balomenos et al., "Carbothermic reduction of alumina: A review of developed processes and novel concepts," *Proceedings of the European Metallurgical Conference*, 2011; International Aluminium Institute; Jeff Keniry, "The economics of inert anodes and wettable cathodes for aluminium reduction cells," *Journal of the Minerals, Metals & Materials Society*, 2001, Volume 53; Mazin Obaidat et al., "Energy and exergy analyses of different aluminum reduction technologies," *Sustainability*, 2018, Volume 10, Number 4; Olivier Lassagne et al., "Techno-economic study of CO_2 capture for aluminum primary production for different electrolytic cell ventilation rates," *Chemical Engineering Journal*, 2013, Volume 230; Vetchinkina Tatiana Nikolaevna, Balmaev Boris Grigorievich, and Tuzhilin Aleksey Sergeevich, "Prospects of chlorine method of aluminium production in modern conditions," *KnE Materials Science*, 2020, Volume 6, Number 1

EXHIBIT 15

Electric or hydrogen-fired boilers may eliminate CO_2e emissions associated with digestion.

	Units	Natural-gas (NG) boiler	Electric boiler	H_2-fired boiler	NG boiler with mechanical vapor recompression
Type of fuel		Natural gas	Green electricity	Green hydrogen	Natural gas and green electricity
Boiler efficiency	%	85	98	94	COP[1] 3
Thermal input required	Gigajoules (GJ)/t alumina (Aa)	8.0[2]	8.0[2]	8.0[2]	8.0[2]
-Natural-gas requirement	Cubic meters/t Aa	232	-	-	12[3]
-Electricity requirement	GJ/t Aa	-	8.2	-	2.5[3]
-Hydrogen requirement	kg/t Aa	-	-	60[4]	-
CO_2 produced	t CO_2/t aluminum	0.94	-	-	0.05 (95% reduction)
Capital expenditure	$/t Aa	**50**	**55**	**50[5]**	**75–200**
Operational expenses	$/t Aa	Fuel costs; Electricity costs; 63[6]	85[7]	270[8]	22
TRL		9	6	5	5

[1] Coefficient of performance (COP) = heat provided; work required.
[2] Based on thermal input required for low-temperature digestion.
[3] Based on assumption of COP 3 and CO_2 emissions reduction of 95 percent.
[4] Based on hydrogen heat content of 141.7 megajoules/kg.
[5] There may be additional capital expenditures for hydrogen transportation as new piping is required.
[6] Based on 2020 natural-gas price of $6.68/GJ.
[7] Based on US 2020 electricity price of $37/MWh, and assuming 3.6 GJ/MWh.
[8] Based on 2022 green-hydrogen price of $4.93/kg.
Source: FLSmidth; Metso Outotec; James H. Williams et al., "Carbon-neutral pathways for the United States," *AGU Advances*, 2021, Volume 2, Number 1

EXHIBIT 16

Decarbonization of calcination technologies may be achieved through a hydrogen-based calciner.

	Units	Natural gas	H_2-based calciner + electrolysis[1]	Natural gas + carbon capture and storage
Thermal input required[2]	Gigajoules (GJ)/t Alumina (Aa)	2.8	2.8	2.8
Natural gas requirement	Cubic meters/t Aa	64[3]	-	64[3]
Electricity requirement	GJ/t Aa	-	3.6[4]	-
Hydrogen requirement	kg/t Aa	-	20[3]	-
CO_2 produced	t CO_2/t aluminum	0.26	-	0.078
Capital expenditure	$/t Aa	33	Electrolysis H_2 97[5] H_2-based calciner 37	75 (assuming transport and storage)[6]
Operating expenditure: fuel costs[7]	$/t Aa	17	Procured H_2 91[8]	17 + 50 (CCS)
Operating expenditure: electricity costs[7]	$/t Aa	-	Produced H_2 48[9]	-
TRL		9	5	8

[1] Based on combustion of hydrogen with pure oxygen produced from electrolysis, assuming coastal region and availability of green electricity.
[2] Based on typical circulating-fluidized-bed (CFB) performance.
[3] Based on 100% thermal efficiency.
[4] Based on electrolysis power requirement of 50 kWh/kg H_2.
[5] Based on $650/kW electrolyzer capital expenditure cost.
[6] Assuming $125/t of CO_2 of capture capital expenditure and $125/t of CO_2 of storage and transport translating into $75/t Aa.
[7] Based on procured hydrogen price of $4.93/kg delivered.
[8] Based on US 2020 electricity price of $37/MWh, and assuming 3.6 GJ/MWh.
[9] Technology readiness level.
Source: "Combustion of fuels - carbon dioxide emission," Engineering Toolbox, accessed February 2022; "Green hydrogen cost reduction," IRENA, 2020.

Model key inputs.

There are three main types of inputs that inform the model: refinery, smelter, and financial.

Main inputs

Refinery overall inputs

- Nominal refinery capacity
- Refinery utilization rate
- Investment scenario plant type (greenfield or brownfield)
- Construction duration (in months)

Digestion-specific inputs

- Digestion type (low temperature, high temperature, and ultrahigh temperature)
- Steam generation type (natural-gas boiler, electric boiler, hydrogen boiler, natural-gas boiler with mechanical vapor recompression)
- Amount of steam generated

Calcination-specific inputs

- Investment scenario (greenfield vs brownfield)
- Calcination firing fuel (natural gas, natural gas retrofitted with carbon capture and storage [CCS], or hydrogen)
- Type of calciner (circulating-fluid bed, flash calciner, fluid flash, rotary kilns)
- Calcination thermal energy input

Smelter overall inputs

Smelter-specific inputs

- Type of smelter (Hall-Héroult, Hall-Héroult with CCS on smelter, Hall-Héroult with CCS on anode baking furnace, Hall-Héroult with CCS on petcoke calcination, inert anode, and carbochlorination with CO_2 regeneration)
- Nominal smelter capacity
- Smelter utilization rate
- Investment scenario smelter type (greenfield or brownfield)
- Construction duration (in months)
- Smelter energy intensity

Power-specific inputs

- Captive, noncaptive electricity source (virtual power purchasing agreement [VPPA])
- Heat loss management installation allowing for energy cost savings
- Type of electricity source (coal, natural gas, coal + CCS, natural gas + CCS, hydropower, small modular nuclear reactor, 100 percent renewables + long-duration energy storage [LDES])
- Electricity price

Financial inputs

- Discount factor
- Debt as share of total capital
- Debt or loan tenure
- Interest rate

ENDNOTES

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MISSION POSSIBLE PARTNERSHIP

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