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Towards Climate Neutrality by 2050: Role of Aluminum for Short- and Long-Term Energy and Hydrogen Storage

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ABSTRACT

Reaching climate neutrality by 2050 requires innovative long-term energy storage (LTES) solutions beyond the current use of fossil fuels. While hydrogen is widely promoted, its low volumetric energy density, complex storage requirements, and limited infrastructure readiness raise questions about scalability. This Perspective paper argues that aluminum deserves attention as a strategic energy carrier. With an exceptionally high volumetric energy density, global availability, and full recyclability, aluminum offers unique advantages for seasonal storage and sector coupling. We highlight the promising high-temperature aluminum–steam oxidation pathway, which produces both heat and hydrogen alongside γ-Al_2O_3, directly recyclable in decarbonized smelting processes. Beyond technical feasibility, we discuss system-level opportunities, from coupling aluminum-based storage with renewable-powered smelting plants to enabling multi-service energy hubs for electricity and mobility. Preliminary techno-economic assessments show that aluminum-based hybrid cycles can achieve round-trip efficiencies of 30–36% in power-to-power applications and competitive levelized costs for electricity and hydrogen production in the power-to-X framework. Moreover, key performance indexes show aluminum-based hydrogen aboveground storage can reach densities exceeding Clean Hydrogen targets by a factor of seven, with competitive CAPEX and OPEX values. These results highlight aluminum's potential to complement or outperform hydrogen in enabling reliable, high-density, and fully recyclable energy storage within decarbonized energy systems.

1 | Introduction

Achieving climate neutrality by 2050 has become a primary objective for the European Union, as laid out by the European Green Deal and the legally enforced European Climate Law [1]. Meeting this ambition requires a rapid and systemic transformation of the energy system, which accounts for 85% of greenhouse gas emissions [2]. Despite significant progress in deploying renewable energy sources, fossil fuels still dominate the EU energy mix, especially in hard-to-abate sectors such as heavy industry, transportation, and residential heating.

According to the Net Zero Emissions pathway modeled by the International Energy Agency (IEA), electricity demand in the EU is expected to rise by over 40% in 2030 as the energy system becomes increasingly electrified and interlinked across sectors. The growing electricity demand is projected to be covered by renewable energy sources, such as wind and solar, that will introduce new challenges to system stability and supply security [3], as well as power quality issues [4]. These sources are inherently intermittent and weather-dependent, leading to significant spatial and temporal imbalances between electricity supply and demand. Moreover, the electrification of transport and heating

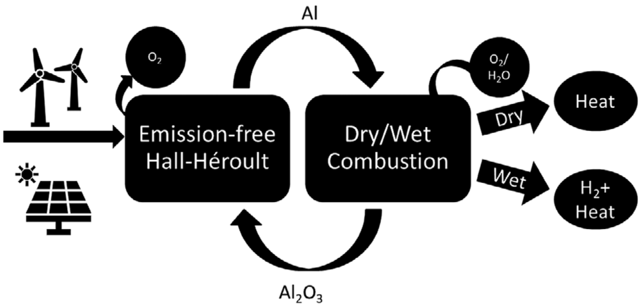

FIGURE 1 | Aluminum energy storage cycle, involving the use of renewable energy for Al production and the generation of heat (dry cycle) and heat and H_2 (wet cycle) for energy production by Al combustion.

systems will introduce new demand peaks, further exacerbating the mismatch between production and consumption profiles. As fossil fuel-based balancing mechanisms are phased out, maintaining grid reliability and meeting daily-to-annual energy demand will rely heavily on the deployment of robust energy storage systems.

Thus, energy storage emerges as an essential enabler of decarbonization. While short- and mid-term storage technologies such as lithium-ion batteries are well-suited for managing intra-day fluctuations and providing grid services [5], they are insufficient for addressing longer temporal mismatches between renewable energy availability and seasonal demand [6]. To grant energy security, flexibility, and emissions reduction goals concurrently, the system requires long-term energy storage (LTES) solutions capable of shifting large amounts of energy across multiple days to months.

Among the proposed LTES vectors, hydrogen has received considerable attention due to its high gravimetric energy density and sectoral flexibility [7, 8]. However, hydrogen's low volumetric energy density, complex storage requirements, and limited infrastructure readiness pose significant scalability barriers, especially in seasonal storage contexts [9]. These constraints have motivated the exploration of complementary carriers with improved energy density, safety, and integration potential.

Reactive metals, and aluminum in particular, are gaining renewed attention as viable energy carriers for LTES [10]. Aluminum's high volumetric energy density (23.5 kWh L^{-1}), global abundance, ease of storage and transport, and full recyclability make it a promising candidate to outperform, in certain scenarios, conventional energy vectors such as hydrogen [11]. Its energy storage cycle relies on the conversion of renewable electricity into metallic aluminum through the Hall–Héroult process (decarbonized and improved through the use of inert anodes and wettable cathodes [12]) and its subsequent oxidation with steam to produce heat and hydrogen, which can be exploited in electricity generation and power-to-x applications. Concerning recent improvements of the aluminum smelting technology supporting the framework here proposed, it is highlighted that aluminum smelters are already modulated up to ± 25% to follow fluctuating power profiles [13].

This paper explores the role of aluminum as a long-term energy storage medium from a system integration perspective. We focus on the most promising pathway (the high-temperature aluminum-steam oxidation) for stationary applications and examine the potential of its implementation in power generation systems and electric mobility infrastructure.

2 | Aluminum Energy Storage Cycle: Oxidation and Regeneration

The aluminum energy cycle leverages the metal's ability to store and release energy through redox transformations, enabling it as both an energy carrier and a long-term storage medium. The energy content of aluminum can be exploited following two main pathways (Figure 1), involving a Dry Cycle or a Wet Cycle.

2.1 | Dry Cycle

Aluminum readily oxidizes upon exposure to air, forming aluminum oxide (Al_2O_3) according to Equation 1:

$$2\mathrm{Al} + (3/2)\mathrm{O2} \rightarrow \mathrm{Al2O3} \quad \Delta H = -1675.7\ \mathrm{kJ/mol} \tag{1}$$

For this reason, aluminum naturally forms a protective oxide layer (2–5 nm thick), which is impermeable to oxygen under standard conditions. As a result, further oxidation ceases unless the material is subjected to high temperatures [14].

Flame combustion of aluminum particles becomes feasible only when the temperature exceeds the melting point of aluminum oxide (2072 °C). At temperatures over 2072 °C, the oxide layer around the aluminum particle melts and coalesces on a reduced area of the particle surface, thus exposing aluminum to the oxidizing environment to advance the oxidation reaction. If the reaction temperature is further increased up to the aluminum boiling point (2470 °C), vaporized aluminum diffuses into the surrounding air, forming a diffusion flame [15]. While this combustion behavior resembles that of hydrocarbons, a key distinction lies in the phase of the products: aluminum oxide forms as a liquid, part of which redeposits on the particle surface, while the remainder disperses as fine "oxide smoke".

From a technological perspective, aluminum-air combustion has traditionally been studied in the context of propulsion systems [16]. Starting from the 90s, studies have focused on the design and development of aluminum combustors to investigate the combustion behavior [17, 18]. Recently, researchers were able to develop lab-scale vortex/swirl burners, demonstrating short-term but stable, self-sustained combustions of micron-sized aluminum [19, 20]. However, literature lacks investigations into aluminum-air combustors designed specifically for stationary energy harvesting. Moreover, as noted by [21], one of the principal challenges in implementing dry aluminum combustion is the selection of construction materials capable of withstanding extreme operating temperatures. Additionally, molten aluminum oxide tends to adhere to surfaces and accumulate, complicating its recovery and recycling [22].

2.2 | Wet Cycle

The above-mentioned technical difficulties make steam-based (wet) combustion a more practical alternative to dry air combustion for energy applications. The proposed energy discharge mechanism in the wet cycle is the high-temperature oxidation of metallic aluminum with steam, a process that occurs at much lower temperatures (<1000 °C) than the direct combustion with O_2 and enables the simultaneous generation of hydrogen and thermal energy. Preferably, the higher temperature range (from 600 °C to 1000 °C) steam oxidation path is preferred to the low-temperature one, because it enables the direct regenerative aluminum cycle, yielding aluminum oxide for the direct regeneration through the Hall–Héroult process without additional treatment steps and related energy consumptions. In fact, the common strategies to enhance reactivity at lower temperatures include adding alkaline compounds (e.g., NaOH, KOH) to dissolve the oxide layer [23], mechanical activation (e.g., ball milling) [24], and alloying with low-melting-point metals to disrupt the formation of aluminum oxide [25], which is needed for the direct aluminum regeneration.

The core reaction of the high-temperature steam oxidation proceeds as indicated by Equation 2:

$$2Al + 3H2O \rightarrow Al2O3 + 3H2 \qquad \Delta H = -815.4\ kJ/mol \quad (2)$$

The reaction, taking place starting from 300 °C, yields up to approx. 0.11 kg of hydrogen and 1.9 kg of aluminum oxide (alumina) per kilogram of aluminum, while releasing about 15.1 MJ of heat [26]. As seen for the dry combustion, the oxidation of aluminum by water steam is regulated by the presence of the oxide layer (alumina, Al_2O_3) that passivates the metal surface. But unlike the previous pathway, water can hydrate the layer, enabling hydroxide ions to diffuse inward toward the unoxidized aluminum. This diffusion process is widely recognized as the rate-limiting step of the reaction and follows Arrhenius-type kinetics, meaning its rate increases exponentially with temperature [27]. Since diffusion is a surface-driven mechanism, reaction rates are also enhanced by increasing the specific surface area, explaining why micrometer-scale powders exhibit much higher reactivity than bulk or larger particles at the same temperature.

Aluminum-steam reaction becomes a full-fledged combustion at elevated temperatures (above 1373 °C), offering a thermodynamically favorable and self-sustaining reaction pathway without the need for chemical or mechanical activation. Steam can penetrate and hydrate the oxide layer before it reaches its melting point, lowering the required temperature for ignition. Once ignited, aluminum combustion in steam can reach flame temperatures exceeding 3000 K, enabling high reaction rates and higher theoretical power densities than liquid water-based systems [21]. These high temperatures also support more efficient thermal integration with downstream energy conversion technologies, such as solid oxide fuel cells or combined heat and power systems, thereby improving the system-level efficiency of aluminum-based long-term energy storage.

Recent work has demonstrated an alternative oxidation approach of aluminum powder at the laboratory scale capable of achieving high degrees of oxidation at significantly lower temperatures, around 900 °C. The solid fraction of oxidation products resulting from simple experiments in small-scale batch reactors is composed of 83.4% γ-Al_2O_3 (i.e., the crystallographic form which can be directly used in the Hall–Héroult process) and 16.6% Al [28], as determined through Rietveld refinement of the XRD pattern. The continuous process could be exploited using alumina as an inert material in the oxidation reactor. As proved at the laboratory scale [29], this approach allows for hindering the clumping tendency of aluminum oxide and enables direct use of oxides in the smelting process for full recyclability.

2.3 | Regenerative Step

For both the “discharging” pathways, i.e., the dry cycle and the wet cycle, the regenerative step is the same. The oxidized product, Al_2O_3, can be reduced to metallic aluminum via the Hall–Héroult electrolytic process, which constitutes the “charging” phase of the aluminum energy cycle. The Hall–Héroult process reduces alumina (γ-Al_2O_3) dissolved in molten cryolite (Na_3AlF_6) at temperatures above 950 °C, according to equation 3.

$$2Al2O3 + 3C \rightarrow 4Al + 3CO2 \quad (3)$$

This process is highly energy-intensive, requiring 12.8–13 kWh of electricity per kilogram of aluminum with the conventional Hall–Héroult process, i.e., storing only slightly more than 50% of the electricity supplied [30].

According to state-of-the-art Hall–Héroult technology, industrial aluminum smelters can be power-modulated up to ± 25% of the nominal electric power [13] thanks to an adjustable heat exchanger, magnetic field compensation, and digital process control; moreover, the technology allows complete plant shutdown for 90 min. Furthermore, it is feasible from an industrial point of view to improve the modulation capability range to ± 30% power modulation [31]. This supports the potential management of short-term and mid-term (over the daily timeframe) fluctuations of feed-ins from wind and solar power plants by means of Hall-Héroult plants.

Additionally, the conventional process generates large amounts of CO_2 and, even worse, fluorocarbon compounds [32]. Technological innovations, however, are underway to improve its sustainability. The introduction of wettable drained cathodes reduces the anode–cathode distance, lowering ohmic losses and improving energy efficiency by up to 15%–20% [30]. Furthermore, the development of inert anode materials (which do not consume carbon and thus avoid direct CO_2 and fluorocarbon compound emissions) is expected to significantly reduce the carbon intensity of primary aluminum production. Industrial prototype cells are already being tested at the industrial scale (TRL 5 was recently reported by JRC [33]) and are projected to become commercially viable within the current decade [34], significantly improving the environmental profile of aluminum as an energy carrier. Recently, Elisys announced the start-up of its 450 kA designed inert anode cell [35].

The alumina entering the Hall–Héroult process, commonly known as SGA (smelter-grade alumina), is produced through the Bayer process. The last step of the process involves a calcination at around 1100 °C of the unrefined Gibbsite ($Al(OH)_3$) to alumina (Al_2O_3). The result is a mixture of mainly theta (θ) and gamma (γ) alumina, with a content of 2–10% α-Al_2O_3 and traces of residual $Al(OH)_3$ [36]. γ- and θ-Al_2O_3 are the most desirable phases since they can rapidly dissolve in the cell's bath, whereas the presence of α-Al_2O_3 can be considered a hindrance to the process, as it melts at a slower rate, tends to segregate, and lowers the flowability [37].

In this regard, it is highlighted that at 900 °C, i.e., the operating temperature fixed for the proposed Al steam oxidation process according to the wet cycle, γ-Al_2O_3 is the more stable form. This is confirmed by findings of XRD analysis performed over the solid fraction of oxidation products resulting from simple experiments in small-scale batch reactors, as detailed above. Therefore, alumina obtained from Al steam oxidation can be directly recycled into the smelter.

3 | Aluminum Integration in Power Systems for Long-Term Energy Storage

3.1 | Long-Term Energy Storage Demand and Aluminum Potential

A central challenge to achieving full decarbonization of the European Union's energy system lies in developing storage solutions capable of balancing long-term mismatches between renewable energy generation and demand. Recent projections estimate that, under a fully decarbonized scenario, the EU would require approximately 1300 TWh of LTES capacity annually to ensure reliable energy availability across seasons [29].

Hydrogen is frequently proposed as a candidate seasonal energy storage medium and energy vector due to its high gravimetric energy density and versatility across power-to-X pathways. However, its practical application is severely constrained by its low volumetric energy density and the associated infrastructure requirements. Specifically, hydrogen compressed at 700 bar exhibits a volumetric energy density of only 1.4 kWh L^{-1}, while liquid hydrogen achieves 2.3 kWh L^{-1} under cryogenic conditions. Based on these values, storing 1300 TWh of energy would necessitate between 556 and 913 million cubic meters of hydrogen. The actual storage volume would need to be significantly larger once allowances are made, considering the different hydrogen storage technologies, for a minimum hydrogen pressure to be guaranteed in underground caverns, insulation, structural containment, access systems, safety margins, and storage site dispersion. Moreover, the infrastructure for large-scale hydrogen storage and distribution remains limited across the EU [2], and the typical round-trip efficiency of hydrogen-based storage cycles (often below 30%) further exacerbates these constraints when deployed for power-to-power applications [38].

In contrast, aluminum offers a markedly higher volumetric energy density of 23.5 kWh L^{-1}, nearly an order of magnitude greater than that of liquefied hydrogen, and over 16 times that of compressed hydrogen at 700 bar. This significant volumetric advantage implies that the same 1300 TWh storage capacity could be achieved with approximately 54.4 million cubic meters of aluminum. This renders aluminum a highly attractive option for high-density, long-duration storage, particularly in spatially constrained or distributed energy system contexts.

Furthermore, the stable solid-state form of aluminum facilitates ease of handling, storage, and transport using existing logistical networks, unlike hydrogen, which requires high-pressure or cryogenic systems. In addition to offering favorable energy density characteristics, aluminum also integrates well into circular economy frameworks, given its full recyclability and the maturity of its industrial recovery pathways. These factors collectively reinforce the viability of aluminum as a strategic vector for long-term energy storage in support of the EU's decarbonization objectives.

The feasibility of aluminum as a large-scale energy carrier depends not only on its energy properties and recyclability but also on the long-term availability of its primary resource: bauxite. Bauxite is the principal ore for aluminum production, composed mainly of aluminum hydroxides and oxides (e.g., gibbsite, boehmite, and diaspore). It undergoes refining into alumina (Al_2O_3), which is then electrolytically reduced to produce metallic aluminum.

According to the United States Geological Survey (USGS) [39], the global reserves of bauxite are estimated to range between 55 and 75 billion metric tons, sufficient to sustain current and future demand scenarios (EU needs for energy storage: approx. 105 million metric tons). The distribution of these reserves is geographically broad, with significant deposits located in politically stable regions, including Australia, Brazil, Guinea, and India. This contributes to the supply security of aluminum as an energy carrier and storage medium. Anyway, it is remarked that the use of aluminum as a storage medium consists of a cycle with inherent recycling of alumina to metal Al, thus not reliant on exploiting bauxite reserves, except for limited material losses.

In terms of current production, the USGS reported that in 2023, global primary aluminum production reached 70 million tons. The largest producer was China, accounting for roughly 58% of global output, followed by India, Russia, Canada, and the UAE.

3.2 | Aluminum Steam Oxidation Integration for Power Generation Systems

In the context of stationary energy systems, aluminum functions as a high-density energy storage medium that can be converted into usable electricity and hydrogen through high-temperature steam oxidation. Specifically, Figure 2 shows an innovative configuration proposed by the authors that involves the co-location of aluminum energy conversion units with aluminum smelting plants [11]. In this scenario, part of the molten aluminum output from the Hall–Héroult process—typically operated at 940–980 °C—is diverted to a pressurized water–steam Al oxidation reactor for hydrogen and heat generation. The resultant alumina byproduct, γ-Al_2O_3 [28], can be reintegrated into the smelting process during periods of renewable energy surplus. This approach facilitates energy and material circularity within a single industrial site and enables a short-term energy buffer that enhances the flexibility of both the power system and the aluminum production chain.

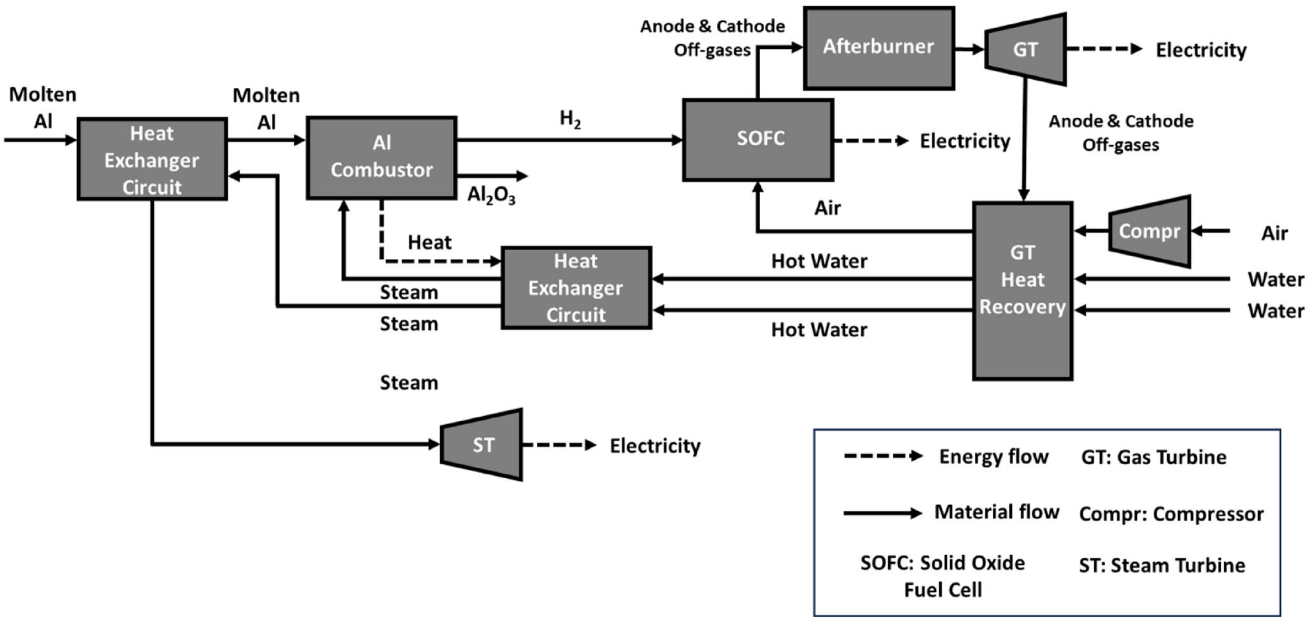

FIGURE 2 | Molten Al power system simplified layout. The system features an aluminum combustor that feeds hydrogen to a Solid Oxide Fuel Cell (SOFC) and heat to a secondary circuit with a Steam Turbine (ST). The excess hydrogen is burned using a Gas Turbine (GT).

Electricity is co-generated through a combined cycle that exploits the heat in a secondary pressurized circuit employing a steam turbine, and the hydrogen is fed into a high-efficiency solid oxide fuel cell (SOFC). With reference to the overall Power-to-Power cycle, the proposed hybrid system exhibits a round-trip efficiency (defined as the ratio of produced power to electric power used for aluminum production) of over 30% and up to 36%, depending on the energy savings that will accompany technological innovations for the smelting process [11].

Given the high electricity demand of smelting operations, coupling these with aluminum-based power generation offers the possibility of dynamic load balancing within an integrated energy-industrial complex and intra-day energy storage service to exploit the surplus of renewables.

The modular nature of aluminum-based systems also enables their deployment at different scales. In addition to large integrated facilities, these systems can function as distributed power units in weak-grid or off-grid areas, serving as autonomous energy hubs that ensure local reliability and grid independence. In these cases, aluminum's stability in solid form allows it to be stored for long periods without energy loss, effectively decoupling the Power-to-Al phase (i.e., Al smelting, energy storage) from the Al-to-Power phase (i.e., Al combustion, energy utilization). This enables aluminum to function as a physical short- (day/night cycle), mid- (dunkelflauten cycle), and long-term (seasonal) energy reserve that can be charged with renewable electricity during periods of surplus generation and discharged during grid shortages.

4 | Aluminum to X Applications

Hydrogen generated through aluminum steam oxidation can either be used directly for power production or stored and distributed to serve external demand in the transport and industrial sectors. This flexibility positions aluminum-based systems as multi-vector energy platforms, capable of supporting both electricity generation and sector coupling in a decarbonized energy landscape. Below, two different application frameworks are investigated. The first one relates to Al-to-X integration in the EV infrastructure, to supply hydrogen and power to fuel cell and battery electric vehicles, respectively. The second one concerns aluminum to hydrogen use of aluminum for large-scale hydrogen storage, enabling a new technology with breakthrough KPIs with reference to aboveground hydrogen storage.

4.1 | Aluminum-to-X Integration in EV Infrastructure

Aluminum is being investigated as a promising energy carrier for future electric vehicle (EV) infrastructure, with the potential to support both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) through localized, zero-carbon energy conversion, according to an Al-to-X framework. Novel system concepts propose the use of powder aluminum steam oxidation reactors to co-generate hydrogen and heat on-site (Figure 3). In such configurations, heat and part of the released hydrogen are used to generate electricity on-site for BEV charging, while the remaining hydrogen is compressed and stored for direct refueling of FCEVs. This dual functionality suggests a path toward modular refueling and charging stations at the multi-MW scale, suited for both highways and off-grid applications that reduce dependence on centralized hydrogen infrastructure and high-capacity grid connections.

In [40, 41], the authors performed a techno-economic analysis of such a charging/refueling station with a 3.9 MW electric power capacity. The evaluation used both deterministic and stochastic methods due to technology immaturity and cost uncertainties.

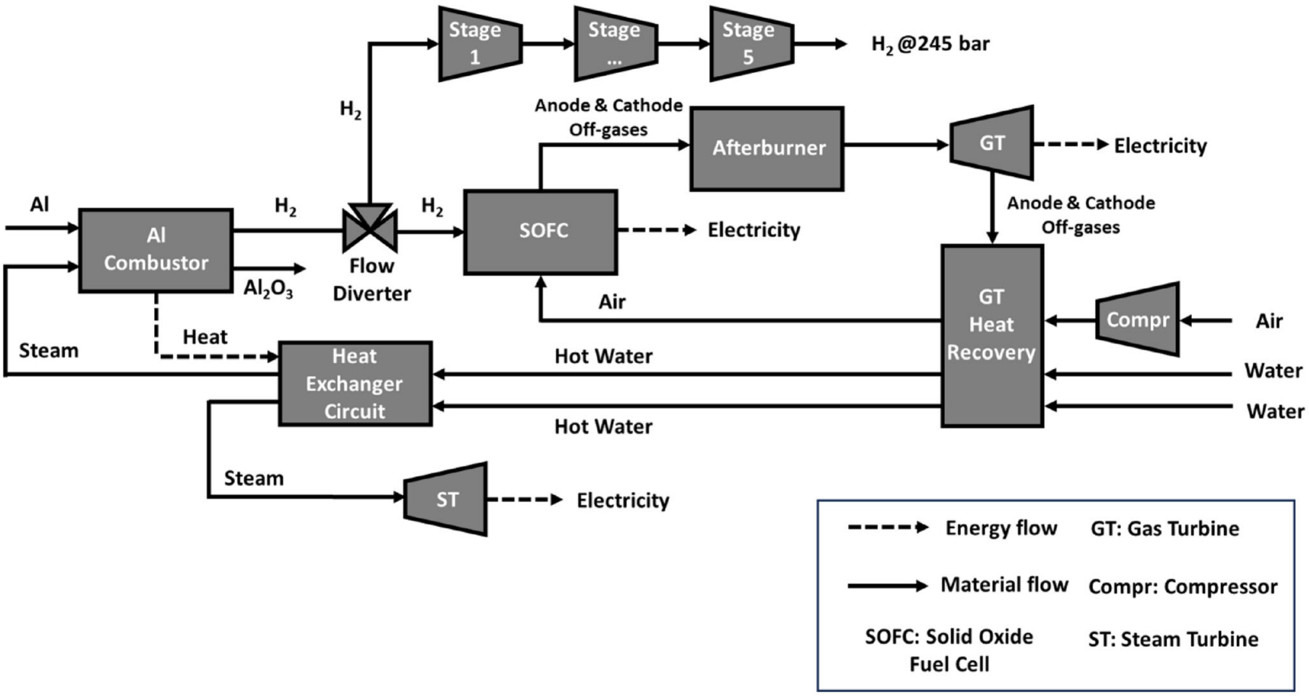

FIGURE 3 | Refueling/recharging station simplified layout. The system features an aluminum combustor that delivers heat to a secondary circuit with a Steam Turbine (ST) and produces hydrogen. Part of it is diverted to a 5-stage compressor to increase the pressure up to 245 bar. The remaining hydrogen is used in a Solid Oxide Fuel Cell (SOFC) and Gas Turbine (GT).

CAPEX estimations included direct/indirect costs, engineering, procurement, construction, and working capital. Results show total CAPEX around €20 M (range €16–24 M), equal to €4200–6200 per kW installed.

Concerning operational expenditures, the business case assumed buying aluminum from producers, transporting it to the station, and selling the produced alumina. The levelized costs of electricity (LCoE) and hydrogen (LCoH) were calculated from the net present value of costs vs. outputs, with different energy price and efficiency scenarios:

- Scenario I "High energy intensity". This scenario assumed the current global average energy demand for Al production (14.25 kWh/kg_{Al}), and relatively high electricity prices (50€/MWh), resulting in an aluminum price of 1.65€/kg_{Al} as detailed in [41].
- Scenario II "High efficiency & low electricity price". This scenario assumed an improved smelting efficiency due to wettable drained cathodes and inert anodes (11 kWh/kg_{Al}), and cheaper electricity from higher renewable penetration (30€/MWh). The resulting aluminum price equals 1.26€/kg_{Al} as detailed in [41].
- Scenario III "Zero electricity price". This scenario assumed the same efficiency as Scenario II, but with a surplus of renewable electricity available at zero cost, which brings the aluminum price to 0.93€/kg_{Al} as detailed in [41].

Moreover, for all the scenarios, alumina price was considered in the range 0.52–0.83€ per kg of equivalent aluminum. Aluminum cost was assessed for the different scenarios, starting from the price range 1.2 – 1.95€/kg_{Al} corresponding to the 2014–2019 period [42]. Moreover, the share of different cost components, as recently reported by the Norwegian aluminum producer Norsk Hydro ASA (see Figure 4), was incorporated into the economic evaluation model, aiming to apply the main business case assumptions detailed above. All details are presented in [41].

Operating conditions related to the electricity/H_2 split generation, as indicated in [41], and 4000 full load hours annual operation duration are considered for the economic evaluation for an annual production of 10.4 – 16 GWh of electricity and 187-112 tons of H_2, depending on the operating condition. Under given scenarios, discounting the expenditures and amount of energy supplied during the system's lifetime, a levelized cost analysis has been conducted for electricity (LCOE) and H_2 (LCOH). The results indicate LCOE ranging from 152–334€ MWh^{-1}, while LCOH of Al-based H_2 corresponds to 5.4–11.8€ kg^{-1} based on various operation modes in the reference scenarios. Findings indicate that aluminum to X systems integration in the EV infrastructure can be a cost-competitive alternative while improving energy security.

Looking forward, aluminum-based systems could offer a scalable, modular approach to the deployment of multi-service mobility hubs, capable of supporting BEV charging, FCEV refueling, and integrated thermal energy services, in addition to multi-service energy providers for buildings and commercial centers. Their flexibility and compatibility with renewable and circular economy principles position them as a strategic candidate for future transport infrastructure, particularly in alignment with European policy targets such as the Alternative Fuels

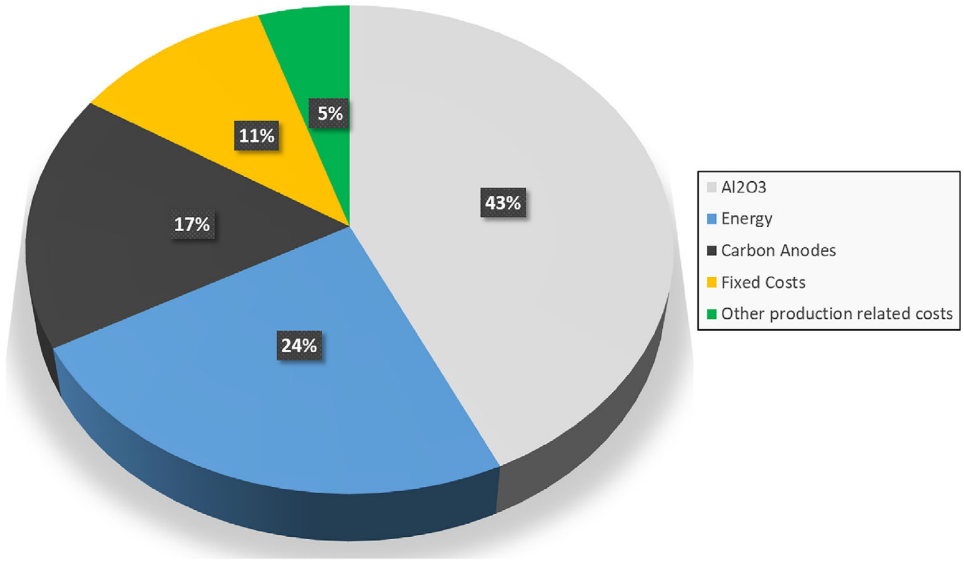

FIGURE 4 | Share of cost components in Conventional Al production [43].

Infrastructure Regulation (AFIR) [44]. Although further research, pilot deployments, and supply chain adaptations are needed, aluminum-based hybrid systems represent a compelling technological pathway toward decarbonized, flexible, and resilient electric mobility.

4.2 | Aluminum to X Integration in LargeScale Hydrogen Storage

Aluminum can be used in the Power-to-X framework, also as a breakthrough hydrogen aboveground storage technology. With respect to the Clean Hydrogen Key Performance Indexes indicated in the SRIA 2021–2027 [45], it allows for advancing aboveground hydrogen storage solutions based on novel solid hydrogen carriers. Some preliminary assessments are discussed below concerning aboveground hydrogen storage in the form of aluminum, according to the circular concept which employs a round-trip conversion cycle, i.e., Power-to-Al and Al-to-H_2 phases, as depicted in Figure 1.

In the following assessment, it is assumed to use 100% renewables for the Power-to-Al step. Moreover, pre-chain emissions (i.e., those related to alumina production) are excluded since the concept is circular and the impacts on the overall life cycle are negligible. Finally, a realistic decarbonization pathway for Al smelting is assumed by the elimination of direct emissions (i.e., CO_2 and fluorocarbon compounds) thanks to the substitution of conventional carbon anodes with inert anodes in the Hall-Héroult process (see earlier discussion and [33]).

Considering the solid aluminum density, 2700 kg of Al per m^3, and the 0.11 kg of H_2 per kg of Al, which can be produced through Al steam oxidation, one cubic meter of Al corresponds to an equivalent storage of 297 kgH_2/m^3. This represents a sevenfold increase in stored H_2 density compared with the threshold indicated by Clean Hydrogen Key Performance Indexes SRIA 2021–2027, i.e., 40 kgH_2/m^3. Moreover, from an energy point of view, the threshold of 40 kgH_2/m^3 corresponds to 1333.32 kWh/m^3 considering H_2's low heat value. Aluminum volumetric energy density achieves 23.5 MWh/m^{3,} considering both hydrogen and high-temperature heat produced through Al steam oxidation. Therefore, the use of aluminum as a H_2 carrier allows overcoming the indicated threshold for hydrogen storage (with reference to the energy storage volumetric density) with a more than 17-fold gain.

With regard to the CAPEX, the target has been set to less than 600€/kg$_{H2}$ on the 20 ton/day H_2 scale (SRIA, KPI Table 11 [45]). For such daily production, an aluminum flow rate input in the steam oxidation reactor of 2.3kg$_{Al}$/s is needed, assuming continuous operation (h24) and 90% reaction efficiency. Consequently, the installed power of the Al steam oxidation reactor is assessed equal to about 35 MW (considering 15.1 MJ of heat released per kg of reacted aluminum. As a very preliminary assessment, Al steam oxidation technology is not available at the industrial scale yet; the cost for the innovative reactor might be assumed similar to that of conventional boilers for steam power plants. For sub-critical boiler section (including the boiler's feeding pump) up to about 100 MW, the cost ranges around 165 US$/kW (i.e., 142€/kW) [46], corresponding to a CAPEX near 5 M€ or about 251€ per kg of delivered H_2 [46].

The main results are summarized in Figure 5.

A preliminary OPEX assessment for hydrogen storage and generation is also performed to compare aluminum exploitation as hydrogen carrier to the conventional technology path constituted by low temperature electrolysis and hydrogen storage in underground caverns. To this aim, it was considered:

1. Aluminum cost (energy included): It was considered that aluminum price ranged between 1.2 and 1.95€/kg in the 2014–2019 period [42]. The share of different cost components is considered according to Figure 4. For the H_2 production OPEX assessment, however, the costs of Al_2O_3 and

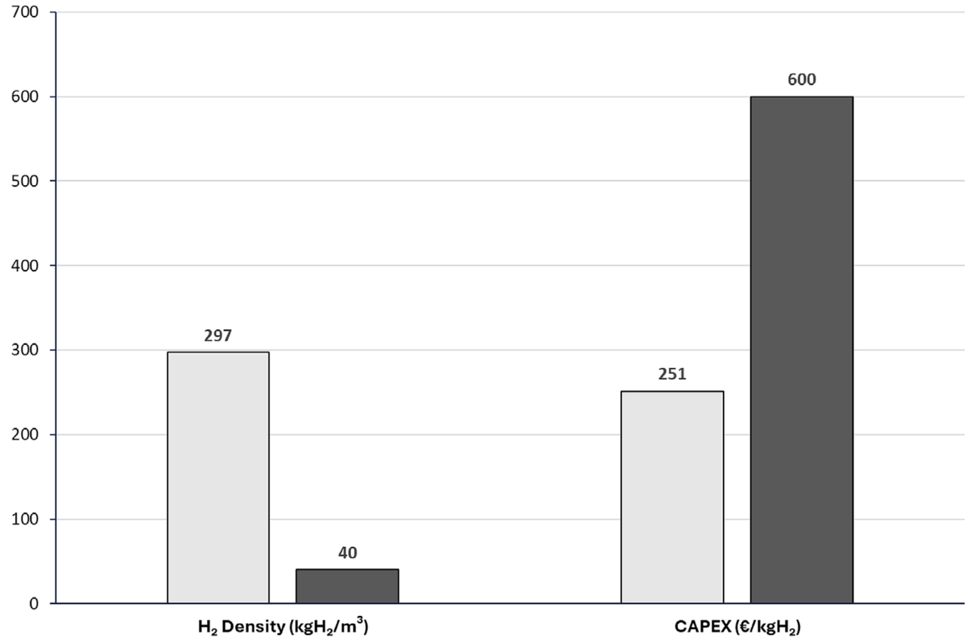

FIGURE 5 | KPIs of the new proposed technology (light gray) with reference to the ones indicated by Clean Hydrogen Key Performance Indexes SRIA 2021–2027 aboveground hydrogen storage (dark gray).

carbon should not be considered because Al_2O_3 is fully recycled, and inert electrodes are used in consideration of the CO_2-free smelter technology recently scaled-up at the industrial scale. Only the 11% fixed costs, 24% electricity cost (it does not correspond to a very high renewable penetration), and 5% other production-related costs were considered. Consequently, based on historical Al costs data (specifically, the 5-year average) reported in Table S3 of [40], Al cost results in 4.91€/kg_{H2} delivered considering only fixed and electricity costs (Equation (4)), while increasing up to 5.63€/kg_{H2} delivered including also other production-related costs (Equation (5)).

$$OPEX\_Al = \frac{(0.17 + 0.37)\ €/kg_{Al}}{0.11\ kg_{H2}/kg_{Al}} = 4.91\ €/kg_{H2} \quad (4)$$

$$OPEX\_Al = \frac{(0.17 + 0.37 + 0.08)\ €/kg_{Al}}{0.11\ kg_{H2}/kg_{Al}} = 5.63\ €/kg_{H2} \quad (5)$$

(2) Water cost: Water consumption is in the 1:1 molar ratio, corresponding to 9 liters of water required to produce 1 kg of hydrogen. Since water vapor is exploited in reaction (2), no ultra-pure water is required. In reference [47], river water and desalinated water relative to real installations are priced at 0.2€/m^3 and 0.7€/m^3, respectively. Therefore, considering additional cost for water management, a cost of 1€/m^3 is assumed, corresponding to a water-supply related cost of 0.9 cent€/kg_{H2}, marginal with respect to the aluminum cost.

The OPEX of the conventional path is assessed to 5.01€/kgH_2, in consideration of 4.7€/kgH_2 for hydrogen low temperature electrolysis as resulting from [48] for a theoretical 100 MWel project in Europe and 0.31€/kgH_2 for compression in caverns (requirements: 2.2 kWh/kgH_2 and 50L/kgH_2 water) as indicated in [49]. This results in comparable OPEX values.

Moreover, the overall cycle efficiency in Power-to-Power applications is considered equal to 36.3% [11], i.e., slightly higher than 30% of systems including alkaline water electrolyzers, PEM stacks, and compressed hydrogen storage at 200 bar, which corresponds to a volumetric energy density of only 0.53 kWh/L [50].

5 | Conclusions and Future Research Perspectives

As the European Union accelerates its transition toward climate neutrality, LTES is emerging as the critical enabler for the realization of a decarbonized, flexible, and secure energy system. This paper has examined the potential of aluminum to serve as a reactive metal fuel for LTES, with a specific focus on the innovative high-temperature steam oxidation process and its applicability in both stationary power generation and electric mobility infrastructure.

The feasible Al oxidation with steam at temperatures around 900°C has been demonstrated yielding γ-Al_2O_3, which is the crystalline form appropriate for the Al smelting. This makes direct regeneration possible, increasing the sustainability of the energy storage cycle. Additionally, γ-Al_2O_3 is demonstrated to prevent clogging while enabling the full recycling of produced powder in the Al smelting process. This represents an advancement with respect to water Al oxidation processes performed at low temperatures as well as to the dry combustion process, which do not yield the proper Al_2O_3 crystalline form for Al smelting. The low-temperature water-based process has additional drawbacks tied to the need for additives to promote the hydrogen generation reaction, which impede the direct recycling of the produced powder in the POWER-to-Al smelting process.

Supporting arguments (CAPEX and OPEX) have also been presented about the suitability of hydrogen generation through aluminum steam oxidation at temperatures in the 800–1000 °C range.

Nonetheless, the development of novel reactor designs able to recover alumina during the aluminum-steam reaction represents the main challenge relevant to the Al-to-Power and Al-to-H_2 conversion systems.

With reference to the POWER-to-Al path, efforts will be needed in the near future to fully implement at the industrial scale innovative technologies (e.g., inert anodes and wettable cathodes electrolysis) to reduce carbon intensity and improve round-trip energy efficiency of aluminum smelting, as well as to allow power supply by fluctuating renewable sources.

From a systems perspective, the integration of aluminum-steam reactors into decentralized or mobile energy infrastructure requires advancements in compact, modular reactor designs, improved thermal integration, and real-time control systems that ensure safe operation under variable loads. Moreover, life cycle assessment and environmental impact modeling for the full aluminum-based energy cycle remain limited in scope and should be expanded to inform sustainability policies. The economic viability of aluminum energy systems is sensitive to fluctuating aluminum market prices related to electricity tariffs for smelting, especially during the transition to the full decarbonized scenario, suggesting a need for policy instruments, such as renewable electricity price guarantees or green aluminum certification, to stabilize long-term deployment conditions.

Compared to conventional energy carriers such as hydrogen, aluminum offers key advantages in terms of volumetric energy density, storability, transport safety, and full recyclability, properties that collectively position it as a viable alternative for bridging seasonal and sectoral mismatches in renewable energy supply and demand. It is also highlighted that the proposed aluminum-based energy cycle completely avoids "forever chemicals." No PFAS are produced according to the used materials.

The high energy content of aluminum can be accessed through thermally integrated reaction pathways that produce both hydrogen and heat, which can be converted to electricity via SOFCs and steam turbines. The integration of these systems with aluminum smelting operations, especially under renewable-powered electrolysis, could enable circular, co-located industrial ecosystems that improve energy efficiency and reduce lifecycle emissions. Additionally, the modular nature of aluminum-based systems supports their deployment in distributed, off-grid, or weak-grid environments, enhancing system resilience and geographic flexibility.

In the mobility sector, aluminum-based hybrid systems represent a promising avenue for enabling multi-service refueling and charging hubs. Through on-site hydrogen and electricity generation, these systems could reduce the infrastructure burden associated with centralized hydrogen production and grid expansion. Preliminary techno-economic assessments indicate that, under favorable electricity pricing and recycling conditions, aluminum systems could reach competitive levelized costs of hydrogen and electricity relative to current technologies.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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