Waipapa Taumata Rau University of Auckland

Energy Centre

Summer School in Energy Economics

Energy Dynamics of the Global Aluminium Industry

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The aluminium story is a story of energy

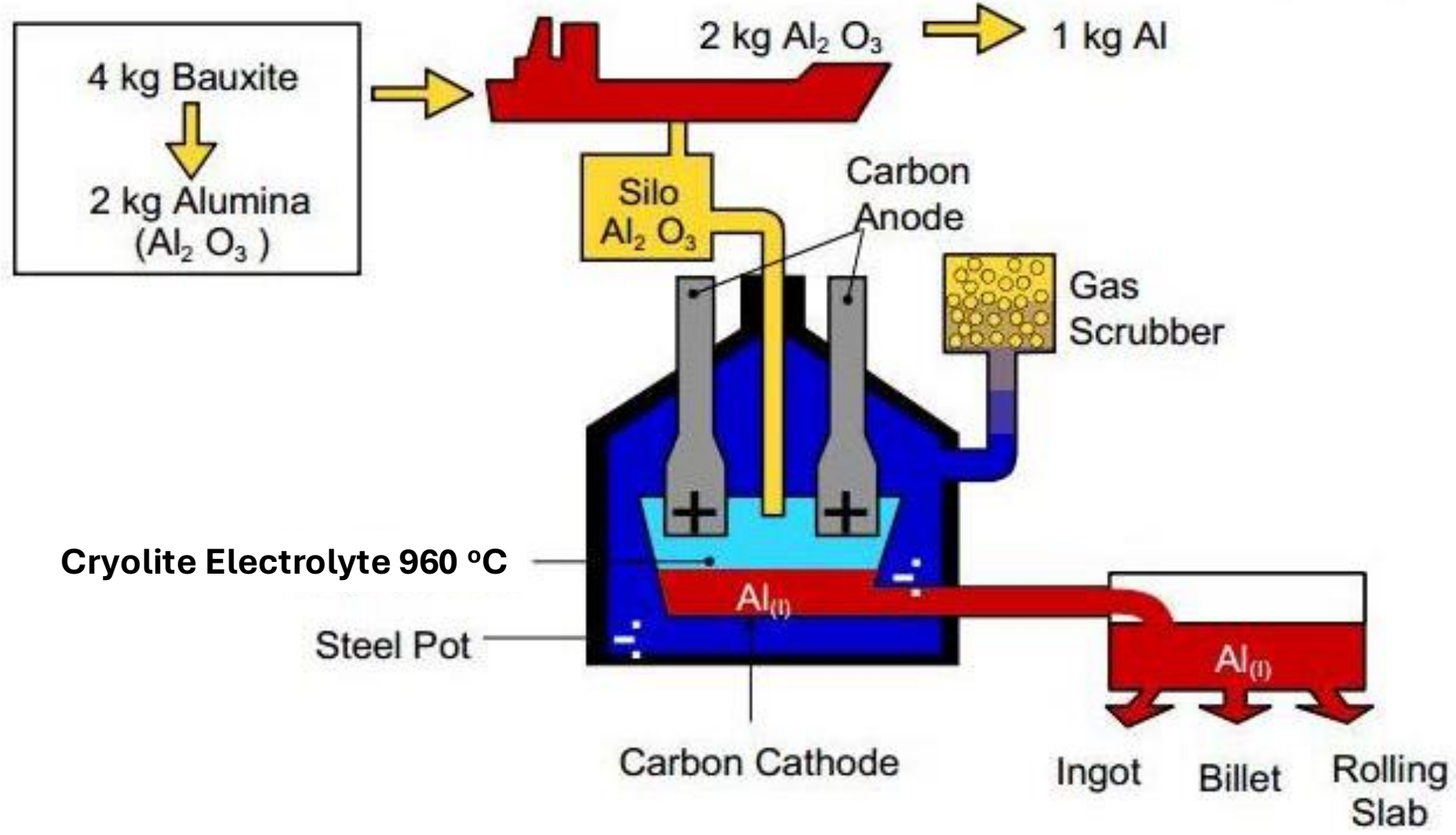
https://alustory.international-aluminium.org/primary-production/energy-water/

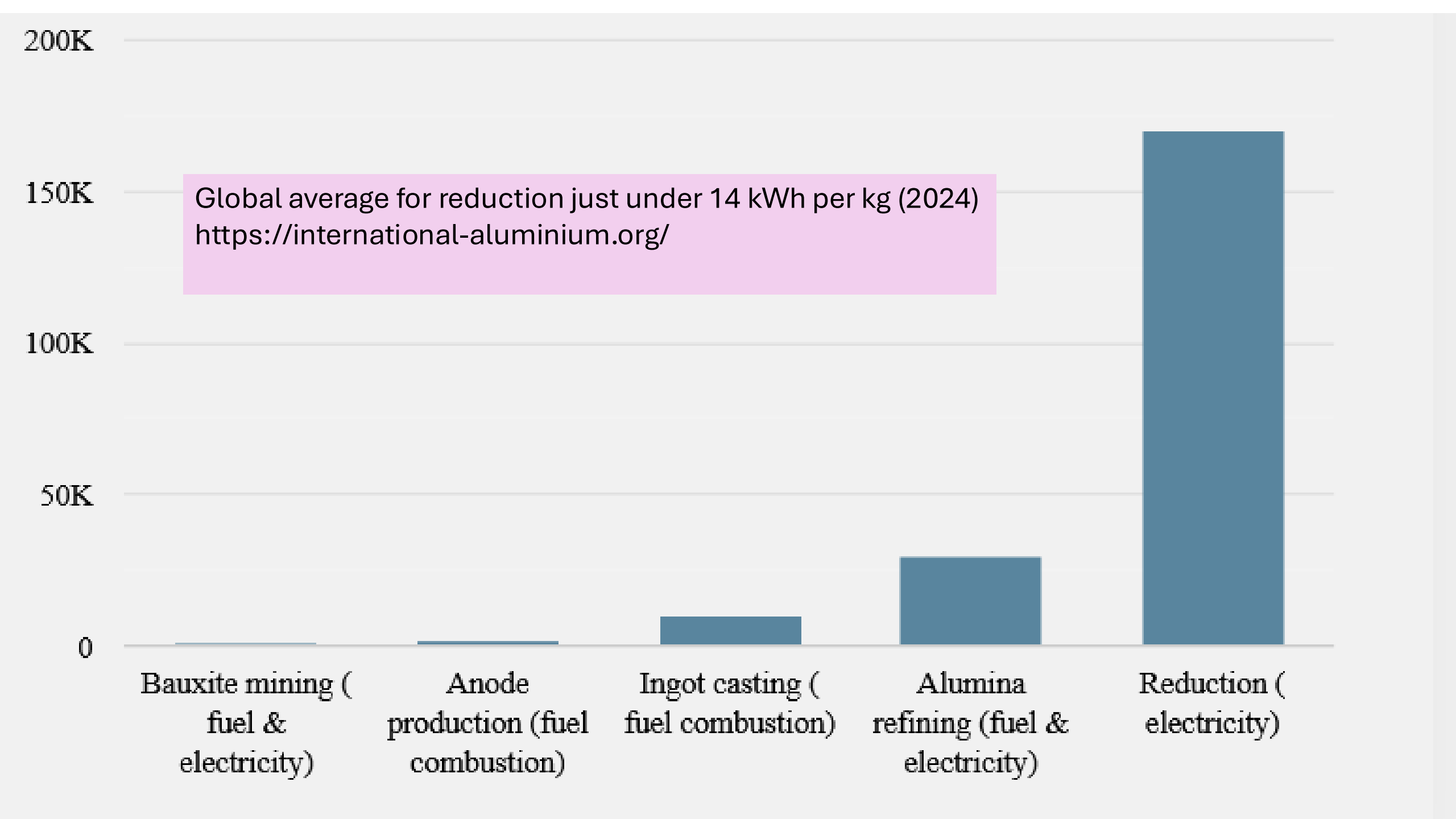
Content

- The Aluminium production process and it’s energy footprint
- What drives the global distribution of production capacity
- Evolution of the power sources used in smelting
- Evolution of technology and the roadmap for the future
- What is realistic in this future vision?

Tiwai Point

Production of Primary Aluminium




200K
150K
100K
50K
0
Global average for reduction just under 14 kWh per kg (2024)
https://international-aluminium.org/
Bauxite mining (fuel & electricity)
Anode production (fuel combustion)
Ingot casting (fuel combustion)
Alumina refining (fuel & electricity)
Reduction (electricity)

Kilowatt hours (kWh) per tonne of aluminium for 2024 (Average)

Oceania	16302
South America	15855
Europe	15619
North America	15016
Asia (ex China)	14677
Gulf Cooperation Council	14618
Africa	14208
China	13262
World	13990

Construction of Tiwai Point Smelter early 70's – from the NZAS website, accessed 27/01/26

https://international-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/

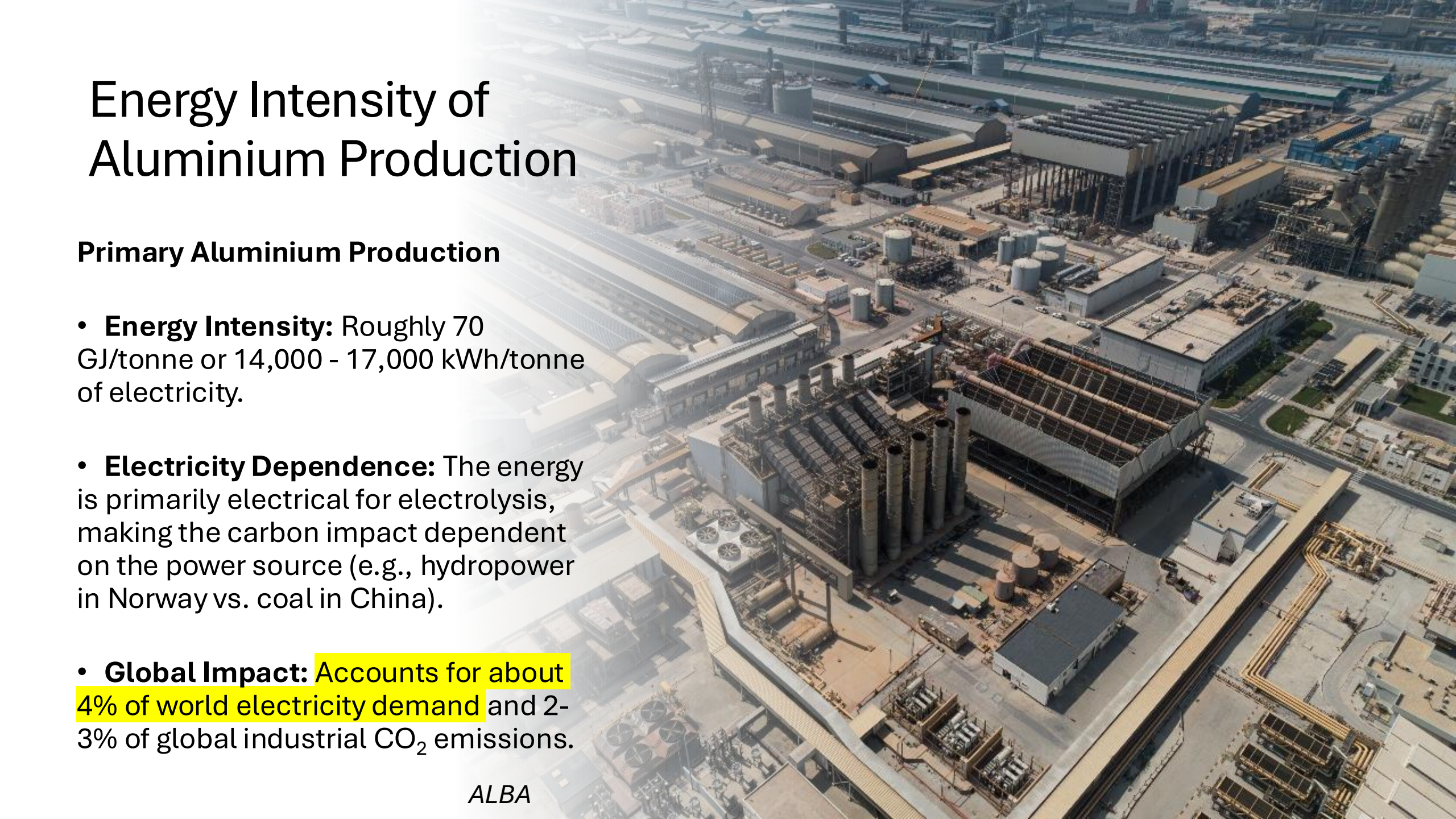
Energy Intensity of Aluminium Production

Primary Aluminium Production

- **Energy Intensity:** Roughly 70 GJ/tonne or 14,000 - 17,000 kWh/tonne of electricity.

- **Electricity Dependence:** The energy is primarily electrical for electrolysis, making the carbon impact dependent on the power source (e.g., hydropower in Norway vs. coal in China).

- **Global Impact:** Accounts for about 4% of world electricity demand and 2-3% of global industrial CO_2 emissions.



ALBA

Global and Regional Electricity Consumption

While the global average for smelting is 3-4%, the impact on national grids varies significantly based on local industrial concentration:

- **China:** Aluminium smelting accounts for **7% of national electricity demand**.
- **Australia:** Making aluminium utilizes **10% of the country's total electricity**.
- **New Zealand: 13% of the country's total electricity**
- **Coal Power Reliance:** The aluminium industry consumed **6% of all global coal-fired electricity** in 2019.

Energy Intensity of Production

The amount of electricity required depends on whether the aluminium is "primary" (newly extracted from ore) or "secondary" (recycled).

- **Recycling Advantage:** Recycled or secondary aluminium production is dramatically more efficient, requiring approximately **95% less energy** than primary production.
- **Cost Factor:** For primary Al, electricity can account for up to **40% of total production costs**.

- “New smelting capacity doesn’t only follow where the most cost-effective long-term sources of available energy are; it also enables the development of new power generation. Smelting plants can bring reliable electricity to new areas, which increases distribution capacity and drives economic development.”

- *Svein Richard Brandtzæg*
Ex CEO Norsk Hydro

Smelting Capacity in the Middle East

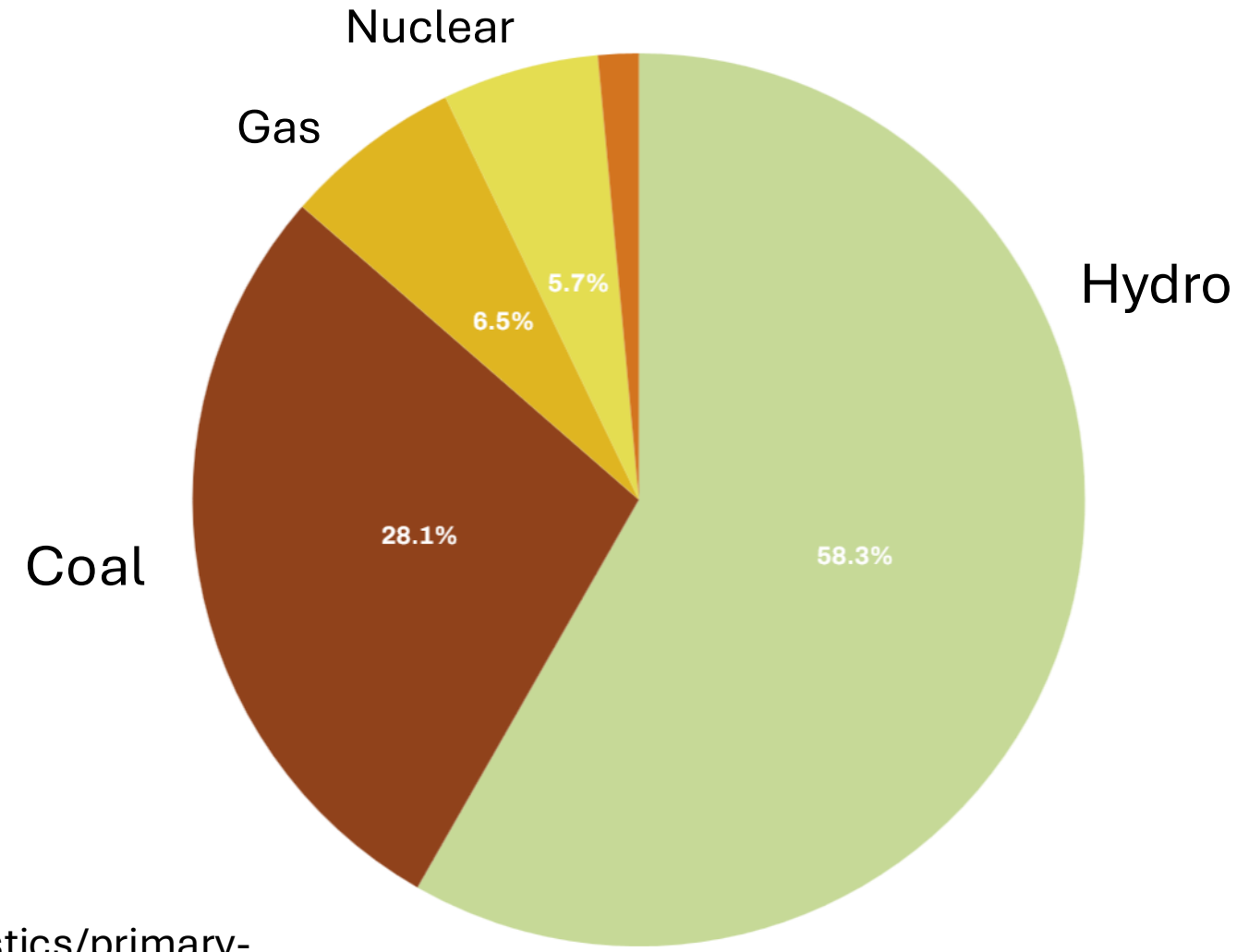
- Production in the region grew by approximately 80% between 2010 and 2023
- The Middle East and Africa (MEA) aluminum market is projected to grow at a CAGR of 4.4% to 5.0% from 2023 to 2030, with the region currently contributing roughly 9-10% of global primary aluminum

- “There are three main elements needed to build aluminium smelters. The first element is energy, and the Gulf is rich in this regard. The second element is capital, which is also available locally and through international banks and financial institutions. The third element is market. The local industry for aluminium is increasing in the Gulf and world demand for the metal is increasing at a rate of 5% annually”

Mahmood Daylami – Secretary General Gulf Aluminium Council GCC ALUMINIUM 2016

Alba’s Power Station 5 …….. a new 680.9MW combined-cycle power plant - Mitsubishi Power

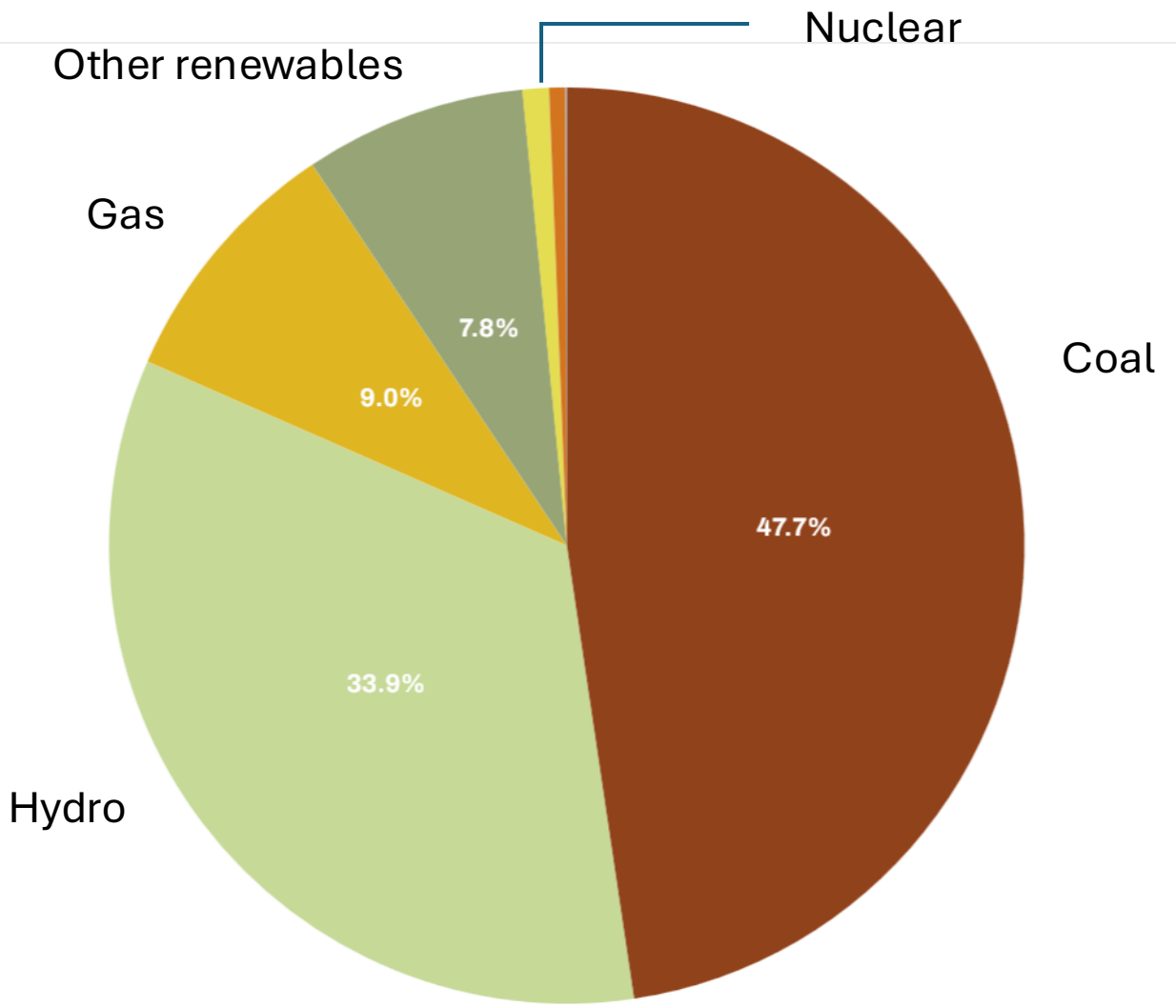
Reduction
Power Mix 1994



https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption

Reduction Power Mix 2024

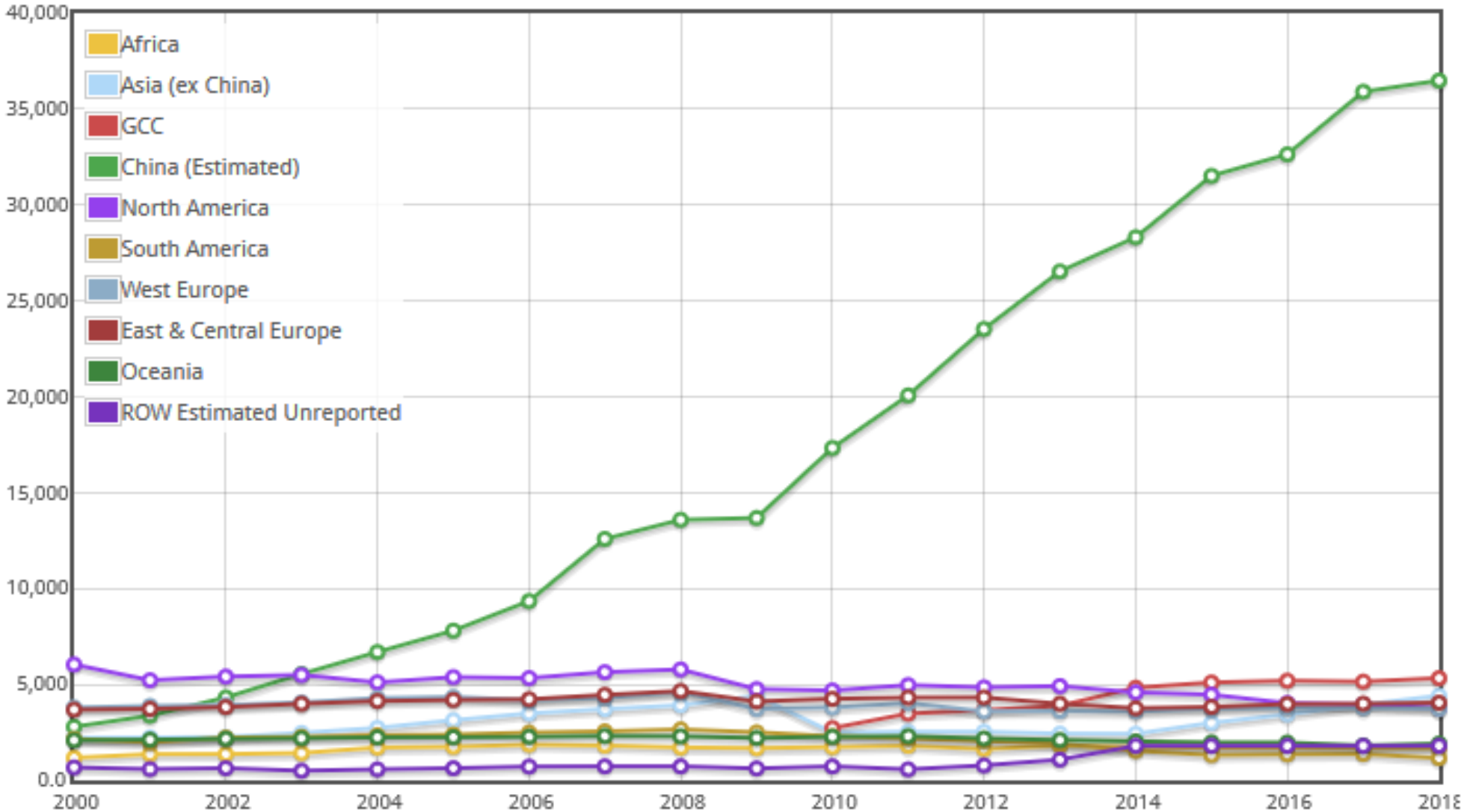
- Reflects the shift of smelting capacity to China, the Middle East and India



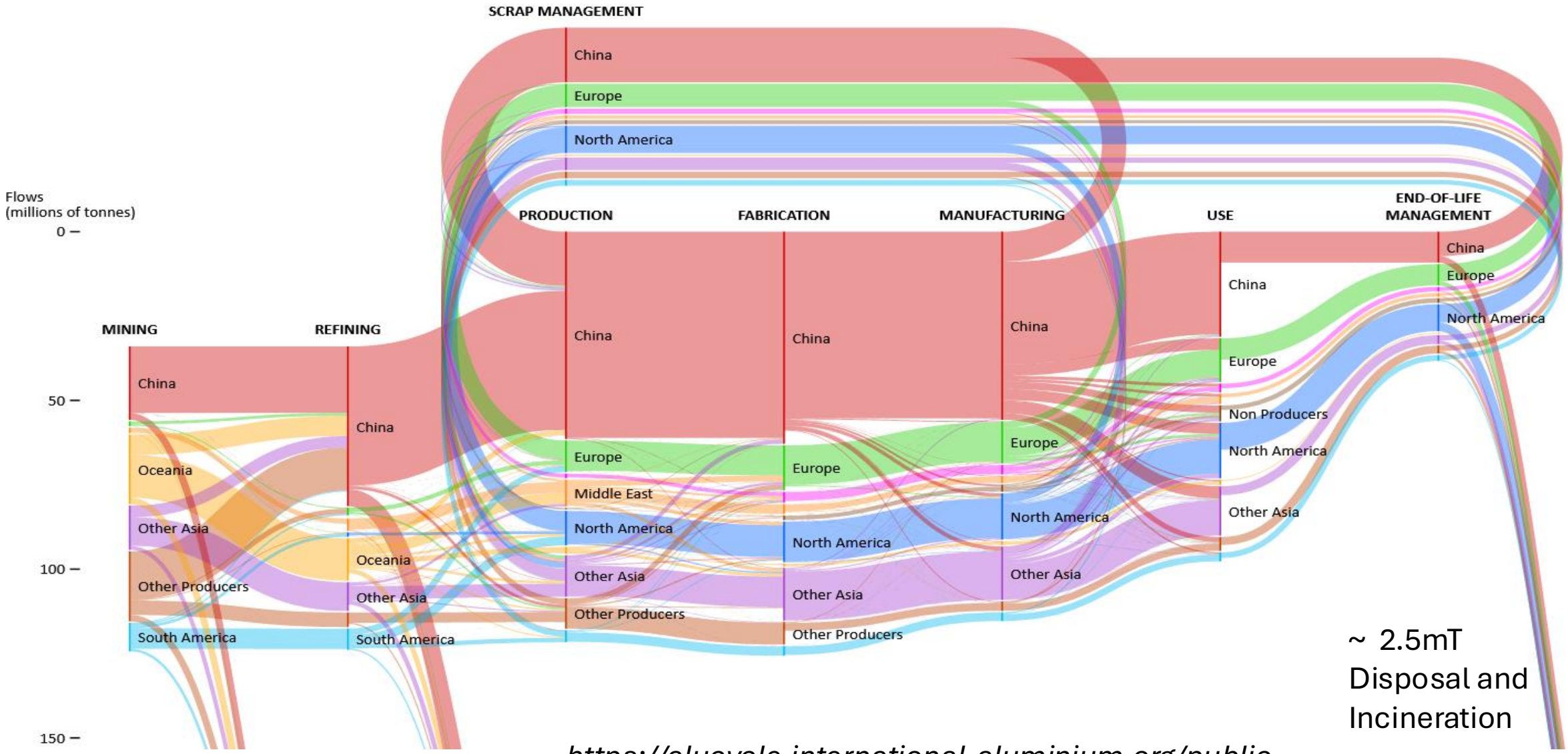
https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption

Total for 2000 to 2018: 805,637 thousand metric tonnes of aluminium

International Aluminium Org.

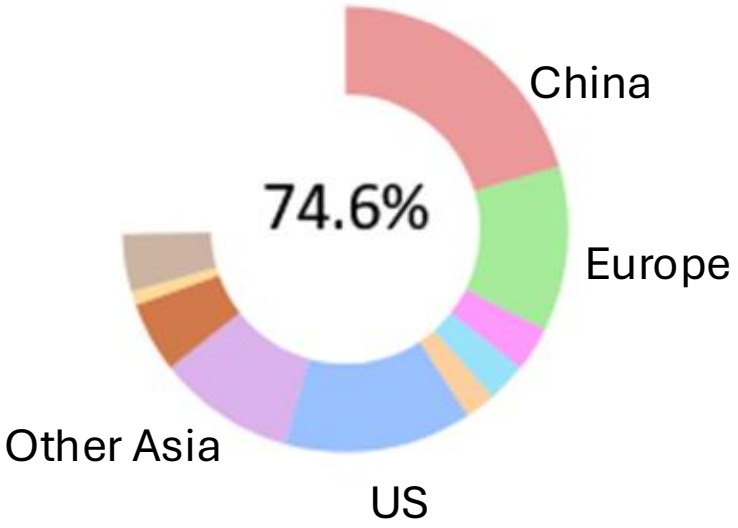


Sankey Diagram for Global Al Flows 2024



~ 2.5mT Disposal and Incineration

https://alucycle.international-aluminium.org/public-access/public-global-cycle/



% of Al ever produced still in use, demonstrates longevity of the metal and ease of recyclability

Inspection of the Washington Monument cap after 100 years of service in 1984 - Courtesy of Stephen Lindsay
- Note that this was before the Hall-Heroult process – Al produced by thermo-chemical reduction of Al Choride

Century to Receive $500 Million from the DOE to Build a Green Aluminum Smelter in the U.S.

Century Aluminum Company was selected by the U.S. Department of Energy (DOE) Office of Clean Energy Demonstrations to begin award negotiations for up to $500 million in Bipartisan Infrastructure Law and Inflation Reduction Act funding to build a new aluminum smelter as part of the Industrial Demonstrations Program (IDP). Century's Green Aluminum Smelter Project is one of 33 projects across more than 20 states to receive funding designed to demonstrate commercial-scale decarbonization solutions needed to move energy-intensive industries towards net-zero ……..

Light Metals Age - March 25, 2024

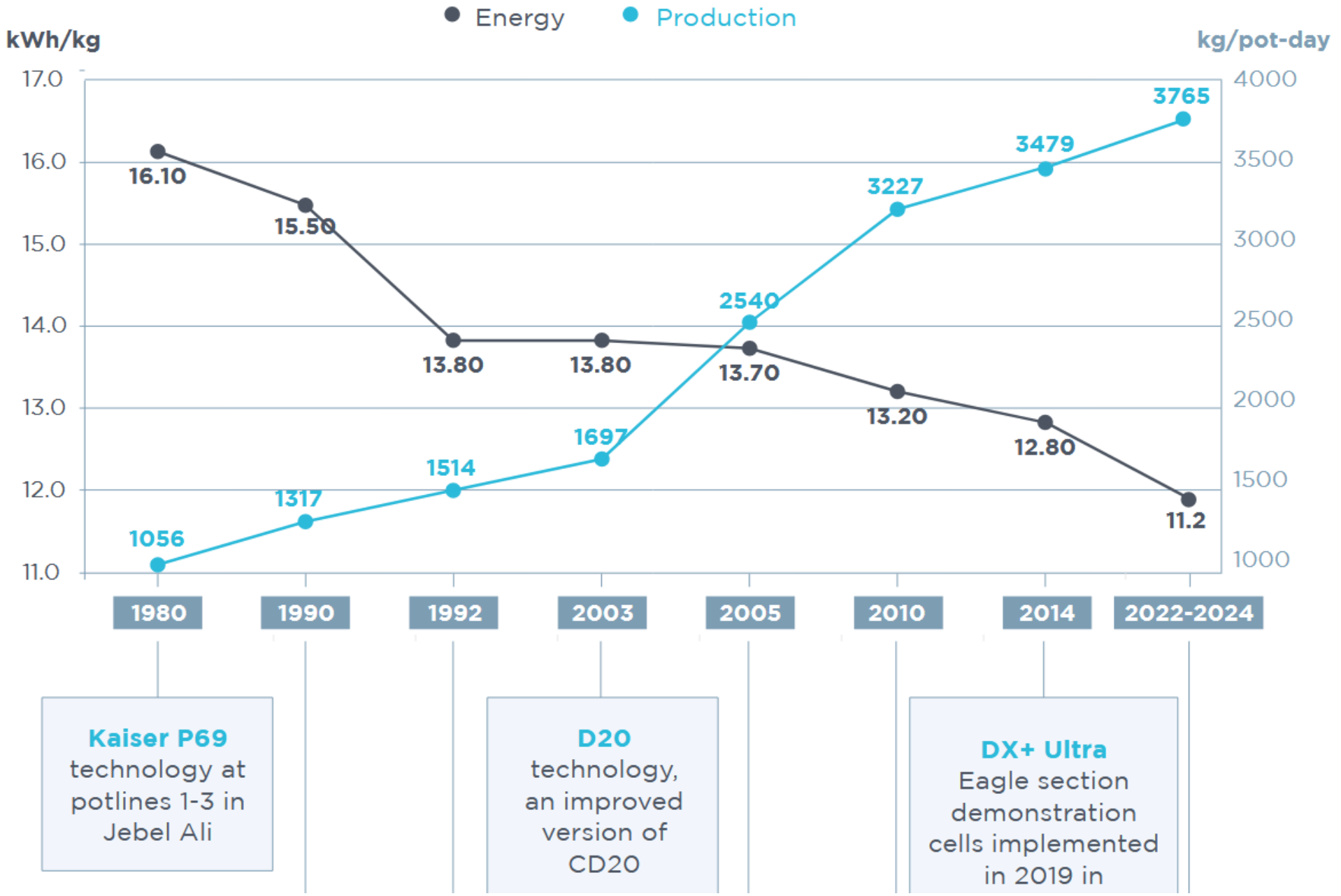
Light Metals Age - January 2026

- “Century Aluminum Company and Emirates Global Aluminium (EGA) entered into a joint development agreement to build the first new primary aluminum production plant in the U.S. since 1980 — .... Previously, the two companies had each separately announced plans to build smelters in the U.S., including EGA’s planned greenfield smelter in Inola, Oklahoma. Both parties will now focus their greenfield development efforts exclusively on the Inola site.....

- Once complete, the plant is expected to produce 750,000 tonnes of aluminum per year..... This will more than double current U.S. production .....”

https://media.ega.ae/ega-begins-production-with-its-next-generation-smart-smelting-technology

Note capacity of the ALBA smelter (Bahrain) currently 1.62 million metric tonnes



Emergence of Emirates Global Aluminium (EGA) as a technology supplier

https://www.ega.ae/media/efubkizk/ega-technology-booklet-dec-2021.pdf

Strategic importance of Aluminium

- “aluminium has been recognised as highly significant across 27 applications in the Green, Digital, Defence, and Aerospace areas……

  ➢ Support the full European aluminium value chain through state aid, carbon leakage protection, and energy cost mitigation.

  ➢ Swift implementation of the Critical Raw Materials Act, including rolling out dedicated financing mechanisms for strategic raw materials and strategic projects which in turn can boost the European aerospace and defence sectors.

  ➢ Invest in innovation to develop next-generation aluminium alloys for lightweighting, enhanced protection, and performance.

  ➢ Introduce export fees on aluminium scrap, to ensure strategic resources remain within the EU for circular use.

  ➢ Integrate specific considerations in public procurement policies for strategic raw materials, such as aluminium, by introducing non-price criteria such as resilience”

** JRC study, Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU - Publications Office of the European Union, Brussels 2023*

What is the role of aluminium in clean energy transitions? (IEA)

Clean energy transitions will increase the demand for aluminium because many technologies require greater use of aluminium – for example, for lightweight vehicles and solar energy (which uses aluminium for various components). Given the considerable amount of electricity consumed in the aluminium subsector, decarbonising its power sources would help reduce indirect emissions and is thus a key complement to reducing direct aluminium emissions.
https://www.iea.org/energy-system/industry/aluminium

Aluminium design for e-car battery frames - Hydro Aluminium
https://www.shapesbyhydro.com/en/industries/aluminium-design-for-e-car-battery-frames/

An Industry Roadmap for Carbon?

	2023	2030	2035	2040	2045	2050	2023-2030	2023-2040	2023-2050
Primary aluminium*	14.8	11.5	4.2	2.2	1.2	0.5	-22%	-85%	-97%

https://international-aluminium.org/landing/low-carbon-aluminium-factsheet/
Accessed 19/01/2025

- This is the modelling for the Al industry requirement to meet 1.5 deg Global Warming by 2050
- The issue is there is no plausible technology pathway for this to happen - especially the period to 2035

The energy/carbon dilemma

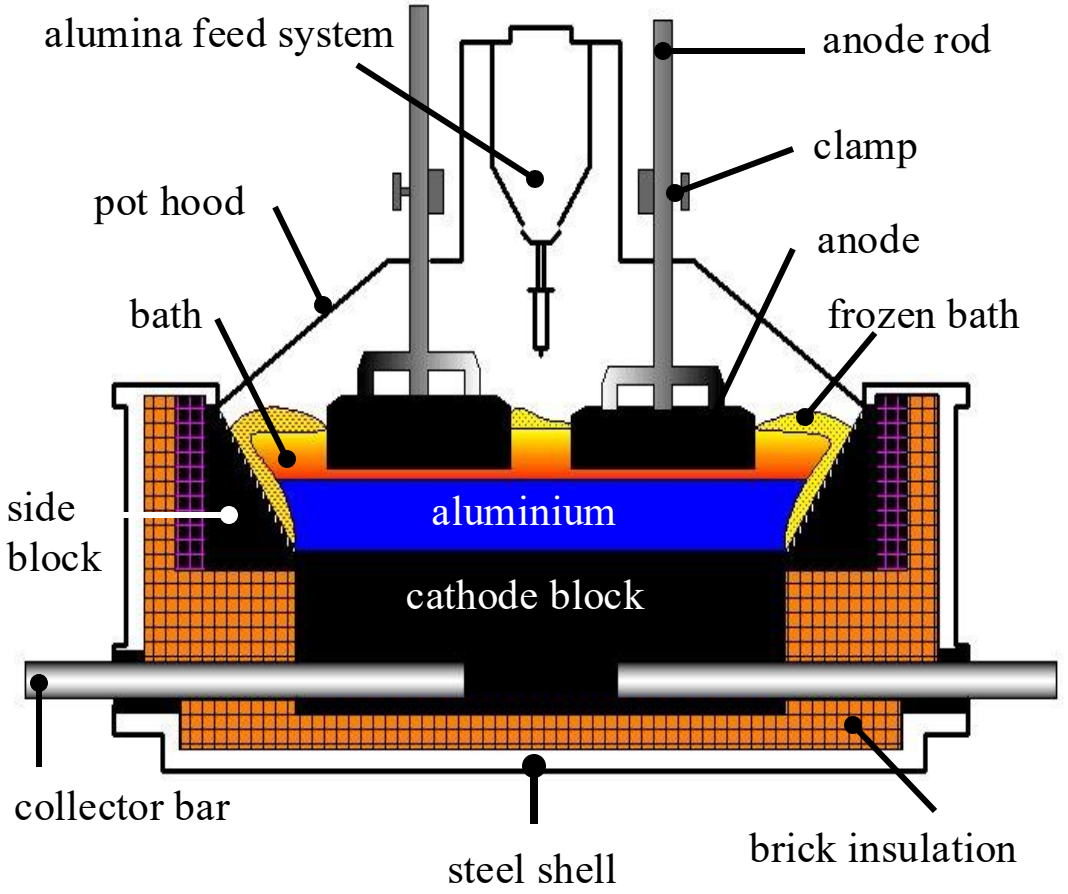
- In Al smelting Electricity is intimately tied to carbon through:
    1. The consumption of carbon anodes in the reduction cell
    2. Global use of thermal power to provide the electricity used in the reduction process.

- Replacement of carbon anodes with “Inert anodes” (under development for some years) lowers direct carbon emissions but increases cell voltage and thus direct electrical consumption

Industrial Cell Features

Need to enable :

- Supply of consumables
- Removal of metal
- Capture of emissions
- Minimize heat loss
- Prevent materials of construction degradation
- Control Energy input
- Since dealing with 2 liquids, must enable separation
- *Generate sufficient thermal energy to maintain process temperature*

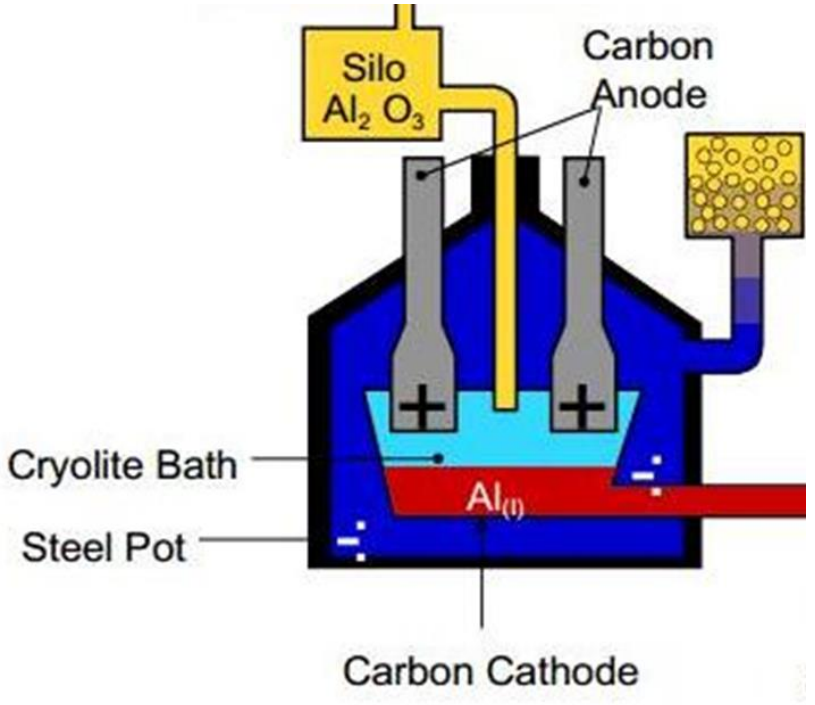


Faraday's Law

- The amount of aluminium produced is proportional to the amount of current / charge passed through the cell. This provides the *theoretical* floor in electrical consumption.

- *Theoretical* metal production is usually calculated from Faraday's Law, assuming only aluminium is produced at the cathode*:*

$$m = \frac{I \times t \times M}{z \times F}$$



where:

m=mass of Al produced (g), *I* = current (A), *t* = time (s), *M* = molar mass of Al (g/mol), *z* = no. electrons transferred per Al ion, *F* = 96,485 C/mol (Faraday's constant)

Energy and carbon improvements?

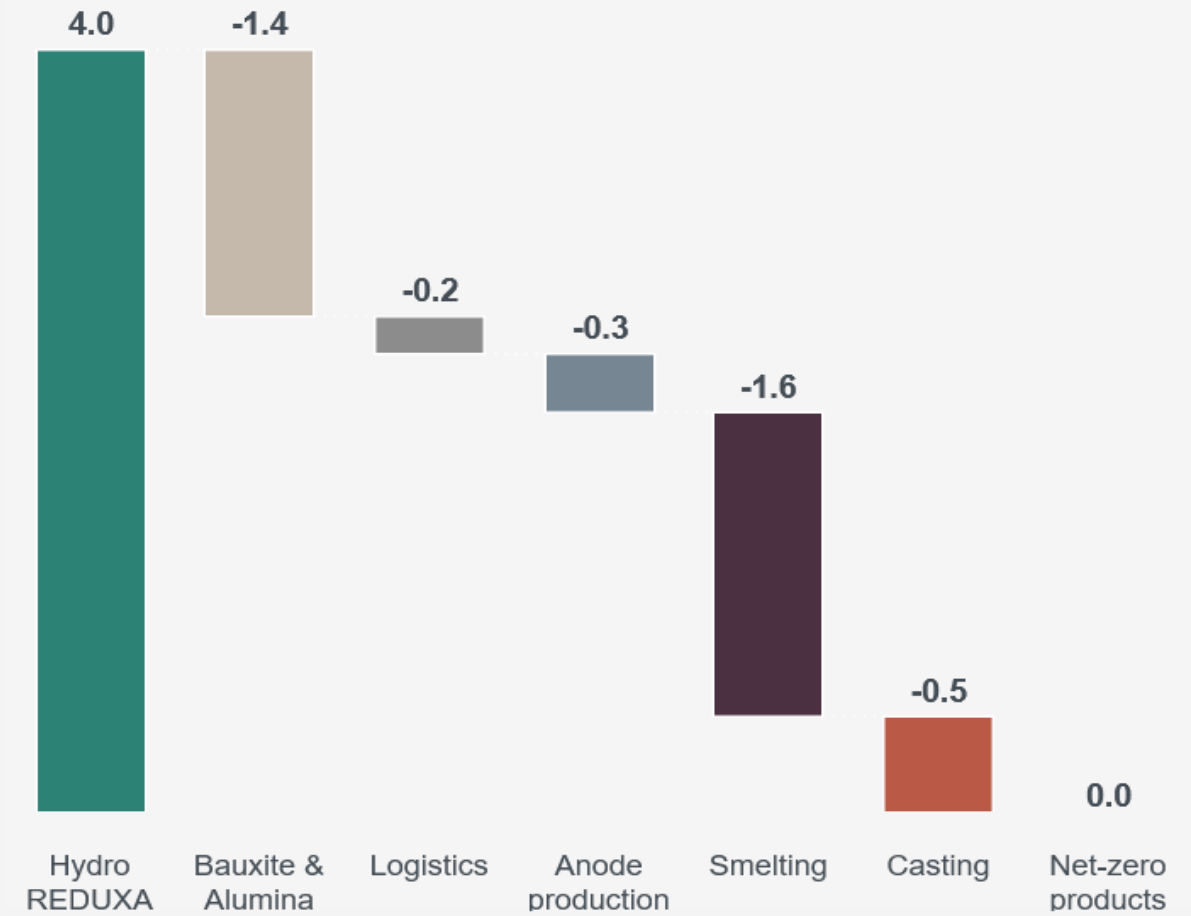
- Electrical (power) input also provides resistive heating to maintain the cell at ~ 960 ^{o}C
- The energy efficiency of the Hall Heroult process is fundamentally limited by the need to shed sufficient heat through the sidewall of the cell to maintain a “frozen ledge” around the cryolite electrolyte.
- This means only incremental gains are possible with existing technology. While small reductions in very large numbers are useful, there is currently no plausible pathway to reach the energy and carbon footprint reduction in current roadmaps.

- Chloride process? .....

Hydro Aluminium - most advanced “green aluminium” roadmap

From Hydro REDUXA to net-zero

Kilos of CO2e emissions per kilo aluminium



Hydro REDUXA primary aluminium has a documented carbon footprint of maximum 4 kg CO2e per kg aluminium, about a quarter of the world industry average. By addressing the different production steps in the value chain, Hydro aims to bring the carbon footprint down to net-zero.

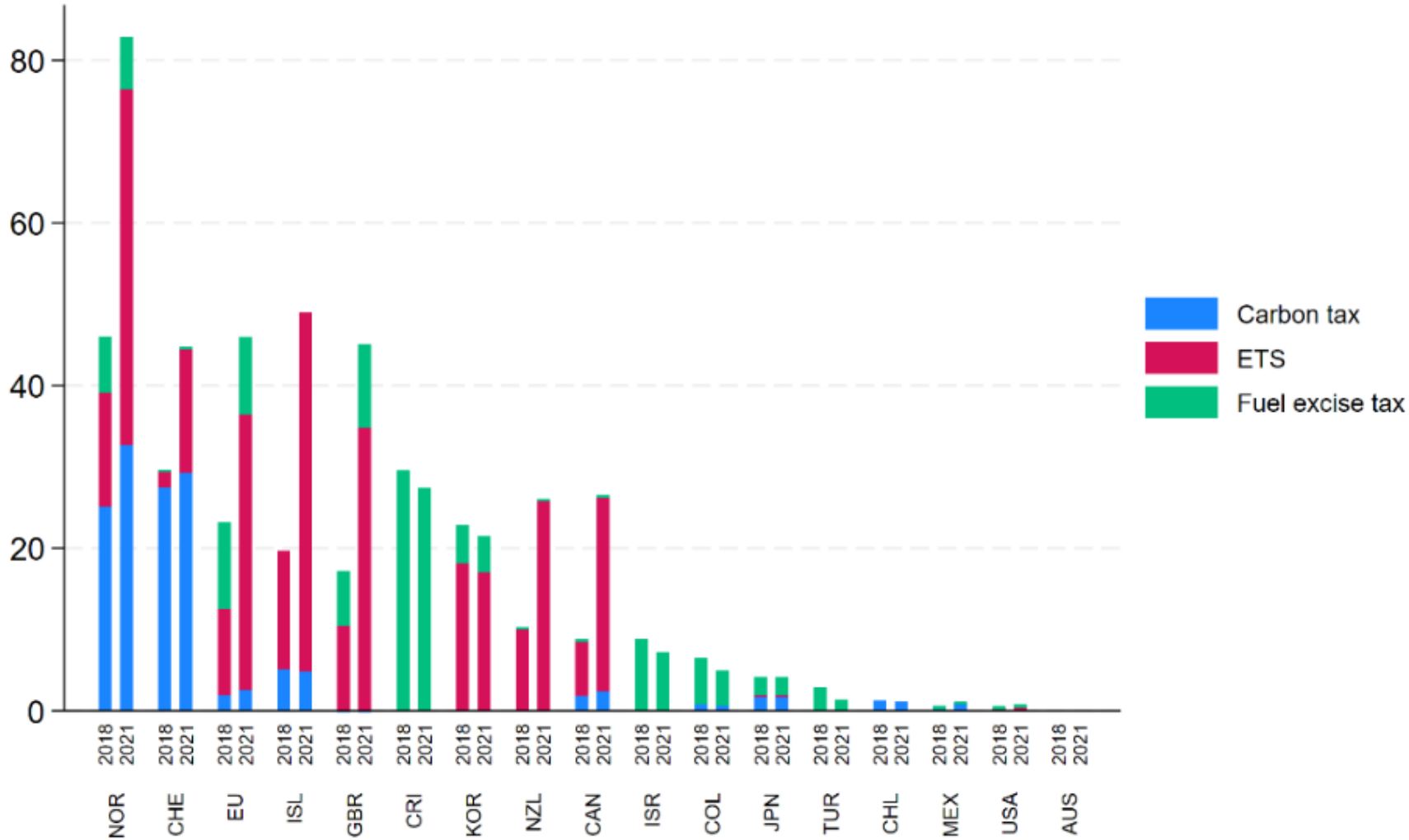
The Chloride route for electrolysis (again)

Emission free electrolysis

Under development by Hydro technologists since 2016, the proprietary HalZero technology is based on converting alumina to aluminium chloride prior to electrolysis. Chlorine and carbon are kept in a closed loop, thereby avoiding CO_2 emissions and emitting only oxygen instead. In 2023, the project won recognition at the COP28 global climate conference as an energy transition changemaker.

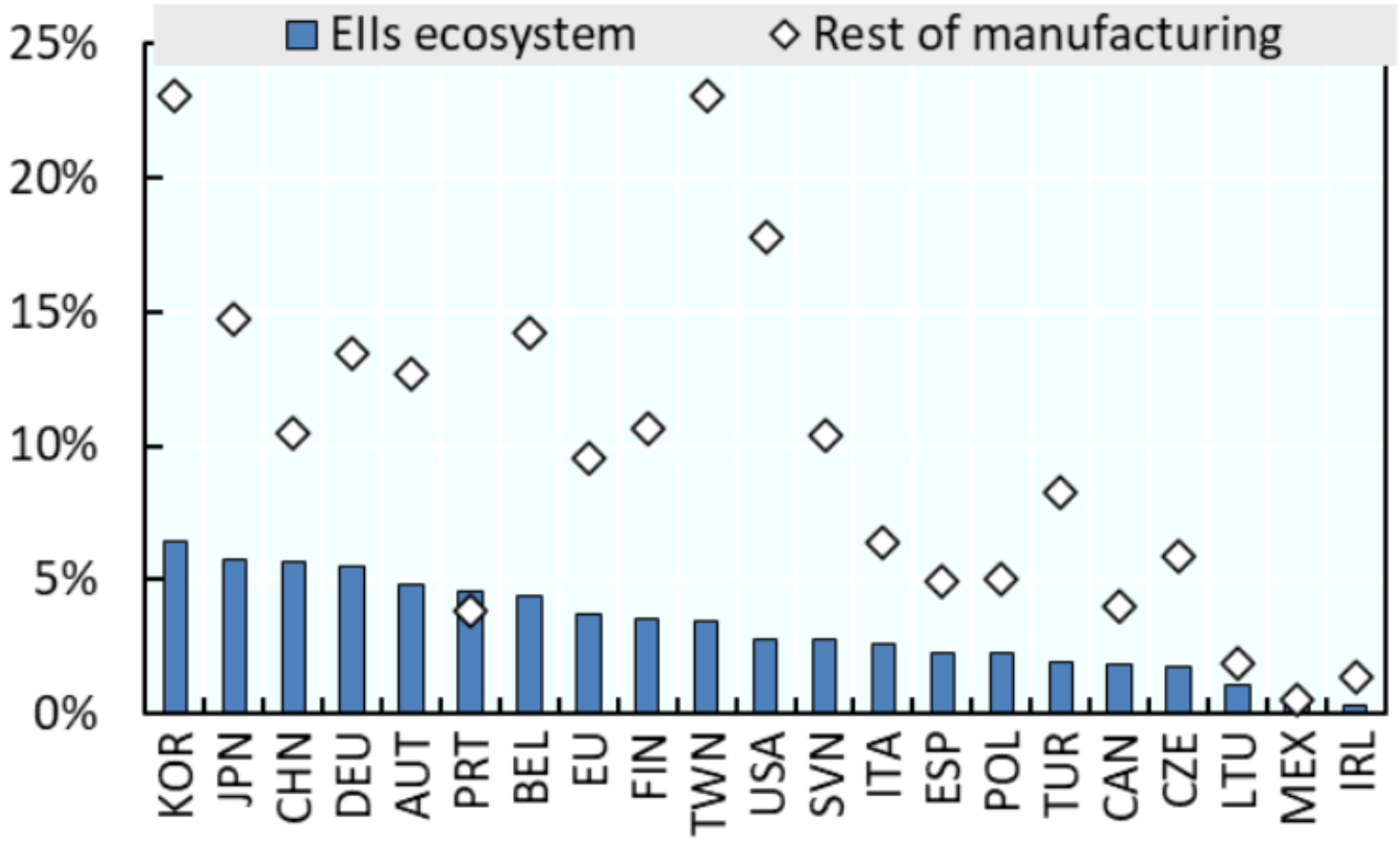
https://www.hydro.com/en/global/sustainability/our-roadmap-to-net-zero-emissions-in-aluminium-production/

Effective carbon rate in manufacturing by country and year, in EUR per tonne of CO_2, 2019 and 2021



OECD's Effective Carbon Rates 2025 report

R&D intensity calculated as R&D business expenditure over value added, 2020



"A comprehensive overview of the Energy Intensive Industries ecosystem"
Dechezleprêtre, Dernis, Díaz, Lalanne, Sancho and Samek
OECD Science, Technology and Industry Working Papers 2025/09 *https://dx.doi.org/10.1787/bbf7d4c2-en*

So what is the prognosis?

- The Hall-Heroult process is approaching 150 years of dominance in production of primary aluminium
- In current and energy efficiency, and emissions control, huge improvements have been made but these are increasingly incremental.
- New technologies are tough. Non carbon anodes have been under development for years, but although they dramatically mitigate carbon emissions, they actually **increase electrical consumption.** Thus if the power source is thermal power this may be going backwards…..
- **We do not do enough research** ……. Typical of established industries with very large capital investments……. Process Automation, AI, let alone new processes ……..
- Right now the global industry is struggling to meet its improvement targets, particularly in carbon and energy my view is that **there is no plausible pathway to the more ambitious targets in the 2050 International Aluminium Organisation plan.**

Thank you

Questions?