Competitiveness of Global Aluminum Supply Chains Under Carbon Pricing Scenarios for Solar PV

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Acronyms

Al	Aluminum
ASI	Aluminum Stewardship Initiative
CAPEX	Capital expenditures
CBAM	EU Carbon Border Adjustment Mechanism
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
EU	European Union
EVs	Electric vehicles
GCC	Gulf Cooperation Council
GHG	Greenhouse gas emissions
HICs	High-income countries
IEA	International Energy Agency
LICs	Low-income countries
MICs	Medium-income countries
OPEX	Operating costs
PFCs	Perfluorinated compounds
PV	Photovoltaic
SDS	Sustainable Development Scenario
SP	Stated Policies Scenario

Brownfield:
Operating existing aluminum smelters

Trends
Value-addition* opportunities

- At the historical range of Al prices, most major Al producers have value-addition opportunities.
- Carbon prices significantly hamper value-addition opportunities in fossil-fuel-fired producers (China, India).
- Carbon prices also reduce the value-addition for producers powered by hydropower (Brazil) due to non-electricity emissions along Al supply chain.

Recommendations
Value-addition opportunities

- In the presence of strong carbon prices, action will be needed to reduce electricity and non-electricity emissions for all producers to retain value-addition opportunities.
- With higher Al prices, existing smelters can be competitive across more locations, potentially leading to a return to production of closed capacity. Support to help such producers decarbonize as required is needed.

Trends
Decarbonization opportunities

- Industry has reduced emissions on a plant-by-plant basis, especially non-CO2 process emissions (e.g., PFC).
- However, average global emissions per tonne have fallen only slightly (approx. 7%) between 2006 and 2019.
- Fossil-fuel powered MICs are the highest emitters per tonne of Al produced.
- MICs fossil (e.g., China and India) account for well over 60% of total emissions.

Recommendations
Decarbonization opportunities

- Strong and stable carbon pricing policies are needed to better incentivize industry to retrofit new and existing technologies for decarbonization such as inert anodes.
- Decarbonization of electricity in existing smelters is necessary, but not sufficient for full decarbonization of Al production.
- Further action is needed on heat and process emissions (along with mining and shipping) to fully decarbonize industry.
- Technology transfer between countries is crucial.

What are the opportunities for developing countries to produce green aluminum for solar PV?

- Opportunities are available to produce more decarbonized bauxite and alumina, allowing for more value-addition to be captured and carbon prices' impact to be minimized.
- For existing Al producers, there is the opportunity to move further along the value chain and produce solar PV technology.
- However, GHG emissions from the production of aluminum will need to be addressed so that the impact of a potential carbon price on solar PV production costs is minimized (e.g., pass-through effect)
    - Direct (process emissions)
    - Indirect (electricity)

Opportunities for developing and emerging economies

Historic prices refer to aluminum priced at USD $2,250 per tonne

*Value-addition is defined on Slide 16

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Greenfield:
Building new aluminum smelters

What are the opportunities for developing countries to produce green aluminum for solar PV?

- It will be challenging for most country producers outside of China and India to establish new Al facilities to meet growing demand for solar PV, given high capital costs in those locations.
- In particular, rising carbon prices will limit new Al smelting capacity, impacting the cost of Al for solar PV.
- This means that GHG emissions from direct and indirect Al production will need addressing.
- Across the Al value chain (bauxite-aluminum), country producers should also consider value-addition opportunities for intermediate products, such as low-carbon alumina products.

Opportunities for developing and emerging economies

Trends
Value-addition opportunities

- Most existing producers outside China and India have limited opportunities for building new smelters at historic price* ranges due to high CAPEX.
- Some MICs, such as China and India, have strong value-addition opportunities at present due to low CAPEX.
- High carbon prices ($100+) could negatively impact value-addition opportunities in MICs even with decarbonization pathways under IEA's SDS and SP scenarios.

Recommendations
Value-addition opportunities

- For LICs, building new smelters seems unlikely, even with high carbon prices. Focusing on improving and expanding bauxite and alumina production may accrue more value for LICs. Policy support should focus on addressing challenges affecting the aluminum sector in LICs: developing energy and transport infrastructure, building skills and promoting decarbonization.
- MICs must decarbonize electricity as fast as possible to retain their competitive position, especially given future regulatory changes.

Trends
Decarbonization opportunities

- Efficiency improvements in smelter technologies have reduced electricity requirements and process emissions, especially non-CO2 emissions.
- Regulatory developments have led to shutdown of inefficient smelters; new, efficient, hydro-powered smelters are emerging in countries such as China.

Recommendations
Decarbonization opportunities

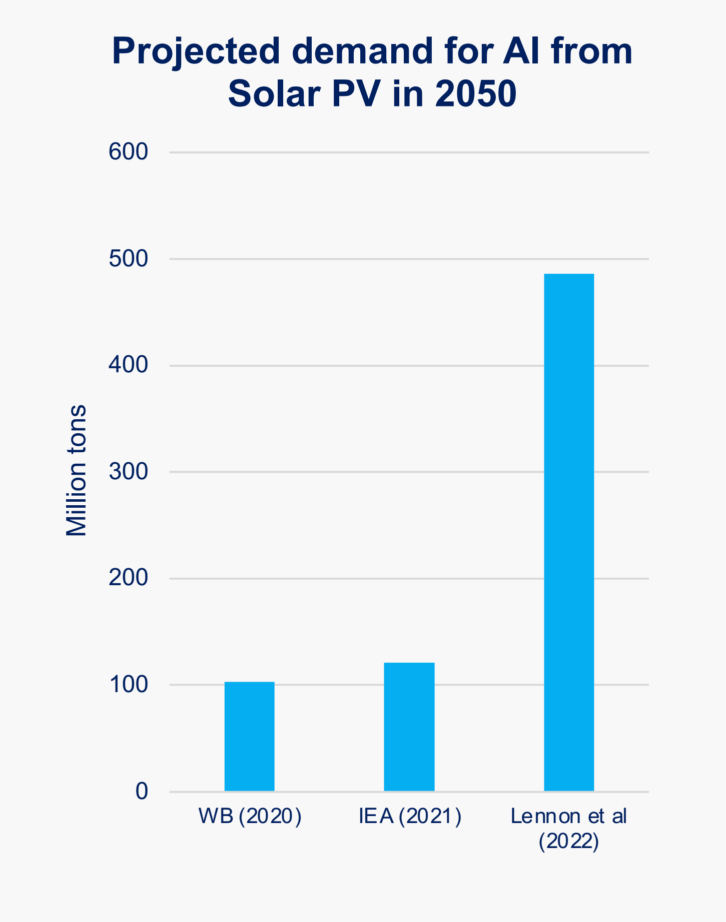
- Policy support is needed to decarbonize electricity and raise energy efficiency for new Al smelters.
- Policy support (e.g., fiscal, R&D) to deploy technology (e.g., inert anodes) for new smelting technologies would help improve efficiency and reduce emissions.
- Promotion of technology transfer between producers to ensure use of best technologies in MICs and LICs.

*Historic prices refer to aluminum priced at USD $2,250 per tonne

What is the problem?

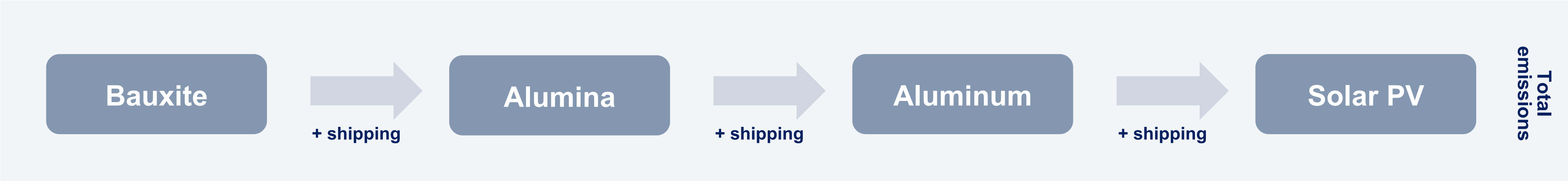
Al demand is expected to grow significantly to supply the clean energy transition

- **Aluminum (Al) is a critical metal for the energy transition**, needed for transmission infrastructure, EVs, solar PV, renewable and low-carbon hydrogen, and wind turbines.*
- Current consumers of aluminum: transport (27%), construction (25%), packaging (16%), electrical engineering, (13%), machinery & equipment (9%), consumer goods (5%).
- Future demand for aluminum from technologies such as **solar PV could be substantial through 2050**. Some estimates place demand from solar PV in 2050 at 35%+ of current demand levels.
- However, demand is also highly variable and will be dependent on assumptions **about material content and technology deployments.**
- Whatever technology scenario emerges, the energy transition is likely to have a **substantial impact on the market for aluminum.**
- **The potential for increasing demand for aluminum raises questions:**
  - *Can LICs and MICs benefit from potential increases in demand across the Al supply chain?*
  - *What role is there for existing capacity? What is the potential for new, greenfield capacity?*
  - *How can the aluminum produced for the low-carbon energy transition be decarbonized to reduce its impact as much as possible?*
  - *How can secondary Al production meet demand while helping to reduce emissions?*



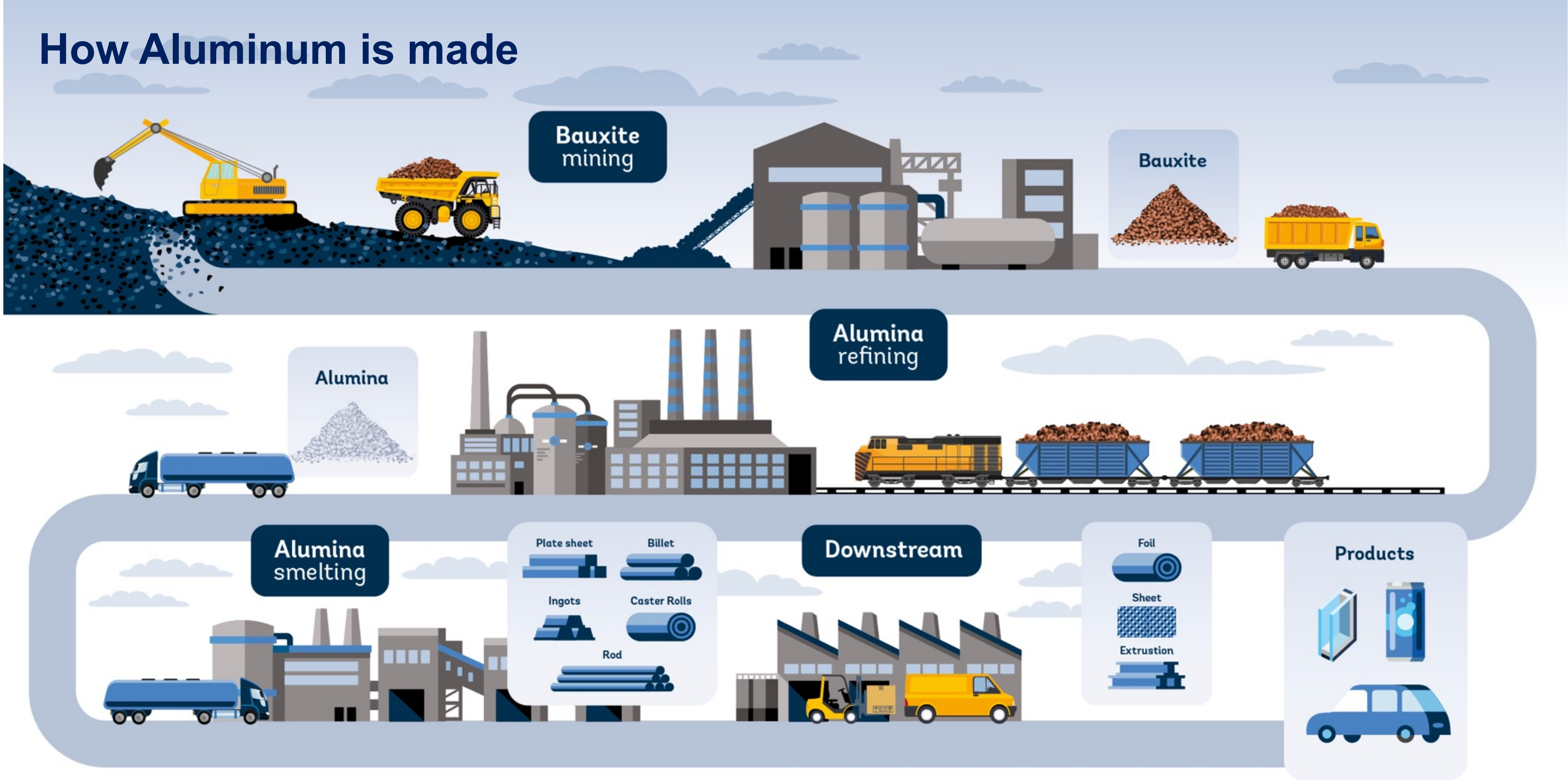
*Substitution for other materials is possible in some applications – but this question is beyond the scope of this study.

Key assumptions: “New” Al supply chain



Assumption	Description	Assumption	Description
Bauxite	Brazil, Guinea	**Low-income economy (LIC)**	Guinea
Alumina	Brazil, Guinea, Australia, UAE, China	**Middle-income economy—hydro (MIC Hydro)**	Brazil, Russia
Aluminum (Al)	Brazil, Guinea (modelled), China, India, Norway, EU, Canada, GCC, Russia	**Middle-income economy—fossil (MIC Fossil)**	China, India
CaPEx, OpEx	Industry sources	**High-income economy (HIC)**	Canada, GCC, EU, Norway
Emissions, Energy	Industry sources, IEA data (2021)	**Scenarios**	• Electricity mix (IEA SDS and SP scenarios) • Assumes future grid average electricity cost and emissions • Carbon prices $50-$150 per ton CO2 • Product prices: historic and high • CapEx assumptions
Al Price	Historic range: $2250 per tonne Al High price: $3000 per tonne Al	**Exclusions**	Model covers energy use and emissions only; forest impact not included

How Aluminum is made

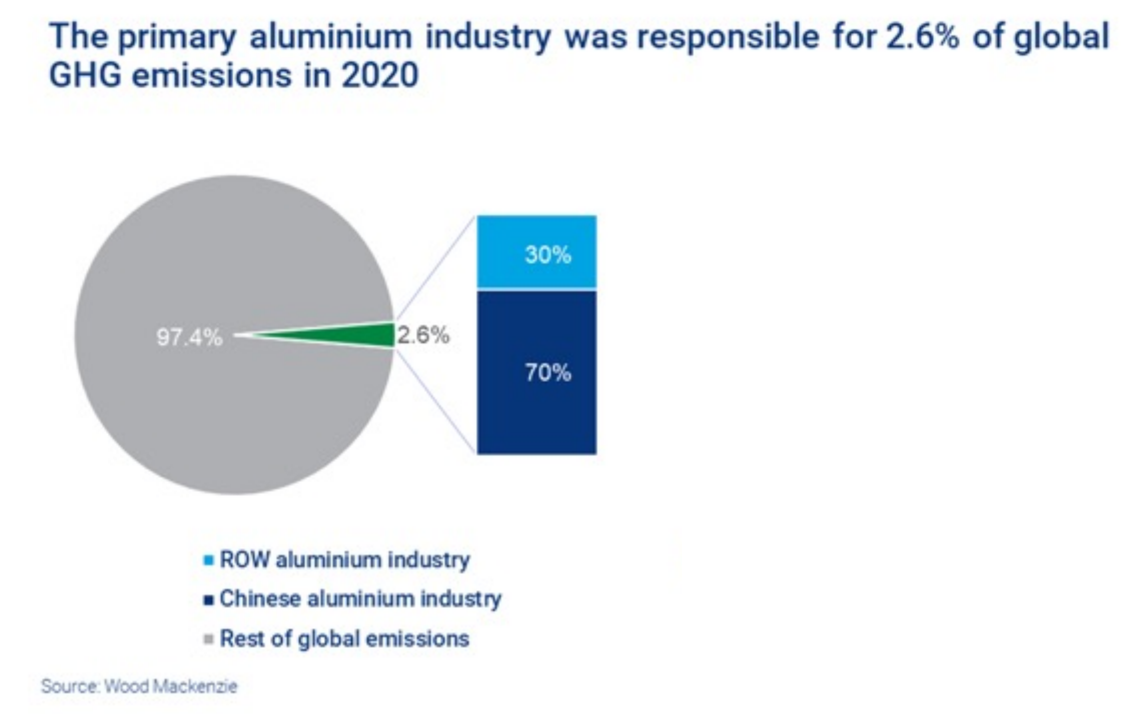


Emissions intensity of Al production and the metal’s role in energy transition

Al is a critical metal for the energy transition, but production comes with a large CO2e footprint

Pressure to decarbonize the sector

- Today, Al accounts for **2% of total GHG emissions globally,** emitting about 1.1 billion tons of CO2e annually; other sources indicate that the range falls between 2-3% of total global emissions.
- Al is also vital in reducing emissions in providing a light-weight, highly recyclable material for solar panels, electric vehicles and other technologies.
- Without concrete actions to address both direct (process) and indirect (electricity consumption) emissions from the sector, GHG emissions are expected **to reach 1.6 billion tons of CO2e annually by 2050.**
    - Other sources suggest that **GHG emissions will increase by 15% in the next 10 years** due to energy transition demand and the inability of power grids to decarbonize fast enough.
- The expected roll out of the **EU’s Carbon Border Adjustment Mechanism** (CBAM), major pricing initiatives launched in China and Germany, and commitments by key financial institutions to reach net zero (including Scope 3) could have major implications for country producers, especially in emerging and developed economies.



The primary aluminium industry was responsible for 2.6% of global GHG emissions in 2020

Source: Wood Mackenzie

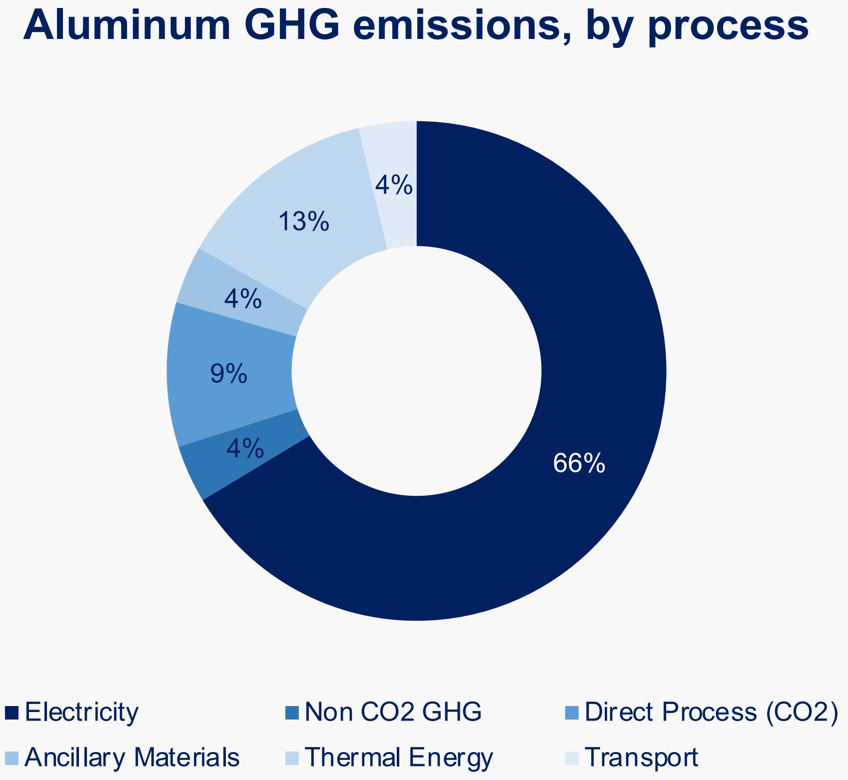
Source: IAI 2021a; Wood Mackenzie: https://www.woodmac.com/news/opinion/decarbonisation-is-aluminium-a-solution-or-a-problem/

Al production emissions are dominated by electricity

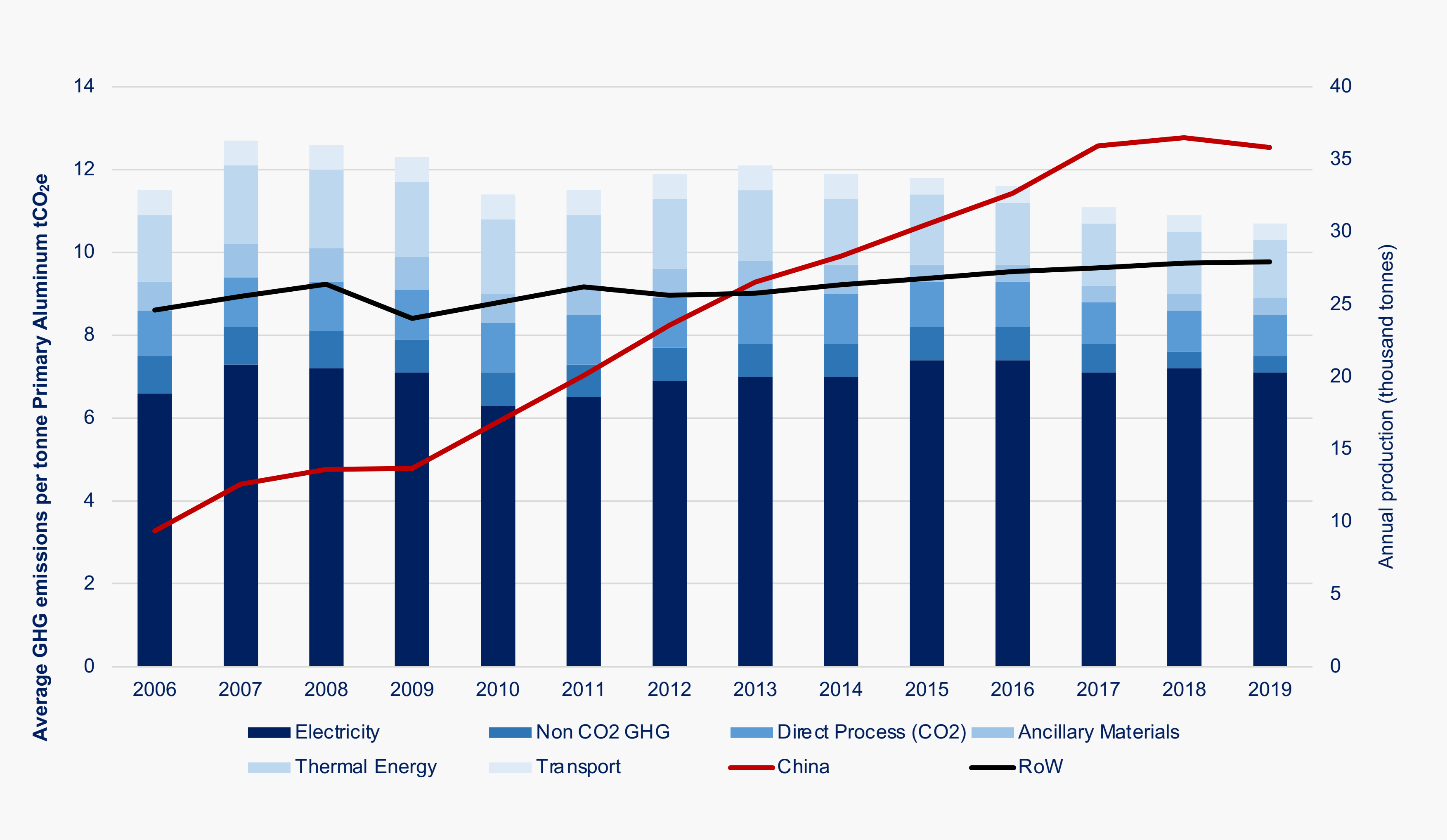
Electricity emissions account for two-thirds of GHG emissions

GHG emissions

- Electricity is required to smelt aluminum from alumina via the Hall-Héroult process (HH process).
- The scale of these emissions is heavily dependent on the source of electricity.
- Non-CO2 emissions (e.g., PFCs) also occur as part of the HH process, although technological advancements have helped reduce this source over the last decade.
- HH process also produces CO2 directly through the use of carbon anodes.
- The Bayer process, transforming bauxite to alumina, requires significant sources of heat (both medium and high).
- Emissions from the production of this heat vary depending on fuel source used.



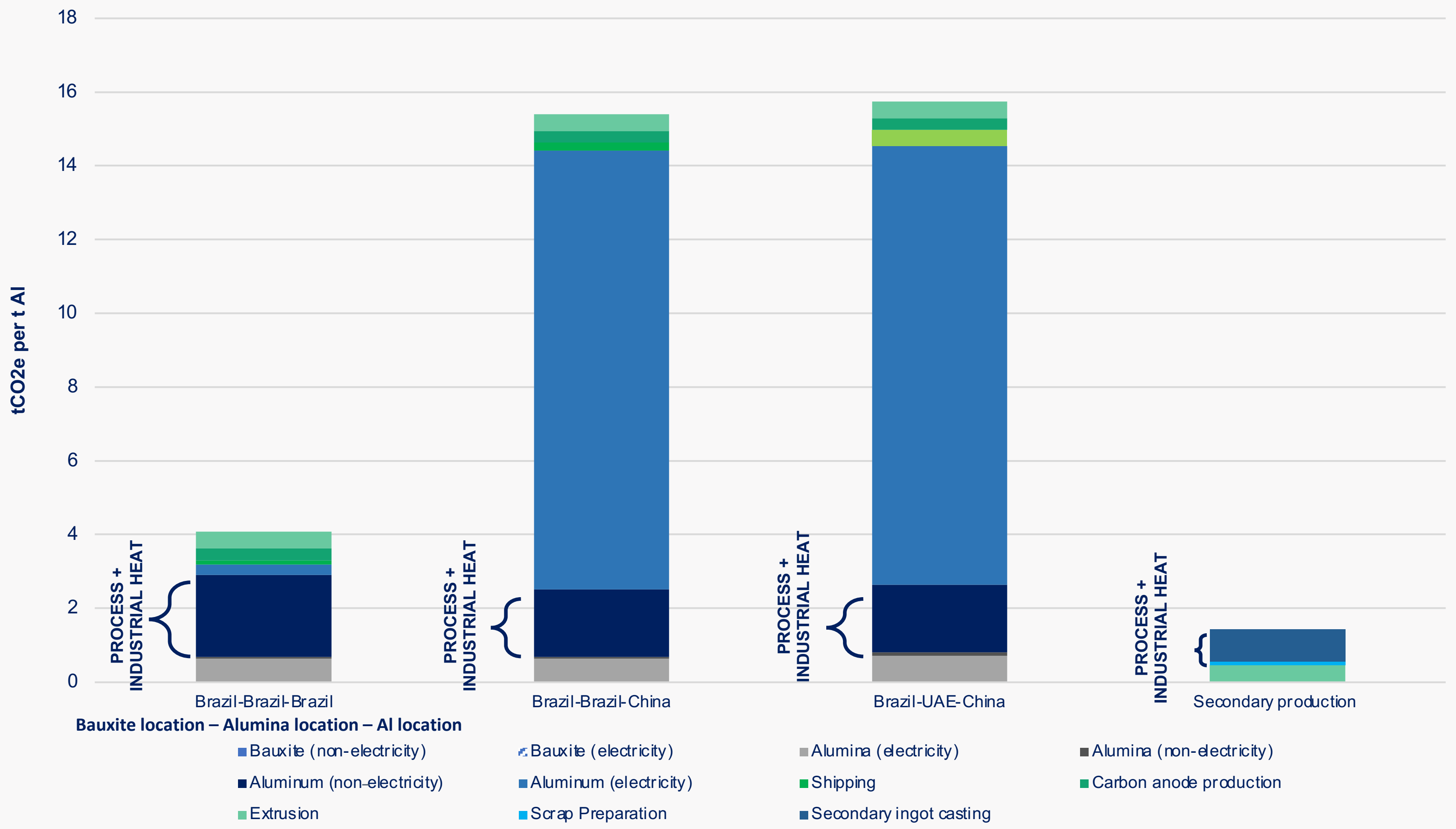
Average GHG emissions per tonne primary aluminium



Al production & emissions trends

- Current production is dominated by China, followed by other MICs and HICs (through legacy investments); LICs have a very small share of production.
- Emissions on a plant-by-plant basis have fallen due to reductions in non-CO2 GHG process emissions, electricity use efficiency improvements, and electricity decarbonization.
- However, average global emissions per tonne have dropped only slightly (7%) since 2006.

GHG emissions across the Al supply chain



Al supply chain overview

- Emissions vary significantly, depending on the supply chain.
- Al smelting location—and thus, the electricity mix—is the major factor.
- Moving from low-emissions smelting locations, like Brazil to China, increases emissions dramatically.
- Shifting alumina locations or increasing shipping distances has much smaller impacts.
- Secondary (recycling) production emissions vary less across locations, and generally represent a very small percentage of emissions from primary production.

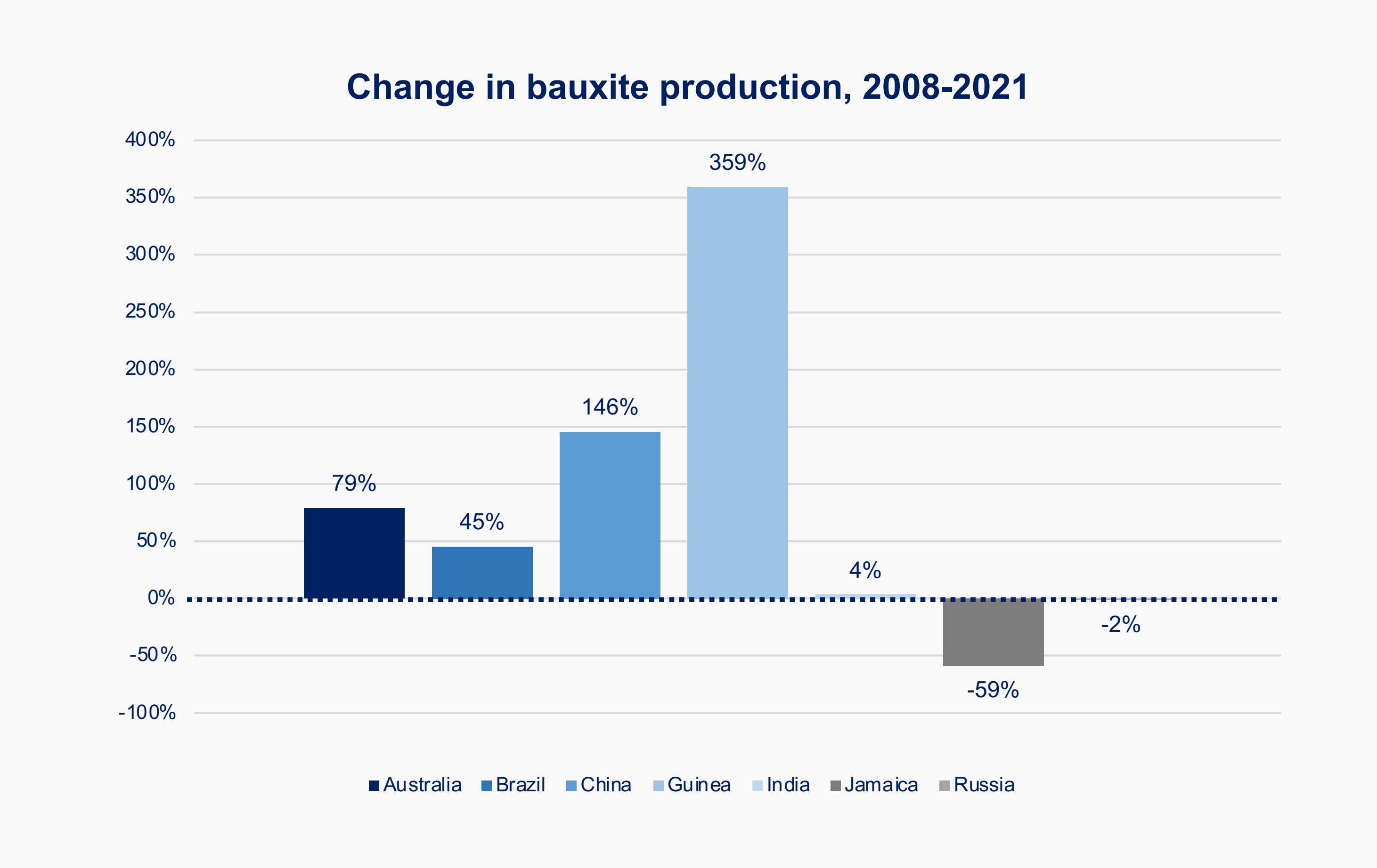
Trends in global bauxite production, 2008-2022

Bauxite reserves changes

- Bauxite reserves increased 14% between 2011 and 2022.
- Largest reserves in Guinea (23% of global total), Vietnam (18%), Australia (17%), Brazil (8%).

Production trends by income group

- Between 2008 and 2021, production increased by 90%.
- **HICs’** production share fell from 31% to 29% but almost doubled in absolute terms with increase in production in Australia and Saudi Arabia.
- **MICs’** market share fell from 57% to 46%. Some have seen large increases (Brazil, China, Vietnam); others have remained steady (India, Russia); others have declined (Jamaica, Suriname).
- **LICs** saw large production increases, from 9% to 22%, due to Guinea’s 350%+ production increase 2008-2021. Vast majority of LICs production from Guinea with Sierra Leone having a small amount of production as well.



Trends in global alumina production, 2014-2021

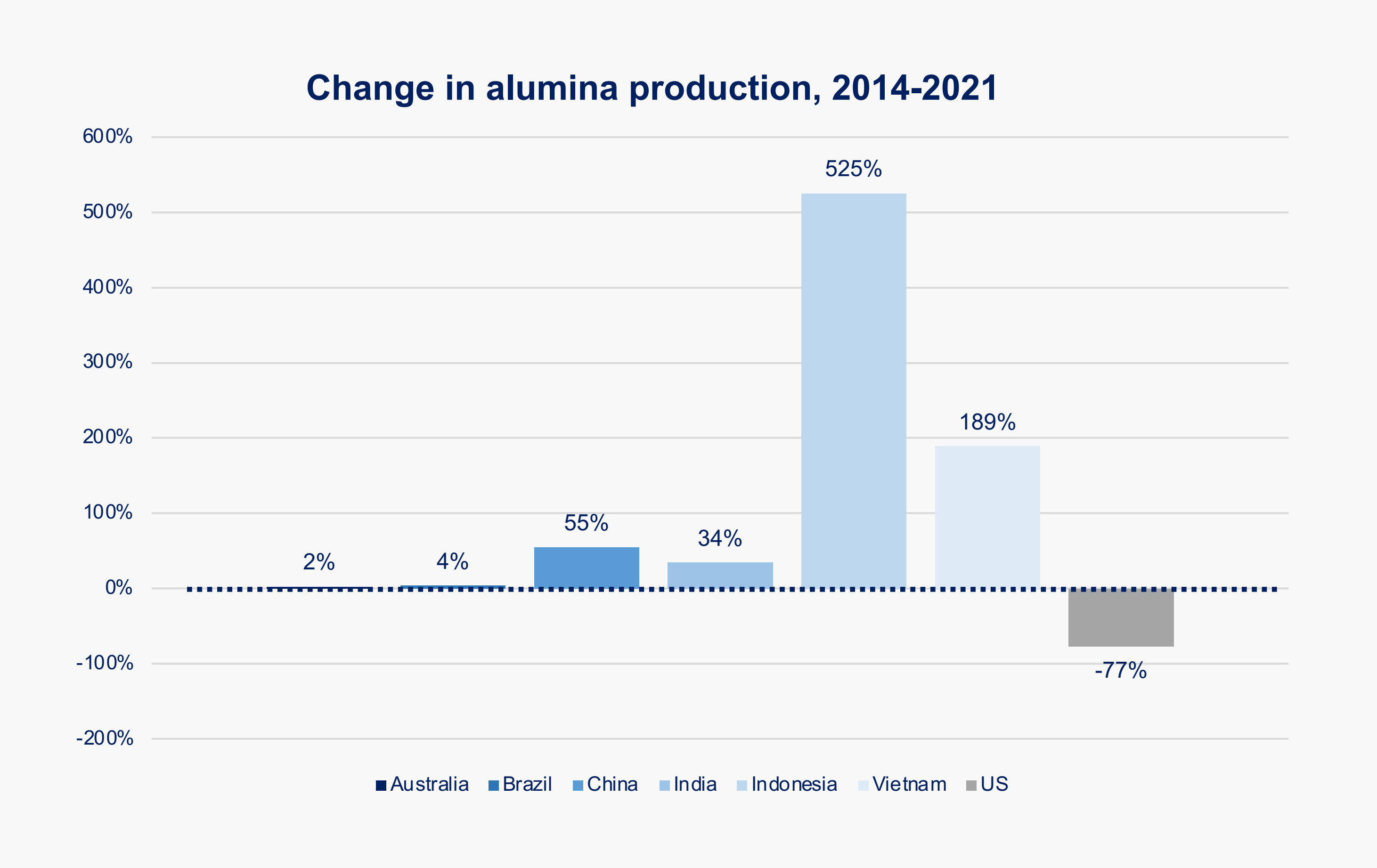
Alumina production changes

- Global alumina production increased by 30% between 2014 and 2021.
- Largest current producers include China (53% market share), Australia (15%), Brazil (8%), and India (5%).

Production trends by income group

Between 2014 and 2021:

- Share of **HICs'** production constant at 24%: decline in US production offset by increase in UAE and Saudi Arabia production.
- **MICs** hold largest market share (67%-74%), with major growth in China (55% between 2014 and 2021), Indonesia (525%), and Vietnam (189%).
- **LICs** have a small market share (0.3% in 2021), due to small but expanding production in Guinea.



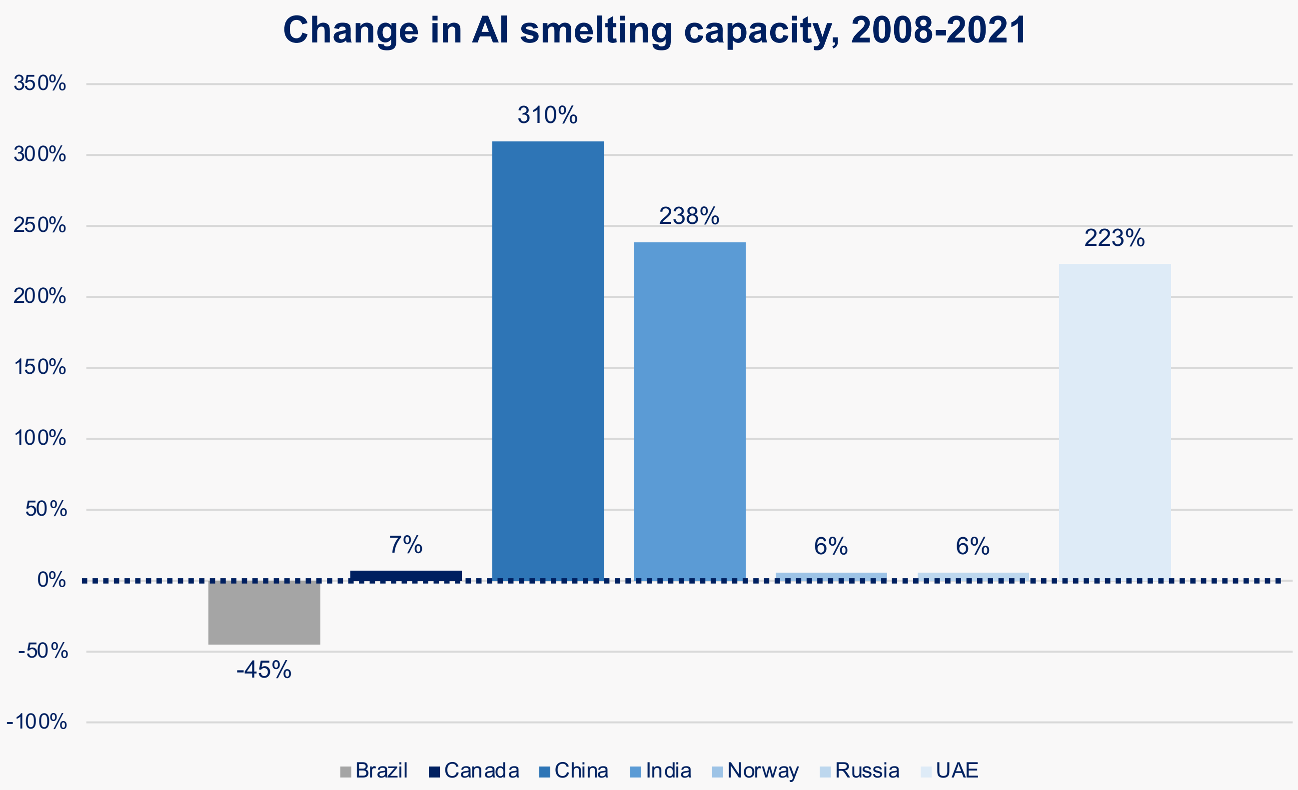
Trends in global Al production by income group, 2008-2021

Aluminum capacity changes

- Global smelting capacity doubled between 2008 and 2021.

Production trends by income group

- Overall, MIC capacity grew, with China and India accounting for 91% of new capacity.
- The same trend did not materialize across all MICs; Brazil's Al capacity decreased 45%.
- Varied trends also observed for HICs: stable Al capacity in Canada and Norway; significant growth in the GCC region, with the UAE at 238%; and slight declines in US and Australia.
- In LICs, smelting capacity remained very low: for example, Mozambique accounts for less than 1% of global capacity.



Value-addition in Al production

Value-addition is the amount by which the value of a good increases at each stage of its production, exclusive of initial costs

In this report, the value-addition per tonne Al is defined as:

- **Greenfield:** benefit of building new Al capacity relative to capital and operation costs

$$Value\ added = Price_{Aluminum} - (OPEX_{Bauxite} + CAPEX_{Bauxite} + CT_{Bauxite}) - (OPEX_{Alumina} + CAPEX_{Alumina} + CT_{Alumina}) - (OPEX_{Aluminum} + CAPEX_{Aluminum} + CT_{Aluminum})$$

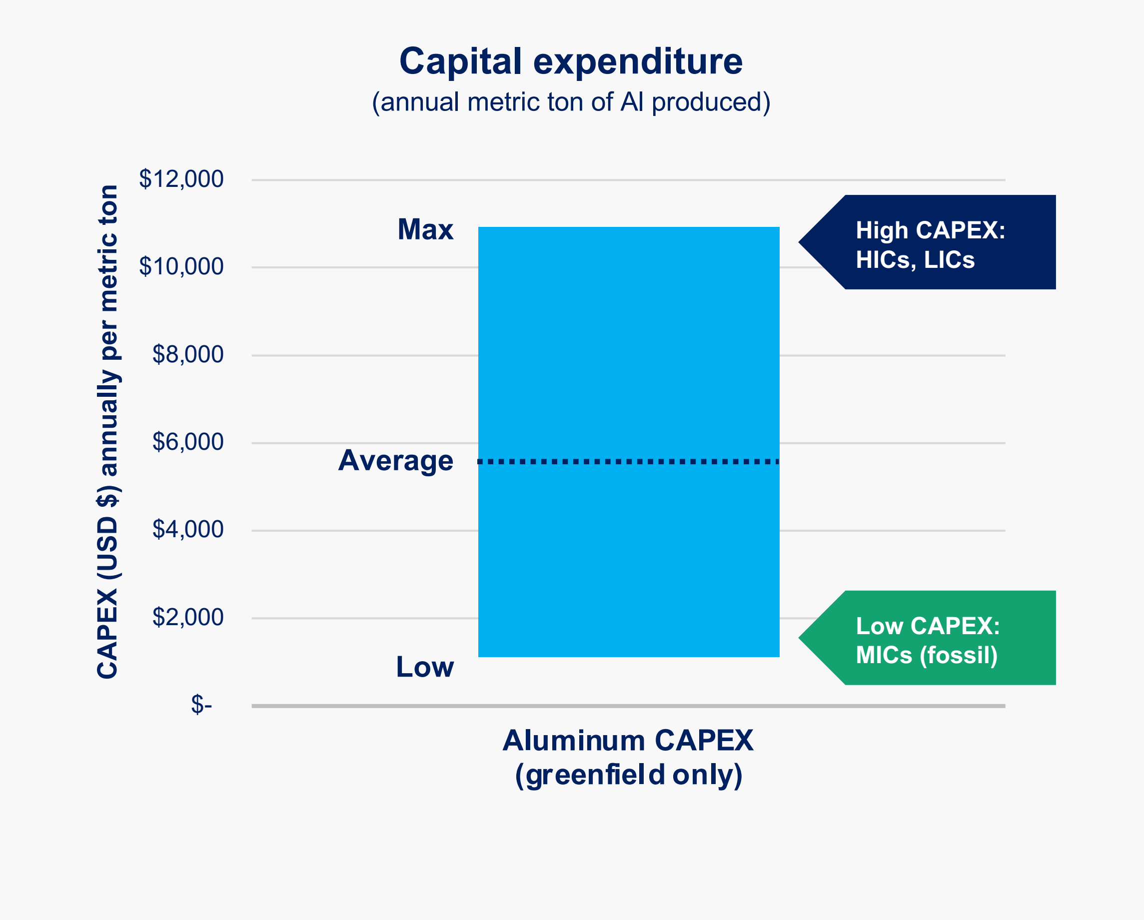
- **Brownfield:** benefit of operating existing Al capacity relative to operation costs, as capital has already been repaid

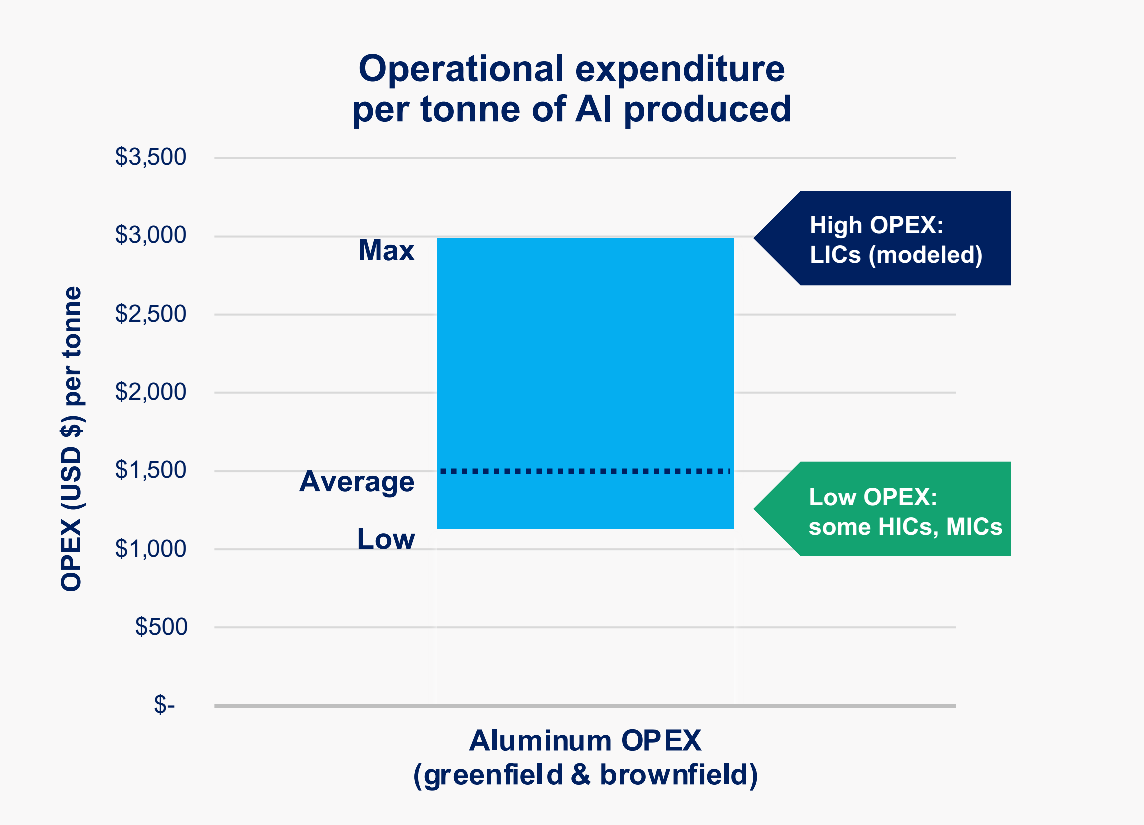
$$Value\ added = Price_{Aluminum} - (OPEX_{Bauxite} + CT_{Bauxite}) - (OPEX_{Alumina} + CT_{Alumina}) - (OPEX_{Aluminum} + CT_{Aluminum})$$

Where $OPEX$ is operating costs, $CAPEX$ is capital costs, CT is carbon costs

Range of CAPEX and OPEX costs for Al production

CAPEX costs tend to be higher than OPEX costs for Al production, with some significant differences between producers on CAPEX costs with a range between ~$1,000 and ~$11,000 per annual tonne of Al produced





Electricity costs are a key part of OPEX – e.g., approx. 30% of costs of Chinese production (S&P Global, 2021)

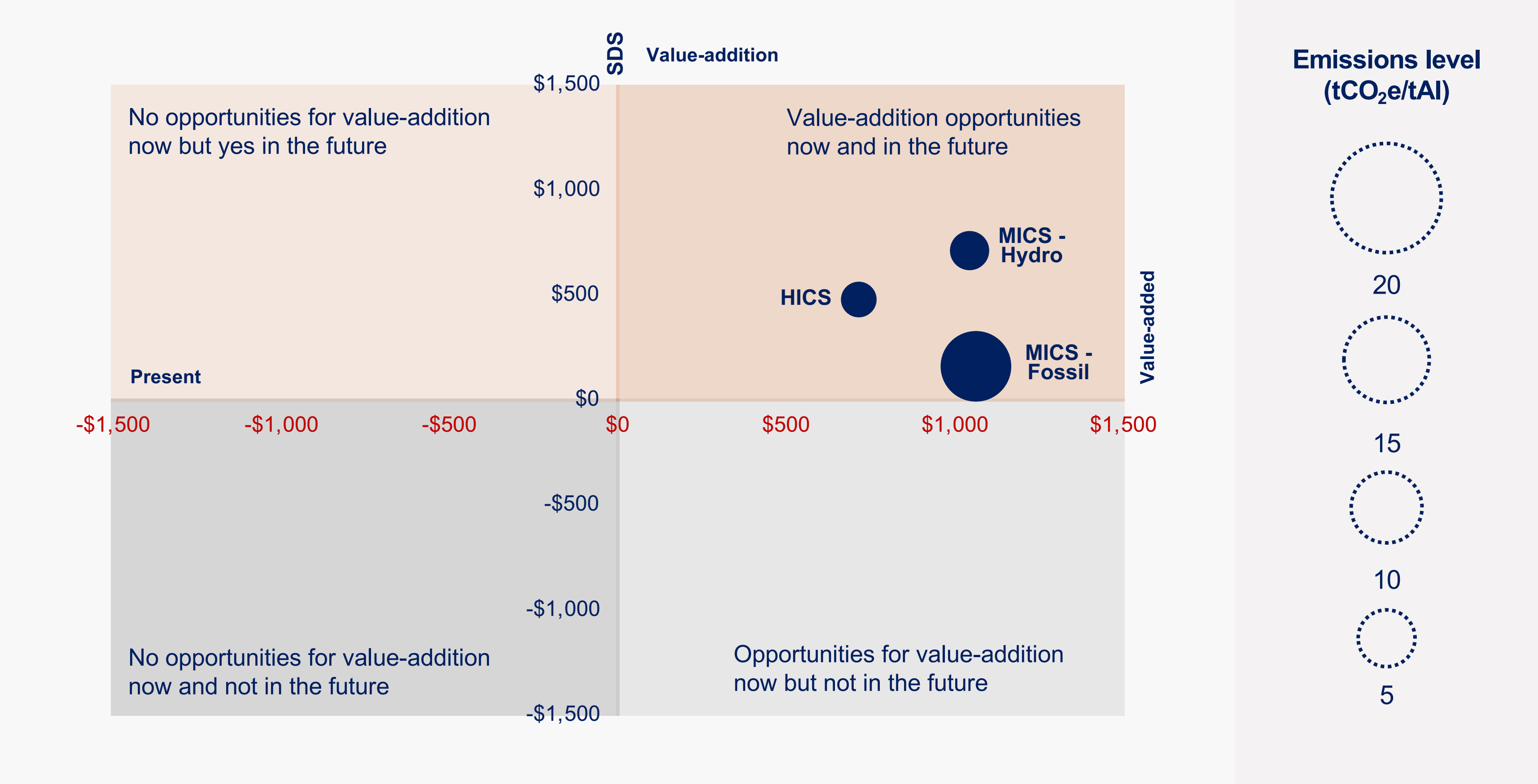
Source: Industry

Can LICs and MICs benefit from potential increases in demand across the AI supply chain?

Brownfield: Operating existing smelters to meet demand

+ the impact of carbon pricing

Brownfield:
The present value-addition of Al production(no carbon price except EU/NOR) vs 2030 IEA SDS $100 global carbon price scenario



Producing aluminum from existing smelters

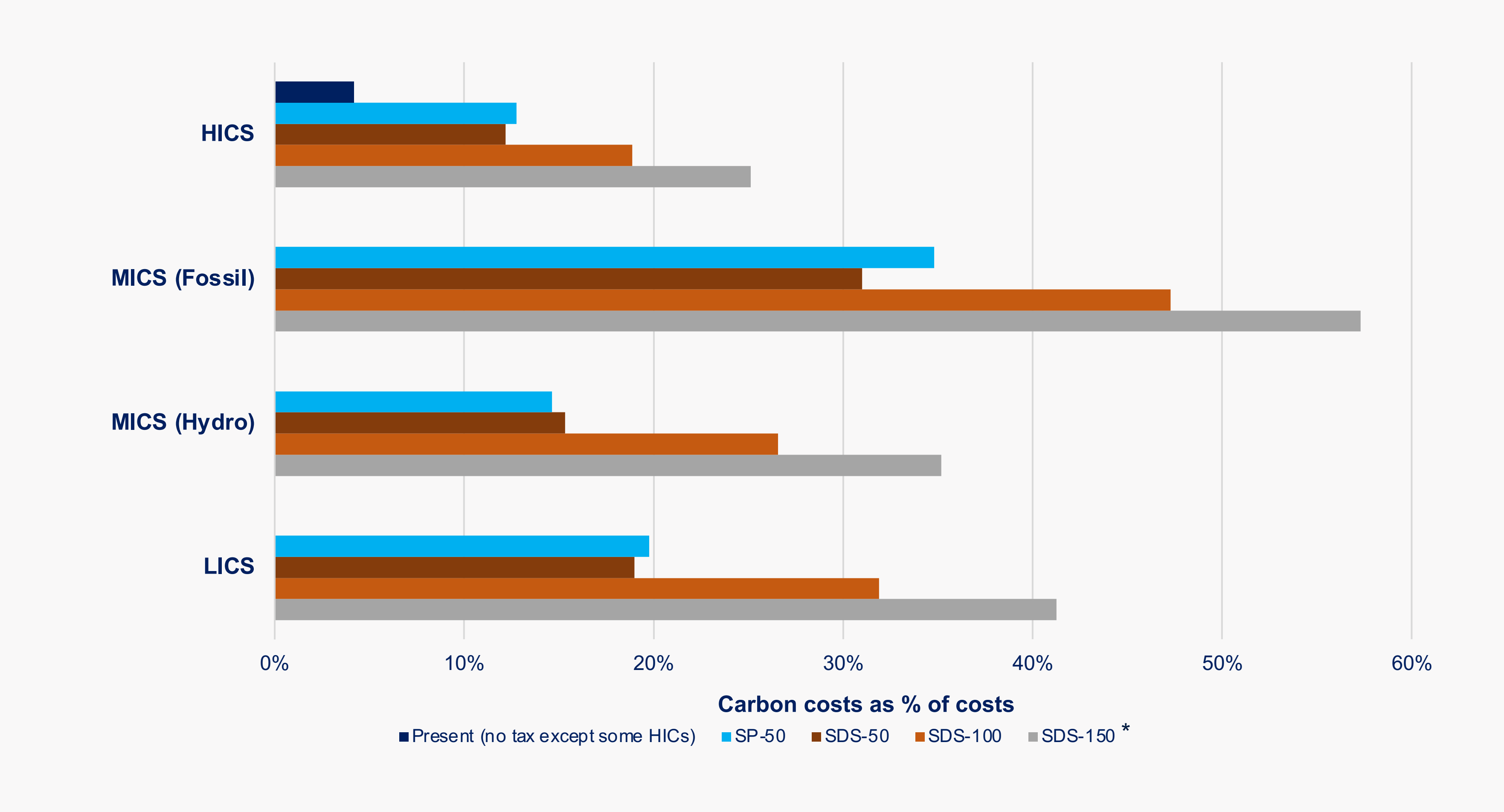
- Existing producers still have opportunities to add value under US $100 carbon price (under historic price assumptions).
- Highest emitters (MICs Fossil) are hit hardest under a new carbon price.
- Those using dispatchable renewables are less affected by a carbon price, although some are impacted through non-electricity supply chain emissions.

Al prices assumed constant at historic range

Brownfield:
Al production cost increases due to introduction of global carbon prices

Impact of higher carbon price

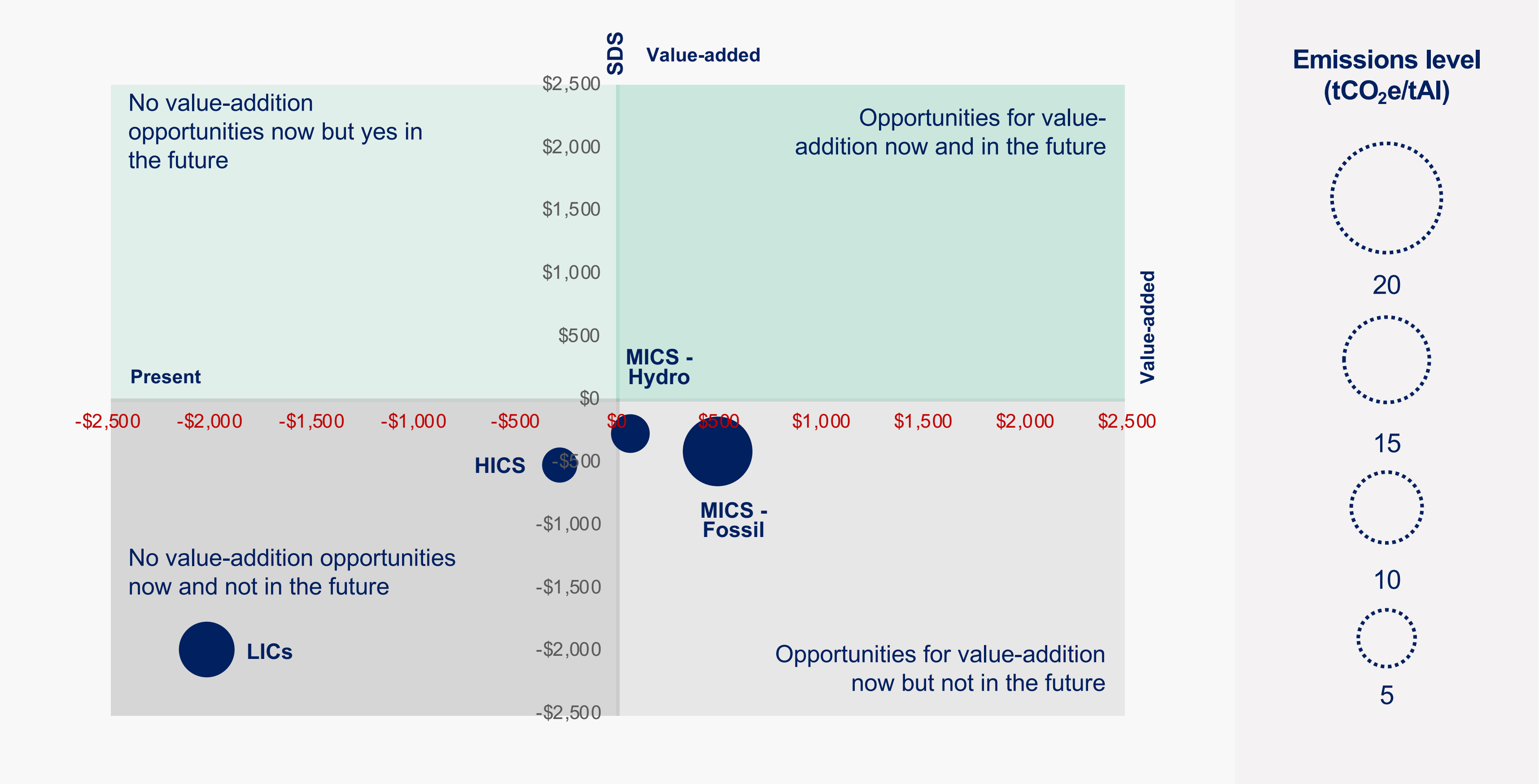
- As carbon prices increase (to $100), the value-addition of existing smelters is affected, but at historic price levels, opportunities to add value still exist.
- Locations with predominantly dispatchable renewables powering smelters see smallest impacts, but they are still affected due to other non-electricity-related supply chain emissions.
- If aggressive decarbonization of electricity occurs in current carbon intensive locations (MICs Fossil), opportunities for value-addition remain.



*Numbers refer to levels of carbon prices

Greenfield: Building new smelters to keep up with new demand

Greenfield:
The present value-addition of Al production (no carbon price except EU/NOR*) vs 2030 IEA SDS $100 global carbon price scenario



Producing aluminum via new smelters

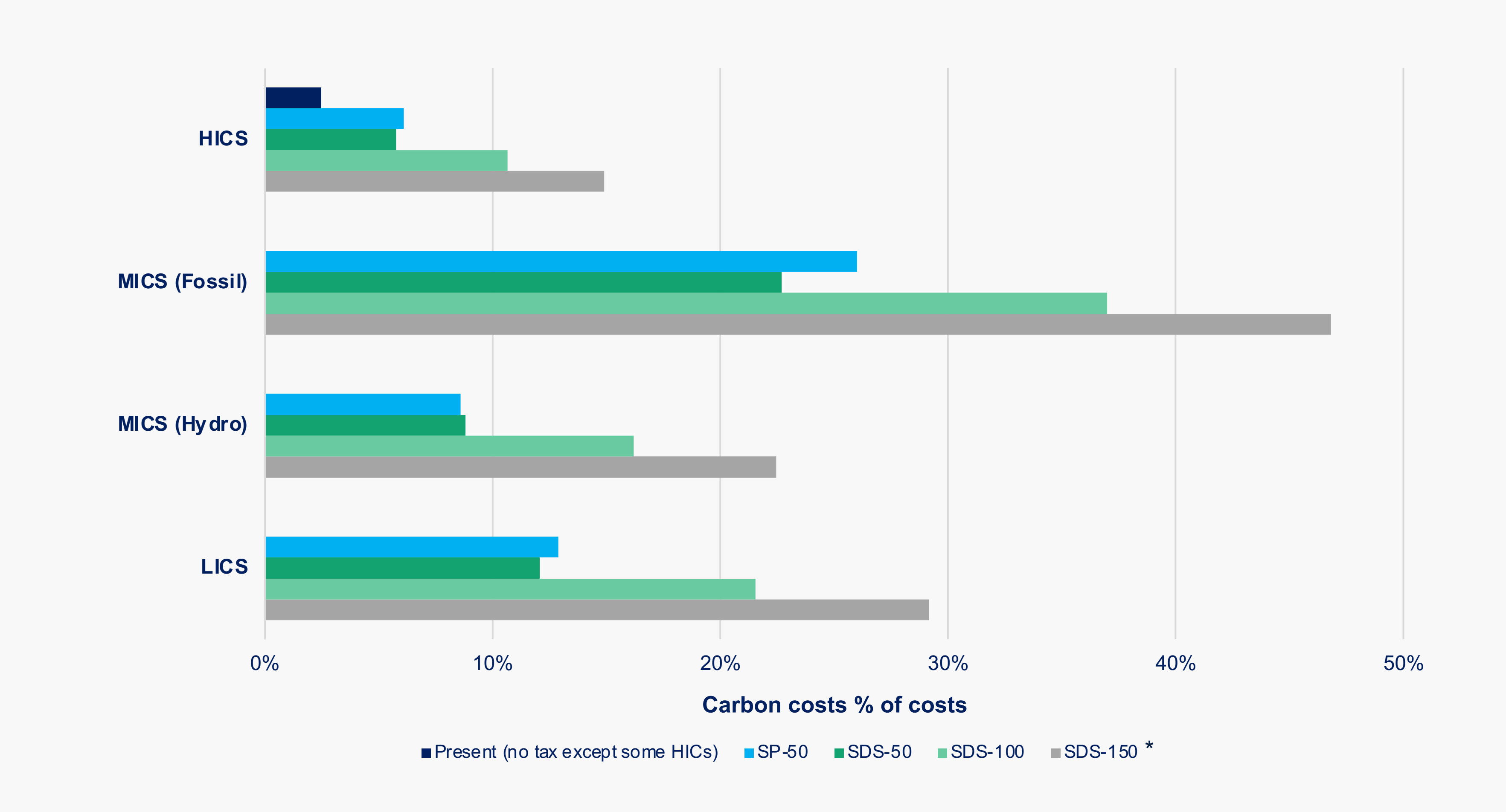
- MIC Fossil & Hydro countries have value-addition opportunities with a $100 carbon price due to competitive electricity prices (OPEX), as well as low CAPEX.
- HICs and LICs struggle to find value-addition opportunities now and in SDS scenarios due to high CAPEX.
- Under the SDS $100 carbon price, all country groups suffer due to non-electricity emissions, making them generally uncompetitive at historic price ranges.

Al prices assumed constant at historic range

Greenfield:
Al production cost increases due to introduction of global carbon prices

Impact of higher carbon price

- Increases in carbon price ($100) reduces the value-addition potential of greenfield smelters (at historic price levels).
- Impact of carbon prices is smallest in renewable-powered smelters (HICs and MICs Hydro). This impact will not reduce to zero, due to other aluminum supply-chain emissions.
- Move to more ambitious electricity decarbonization scenarios reduces impact on MICs fossil-fuel users, but under very high carbon price scenarios, costs could still increase by more than 50%.



*Numbers refer to levels of carbon prices

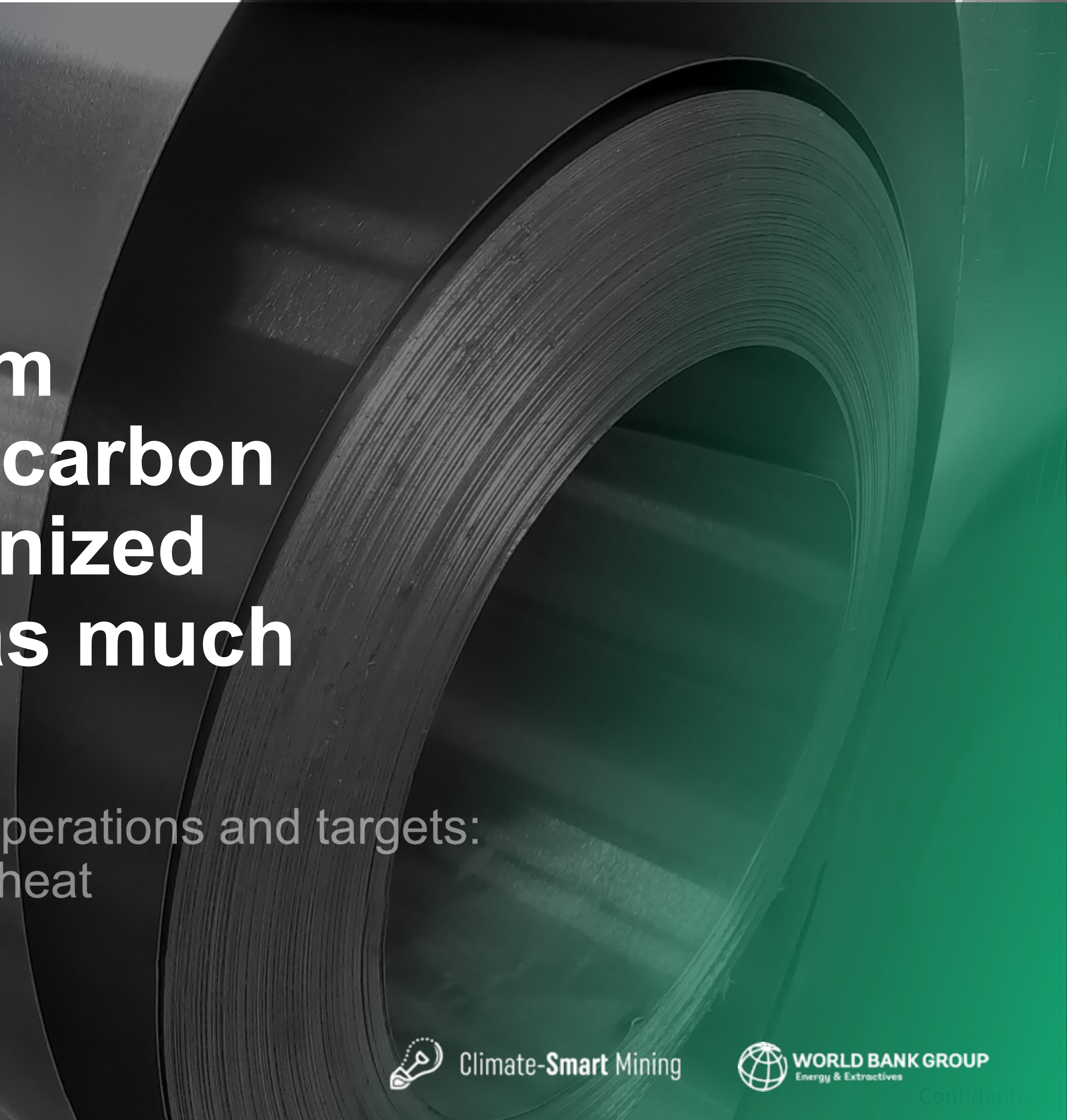
Summary of value-addition opportunities for existing and new Al smelters

NOTE: Opportunities depend on the **price** of aluminum

Aluminum price: **$2,250** (base case)		High-income economies		Upper-middle-income economies		Low-income economies	
		Dispatchable Renewable	**Fossil**	**Dispatchable Renewable**	**Fossil**	**Dispatchable Renewable**	**Fossil**
Brownfield	No carbon price	High value-addition opportunities	Medium value-addition opportunities	High value-addition opportunities	High value-addition opportunities		
	Carbon price	Medium value-addition opportunities	Medium value-addition opportunities	Medium value-addition opportunities	Marginal value-addition opportunities		
Greenfield	No carbon price	Unlikely to add value	Marginal value-addition opportunities	Medium value-addition opportunities	Medium value-addition opportunities	Unlikely to add value	Unlikely to add value
	Carbon price	Unlikely to add value	Unlikely to add value	Marginal value-addition opportunities	Unlikely to add value	Unlikely to add value	Unlikely to add value

Aluminum price: **$3,000** (high price scenario*)		High-income economies		Upper-middle-income economies		Low-income economies	
		Dispatchable Renewable	**Fossil**	**Dispatchable Renewable**	**Fossil**	**Dispatchable Renewable**	**Fossil**
Brownfield	No carbon price	High value-addition opportunities	High value-addition opportunities	High value-addition opportunities	High value-addition opportunities		
	Carbon price	High value-addition opportunities	Medium value-addition opportunities	High value-addition opportunities	Medium value-addition opportunities		
Greenfield	No carbon price	Medium value-addition opportunities	Medium value-addition opportunities	High value-addition opportunities	High value-addition opportunities	Unlikely to add value	Unlikely to add value
	Carbon price	Unlikely to add value	Unlikely to add value	High value-addition opportunities	Medium value-addition opportunities	Unlikely to add value	Unlikely to add value

*For details on the high price scenario see Methodological Annex

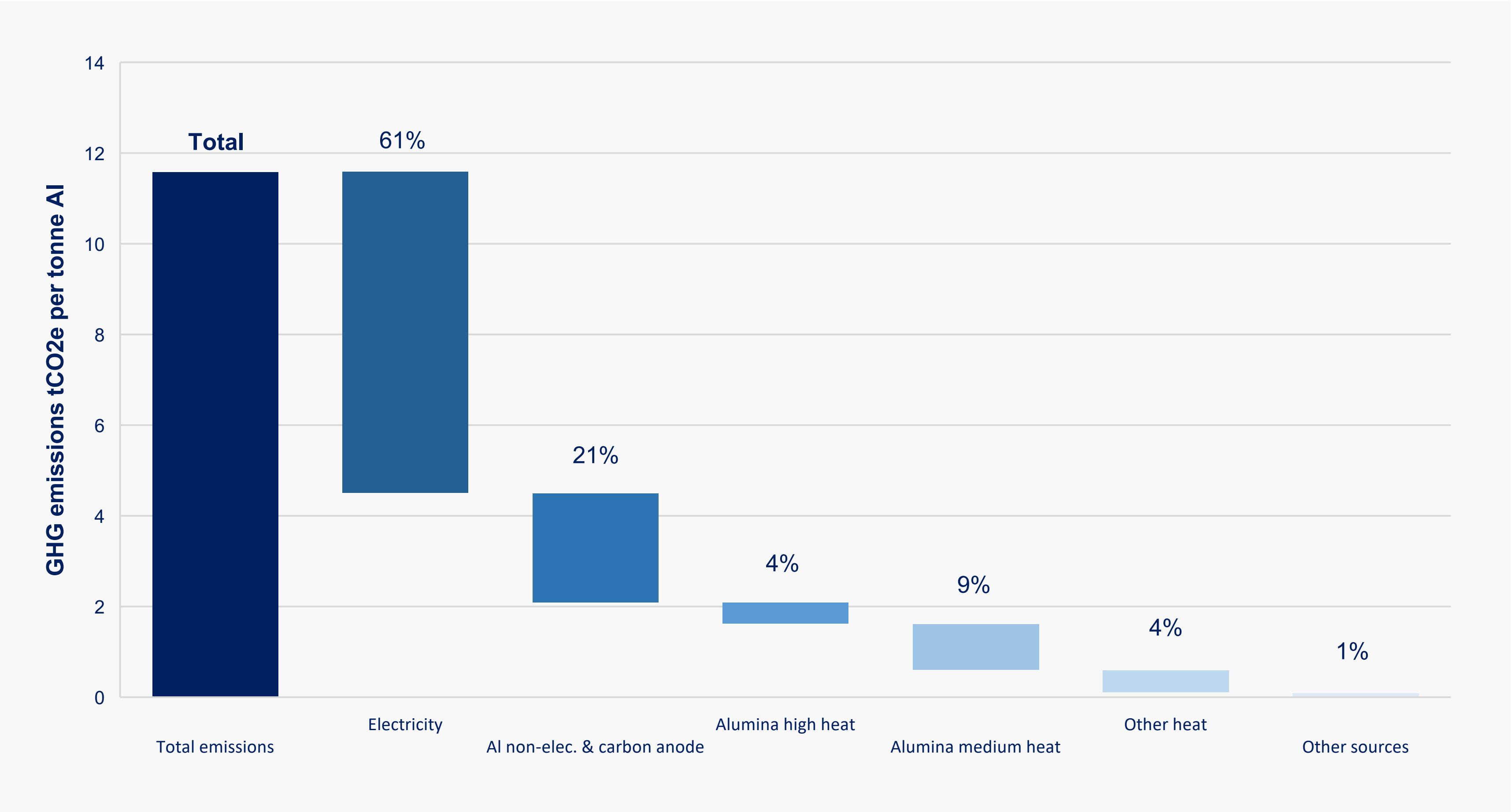


How can the aluminum produced for the low-carbon transition be decarbonized to reduce its impact as much as possible?

Applies for brownfield and greenfield operations and targets:
1) electricity, 2) process emissions, 3) heat

Overview of Al production decarbonization opportunities

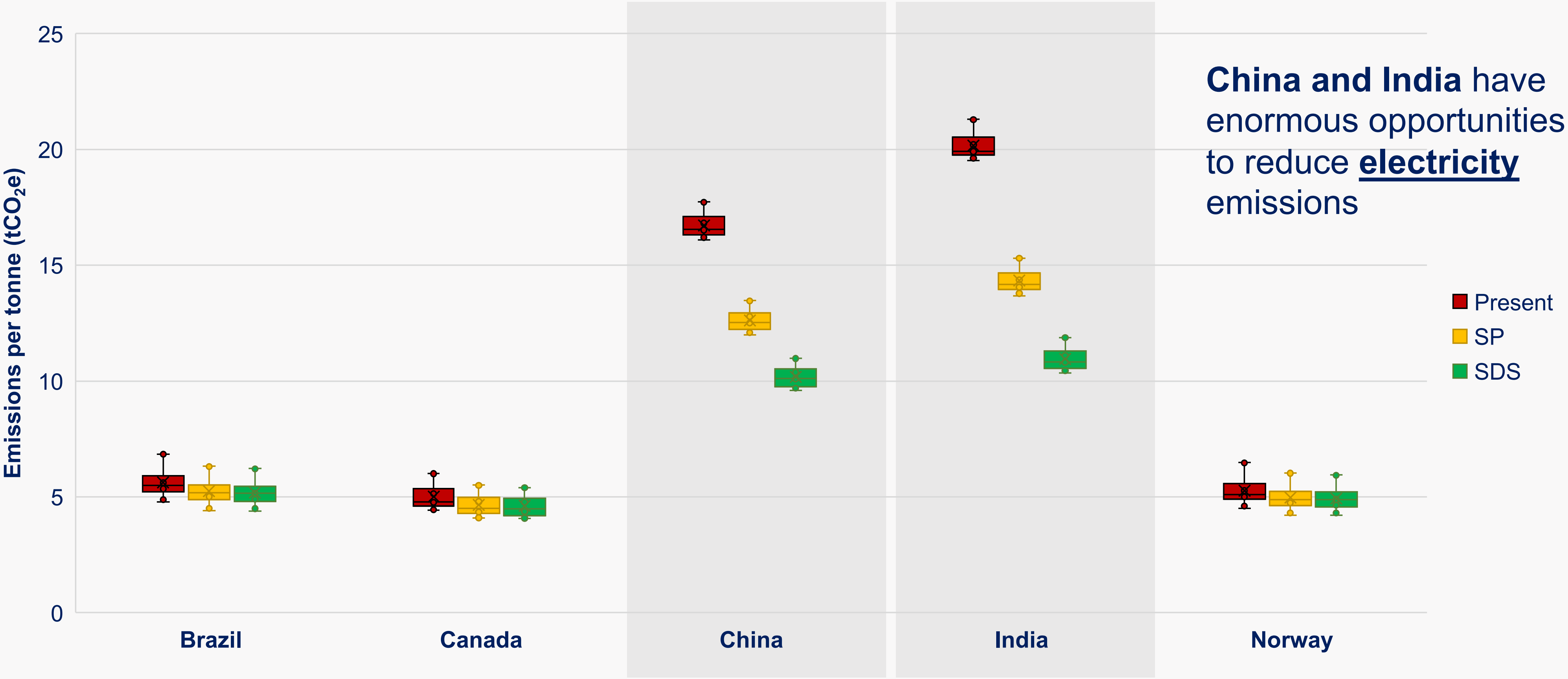
Most GHG emissions along the Al supply chain come from the **smelting process** to transform alumina into aluminum



Overview of GHG emissions

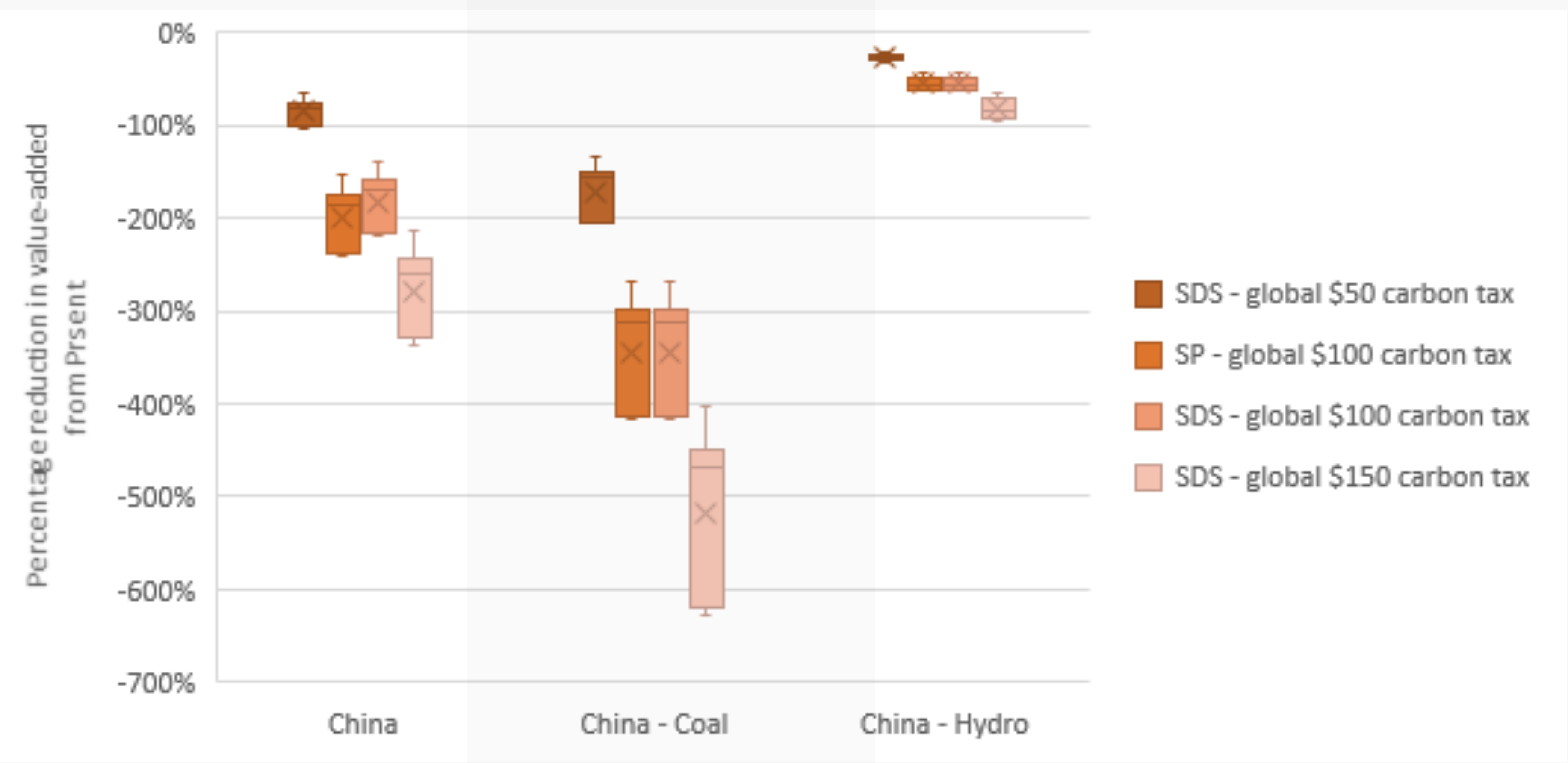
- On average, the greatest opportunities for emissions reductions come from decarbonization of electricity (some have already done this).
- The next most important areas are related to aluminum process (and carbon anode production), and heat, mainly in alumina production.

Future changes in GHG emissions from electricity decarbonization



China and India have enormous opportunities to reduce **electricity** emissions

Deep dive:
China Al production electricity decarbonization opportunities and risks



China's current mix consists of 66% Coal, 18% Hydro, 5% Nuclear, 3% Gas, 3% Wind, 3% Solar PV, 1% Biofuels, 1% Others

Process emissions reduction through inert anodes technology

Assumption: extra electricity required, at 3KWh per 3kg of Al

Potential emission reductions with inert anodes technology

- Brazil could save about 2-2.5tCO2e/t Al produced.
- China could emit even more emissions due to higher electricity requirements under a current, highly coal-dependent grid.
- Under SDS, China could gain nearly a ton of CO2e per tonne Al produced via a cleaner grid or from dedicated renewable electricity for Al production (e.g., hydro).

Cost implications

- Savings: approx. $110-120 per tonne carbon anodes + future carbon costs savings.
- Expenditure: costs of extra electricity + investment costs in inert anodes.
- Inert anodes technology investment costs could be lower with new smelters since they won't need retrofitting and they avoid sunk cost of carbon anode production facilities.

Country	Scenario	Emissions saved (with extra electricity)	Emissions saved (without extra electricity)
Brazil	Current electricity mix	**2.01 tCO2e/t Al**	2.5 tCO2/t Al
China	Current electricity mix	**–0.46 tCO2e/t Al**	2.1 tCO2e/t Al
China	SDS electricity mix	**0.94 tCO2e/t Al**	2.1 tCO2e/t Al

Managing heat emissions from alumina and extrusion

Heat is mostly used to **transform bauxite into alumina**

Heat use across Al supply chain

- Variety of heat used at different stages in the Al process; some at high; some at medium.
- High heat is very difficult to decarbonize due to technical constraints and lack of commercially viable solutions
- Medium heat has more emissions compared to high heat, but it comes with more decarbonization options.

Heat decarbonization opportunities

- Decarbonization options:
    - Clean hydrogen
    - Biofuels
    - Electrification (e.g., electric ovens)
- Key challenges
    - Costs: capital and fuel
    - Ability to retrofit into existing facilities
    - Access to low-emissions fuel sources (in all categories)

Type of heat	Emissions reduction potential	Clean Hydrogen costs	Biofuel costs	Electrification costs
Alumina refining (high temperature heat)	**0.4 – 0.7** tCO2e/tAl	**$120 - $490** t/Al	**$290- $510** t/Al	**$35 - $150** t/Al
Alumina refining (medium temperature heat)	**0.8-1.5** tCO2e/tAl	**$260 -$1060** t/Al	**$600 - $1100** t/Al	**$70 - $330** t/Al
Other heat (e.g., extrusion)	**0.5** tCO2e/tAl	**$310 - $725** t/Al	**$720** t/Al	**$80 – $230** t/Al

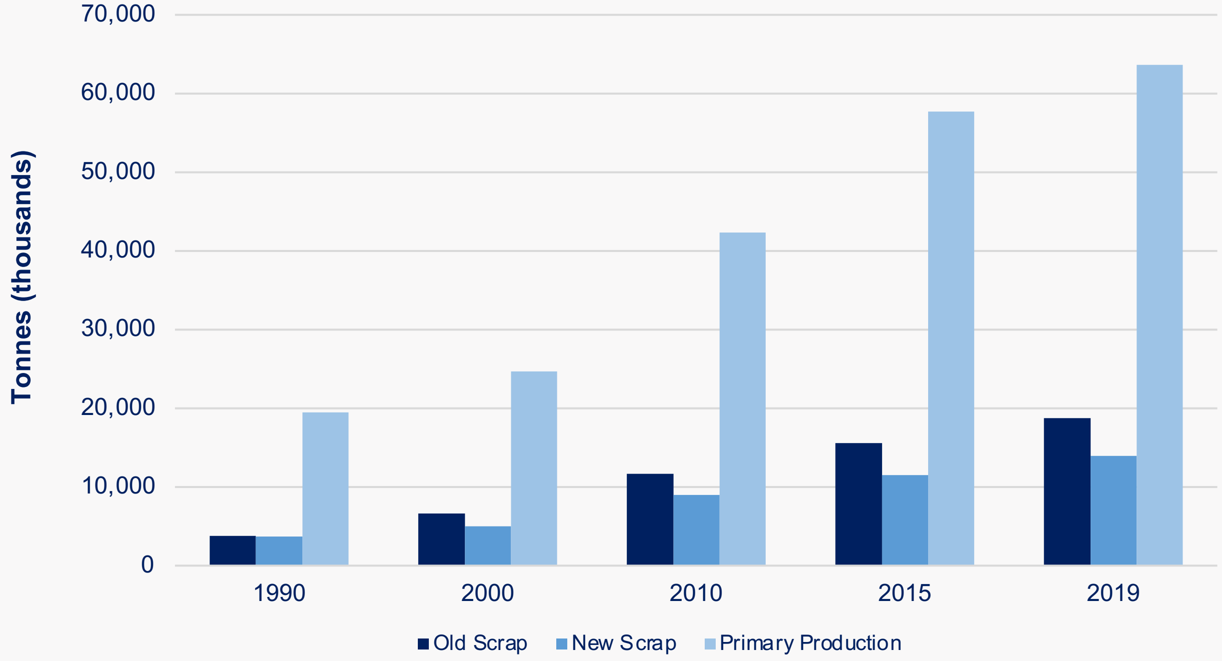
Note: This graph only covers fuel costs and does not account for capital costs

Recycling

How can secondary Al production meet demand while helping to reduce emissions?

Role of recycling for Al sector

Secondary Al can **help reduce emissions** significantly, but supply cannot meet growing demand



Source: IAI, 2021

Overview of GHG emissions

- Al is one of the most recycled metals in the world.
- Al recycling is technically and economically feasible, provided that scrap can be easily collected and processed.
- Recycling has accounted for ~34% of total global production since 2000.
- Emissions of secondary Al are much lower than primary production: ~5%, or 0.5CO2e/t Al compared to 11CO2e/t Al from primary.
- Limited data on the economics of recycling:
    - Key issues are price, quality of scrap, and transportation costs.
    - Costs of energy (heat) for re-melting are also important.

Al recycling challenges and opportunities

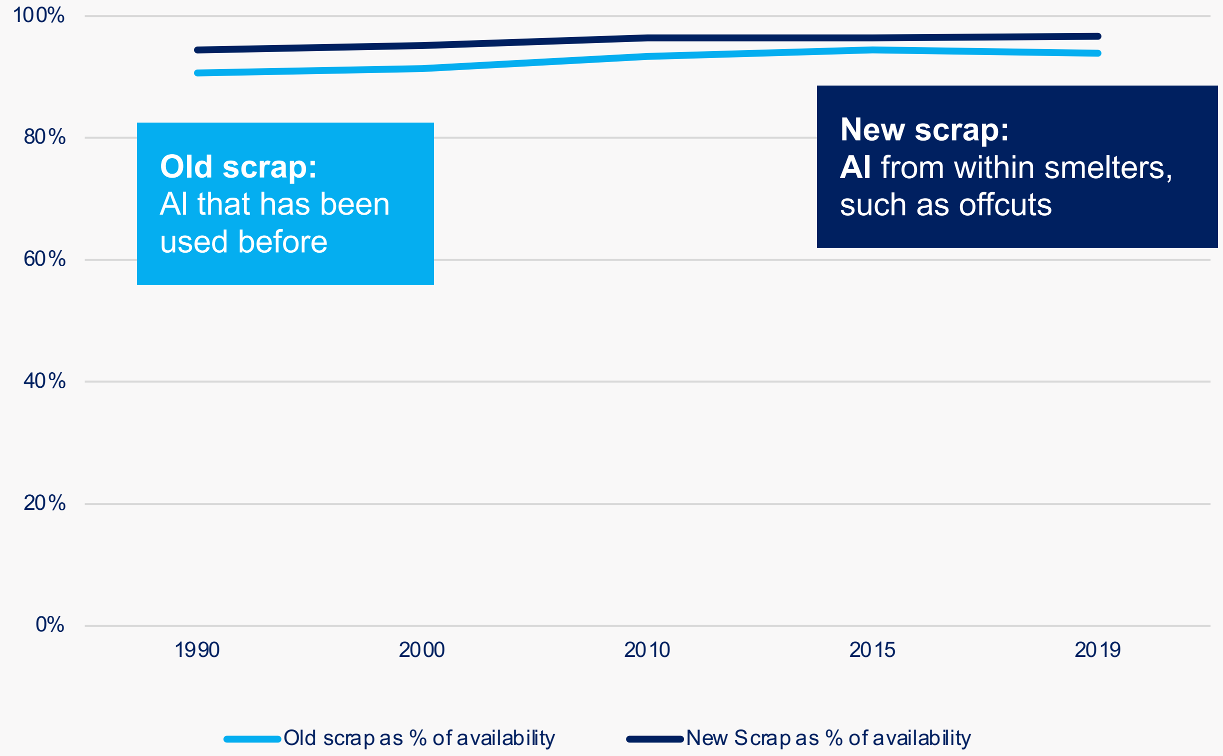
Key challenges

- Today, almost all available scrap is recycled, hovering around 95%:
    - Availability is limited by growth in Al demand, long-life Al uses, and recovery challenges in some sectors (e.g., consumer packaging and technology).
- Lack of economic opportunities in some countries, like Brazil, may be contributing to higher scrap collection rates through informal markets.
- Further action is needed to decarbonize heat from recycling process (e.g., re-melting and extrusion).

Key opportunities

- Secondary Al offers large emissions reductions relative to primary production and promotes a circular economy approach.
- Recycling provides opportunities to develop new supply chains, especially in developing countries, and formalize the scrap collection market.

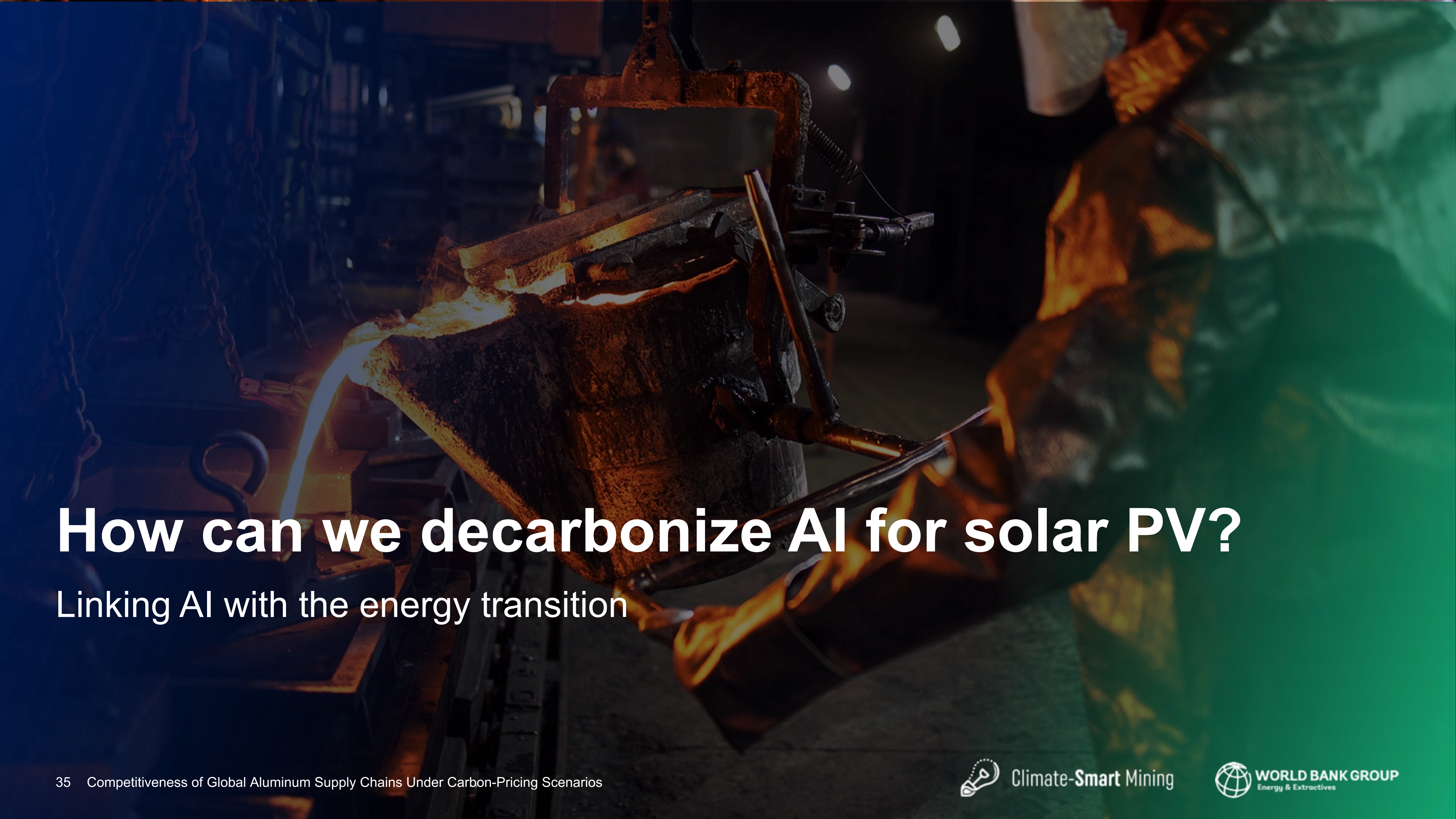
Percentage of available scrap used worldwide



Old scrap:
Al that has been used before

New scrap:
Al from within smelters, such as offcuts

Source: IAI, 2021



How can we decarbonize AI for solar PV?

Linking AI with the energy transition

Al for solar PV: Emissions for 10mw solar PV plant, Present and SDS

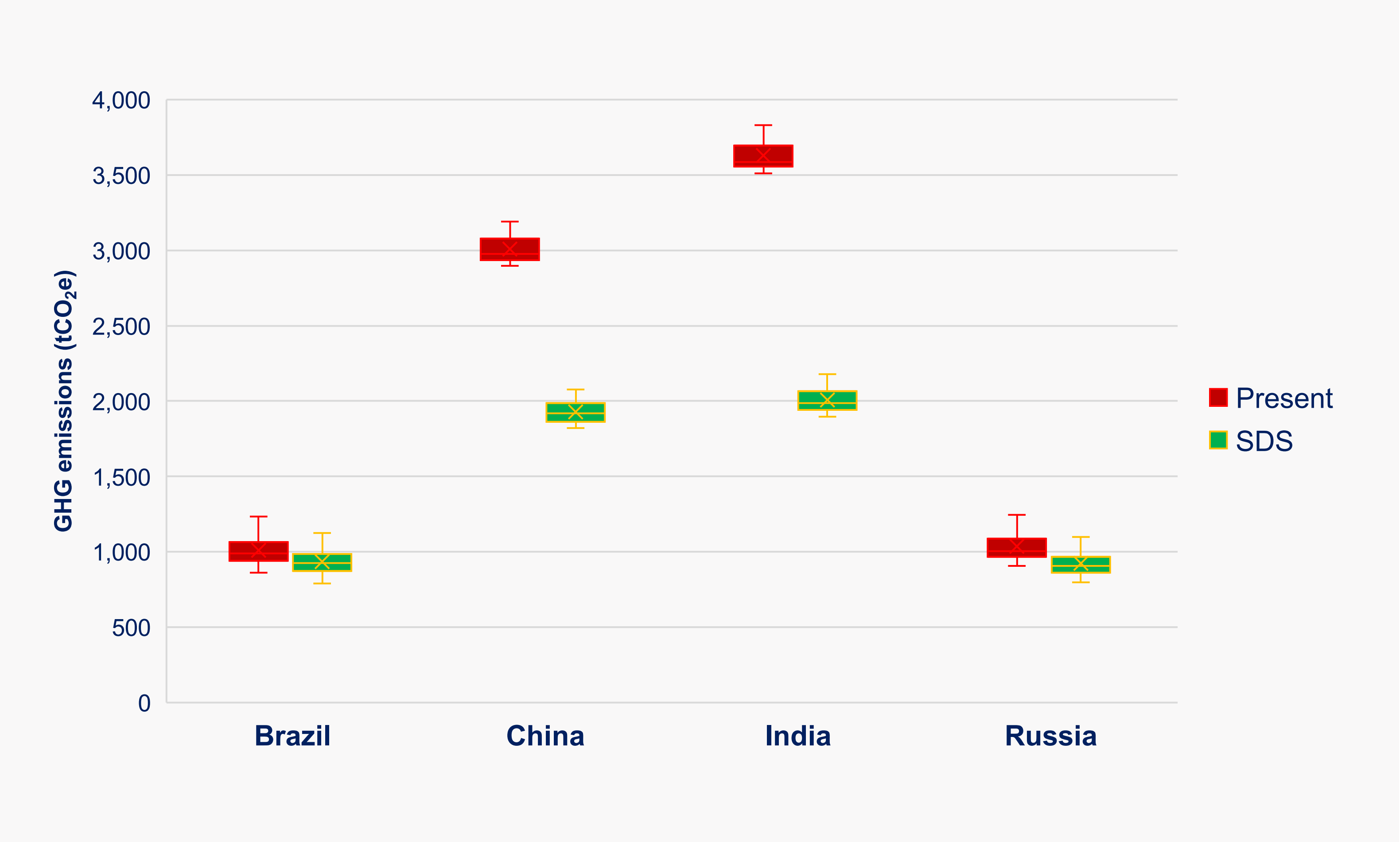
Al sourcing location could negatively impact solar PV emission savings

Al sourced from high emissions locations will lead to higher embodied emissions for solar panels. Decarbonization of electricity for aluminum smelting will help to reduce these emissions.

Comparison emissions (present)

- **Hard coal**: 414 kg /MWh
- **Hydro in Brazil**: 39 – 133 kg/MWh
- **Al for solar PV**
  - 22 kg/MWh (*Brazil-Brazil-Brazil*)
  - 73 kg/MWh (*Brazil-Brazil-China*)

Solar PV: Assuming 15-year lifetime, 30% capacity factor; moderately intensive solar PV panels



Environmental challenges beyond decarbonization

Al production can lead to a wide range of environmental impacts

Environmental impacts

Al production could contribute to a wider set of environmental impacts, beyond GHG emissions

Forestry and Biodiversity

- About 60km2 of land is mined for bauxite globally of which 60% in forested areas,.
- The nature of resource means that ore extraction requires comparatively more land than other resources (albeit for a shorter period of time).
- Induced, indirect deforestation is likely to be much larger than direct impacts: Sonter et al (2017) in Brazil estimated a deforestation rate 12 times higher outside mining licenses compared to within.
- Biodiversity impacts may follow from deforestation: This is especially important given tropical location of much of bauxite production.
- Industry activities focusing on reforestation (such as RUSAL) and biodiversity protection standards (such as ASI) are emerging.

Waste and Water

- **Water** is needed for washing bauxite ore, washing bauxite residue away to form alumina, production of steam and caustic soda, and colling power plants.
- 40% of bauxite mines occur in high and extremely high water-risk areas.
- **Waste:** The production of red mud from the conversion of bauxite to alumina requires careful management, with each tonne of alumina producing 600-1,500 kg of waste.
- This calls for careful tailings management, with emerging options such as dry-stacking, use of red-mud as an input to clinker, and reworking tailings.

Conclusion

Al production emissions:
Tackling electricity emissions is necessary but not sufficient

Electricity emissions

- On average, most Al emissions come from **electricity use**, accounting for about **61% of overall emissions.** Some countries have already decarbonized electricity via hydropower sources while other countries are implementing the same approach. Historically, most of the industry focus has been on reducing electricity-related emissions from the Al smelting process and decarbonizing electricity use in general.
    - More progress on sourcing electricity from renewables, including solar and wind, will be needed to further reduce emissions.
    - **About~40% of non-electricity emissions remain** and must be addressed (when looking at industry’s average emission levels).

Heat emissions

- **Heat currently accounts for 17% of GHG emissions.** Alumina production requires the most heat, typically using high amounts of heat to transform bauxite into alumina. It is also used in the final manufacturing of aluminum.
- Technical options exist to decarbonize heat, but there are challenges with basic economics, retrofitting existing refineries, and sourcing low-carbon fuels such as clean hydrogen, biofuels, and electricity.

Process emissions

- Historically, there has been good progress on reducing process-related emissions (e.g., PFCs), but more work is needed to decrease CO2 from **carbon anodes**
- Technological solutions, such as inert anodes are being developed to address this issue. However, concerns remain around the economic feasibility and potential additional energy requirements to deploy this technology (which could increase Opex)
- Retrofitting innovative technology solutions (e.g., inert anodes) into existing facilities could prove to be more challenging than for new Al smelters

Recycling emissions

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- Sourcing recycled aluminum is one of the most effective ways tor reduce emissions since **it only accounts for about ~5% of average primary aluminum emissions.**
- There are many challenges associated with sourcing recycled aluminum including availability of scrap.

Implications for the supply of green Al and maximizing value-added opportunities in LICs and MICs

The limited potential for value-addition in existing and new Al smelters under carbon prices raises questions about the supply of green Al for the low-carbon energy transition

Limited opportunities for value-addition could lead to price hikes

- The potential for value-addition in new and existing smelters are limited with carbon prices in place, at historic Al price ranges.
- This implies that either production will be restricted to a limited set of producers (using either new or existing smelters) or the price of Al will have to rise above historic levels.
- Al price increases create likely cost increases for low-carbon technologies such as solar PV, transmission, and EVs.

In the presence of carbon prices, decarbonization increases competitiveness

- With higher carbon prices, decarbonization across the supply chain becomes essential to retaining competitiveness.
- For countries using fossil-fuel-based electricity, decarbonization of electricity is crucial.
- Even if this is achieved, further decarbonization is required to ensure a positive value-add at historic price ranges.
- Decarbonization could also play a role in enhancing competitiveness, by facilitating access to markets and supply chains.
- Differentiated market involving price spreads between ‘green’ and ‘non-green’ Al could emerge, Further work is needed to ascertain firms’ willingness to pay for such products.

Value-added opportunities

Decarbonization

*Historic prices refer to aluminum priced at USD $2,250 per tonne

Al production value-addition opportunities:
High- and upper-middle-income economies tend to have an advantage

LIC

Low-income economies*

- Modelled data shows limited Al production opportunities for LICs such as Guinea, even with the construction of cheap and reliable renewables, due to **higher CAPEX and OPEX relative to MICs and HICs.**
- Modeled scenarios show that high carbon prices might help to a limited extent, but it will also depend on the **pace of other country producers' decarbonization efforts.**
- Instead, value-addition opportunities could be found in bauxite and alumina production. Decarbonization of these points in the aluminum value chain is important in retaining competitiveness in the presence of carbon prices.

MIC

Middle-income economies

- With no high carbon price, industry data shows that in most MICs new/existing Al smelters can add value due low CAPEX/energy costs.
- While several countries fall under the MIC category, differences in reported capital costs can significantly impact opportunities for value-addition, especially when it comes to building a new Al smelter.
- Modeling shows that MICs dependent on fossil fuel sources, such as China and India, could lose significant opportunities for value-addition under high carbon pricing scenarios, unless they significantly decarbonize their electricity mix.
- MICs that are highly dependent on dispatchable renewable sources, such as Brazil and Russia, would also lose value-added opportunities under a high carbon price due to supply chain-related and non-electricity emissions(direct).

HIC

High-income economies

- Modeling shows that HICs such as Canada, Norway, EU countries, GCC nations, retain opportunities for value-addition in existing Al smelters under low-to-high carbon prices.
- Due to **higher CAPEX relative to MICs,** some HICs building new Al smelters might not have opportunities for value-addition, regardless of whether there is a carbon price.
- Higher Al prices, rising to about $3,000, could help several HICs tap into value-addition opportunities in the absence of carbon prices. Still, without addressing GHG emissions coming from non-electricity sources and the overall supply chain (direct emissions), HICs could miss out on opportunities for value-addition in the presence of a carbon price (<$50+).

*Historic prices refer to aluminum priced at USD $2,250 per tonne

*Conclusions for LICs are drawn from the single data point and thus application beyond Guinea may be limited.

Recommendations on decarbonizing Al production while benefiting emerging and developing economies along the Al supply chain

Sector	Opportunity	Recommendation
Value-addition opportunities	For LICs, focusing on expanding bauxite and alumina production is likely to offer the most opportunities for value-addition For MICs, value-addition opportunities exist in re-opening closed capacity and in building new smelters	• Policy support for LICs should focus on addressing challenges by building skills, investing in energy and transport infrastructure for bauxite and alumina production, and reducing wider investment risk. • In the presence of carbon prices, decarbonizing bauxite and alumina production will be important to retain competitiveness. Decarbonization will likely be needed to address broader competitiveness dimensions, including access to markets through green certification or other programs. • For MICs, retention of opportunities for value-addition in the presence of carbon prices requires decarbonization of electricity and other emissions across the supply-chain. • Due to CAPEX challenges, policy support for re-opening and retrofitting closed capacity could be more appropriate than supporting greenfield capacity.
Decarbonization Opportunities	Decarbonization of electricity is necessary but insufficient. Non-electricity emissions also must be addressed	• Carbon prices are a vital signal to producers and the industry that they must invest in new electricity- and non-electricity-related technology to decarbonize the entire Al supply chain and remain competitive. • Policy support will be needed in the demonstration, deployment, and transfer of new and innovative technologies to address remaining non-electricity emissions, particularly in LICs and MICs. • Policymakers should support the deployment of low-carbon energy sources, such as low-carbon hydrogen, biofuels, and electricity for heat, because they are largely uneconomic.
Recycling Opportunities	Secondary production (recycling) can help reduce emissions, but challenges remain with scrap availability and technology barriers	• Policy support in all countries will be needed to encourage the production of secondary Al, including improving scrap collection, incentivizing scale up of recycling, and promoting the integration of a circular economy approach to product design and manufacturing. • In LICS and MICs, policymakers can work with industry to formalize the scrap collection market by setting internationally accepted standards. • Policy support is needed for innovative business models such as aluminum-as-a-service, in which Al is rented to technology developers and then recovered.

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