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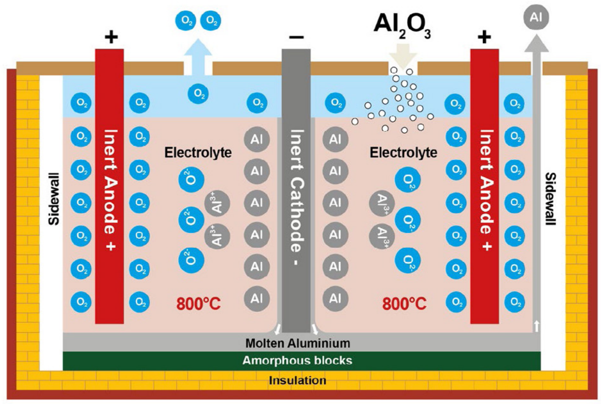
Renewable Metal Energy Carrier: Power-to-Aluminium

Seasonal energy carrier – Power-to-X technology

The global primary aluminium sector produced approximately 72.7 million tonnes of aluminium in 2024 [1]. Current primary aluminium production relies on the Hall-Héroult process, which electrolytically reduces aluminium oxide (alumina) using carbon anodes as the reducing agent, generating substantial direct CO_2 emissions. Reducing these emissions has become a key priority for the industry.

$2\,Al_2O_3 + e^- \rightarrow 4\,Al + 3\,O_2$



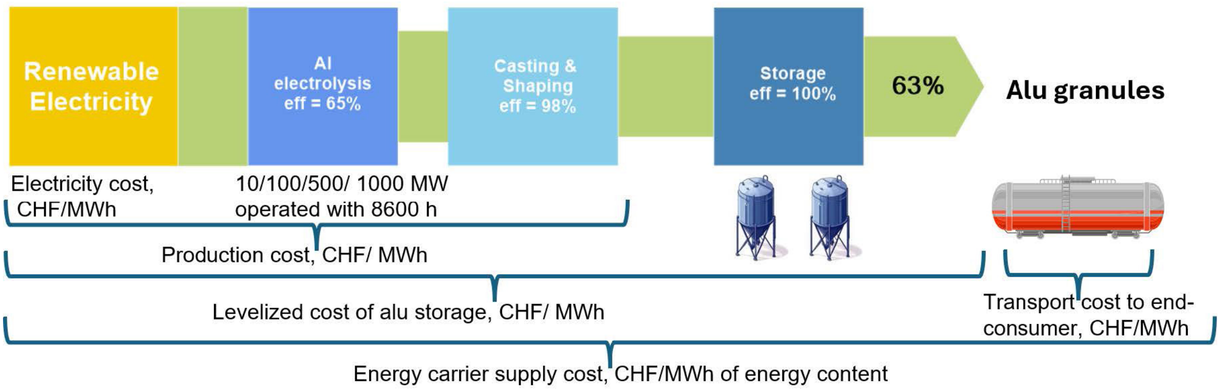
Schematic of the vertical inert anodes and cathodes in low-temperature electrolyte for aluminium production without direct CO_2 emission from Arctus Aluminium. Illustration: Copyright © Arctus 2025; printed with permission.

In recent years, progress has been made in developing smelting technologies with no direct carbon emissions. Companies like Trimet Aluminium, ELYSIS, and RUSAL are advancing the creation of inert anodes and are currently constructing demonstration plants on an industrial scale, with an expected full commercialisation in 2030.

Arctus Aluminium, in collaboration with an Icelandic research organization, has developed a vertical electrode cell that incorporates inert anodes and wettable cathodes, operating at a relatively low temperature of 800 °C (schematic on the right) [2].

In 2025, a 500 A inert anode pilot cell has successfully produced aluminium with a commercial purity of 99.8%, emitting one tonne of oxygen for every tonne of aluminium, and achieving a reduction of over 98% in direct CO_2 emissions compared to the Hall-Héroult process.

Considering aluminium granule production with the Arctus Aluminium technology (Technology Readiness Level, TRL4 of 9 in 2025), a Power-to-Aluminium-to-Storage efficiency of 63% can be achieved, as shown in the illustration below [3].



The total energy carrier supply cost for aluminium includes production costs (covering Power-to-Alu process), storage costs, and transport costs to the end consumer. Combined, these cost components reflect the full supply cost of using aluminium as a storable and transportable medium for renewable energy.

Availability

Abundance/World reserves	Third most abundant element / 7425 Mio. tonne [4]
Global production of aluminium in 2024	72.7 Mio. tonne [1]
Total global production (accumulated)	1517 Mio. tonne [3]
CH production of renewable aluminium in 2024	0

Chemical properties

Volumetric bulk energy density	>23 000 kWh/m3 for bulk material / 15 000 kWh/m^3 for granules
Gravimetric energy density	8.6 kWh/kg
Melting point / Boiling point	660 / 2470 °C
Auto ignition	Bulk aluminium is not self-igniting, but fine powder can ignite at 400–600 °C.
Flammability in air as bulk or granules	Not flammable for granule sizes < 500 um
Flammability in air as powder	Combustible as fine powder (<100 um); dust explosion risk class St1-St2 depending on fineness

Circular economy concept

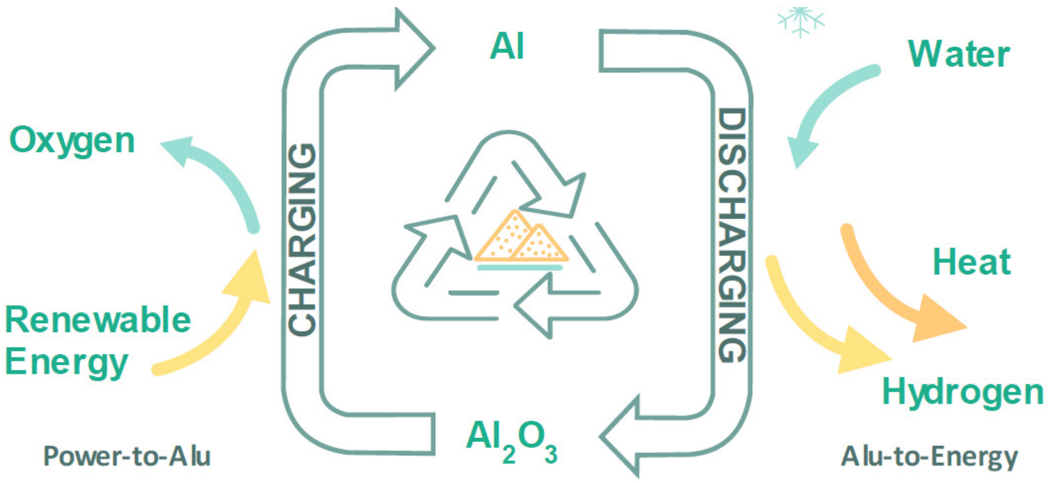
Renewable electricity can be stored by producing aluminium in centralized facilities (Power-to-Alu, charging process). In this process, renewable energy is used to reduce alumina (Al_2O_3) into aluminium metal using the above-described inert anode technology that emits only oxygen.

The resulting aluminium acts as a renewable metal energy carrier (ReMEC), storing up to 23 MWh per m^3 of energy for bulk material or up to 15 MWh/m^3 as granules without losses over time [2]. Like wood chips or pellets, aluminium can be transported using existing infrastructure to buildings or industries to meet peak energy demands during winter.

Simplified concept of aluminium ReMeC storage cycle

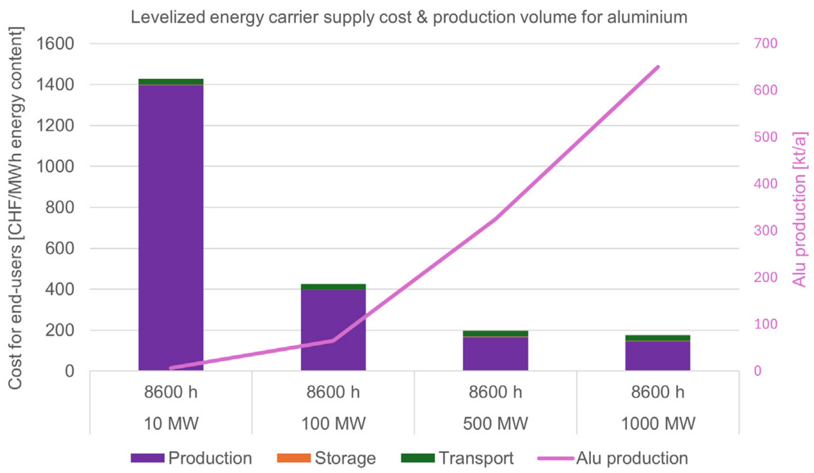
When energy is needed, aluminium reacts with water in the Alu-to-Energy or discharging process, releasing hydrogen and heat. The hydrogen can be used in H_2 boilers to produce more heat, or it can be converted in fuel cells to generate both electricity and heat in a combined heat and power (CHP) system, enabling grid stabilization during high-demand periods.

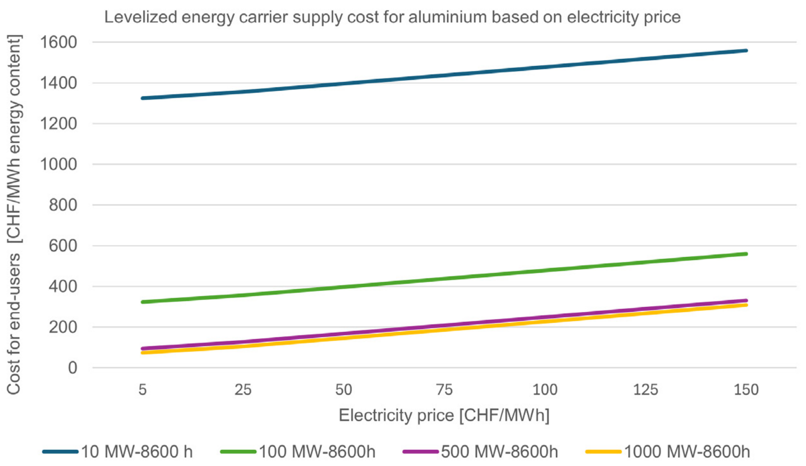
At reaction temperatures below 280 °C, the byproduct of this process is aluminium hydroxide, which is collected when new aluminium is delivered and returned to the Power-to-Alu facility [2]. There, it is converted back into aluminium oxide for recharging, creating a closed-loop material cycle. Aluminium shows high potential for integration as a ReMEC into buildings and district heating networks in Switzerland, supporting winter heat and electricity demand coverage and contributing to reduced electricity imports and external dependencies.



Simplified concept of aluminium ReMeC storage cycle.

Cost analysis





The upper left graph illustrates the relationship between aluminium levelized supply costs (bars) and production volumes (pink line) across installed Power-to-Alu capacity scenarios for 10 MW, 100 MW, 500 MW, and 1000 MW, considering an electricity price of 50 CHF/MWh, 5% interest rate and 40 years economic lifetime. It is important to note that aluminium production is assumed to operate at full-load hours only (8600 h), as the Power-to-Alu process cannot be interrupted without significant effort and cost. The observed economies of scale are derived using the capacity-scaling relationship reported by Stinn and Allanore, where capital expenditures (CAPEX) are estimated as $CAPEX = \alpha \cdot Capacity^{\beta}$ with scaling exponent β of 0.7, indicating that investment costs grow sublinearly with capacity [5]. Consequently, as production capacity increases, the overall production cost per tonne of aluminium decreases sharply, demonstrating strong economies of scale.

While production costs remain the largest share of total supply costs, storage and transport costs remain comparatively minor across all scenarios. The pink line overlay shows the aluminium production volume, highlighting the significant output benefits of large-scale systems.

The lower left graph shows how levelized aluminium supply costs respond to different electricity price levels, ranging from 5 to 150 CHF/MWh for each of the four capacity scenarios. The results indicate that supply costs increase linearly with rising electricity prices, demonstrating consistent price sensitivity across all capacities.

Together, these cost analysis shows that increasing production capacity can significantly lower the cost of producing aluminium per tonne. However, all production scales remain affected by changes in electricity prices.

This highlights the importance of combining **large-scale production** with strategies that **protect against electricity price fluctuations** to keep aluminium production costs competitive and stable. Therefore, locations with low-cost, abundant renewable electricity available year-round, such as Iceland - which already produces about 1 Mio. tonne of aluminium per year - are very promising sites for the Power-to-Alu process.

Sources / additional information

[1] International Aluminium Institute, International Aluminium Institute, https://international-aluminium.org/.
[2] REVEAL Project, «REVEAL: Reversible large-scale energy storage.», https://www.reveal-storage.eu/.
[3] Y. Baeuerle and M. Haller, «PeakMetal-final report». Available: www.spf.ch/peakmetal
[4] U.S. Geological Survey, Mineral Commodity Summaries 2024. U.S. Geological Survey, 2024, https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf.
[5] Caspar Stinn and Antoine Allanore, «Estimating the Capital Costs of Electrowinning Processes,» The Electrochemical Society Interface, vol. 29, no. 2, p. 44, Jun. 2020. [Online]. Available: https://hdl.handle.net/1721.1/131073

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