Aluminium as a means for chemically storing and transporting renewable energies

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Abstract

While solar energy is abundant and clean, its intermittency presents a major challenge for reliable integration into energy systems at a large scale. Conventional storage technologies such as lithium-ion batteries, pumped hydro storage or hydrogen face limitations such as high capital cost when used for seasonal storage or lack of scalability due to geographical or socio-political constraints. In this context, aluminium, one of the most abundant metals in the Earth's crust, emerges as a promising renewable metal energy carrier (ReMEC) that addresses many of these challenges. Due to its high energy density, stability in solid form, and ability to release large amounts of energy upon oxidation, aluminium offers a promising alternative to traditional fossil fuels and hydrogen-based energy vectors. When reacting with water, aluminium releases thermal energy and, depending on conditions, produces hydrogen gas, making it suitable for both heat and electricity supply.

Keywords: metal energy carrier, energy storage, energy transport, aluminium

1. Introduction

The intermittent nature of solar energy poses a significant hurdle to its integration into energy systems at large scale. Conventional storage technologies such as lithium-ion batteries or pumped hydro storage face limitations such as high capital cost when used for seasonal storage or lack of scalability due to geographical or socio-political constraints. Hydrogen has attracted considerable interest as a chemical energy carrier, but its low volumetric energy density and the complexities associated with its safe and economical storage continue to be challenges. Against this backdrop, aluminium (Al) - one of the Earth's most abundant elements - stands out as a compelling renewable metal energy carrier (ReMEC), offering the potential to overcome several of these limitations. This article explores the principles, advantages, and challenges of using aluminium as a chemical energy carrier in future energy systems.

2. The Aluminium Energy Storage Cycles

2.1 Power-to-Alu – the charging process

The process of charging aluminium with energy corresponds to the reduction of alumina (Al_2O_3) to metallic aluminium. Thereby, the state of oxidation of aluminium changes from +3 to 0 ($Al^{3+} \rightarrow Al$). Conventionally, this reduction is achieved by the Hall-Héroult process in electrolysis cells. These cells are equipped with carbon anodes that act as the reducing agent, combine with the oxygen of the alumina and produce CO_2:

$$2\ Al_2O_{3(s)} + 3\ C_{(s)} \rightarrow 4\ Al_{(s)} + 3\ CO_{2(g)} \qquad \Delta H_R^0 = 2168\ kJ/mol \qquad \textit{(eq. 1)}$$

While the Hall-Héroult process is mature and industrially dominant, it has two major drawbacks:

- Low efficiency of about 50% if the energy input from carbon is also accounted for, and
- direct CO_2 emissions from carbon anode oxidation.

Although renewable electricity can be used to power Hall-Héroult cells, CO_2 emissions that stem from the oxidation of the carbon anodes remain inherent in this process, thus contributing to greenhouse gas (GHG) emissions worldwide. To eliminate these direct CO_2 emissions of the alumina reduction process, aluminium industry and researchers worldwide are developing carbon-free anodes that are largely inert and enable the electrolysis of alumina without CO_2-emissions (Jamieson et al., 2025; Kvande, 2025; Singh et al., 2023):

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$$2\ Al_2O_{3(s)} \rightarrow 4\ Al_{(s)} + 3\ O_{2(g)} \qquad \Delta H_R^0 = 3350\ kJ/mol \qquad (eq.\ 2)$$

The key benefits of carbon-free electrolysis are:

- No direct CO_2 emissions, aligning with net-zero GHG emission targets,
- improved anode longevity, as inert anodes degrade much slower than carbon anodes, and
- for vertical electrode arrangements in ledge-free cells:
  - the efficiency is estimated to reach 65%, which corresponds to less energy input compared to the total of electric energy and carbon that is used for conventional cells, and
  - more flexibility for power modulation.

2.2 Alu-to-Energy – the discharging processes

Aluminium's potential as an energy carrier lies in its highly exothermic oxidation reactions that may also be used for water splitting and hydrogen production. The three primary pathways for energy extraction are thermal oxidation (combustion) with oxygen (eq. 3), reaction with supercritical water at high temperatures (eq. 4), and reaction with steam or water at lower temperatures (eq. 5):

$$4\ Al_{(s)} + 3\ O_{2(g)} \rightarrow 2\ Al_2O_{3(s)} \qquad \Delta H_R^0 = -3350\ kJ/mol \qquad (eq.\ 3)$$

$$2\ Al_{(s)} + 3\ H_2O_{(g)} \rightarrow Al_2O_{3(s)} + 3\ H_{2(g)} \qquad \Delta H_R^0 = -951\ kJ/mol \qquad (eq.\ 4)$$

$$2\ Al_{(s)} + 6\ H_2O_{(l)} \rightarrow 2\ Al(OH)_{3(s)} + 3\ H_{2(g)} \qquad \Delta H_R^0 = -839\ kJ/mol \qquad (eq.\ 5)$$

If the product of the reaction is aluminum-hydroxide ($Al(OH)_3$), it needs to be calcined at several hundred °C in order to obtain alumina, from which new aluminum can be produced by eq. 2:

$$2\ Al(OH)_{3(s)} \rightarrow Al_2O_{3(s)} + 3\ H_2O_{(l)} \qquad \Delta H_R^0 = 22\ kJ/mol \qquad (eq.\ 6)$$

$$2\ Al(OH)_{3(s)} \rightarrow Al_2O_{3(s)} + 3\ H_2O_{(g)} \qquad \Delta H_R^0 = 155\ kJ/mol \qquad (eq.\ 7)$$

For aluminium-water reactions that produce H_2, the energetic use of hydrogen yields additionally:

$$2\ H_{2(g)} + O_{2(l)} \rightarrow 2\ H_2O_{(l)} \qquad \Delta H_R^0 = -572\ kJ/mol \qquad (eq.\ 8)$$

Fig. 1 gives an overview of the charging (Alu-to-Energy) as well as the different options for discharging (Alu-to-Energy) of a renewable energy carrier based on oxidation and reduction of aluminium species.

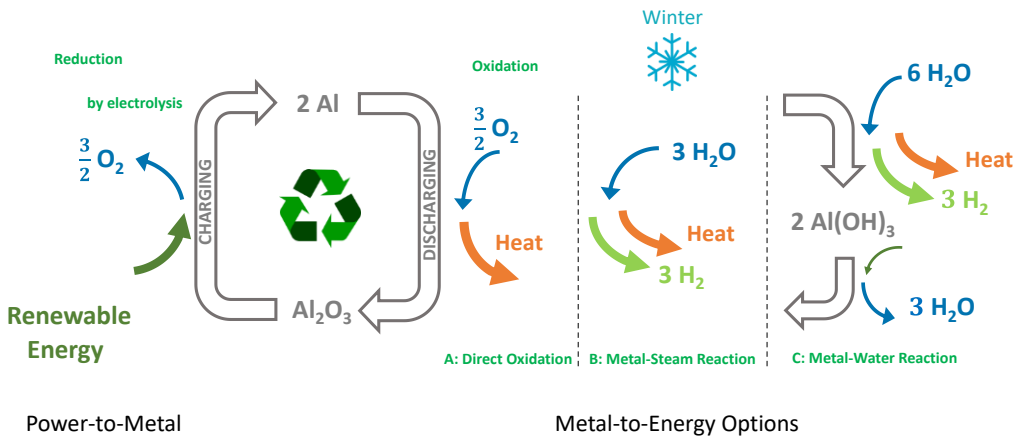

Fig. 1: Renewable Metal Energy Carrier (ReMEC) cycles based on aluminium

2.3 Energy balances and efficiency of the aluminium storage cycle

2.3.1 Reduction of alumina to aluminium (Power-to-Alu)

With new inert anode processes, the minimum required energy input for alumina reduction, based on the enthalpy of

reaction, increases (eq. 1 & eq. 2). This is a result of carbon, which is also an energy carrier and can be thought of as an additional energy input, now being missing as a reducing agent. Thus, the minimum energy input $E_{el,in,min}$ for the production of 1 kg of aluminium from alumina with CO_2-free inert anode technology is:

$$E_{el,in,min} = \Delta H_R^0(eq.2)/(4 \cdot m_{Al}) \cdot 1h/3600s \cdot 1000g/kg \; = 8.62 \; kWh/kg \qquad (eq.\ 9)$$

In real-life, much more electric energy than the min. required according to eq.1 or eq. 2 is invested in the process of producing aluminium from alumina. Current best practice for aluminium production with the Hall-Héroult process is around 13 kWh per kg Al (Haupin and Frank, 2025). Losses are due to current and voltage efficiencies and the fact that conventional Hall-Héroult cells must maintain a frozen sideledge along the inner sidewalls of the cells, in order to protect them from corrosion. This is only possible with a significant temperature gradient towards the sidewalls, which in turn defines heat losses and thus heat required to maintain the cell's temperature of around 960°C.

For inert anode technology, the cell temperature is usually lower, around 800 °C, and new options for increasing the energy efficiency are in reach, such as vertical instead of horizontal electrode arrangements, with less distance and thus electric resistance between the electrodes. Thus, it is commonly thought that the real-life required electric energy input of inert-anode cells will be roughly the same as for the Hall-Héroult process (see also 3.1 for laboratory results of REVEAL).

2.3.2 Oxidation of aluminium (Alu-to-Energy)

Naturally, the minimum amount needed for reduction (eq. 9) is also the maximum amount of energy that can be released by direct oxidation with air (eq. 3). If aluminium-water reactions (eq. 4 and 5) are chosen for the release of energy, then the energy is set free in two steps: first the aluminium-water reaction is producing heat and hydrogen, then the energy contained in the hydrogen can be used by its oxidation with oxygen as well (eq. 8).

If water is provided in gaseous $H_2O_{(g)}$ instead of liquid $H_2O_{(l)}$ state, i.e. as steam, the enthalpy of the aluminium-water reaction (eq. 4) is higher. However, considering the fact, that in most cases steam will have to be produced from liquid water beforehand, and taking this energy of evaporation into account, this difference vanishes. For the sake of simplicity, let's assume that water as educt or product is always in a liquid state, and take into account the energy that can be released from the oxidation of reaction products such as hydrogen. Consequently, the energy that can be released by the oxidation of aluminium and hydrogen from the aluminium-water reaction equals the value of eq. 9:

$$E_{el,out,max,Al2O3} = E_{el,in,min} = 8.62\ kWh/kg \qquad (eq.\ 10)$$

2.3.3 Oxidation to aluminium-hydroxide and calcination of aluminium-hydroxide

When the reaction produces aluminium-hydroxide instead of alumina, the amount of energy released in the form of heat and hydrogen increases by the energy that has to be invested later for calcination (eq. 6):

$$E_{out,max,Al(OH)3} = E_{el,in,min} + E_{calcination}$$
$$= 8.62\ kWh/kg + \Delta H_R^0(eq.6)/(2 \cdot m_{Al}) \cdot 1h/3600s \cdot 1000\ g/kg \; = \; 8.73\ kWh/kg \qquad (eq.\ 11)$$

The minimum required energy for calcination based on the enthalpy of reaction ΔH_R^0 is 0.110 kWh per kg Al, if it is assumed that water is leaving the system in liquid state, and 0.800 kWh/kg if it is assumed as a gas. However, best-practice reported from industrial plants is roughly 0.8 kWh per kg alumina (Ishihara et al., 2016) despite of proclaimed heat recovery (i.e. 1.6 kWh per kg Al). The big difference between the theoretical minimum and the practical results indicate that there might be considerable room for improvement of energy efficiency in this process.

2.3.4 Efficiency of the cycle

For aluminium-water reactions, it has been shown that 100% of the energetic potential of aluminium can be converted to hydrogen and heat. Heat losses of small Alu-to-Hydrogen systems may be in the order of 14% of heat released (Haller et al., 2021), which corresponds to 7% of the energetic potential of aluminium (8.7 kWh/kg). With larger reaction volumes and lower surface-to-power ratios, this value can be brought further down, such that values below 4% of the energy content of aluminium seem to be feasible.

Since the aluminium-water reaction at low temperatures – in our case 60 – 90 °C - yields aluminium-hydroxide, also the subsequent calcination step to get back aluminium oxide for new aluminium production must be considered for an overall energy balance. In real-life, best-practice calcination today requires approx. 1.4 kWh per kg aluminium, which is still considerably higher than the 0.1 kWh/kg that corresponds to the minimum required according to the enthalpy of reaction (eq. 6). Considering this energy input and assuming that the calcination is done in electric rotary kilns and thus also run on renewable electricity, the energy input-output balance is:

$$\eta = \frac{\eta_{th} \cdot Q_{max,heat} + E_{H2}}{E_{el,smelter} + E_{el,calc}} = \frac{0.96 \cdot 4.32\ kWh + 4.41\ kWh}{13\ kWh + 1.4\ kWh} = 59\%$$

2.3.5 Influence of granulation and transport

For aluminium granulation into a transportable energy carrier, we assume max. 0.1 kWh per kg of aluminium if granules are produced directly from liquid aluminium without the need for re-melting.

Transporting 1 ton of aluminium in one direction requires transporting 2 tons of material in the form of alumina in the other, because producing aluminium from alumina consumes roughly two tons of alumina per ton of aluminium according to the stoichiometric ratio (ep. 2). If aluminium-hydroxide is transported back, it would need at least 3 tons in the backward direction for dry aluminium-hydroxide. Therefore, we assume that calcination takes place close to the point of Alu-to-Energy conversion. Table 1 gives an overview of the energy required to transport 1 ton of aluminium from Iceland to the harbour of Rotterdam (NL) by cargo ship (Gucwa and Schäfer, 2013), and from there to Zürich in electric trucks (Shoman et al., 2023), including also the transport of 2 tons of material on the same route back. In total, this adds another 0.23 kWh/kg of aluminium. Therefore, the efficiency of the storage cycle, including energy input into granulation and transport, is:

$$\eta = \frac{\eta_{th} \cdot Q_{max,heat} + E_{H2}}{E_{el,smelter} + E_{el,calc} + E_{gran} + E_{trans}} = \frac{0.96 \cdot 4.32\ kWh + 4.41\ kWh}{13 + 1.4 + 0.1 + 0.23} = 58\%$$

Table 1: Energy required for transporting 1 ton of aluminium in one direction and 2 tons of alumina in the other.

Transport	Means	Distance (km)	2 ways (ton-km)	Specific energy (kWh/ton-km)	Total energy (kWh)
Rotterdam-Zürich	Electric Truck	800	2’400	0.06	144
Rotterdam-Iceland	Cargo ship	2’200	6’600	0.015	99
Total		**3’000**	**9’000**		**233**

2.4 Advantages and Applications for aluminium as a ReMEC

Advantages of using Al as a ReMEC for energy storage and transport are:

- **Energy density:** Al has an outstanding energy storage density of ~15 MWh/m^3 (bulk material in granular form).
- **Stability and safety:** Al grains are stable in natural environment (air, water) and, unless ground into fine powders, do not form explosive mixtures and are not toxic.
- **Transportability:** Unlike hydrogen or batteries, Al can be shipped using existing logistics networks without specialized containment.
- **Carbon-free:** Unlike hydrocarbons (e.g. methane and methanol), there is no carbon contained in the Al energy carrier and hence also no CO_2 emissions evolving from its combustion or other energetic use.

Energy systems that are based on Al as a ReMEC have potential across a wide range of applications:

- **Transport of energy:** Al can be produced at locations that are blessed with abundant and cheap renewable electricity, transported over long distances, and used at locations and times of energy scarcity all over the globe.
- **Seasonal energy storage:** Al could serve as a long-duration energy storage medium to buffer seasonal or multi-week renewable energy fluctuations.

- **Remote and off-grid energy systems:** Solid Al can be transported to remote areas and used to produce electricity or hydrogen on-site without the need for grid infrastructure.
- **Backup and emergency power:** Its long shelf-life and high energy density make Al an ideal energy carrier for the application in disaster preparedness and emergency response.

3. Insights from the EU REVEAL project

Within the EU Horizon Europe REVEAL project (https://www.reveal-storage.eu/) a team of nine partners from seven countries in Europe developed different parts of a closed material cycle for using Al as a ReMEC.

3.1 Power-to-Alu: The CO_2-free production of aluminium

An inert anode process for the production of Al was developed at IceTec / Taeknisetur together with Arctus Aluminium Ltd, operating at temperatures of around 800°C [5]. The process was demonstrated in a 400 Ampère cell producing several kg of Al per day with vertical electrodes and wetted cathodes, and was operated for several days. Energy consumption in the (not self-heated) cell was as low as 13.7 kWh per kg of Al produced. Thus, the process reached an efficiency of 63.5% with respect to the energy stored in aluminium according to the enthalpy of its oxidation reaction, if only the electricity input is considered. Purity of the Al was above 99.4%.

3.2 The shaping of aluminium into a usable energy carrier

To release the energy contained in the aluminium, the reactions of equations 3-5 can be used. While some approaches let liquid aluminium (700 - 1000 °C) react with steam (Barelli et al., 2022; Shmelev et al., 2016), solid aluminium particles are used more commonly.

Aluminium is a base metal and its surface is easily oxidized when in contact with air, forming a protective passivating layer that prevents the oxidation underneath. While this is advantageous for the safety of transport and handling, it is hindering the process of oxidizing aluminium in order to set free heat and hydrogen or heat only as energy vectors. Several techniques are used to overcome the barrier of passivated aluminium surfaces and increase the capacity of energy release by aluminium oxidation reactions (Haller et al., 2020):

1. Ball-milling the aluminium into fine powders
2. Alloying with liquid metals such as In, Ge, etc…
3. Combined effect of alloying and mechanical stress of cold-forming (patent submitted), (Agote-Arán et al., 2025)

Within the REVEAL project, the third option was chosen, and it was decided that the grain-size of the aluminium particles should be above 0.5 mm in order to avoid explosion risks that may arise from mixtures of powders with grain-sizes lower than 200 microns and air (Haller et al., 2019).

3.3 Alu-to-Energy conversion

3.3.1 Kinetic studies of Al-water reactions

Within the REVEAL project, high temperature and low temperature aluminium-water reactions were analysed for their reaction kinetics and yield. Models for predicting hydrogen and heat development under different conditions (temperature, alkalinity, saturation of solution, type of alloy and material, Fig. 2) were developed based on Al6060 cut-wire (Agote-Arán et al., 2025) and subsequently used for the design of a 4 kW Alu-to-Energy conversion unit that was equipped with automatic Alu-fuel feeding as well as removal of hydrogen gas and solids in the form of aluminium-hydroxide.

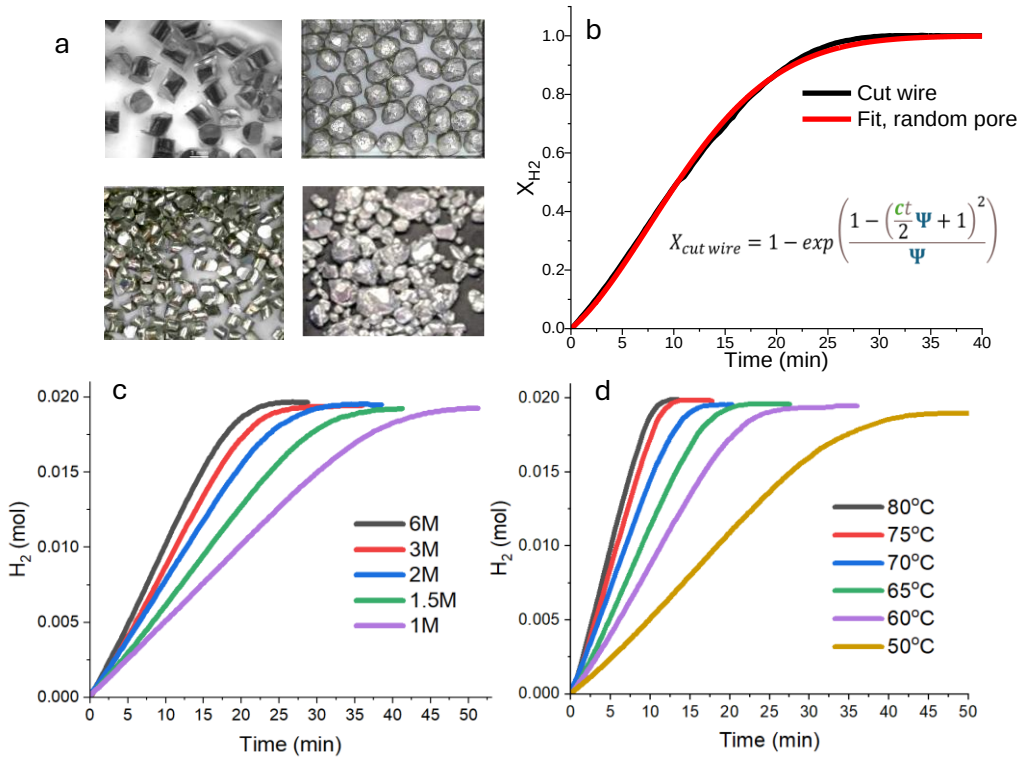

Fig. 2: Overview of Al-water reaction comprising the evaluation of different Al morphologies and alloys (a), fitting into kinetic models (b), using Al6060 cut wire granules for reaction kinetic evaluation as function of alkalinity (at 60°C) (c) and temperature (at 3M NaOH) (d), according to (Agote-Arán et al., 2025).

3.3.2 Experimental setup

The experimental system (Fig. 3) was designed, constructed and tested within a laboratory at OST – University of Applied Sciences Rapperswil. The main process was operated in a pressurized reaction vessel (RV) with a working liquid volume of 13 L. The RV was designed to enable:

- Continuous feeding of aluminium into 2 M NaOH solution,
- turbulence generation via a magnetic stirrer,
- heat removal through an internal heat exchanger coil,
- automated water supply to sustain the reaction (eq. 5),
- continuous extraction of aluminium-hydroxide ($Al(OH)_3$) and
- controlled release of hydrogen over a condenser and buffer tank (25 L) into a fuel cell system.

Prior to each test run, the reactor was filled with 2 M NaOH solution, and the setup was inertised and preheated to 65 °C. Aluminium was then continuously introduced via a valve-controlled feeding system. Reaction heat was dissipated by circulating a heat transfer fluid through the internal heat exchanger connected to a thermostatic bath.

Within the RV, aluminium oxidation produced hydrogen and $Al(OH)_3$. The $Al(OH)_3$ initially dissolved in the alkaline solution, with crystallization occurring once supersaturation was reached. At defined intervals, a fraction of the NaOH suspension containing crystalline $Al(OH)_3$ was transferred through an in-line filter into a secondary crystallization vessel (CV). This vessel was equipped to accommodate residual hydrogen generation as a result of small particles of unreacted aluminium that passed the inline-filter.

The crystallization vessel was subsequently emptied into a third sedimentation vessel (SV), where sedimentation of $Al(OH)_3$ occurred. The settled solid was shifted to a reception tank, while the NaOH solution was recirculated to the RV.

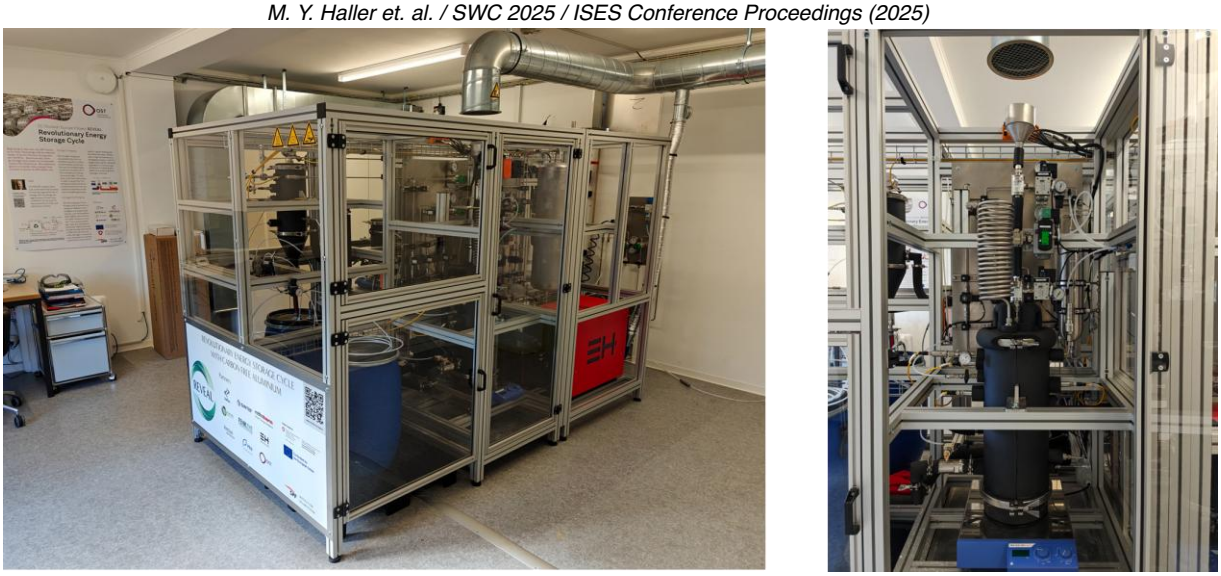

Fig. 3: Pictures of the Alu-to-Energy prototype; Left: entire prototype including all vessels and appliances. Right: reaction vessel, feeding system and condenser.

3.3.3 Results

After starting to feed aluminium at ~3 g/min, hydrogen production increased steadily and reached a first plateau after approximately 20 minutes (Fig. 4). Because both molarity and aluminate concentration strongly influence the reaction rate, the system requires time to approach a quasi-steady state. Following the initial startup, the reaction slows down slightly as the solution approaches $Al(OH)_3$ saturation towards hour 2:30. Once supersaturation is reached and crystallization began, the reaction rate increased again (2:45 – 3:30). After reaching the maximum hydrogen flow, a slight decline was observed (4:00 – 5:30). Within the experimental timeframe, a fully stable state could not be established due to the influences of the mentioned process parameters, in particular due to the fluid exchange between the vessels. Nevertheless, Fig. 4 illustrates a near steady state (5:30 – 7:00), accompanied by high hydrogen conversion.

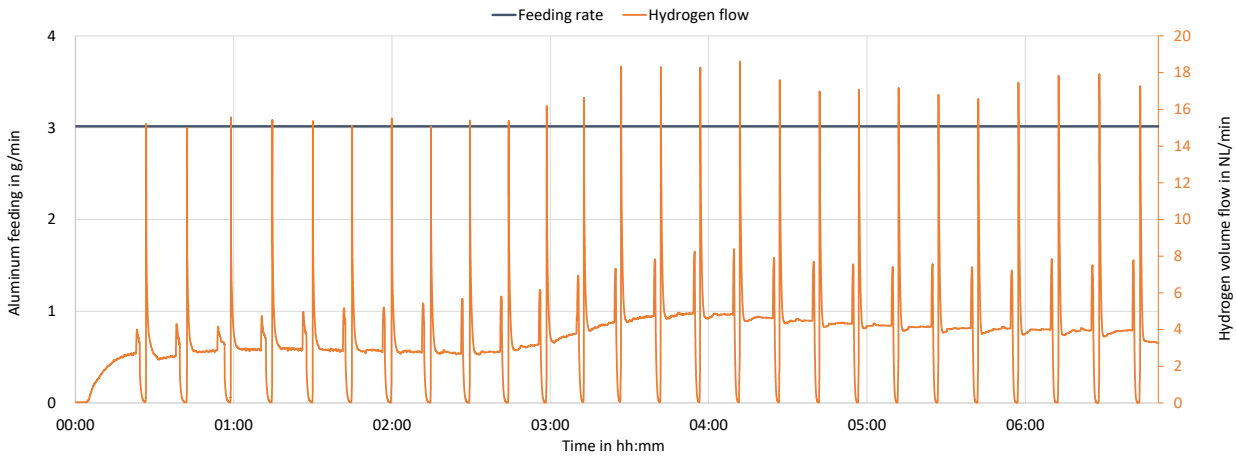

Fig. 4: Resulting hydrogen volume flow over an entire day of measurement.

This visualization includes aluminium feeding in grams per min. The hydrogen flow curve demonstrates periodic valleys and peaks, caused by periodic fluid exchange between the RV, CV and SV, which affects the pressure in the RV. Although the exact hydrogen production during these fluctuations cannot be quantified, it was assumed to remain constant, as aluminium feeding continues uninterrupted and both temperature and alkalinity do not change drastically.

3.4 Closing the material cycle

In order to close the material cycle, either alumina is produced directly in the Alu-to-Energy conversion (at high temperatures) or the aluminium-hydroxide is calcined into alumina in an intermediate step, as described in chapter

2.3.3 (eq. 5). Resulting alumina has to fulfill a number of requirements to be considered "smelter grade" or "metallurgical grade" alumina. Typically, these are:

- Chemical purity of 99.5%, limiting particularly the amount of Na_2O, SiO_2, Fe_2O_3 and other metal-oxides, as well as low loss on ignition (LOI, remaining moisture and hydroxyls)
- Particle size of ~75 – 150 microns and surface area of 60 – 100 m^2/g
- Bulk density of 0.9 – 1.1 g/cm^3
- Flowability (for efficient feeding of electrochemical cells)

3.5 Logistics for material transportation

Aluminium can be distributed as a dry bulk material using conventional logistics in standardized equipment, which can be used both for aluminium granules and alumina powder. These containers are intermodal, suitable for ship, rail, and truck transport, allowing flexible logistics, simplifying return logistics and improving cost efficiency. Such two-way bulk transport allows a closed-loop supply chain between Power-to-Alu production and decentralised energy conversion units (Alu-to-Energy). Compared to cryogenic hydrogen tankers, which currently require extensive safety measures and even military supervision when approaching harbours in some regions, aluminium offers a far more secure and economically viable bulk-shipment alternative.

Materials can be charged via loading hatches located on the top of the pressurized container, while discharged through a hose by air pressure and/or hydraulic tilting.

3.6 Greenhouse gas emissions

Compared to a gas-fired mini-CHP (combined heat and power) unit, a CHP unit that is based on CO_2-free Al as energy input reduces greenhouse gas emissions substantially (Fig. 5). This is even the case when Al is produced in Iceland from renewable electricity from hydro and geothermal sources (12.8 g CO_2-eq/MJ of electricity), the aluminium granules are transported to Switzerland under current transport conditions (cargo-ship, electric train, diesel lorry), and the resulting alumina or aluminium-hydroxide is returned to Iceland to produce new "recharged" aluminium granules.

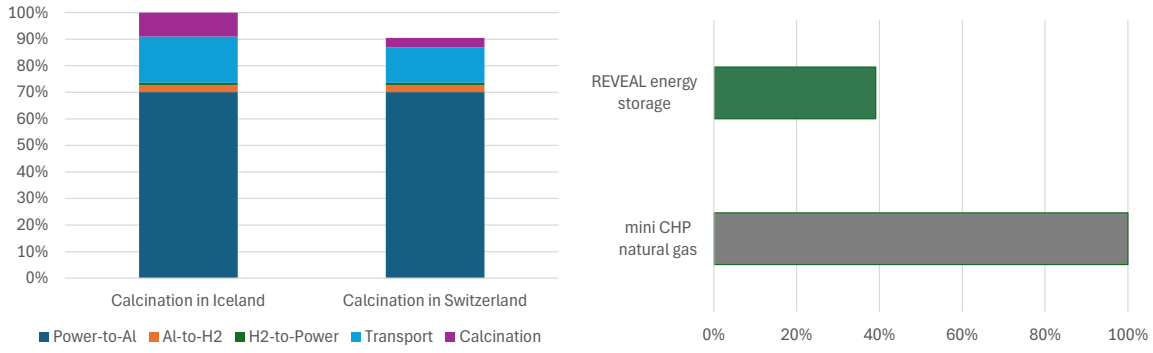

Fig. 5: Left: Share of carbon footprint from the different process steps of the Al ReMEC cycle when using Iceland electricity mix (12.8 g CO_2eq/MJ of electricity) for both Power-to-Alu and calcination steps, with aluminium hydroxide transported back to Iceland, compared to Swiss consumption mix for calcination at the Alu-to-Energy location, with alumina transported back to Iceland for recharging; Right: comparison of total carbon footprint between the Al storage cycle and a gas-fired mini-CHP plant.

The overall carbon footprint is dominated by the electricity consumption of the Power-to-Alu conversion stage, followed by transport and calcination. Calcining in Switzerland and therefore using the Swiss consumption mix for calcination instead of Iceland mix decreases total CO_2 emissions by around 10%. Despite including round-trip transport of aluminium hydroxide and alumina between Iceland and Switzerland, where transport emissions could be further reduced in the future via renewable electric logistics, the aluminium energy storage cycle achieves a markedly lower total carbon footprint than a gas-fired mini-CHP plant—reducing life-cycle greenhouse-gas emissions by roughly 60% under current conditions of embodied energy in renewable electricity production systems (PV, hydro, geothermal) and means of material transport. This reduction results primarily from the use of low-carbon electricity in Iceland and the absence of direct CO_2 emissions for the Power-to-Alu process, but also during Alu-to-Energy heat and power generation at the end-use site. The results confirm that aluminium can act as a viable CO_2-

free energy carrier for long-distance, seasonal energy storage, even when current material transport is considered. While emissions of a gas CHP unit are inherent and could only be reduced by carbon capture and sequestration, emissions of the aluminium storage cycle will further decrease with the decarbonization of energy production and thus embodied energy in renewable energy systems and transport in coming years.

4. Challenges and Further Research

Despite its potential, several technical and economic challenges must be addressed for Al energy systems to become commercially viable:

Maturity of carbon-free Al production: Commercial cells range from 200 to 600 kA. While Trimet SA announced the construction of a 10 kA cell in 2024 with the intention to upscale to 40 kA in 2025[1], Elysis announced the construction of 10 cells with 100 kA each in 2025[2] and Rusal claims to produce already inert anode Al in 140 kA cells since at least 2021[3]. Despite of these claimed advancements, it is yet difficult to buy large amounts of CO_2-free Al stemming from these processes, let alone buying with a certificate that would testify its "renewable" origin.

Adaptability of Power-to-Alu to fluctuating electricity supply: While inert anode cells are expected to offer higher flexibility for ramping up and down production within a certain range, a full shut-down of a cell would come with the risk of damage to the cells due to thermal stress when cooling to ambient or re-heating to over 700 °C. Thus, operating these cells only during seasons with excess renewable electricity (e.g., summer months) to produce aluminium for ReMEC storage intended for use during high-demand periods (e.g., winter months) at the same or nearby geographical location appears to be an unlikely business case at present.

Material activation for Alu-to-Energy: The natural oxide layer on aluminium inhibits spontaneous reaction. Al powders or liquid Al react fast with oxygen and with water, but require considerable safety measures. While safe transport of the Al ReMEC requires grain sizes larger than 0.2 mm, the larger the grain size, the slower the oxidation reaction. However, recent research shows that with proper alloying and production mechanisms, reaction kinetics may be influenced quite positively (Agote-Arán et al., 2025).

Cost: The economics of Al-based energy depend heavily on prices of electricity for Al production as well as on the CAPEX and the full-load hours of the production plant, as well as transport costs and re-conversion cost of the Al-to-Energy unit.

5. Discussion & Conclusions

Aluminium offers a compelling and underexplored pathway for renewable energy storage and transport. As a high-energy-density, recyclable, safe, and non-toxic material, it aligns well with the decentralized, resilient, and sustainable energy systems of the future. Further interdisciplinary collaboration across materials science, electrochemistry, energy engineering, and systems design will be crucial to unlocking the full potential of aluminium as a ReMEC in the solar age.

6. Acknowledgments

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7. References

Agote-Arán, M., Welte, B., Freeman, R., Mutti, N., Haller, M., Heel, A., 2025. Al6060 cut wire granules for Al-water reaction: Evaluation of reaction conditions and granule treatments. Int. J. Hydrog. Energy 117, 430–441. https://doi.org/10.1016/j.ijhydene.2025.03.117

Barelli, L., Trombetti, L., Di Michele, A., Gammaitoni, L., Asenbauer, J., Passerini, S., 2022. Aluminum Steam Oxidation in the Framework of Long-Term Energy Storage: Experimental Analysis of the Reaction

[1] https://www.trimet.eu/en/trimet/sustainability/environmental-and-climate-protection/production-of-inert-metallic-anodes, accessed 28.10.2025.

[2] https://elysis.com/en/issuing-first-smelter-technology-licence, accessed 28.10.2025.

[3] https://www.lightmetalage.com/news/industry-news/smelting/rusal-produces-low-carbon-aluminum-using-inert-anode-technology/, accessed 28.10.2025

Parameters Effect on Metal Conversion Rate. Energy Technol. 10, 2200441. https://doi.org/10.1002/ente.202200441

Gucwa, M., Schäfer, A., 2013. The impact of scale on energy intensity in freight transportation. Transp. Res. Part Transp. Environ. 23, 41–49. https://doi.org/10.1016/j.trd.2013.03.008

Haller, M., Amstad, D., Dudita, M., Carbonell, D., Zenhäusern, D., 2021. HybridStock - Hybrid Seasonal Storage of Renewable Heat and Electricity with an Aluminium Redox Cycle. SPF Institut für Solartechnik, Rapperswil.

Haller, M., Carbonell, D., Dudita, M., Zenhäusern, D., 2019. HePoStAl – Heat and Power Storage in Aluminum (Final Report), On behalf of Swiss Federal Office of Energy SFOE. SPF Institute for Solar Technology, Rapperswil.

Haller, M.Y., Carbonell, D., Dudita, M., Zenhäusern, D., Häberle, A., 2020. Seasonal energy storage in aluminium for 100 percent solar heat and electricity supply. Energy Convers. Manag. X 5, 100017. https://doi.org/10.1016/j.ecmx.2019.100017

Haupin, W., Frank, W., 2025. Current and energy efficiency of Hall-Héroult cells - Past, present, and future. Light Met. Age 60, 6–13.

Ishihara, M., Hirano, T., Yajima, H., 2016. Conversion of Conventional Rotary Kiln Into Effective Sandy Alumina Calciner, in: Donaldson, D., Raahauge, B.E. (Eds.), Essential Readings in Light Metals: Volume 1 Alumina and Bauxite. Springer International Publishing, Cham, pp. 636–640. https://doi.org/10.1007/978-3-319-48176-0_88

Jamieson, T., Decker, P., Yasinskiy, A., Düssel, R., Gunnarsson, G., Magnusson, J., Adam, B., Busch, R., Gallino, I., 2025. On the Alloy Development of Ni–Fe–Cu Inert Anodes for Sustainable, CO2-Free Aluminium Electrolysis, in: Edwards, L. (Ed.), Light Metals 2025. Springer Nature Switzerland, Cham, pp. 842–849. https://doi.org/10.1007/978-3-031-80676-6_105

Kvande, H., 2025. Inert Anode Aluminum Cells—Present Status and Future Prospects, in: Edwards, L. (Ed.), Light Metals 2025. Springer Nature Switzerland, Cham, pp. 805–810. https://doi.org/10.1007/978-3-031-80676-6_100

Shmelev, V., Yang, H., Yim, C., 2016. Hydrogen Generation by Reaction of Molten Aluminum with Water Steam. Int. J. Hydrog. Energy 41, 14562–14572. https://doi.org/10.1016/j.ijhydene.2016.05.277

Shoman, W., Yeh, S., Sprei, F., Plötz, P., Speth, D., 2023. Battery electric long-haul trucks in Europe: Public charging, energy, and power requirements. Transp. Res. Part Transp. Environ. 121, 103825. https://doi.org/10.1016/j.trd.2023.103825

Singh, K., Gunnarsson, G., Magnusson, J.H., Haarberg, G.M., Saevarsdottir, G., 2023. Performance Evaluation of Low-Temperature KF-NaF-AlF3 Electrolytes for Aluminum Electrolysis Using Vertical Inert Cu–Ni–Fe Alloy Anodes. J. Electrochem. Soc. 170, 113507. https://doi.org/10.1149/1945-7111/ad0bae