Hybrid Energy Storage System for BEV and FCEV Charging Stations—Use Case for Aluminum as Energy Carrier

Nicola Musicco, Hüseyin Ersoy, Linda Barelli, Manuel Baumann, and Stefano Passerini

Abstract The development of electric vehicle (EV) charging infrastructure and load management remains a significant challenge in the transition to sustainable mobility. This chapter explores the use of aluminum (Al) as an energy carrier to enable a hybrid management of BEV charging and fuel cell electric vehicle (FCEV) hydrogen (H_2) refueling. The use of aluminum enables on-site power and flexible H_2 generation, enhancing flexibility and versatility in EV charge management strategies. The study introduces this emerging concept, providing a theoretical foundation for its techno-economic implications and presenting a formulated use case that examines the potential of the Al wet-combustion process for large hybrid charging stations. By leveraging aluminum's high energy density, recyclability, and multi-functionality, this approach offers a promising pathway to improve charging infrastructure resilience and energy efficiency.

Keywords Aluminum · Power-to-X · EV charging · Mobility · Energy transition · Metal fuels

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1 Introduction

There is a high need of energy storage systems to mitigate flexible generation and charging behavior of a growing number of electric vehicles (IEA 2024). Here, hybrid energy storage systems (HESS) can play a crucial role in providing such flexibility services. These services are needed on several levels, starting from private owners using home charging stations, up to large fast charging stations located at a highway level. Other larger applications are electric buses or trucks where charging power can reach multiple MW-scales. However, considering a high equality factor of charging can lead to local grid parameter violation or worse, a breakdown of power supply (Mahmud et al. 2023). There are several energy storage alternatives to support the charging of electric vehicles via renewable energies, in particular hybrid energy storage solutions (Yadav et al. 2023; Al Wahedi and Bicer 2020; Gonzalez-Rivera et al. 2021). Here, a broad variety of combinations of storage solutions is proposed, starting from batteries with supercapacitors, thermal storage, H_2 production and batteries and more recently the use of reactive metals. The latter represents a rather new way of storing energy for both short and long term with the possibility of offering multiple services for electric mobility and are considered as hybrid energy storage systems.

Moreover, the realization of a decarbonized economy requires the development of large energy storage solutions capable of buffering the daily, weekly and seasonal fluctuations of energy (electricity) generated from renewable energy sources (RES), as, solar and wind power (Denholm and Mai 2019). The implementation of such sustainable, low-cost, and large-scale storage systems is urgently required, but still full of challenges.

Reactive metals as aluminum, magnesium, iron have both high volumetric and gravimetric energy densities and can be converted in different ways on multiple power levels. In addition, they are highly suitable for long term storage and can be transported using existing infrastructures (trains, ships, road transport) (Barelli et al. 2020). After their use, metal oxides can be collected and then be recycled (i.e., reduced to the metal state) using processes powered by renewables (Bergthorson 2018). Aluminum is one of the most promising candidates due to its favorable properties. It is as a functional construction and energy material with vital significance for achieving the determined sustainable development goals. Mainly, Al demand is dominated by the transport (27%), construction (24%), and packaging (15%) sectors. One notable point is the anticipated demand growth in the transport and energy applications of aluminum. Until 2050, expected demand growth of the transport sector corresponds to 55% in relation to the year 2017 (Aluminium 2019). This increased demand may support the sector coupling of aluminum production for a case where aluminum is used as an energy storage material at the same time.

A kg of aluminum under theoretical considerations has an energy density of 8.6 kWh, as 4.2 kWh in the form of heat and about 4.4 kWh of energy in the form of H_2, i.e., 0.111 kg equivalent based its lower heat value (LHV = 33,3 kWh kg^{-1}) when it is oxidized with water (Petrovic and Thomas 2011). The volumetric energy density equals 23.5 kWh l^{-1} versus 2.3 kWh l^{-1} of liquefied H_2, making aluminum also a potentially viable solution as a H_2 storage carrier.

This chapter provides an overview of current strategies for using HESS for the integration and charge management of EV charging stations. The focus is set on Aluminum as energy carrier as a possible solution to do so. Different Al-conversion paths and current system designs are briefly introduced. Then a use case for an Al wet combustion system and its techno-economic performance is provided. Finally, relevant KPIs and sustainability implications are discussed.

2 Hybrid Energy Storage System for Integration Charge Management of EV Charging Stations

In the following some selected examples are provided to display how HESS can support the charge management of EV-charging stations. (See Table 1) The aim of the section is to provide an overview of current potential solutions for hybrid energy storage systems and how they can support the transition towards electric vehicles.

The work of (Yadav et al. 2023), presents a power management scheme for EV-charging on AC and DC side via the combination of a supercapacitor with a generic EV battery. Here the supercapacitor reduces the stress on the non-defined EV battery due to sudden changes in generation and normal operation and allows to reduce overall power consumption.

A broader HESS concept has been proposed by (Al Wahedi and Bicer 2020) for the off grid-based charging of up to 80 electric vehicles per day through renewables, in particular with PV, wind turbines, and biomass based Rankine cycle located in Qatar. The system consists of lithium-ion batteries, H_2, Ammonia, and a phase change based thermal storage unit. The H_2, and NH_3, produced via renewables and stored on site is combined with fuel cells. The latter are supported by lithium-ion batteries. The main advantage of the hybrid solution is a high exergy efficiency, with positive impacts on the single components during their operation.

A Model Predictive Control-Based Optimized Operation of a Hybrid Charging Station for Electric Vehicles has been investigated by (Gonzalez-Rivera et al. 2021). Here a combination of a PV-system, a battery, fuel cells and electrolyzers to support six fast charging units is modelled. The results indicate a positive impact of HESS regarding overall operation cost, NPV, and reduces grid utilization.

Roslan et al. proposed a combination of a H_2 storage system including an electrolyzer and fuel cell in combination with a AC/DC conversion multiport network and a Li-ion battery for EV charging in Malysia (Roslan et al. 2024). Here a set of economic (COE, NPC and LCOH,) and one environmental KPIs (e.g., CO_2 emission reduction) is calculated using HOMER®. The calculations indicated promising results of the proposed HESS system, helping to achieve a stable electricity supply

Table 1 Comparison of selected studies on HESS for EV-charging support

Source	Scope	Technology	KPIs	Hybrid storage benefit
Yaday et al. (2023)	Power management system for PV based charging	Supercapacitor with battery	Power consumption reduction	Avoiding battery stress, lower power consumption
Wahedi et al. (2020)	Proposition of a stand-alone fast EV charging station running on purely hybrid RES	PV, Li-Ion batteries, Phase Change Material thermal storage, wind turbine, H_2 and ammonia electrolyzers and fuel cells, biomass conversion	Energy efficiency, Exergy efficiency	Improvement of overall exergy efficiency
Gonazles-Rivera et al. (2021)	Provision of an energy management system based on a novel approach using model predictive control	PV system, battery, H_2 system based on a fuel cell, electrolyzer, and tank as an energy storage system	Grid use reduction, efficiency, utilization cost, net present cost	Lower utilization cost (−25.3%), grid use reduction (−60%) and efficiency improvement
Roslan et al. (2024)	Techno-economic analysis of hybrid energy storage system for electric vehicles charging stations using renewables	H_2 electrolyzer, tank and fuel cells. Li-Ion batteries, Wind and PV-system, and an AC/DC conversion multiport network	COE, NPC and LCOH, Emissions: CO_2, CO, SO_2, NOx, particulate matter, and unburned H_2	Provision of environmental and economic benefits
Güven et al. (2025)	Identify hybrid systems to ensure the electricity supply to EV charging stations	PV, wind turbine, biomass, electrolyzer, H_2 tank, fuel cell, batteries, inverter	LCOE, NPC, Payback Period, OPEX, CAPEX, Emissions: CO_2, CO, SO_2, NOX, particulate matter	Provides favorable economic performance due to high renewable potential, emissions are reduced

with reduced CO_2 emissions. Also, several recommendations for EV-charging infrastructure are provided in terms of modelling, optimization or potential of exploring further technologies for electricity conversion.

Güven et al., investigate hybrid systems to ensure electricity supply to EVs in the Çukurova region of Adana, Turkey (Güven et al. 2025). A combination of a biomass gasifier, a H_2 electrolyzer, tank and fuel cell, photovoltaics and wind turbines to support local EV charging stations has been analyzed via six different design scenarios. In sum, the system is regarded as beneficial in terms of net present cost, and levelized cost of electricity in areas with a high solar irradiation. Again, as in Roslan et al., HOMER® has been used for modelling.

There are several studies on HESS in the specific application field of supporting EV-charging infrastructure. Interestingly, all systems include batteries, and mostly H_2 to exploit the benefits of short and long terms storage. The used KPIs are mainly techno-economic in the selected studies, with the inclusion of different emission factors.

3 State-of-the-Art: Use of Aluminum as an Energy Carrier

3.1 Electrochemical Conversion

The combination of Al production via inert-anode smelting and Al conversion to electricity via Al-air batteries is a potential option to achieve cost-effective and zero-carbon-emission seasonal/annual energy storage is highly required for the Zero Emission Scenario (ZES) by 2050. (See Fig. 1) Although Al-air batteries may play a significant role, two main issues of this battery technology need to be addressed for the realization of Al production/conversion systems (APCSs) with high round-trip energy efficiency (RTE) (Xu et al. 2024). The first one is the limited energy conversion efficiency of Al metal into $Al(OH)_3$ (later transformed into Al_2O_3 for reuse in Al production), which is determined by the effective Al utilization and the cell discharge voltage. The spontaneous chemical reaction of Al metal in alkaline electrolytes leads, in fact, to H_2 evolution and thus low coulombic efficiencies (although the evolving H_2 could be collected and utilized). Additionally, the polarization occurring at both the Al metal anode and the air cathode leads to low cell discharge voltage, i.e., low voltage efficiency. Both hurdles contribute to the low specific energy and RTE of Al-air batteries. The second issue is the difficulty in collecting the discharge product (Ersoy et al. 2022), e.g., $MAl(OH)_4$ (M = Na, K) and/or $Al(OH)_3$. In alkaline electrolytes, the typical discharge product $MAl(OH)_4$ is highly soluble, converting to the $Al(OH)_3$ precipitate only at very high concentrations, i.e., when its solubility limit is reached. However, reaching the solubility limit inside the cell results in the precipitation of the solid product in the cell itself, causing the formation of an inert coating on the Al electrode as well as the clogging of the positive air electrode, which reduces the RTE even further. Therefore, these two aspects crucially affect the RTE of an APCS.

To solve these obstacles, Al-air batteries have been extensively studied in the past decades, but mainly from the materials aspects, including cathode catalysts for oxygen reduction reactions, doping of the Al metal anode to suppress self-corrosion, and electrolytes additives for more protective electrolyte/electrodes interphase (Liu et al. 2022). However, little attention has been paid on factors beyond materials, that actually affect the energy density delivered by Al-air batteries, particularly the RTE

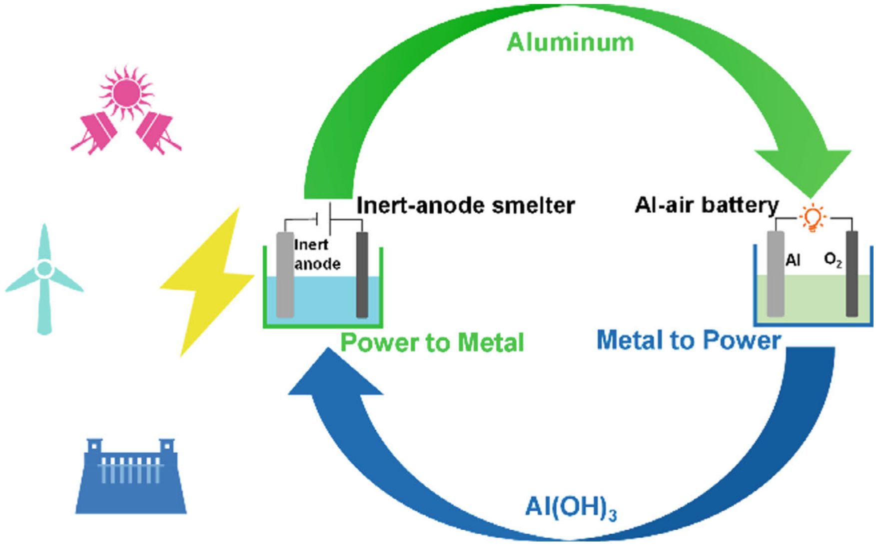

Fig. 1 Al production/conversion (P2Al2P) system. Schematic of the combination of Al-air batteries and inert-anode based Al electrolysis from Ref. (Xu et al. 2024). (Copyright of the authors)

of an APCS. In a recent publication (Xu et al. 2023), the accumulation of aluminate in the electrolyte has been identified as one of the causes of the poor efficiency. To address this problem, a seeded precipitation process has been demonstrated, allowing the aluminate removal and electrolyte regeneration. A wider operation temperature range is required to make it more efficient. A new cell design is also proposed, integrating more functions. Since self-corrosion and energy inefficiency during the electrochemical operation led to simultaneous heat release, cell design to maintain the operating temperature at the optimal state and even utilize the released heat is vital for overall energy utilization.

Figure 2 illustrates the operation of the cells employing 10 mL electrolytes upon long-term discharge at 100 mA cm^{-2} and 50 °C. The Al foil electrode was nearly consumed after 8 h and therefore changed with a new Al foil, while the same cathode was used for the whole measurement. The initial electrolyte, 4 M KOH aqueous solution with 5 g L^{-1} $Na_2SnO_3{\cdot}3H_2O$, was used for the initial 24 h discharge. Afterward, the electrolyte was regenerated via seeded precipitation at 20 °C. Operating under these conditions, the cell delivered the highest specific energy (4.29 kWh kg^{-1}) at 50 mA cm^{-2} resulting from the best combination of conversion efficiency and average voltage.

Besides the electrochemical conversion of aluminum into alumina, generating electricity, there are two main approaches to exploit the high energy content of aluminum through thermodynamic conversion as schematized in Fig. 3.

These approaches are (Bergthorson 2018):

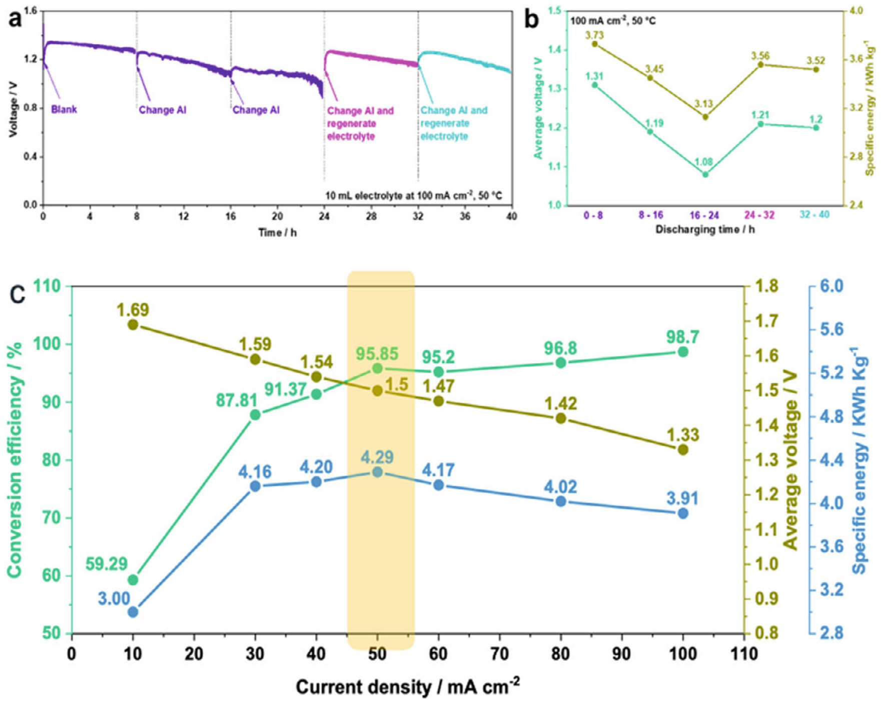

Fig. 2 **a** Voltage evolution and **b** average voltage and specific energy of a mechanically recharged Al-air cell including electrolyte regeneration by seeded precipitation. **c** Conversion efficiency, Average voltage and Specific energy of the same cell subjected to discharge at different current densities. Figure redrawn from Ref. (Xu et al. 2023) (Copyright of the authors)

Dry cycle: the energy of metallic powders is harnessed through direct combustion with air and utilized by external combustion thermal engines.

Wet cycle: the reaction between aluminum powders and H_2O, and consequently the conversion of H_2O into H_2, can occur with either activated (activation methods) or non-activated powders (conversion methods).

This distinction can be categorized as it follows.

3.2 Dry Cycle

3.2.1 Direct Metal-Air Combustion

Under the right conditions, aluminum reacts vigorously with oxygen to form aluminum oxide (alumina). The fundamental reaction is: $4\ Al + 3\ O_2 \rightarrow 2\ Al_2O_3$ (Bergthorson et al. 2015). This oxidation is highly exothermic, releasing about 31 MJ per kilogram of aluminum. However, the activation of Al by removal of the thin

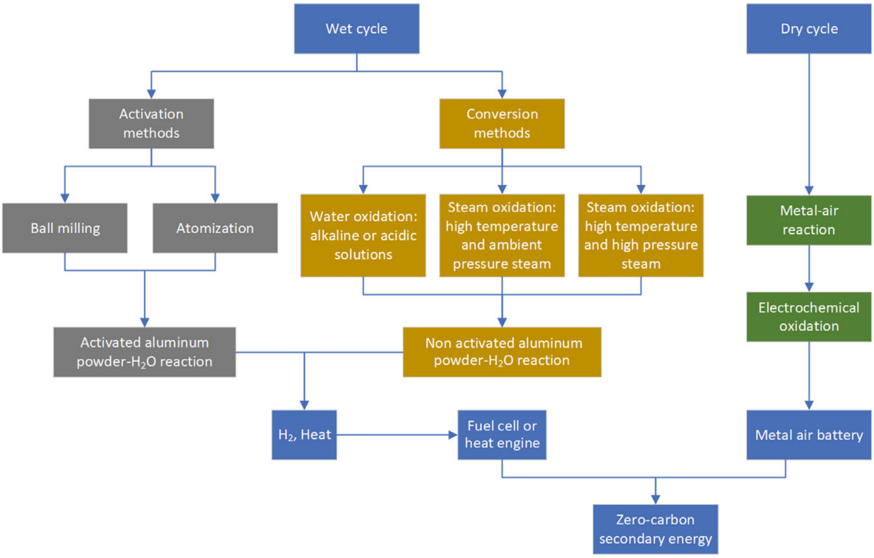

Fig. 3 Diagram of the different methods for water-aluminum and metal-air reactions to produce zero-carbon energy

alumina layer requires extreme temperatures (> 2,300 K) or Al needs to be fed into the combustion chamber as fine powder for efficient ignition at lower temperatures (around 930 K) (Puri and Yang 2010). Benefitting from the substantial heat release, Al is used in solid rocket fuels, offering high thrust and compact energy storage. Its use in combustors for thermal energy and power supply purposes appears to be only viable in external combustion engines where the extracted heat via reactor cooling is utilized (Bergthorson 2018). Its utilization in external combustion engines is expected to enable fine Al power combustion without sticking and wearing issues, similar to the use of pulverized coal in thermal power plants. Nevertheless, the combustion stabilization issue remains as the main hurdle in a combustor to transfer the heat while capturing the alumina combustion products (Bergthorson et al. 2015).

3.3 Wet Cycle

Techniques aimed at overcoming the oxide barrier on aluminum, thereby enabling reactions with water or steam, fall into two principal classifications: activation, which necessitates a preparatory treatment that endows aluminum powders with the capacity to react in the presence of water, i.e., conversion with water, and conversion with steam, which is achieved through a single-phase steam oxidation process.

3.3.1 Activation Methods

Activation methods prepare the material, rendering it reactive upon contact with water. It is, therefore, upon contact with water that the effective production of H_2 is enabled. To achieve this, activation methods involve a mechanical treatment with the addition of additives (salts) in the case of ball milling, and a thermal and pressurization treatment in the case of atomization. In both instances, there is a significant energy expenditure that impacts the energy balance.

Ball Milling

Mechanical ball milling emerges as an efficient method for the activation of aluminum particles, optimizing their reactivity, particularly pertinent in the reaction with water. This process conducted under inert atmosphere, combines mechanical alloying and milling, resulting in the dimensional reduction of particles and the augmentation of specific surface area. Such structural modifications expedite induction times and increment H_2 production (Zhang et al. 2014; Alinejad and Mahmoodi 2009).

The reduction of particles to nano-powders, via high-speed milling, introduces lattice defects and dislocations, fracturing the Al_2O_3 passivation layer. The introduction of specific additives, such as salts, metals, or oxides, during milling, facilitates the formation of reactive composites and creates pathways for water penetration, enhancing contact between aluminum and reactant (Du Preez and Bessarabov 2021).

The resulting composites exhibit irregular morphologies, with fissures and rough surfaces, which amplify the reaction area. This increment, coupled with structural defects, boosts hydrolysis kinetics, promoting a more efficient and sustained H_2 generation. In summary, ball milling, through mechanical and chemical modifications, transforms aluminum into a highly reactive material, optimizing H_2 production (Dossi 2024; Irankhah et al. 2018).

Atomization

Gas atomization represents a technique for the production of metallic powders activated for the reaction with water to produce H_2. The process is based on the melting of the metal in an inert atmosphere, followed by its fragmentation into micro-droplets via high-pressure gas jets. The rapid solidification of these droplets generates spherical particles, collected in a controlled environment to prevent contamination (Yang et al. 2019; Wang et al. 2015).

This method is distinguished by its capacity to obtain powders with homogeneous composition, essential for consistent hydrolysis performance and high H_2 yields. The reduction of grain size and the use of inert gases minimize oxidation, increasing reactivity. Atomization also promotes the disruption of the oxide layer, ensuring complete reaction of the material. In summary, this technique offers precise control over the microstructure and reactivity of the powders, optimizing H_2 production (Chen et al. 2021; Deng et al. 2024).

3.3.2 Conversion Methods

Alkaline or Acidic Water Solutions

The utilization of acidic or alkaline solutions represents an alternative methodology for the conversion of water into H_2 through the reaction with aluminum powders. Specifically, alkaline solutions demonstrate a greater efficacy compared to acidic ones in the dissolution of the oxide layer, which impedes the reaction (Alviani et al. 2019). The efficiency of the conversion process is influenced by a multiplicity of parameters, including the molarity and pH of the solution, the porosity of the aluminum powders, the dimensions of the particles, and the temperature of the water (Yang et al. 2019).

Sodium hydroxide (NaOH) is extensively utilized in alkaline solutions due to its low cost, simplicity of using, and its nature as a strong base (Bolt et al. 2020; Testa et al. 2024). This chemical compound proves particularly effective in disrupting the superficial oxide layer, accelerating the reaction kinetics and reducing the induction period. NaOH acts as a catalyst, promoting the exposure of fresh metallic surfaces to contact with water and facilitating the production of gaseous H_2, with the formation of sodium aluminate as a byproduct.

Steam Oxidation

H_2 and heat production through reaction between aluminum powders and steam is influenced by several factors, including steam temperature and pressure, purity, specific surface area (the presence of pores facilitates the reaction), and particle size of aluminum (Gao et al. 2023; Setiani et al. 2018).

The presence of high temperatures and pressures provides the advantage that no additives or catalysts are required for the combustion of the powders to occur. However, the energy used to superheat the steam can be recovered, for example, using a steam turbine, resulting in a positive energy balance for the overall system (Farmani and Eskandari Manjili 2024). The reaction products are $Al(OH)_3$ and AlO(OH) at temperatures ranging between 120 and 200 °C (Gao et al. 2023), and only AlO(OH) up to 370 °C (Setiani et al. 2018; Kirton et al. 2024; Gao et al. 2024).

Typically, the system comprises several components: a steam generator, an inert gas flushing system, a high-temperature furnace or reactor (ceramic or quartz) (Etminanbakhsh and Reza Allahkaram 2023), a condensation system, a condensate collector, a dryer, and a H_2 analyzer (Gao et al. 2023; Li et al. 2017). For high-pressure systems, the reactor is usually cylindrical and made of stainless steel (Setiani et al. 2018; Trowell et al. 2022).

The reaction can be divided into three phases. The first phase, known as the induction phase, involves the weakening of the oxide layer due to temperature and pressure, but the reaction has not yet started. The second phase begins with the penetration of steam through the pores and the initiation of the reaction. In this phase, the highest H_2 production occurs alongside the concurrent production of $Al(OH)_3$ or AlO(OH). In the third and final phase, H_2 production slows due to the deposition and clogging of pores by $Al(OH)_3$ or AlO(OH) (Gao et al. 2023; Trowell et al. 2020).

High temperature and ambient pressure steam oxidation

For micrometric aluminum powders (25 μm), experiments have shown that at ambient pressure and temperatures between 130 °C and 200 °C, a maximum H_2 production yield of 14–31% can be achieved (Gao et al. 2023).

At higher temperatures, ranging from 450 °C to 650 °C, the effects of additives such as $NaBH_4$ (Li et al. 2017) and NaF (Zhu et al. 2019) were studied to reduce ignition temperature and time. However, in the case of $NaBH_4$, a very low hydrogen yield was observed, varying from 0.8% to 1.6%, with a slight increase linked to higher temperatures or the presence of the additive. Conversely, adding 10 wt.% NaF can lower the ignition temperature from 960 °C to 743 °C and reduce the ignition time from 60 to 27 s.

An alternative method to facilitate the reaction at high temperatures (600 °C) within seconds, without requiring high pressures, involves electrically heating a graphite rod (to temperatures above the melting point of alumina) inside the reactor. This approach breaks the alumina layer (Etminanbakhsh and Allahkaram 2023).

A highly promising method is the aluminum steam oxidation proposed in (Barelli et al. 2022a, b). Such a process allows to achieve in a fixed-bed reactor, at 900 °C and ambient pressure, very high Al conversion rate to H_2, using non-activated Al micrometric powder (particle size < 44 μm). No additives or catalysts are used. Produced powder consists mostly of spherical micro particles γ-Al_2O_3 (83.4%w). The remaining portion is Al (16.6%w). In a further phase of the study, the addition in the reactor of alumina itself as inert material is proposed to avoid agglomeration and reactor clogging. The tendency of alumina clumping is proved to be hindered (Barelli et al. 2024), thus enabling a continuous process. Moreover, since only Al and Al_2O_3 are added in the reactor, also the direct use of produced oxides in the smelting process for fully recyclability is enabled as implemented in the power-to-X framework described in Sect. 4.

High temperature and high-pressure steam oxidation

Setiani et al. studied the effect of temperature in the range from 230 °C to 340 °C (Setiani et al. 2018), showing that higher temperatures corresponded to higher H_2 yields. This study also examined the effect of pressure, which significantly increased H_2 yield from 51% (270 °C, 55 bar) to 94% (280 °C, 62 bar). Trowell et al. demonstrated that at higher pressures (130–250 bar) and temperatures between 280 °C and 330 °C, yields of 100% can be achieved (Trowell et al. 2022, 2020). Gao et al. observed that increasing the yield from 60 to 100% required raising the temperature from 264 °C at 50 bar to 343 °C at 137 bar (Gao et al. 2024).

3.3.3 Activation and Conversion Methods Comparison

Considering these methods of water-to-vapor conversion or activation of aluminum powders for H_2 production, it is essential to acknowledge the limitations inherent to each technique. In particular, according to a recent review focused on the subject (Musicco et al. 2025), the following have to be considered:

- Atomization emerges as a technique for the rapid production of H_2 from ultrafine aluminum particles; however, it necessitates specific alloys containing bismuth, tin, and iron, which are subsequently present in the byproducts, and entails a high energy consumption.
- The activation of aluminum powders via ball milling with salts is distinguished by its simplicity and the cost-effectiveness of additives, offering environmental advantages due to the absence of metals. However, the energy consumption of the milling process limits its overall energy balance.
- The utilization of acidic or alkaline solutions, while simple and low-cost, presents environmental and safety challenges related to byproduct management and plant corrosion.
- The reaction with water steam, despite its high energy demand and severe operational conditions, offers a favorable environmental profile due to the production of readily recyclable alumina, i.e., γ-Al_2O_3 can be used in the smelting process without additional steps, and the potential recovery of thermal energy utilized for steam generation.

In summary, the selection of the optimal methodology depends on the application context. Milling, atomization, and acidic/alkaline solutions exhibit limitations related to byproducts and energy costs, whereas steam oxidation, although requiring critical conditions, proves promising for sustainability and circular economy, owing to the potential for energy recovery. Therefore, in the context of wet combustion, steam oxidation emerges as the most promising technique for the utilization of aluminum as an energy carrier, due to its potential energy sustainability and minimization of environmental impact.

4 Use Case: Al Wet Combustion System

Herein we propose a flexible operating energy storage system to cope with the energy demand using Al as a renewable electro-fuel (Barelli et al. 2020; Baumann et al. 2020). In particular, the wet combustion of Al yields heat, to generate electricity, as well as H_2, which can be used either for generating additional electricity or its direct use for refueling FCEVs (Shkolnikov et al. 2011; Vlaskin et al. 2011). According to the steam oxidation process of non-activated Al powder at 900 °C and ambient pressure (Barelli et al. 2022a, b), the solid product (Al_2O_3) can be directly used in the existing commodity-scale production of aluminum, allowing for the full recycling

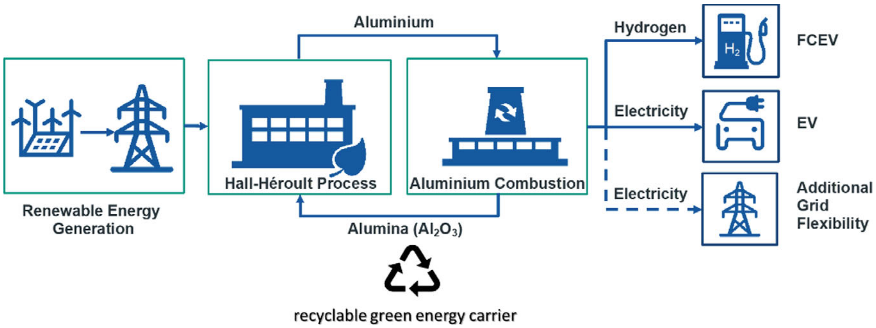

Fig. 4 Circular approach enabled by Al as a green energy carrier in power-to-X applications (Copyright of the authors)

of the energy carrier without additional investments and leading to the full decarbonization using renewable energy surplus for the Al production (World Aluminium 2021).

For what above, the use case here investigated is the one represented by a large scale multiservice station for FCEV/BEV in the framework of hybrid multifunctional refueling/recharging stations for EVs. These stations, with an installed electric power in the MW range, are usually installed along or close highways infrastructure. The overall concept complies strongly with the circular economy considering the whole life cycle of the material avoiding any need of intermediate transformation (Gislev et al. 2018) as depicted in Fig. 4.

Regarding the reduction phase from the oxide to the metal, improvements in the conventional Hall-Héroult aluminum production process towards the use of inert electrodes are considered in the following. This to enable the CO_2- and other GHG-free production (Reverdy and Potocnik 2020; ELYSIS 2019), considering their potential implementation at the industrial scale in the decarbonized European scenario.

Moreover, the high volumetric energy density and the consequent high locally storable capacity, enable the proposed concept of a multiservice station for EVs as a source of flexibility for the grid, rather than a further load. Thus, the proposed concept can provide an infrastructure development aligned with the electric grid's capabilities, aiming to potentially serve as a flexible component by integrating energy storage systems to exploit surplus renewable energy generation, as well as for energy self-sufficiency (Pelosi et al. 2023; Barelli et al. 2022a, b).

Regarding the potential implementation impact of the proposed concept, it is highlighted as fast-charging infrastructure is not yet implemented in an extended way in the continental Europe, except for Germany, Netherlands and France (European Automobile Manufacturers' Association (ACEA) 2024). As regards H_2 refueling stations, only a few points are present in the middle of Europe, mostly in Germany. Therefore, an extended fast charging and H_2 refueling infrastructure has to be developed to support the transition to EVs. To this regard, the Alternative Fuel

Infrastructure Regulation (AFIR) targets 1,100 H_2 refueling stations across Europe by 2030, even if such a target is considered significantly inadequate. Moreover, to speed up infrastructure deployment and the transition to a sustainable mobility, a multi-technology approach is recommended, creating hybrid stations to supply both FCEVs and BEVs (Hydrogen Council 2021; IEA 2021; Bernard 2023).

4.1 System Configuration

According to these requirements, this use case considers a refueling/recharging station for EVs consisting of 26 points of fast charging (150 kW each). This design corresponds to the mean number of charging points per fast charging station assessed in (Jochem et al. 2019) for the highway networks in France and Germany.

Therefore, an overall nominal electrical power of about 3.9 MW is considered to be installed as illustrated in Fig. 5. Such a power is produced by exploiting both H_2 and heat released by aluminum steam oxidation process.

Steam for the reactor feeding is produced by internal heat recovery, while aluminum is fed in the powder form. The reactor temperature is maintained through a further cooling by a secondary pressurized circuit feeding a steam turbine for electricity generation.

Produced H_2 is used to fed a solid oxide fuel cell (SOFC). Downstream the SOFC, operated at 750 °C and with a fuel utilization factor of 0.8, unburned H_2 is oxidized in a suitable afterburner. The exhausts from afterburning are expanded in a gas turbine, producing additional electric power, which activates the compressor to

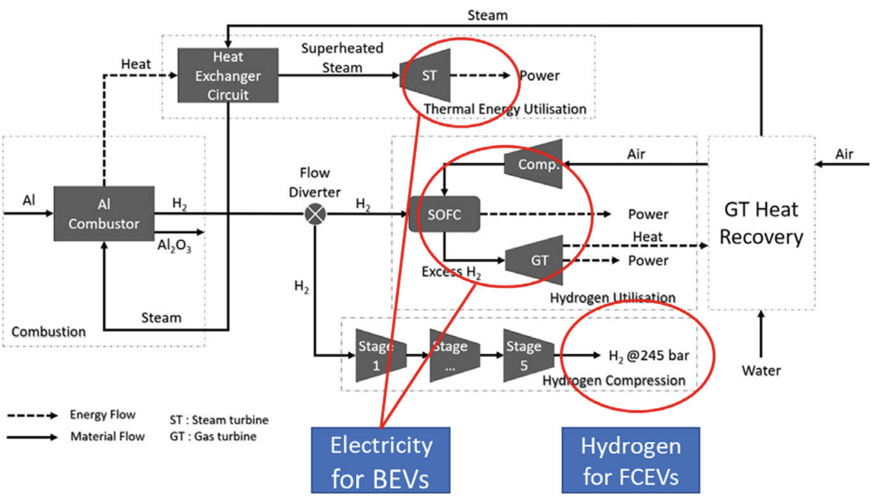

Fig. 5 Simplified layout of the multi-functional refuelling/recharging stations for EVs. (Copyrights of the authors)

supply pressurized air to the SOFC. The cathode feeding is subsequently preheated by the turbine exhaust and then heated up to 800 °C through the cathodic thermal regeneration.

This is the operation of the simplified layout of Fig. 5 when only electricity production occurs. For the complete system layout and details on operating conditions at both plant and components' levels refer to ref. It is highlighted as the SOFC polarization curve implemented in the model has been determined by tests at the laboratory scale under the specific operating feeding conditions resulting from the coupling with the aluminum steam oxidation process.

Moreover, to allow H_2 production for FCEVs, SOFC part load operation at 80% and 65% of the nominal power (2 MW) is implemented (see Table 2), according to the possible SOFC regulation at constant operating temperature within the 65–100% range investigated and presented in (Barelli et al. 2017). Therefore, in relation to the electricity and H_2 demands, part of the produced H_2 stream is delivered to a 245-bar storage tank via a 5-stage compression section.

Performance is assessed through simulation at the different required electric loads. Obtained results, summarized in Table 2, are processed to determine the Al-to-Power ($\eta_{M\text{-}P}$) and Metal-to-X ($\eta_{M\text{-}X}$) efficiencies. Increasing the part load degree, $\eta_{M\text{-}X}$ increases while $\eta_{M\text{-}P}$ decreases. The $\eta_{M\text{-}X}$ increase is reflected also in the cycle efficiency ($\eta_{P\text{-}X}$), determined in reference to the Power-to-X overall cycle.

To this aim, 11 kWh $kg^{-1}{}_{Al}$ specific energy consumption is considered. It corresponds to a 15% reduction of the specific consumption typical of current best practice Hall–Héroult electrolysis cells (ca. 13 kWh $kg^{-1}{}_{Al}$) due to the implementation of the wettable drained cathode technology, as remarked by Moya et al. (2015). Moreover, further improvements are expected to result from the implementation of inert and dimensionally stable non-carbon anodes. Finally, it is observed that the assumed specific energy consumption for Al production (11 kWh $kg^{-1}{}_{Al}$) is only slightly lower than the one already achieved in Norway (Segatz et al. 2016).

For these reasons, the assumption made on energy intensity of CO_2-free Al smelting process is considered comparable with reference to the decarbonized scenario by 2050.

4.2 Techno-Economic Evaluation

Defossilisation of the mobility sector is a complex problem, the offered solutions aim to respond to this demand with various environmentally-friendly solutions within techno-economic limits. Consideration of techno-economics in this context is vital for supporting decisions for the wide deployment and development of the infrastructure to mitigate the environmental and economic burdens associated with the energy demand of the mobility sector while ensuring the grid stability. In this sense, use of Al as an energy carrier in this context is potentially a suitable alternative. Hence, to be able to have a better understanding if the proposed conversion path is applicable in techno-economic terms, a 3.9 MW power capacity Al wet combustion system

Table 2 Plant simulated performances at different electric load conditions

% P_{SOFC} (%)	P_{SOFC} [kW]	P_{GT} [kW]	P_{ST} [kW]	P_C [kW]	P_{TOT} [MW]	H_2 [kg h^{-1}]	$\eta_{M\text{-}P}$ (%)	$\eta_{M\text{-}X}$ (%)	$\eta_{P\text{-}X}$ (%)
100	2.000	906	1.064	0.0	3.9	–	81	81	35.6
80	1.600	683	916	53.2	3.1	28	65	88	38.8
65	1.300	520	884	89.0	2.6	46.8	54	93	40.7

is considered for simultaneous supply of H_2 and electricity based on (Ersoy et al. 2022). The most important findings are briefly summarized here. The formulated business case is assessed from a techno-economic perspective utilizing deterministic and probabilistic estimation approaches.

First, the capital expenditures (CAPEX) are estimated considering equipment cost (i.e., steam turbine, gas turbine, solid-oxide fuel cell (SOFC), heat exchangers, pumps and other process equipment) utilizing learning curves. Furthermore, the installation factors are introduced to estimate installed system costs. Additionally, other CAPEX costs (i.e., engineering and procurement and construction (EPC) costs and working capital) are included. Under these considerations the analysis estimates a CAPEX of 4,200–6,200 € kW^{-1}. The depreciable capital is then used for estimation of fixed asset costs and salvage value of the system using Modified Accelerated Cost Recovery System (MACRS) rates.

Accordingly, operational expenditures (OPEX) are included considering fixed operation and maintenance (O&M) cost and insurance costs. The variable OPEX consists of variable O&M cost of system, fuel costs and transportation costs (aluminum or oxides) assuming a 400 km distance based on the annual operation scenarios. Considering historical prices, probabilistic approaches are implemented to incorporate the market price of Al ranging from 1.2 to 1.95 € kg^{-1} (from 2014 to 2019). Considering the presented average price breakdown of Al in Table 3, the share of different cost components is also incorporated to the economic evaluation model.

Since the Al is not consumed but converted to its oxide, in this circular context it makes more sense to consider a net price of Al accounting the reduced price due to return of alumina to the smelter. The net cost of Al is estimated by deducting the cost of alumina from the price of the Al, and it is assumed the other cost shares except energy costs remain constant. Since the study exploratively evaluates the techno-economics, energy costs scenarios are implemented considering the low price of electricity during hours where renewable generation exceeds the demand, resulting in an electricity price of 0–50 € MWh^{-1}. Considering that the provided price breakdown refers to Norway where electricity is provided at a cost-effective price (*ca.* 35 € MWh^{-1}) (Statistics Norway 2021), it is assumed that this scenario approximates the case as summarized in the scenario overview in Table 4.

Table 3 Aluminum price breakdown from Norsk Hydro (Norsk Hydro 2020)

Price cost components	Share of cost components (%)
Aluminum oxide	43
Energy costs	24
Carbon anodes	17
Fixed costs	11
Other process related costs	5

Table 4 Scenario-specific parameters, Al price, electricity price and energy intensities (Norsk Hydro 2020)

Scenario	Al price [€ kg_{Al}]	Al_2O_3 price [€ kg_{Al}^{-1} eq.]	Energy intensity [kWh $kgAl^{-1}$]	Electricity price [€ MWh^{-1}]
Scenario-I	1.44–1.86 (μ = 1.65)	0.52–0.83	14.25	50
Scenario-II	1.06–1.48 (μ = 1.26)	($\mu = 0.67$)	11	30
Scenario-III	0.73–1.15 (μ = 0.93)		11	0

Partial operation loads introduced in the system configuration part, and 4,000 full load hours annual operation duration are considered for the economic evaluation similar to what is expected from other Power-to-X technologies. Hence, the system will supply 10.4–16 GWh of electricity and 112–187 tons of H_2 annually depending on the chosen partial operation load. Under given scenarios, discounting the expenditures and amount of energy supplied during system's lifetime a levelized cost analysis has been conducted for electricity (LCOE) and H_2 (LCOH). The results indicate an LCOE ranging from 152 to 334 € MWh^{-1}, while the LCOH of Al-based H_2 corresponds to 5.4–11.8 € kg^{-1} based on various operation modes in the reference scenario. The breakdown of costs highlights that the cost is mainly driven by the net cost of Al followed by CAPEX. Also, to analyze the sensitivity of the full load hours, a sensitivity analysis is conducted as shown in Fig. 6.

Both LCOE and LCOH indicate a declining trend with the increasing full load hours. The evaluation results suggest that the system remains viable under various electricity pricing conditions, especially in low-cost or surplus renewable energy scenarios. Findings indicate that aluminum-based energy storage can be a cost-competitive alternative while improving energy security. In the context of EV

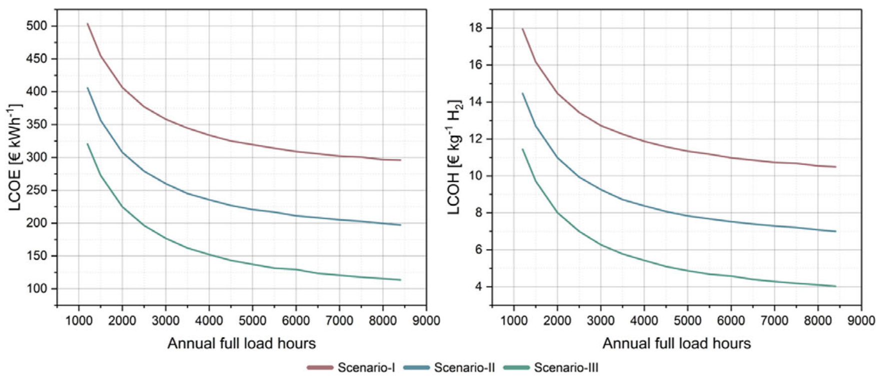

Fig. 6 LCOE and LCOH estimations reference values (median of probability distributions) for the considered scenarios

charging infrastructure, this system supports both BEV charging and FCEV refuelling by stabilizing grid demand through on-site energy generation, reducing dependence on large-scale H_2 transport and storage. In particular, on the system level, hybrid aluminum-powered EV charging stations can reduce peak load stress.

In conclusion, aluminum-based hybrid storage presents a flexible, scalable, and prospectively sustainable solution for H_2 production and energy storage. While challenges remain in production efficiency and recycling, this technology has the potential to complement conventional batteries and H_2 storage, with strong potential for EV charging and broader energy applications.

4.3 Sustainability Aspects

Reactive metals such as Al offer a potential solution for improving the efficiency and sustainability of EV charging stations, which are crucial for the transition to clean energy and the reduction of global warming. However, several challenges need to be addressed before these technologies can be fully utilized. These technologies, including the solutions presented here, are still in the early stages of development, making it difficult to assess their long-term viability and sustainability. The sustainability considerations of using Al as an energy carrier are mainly associated with its supply chain and circular use. Considering the entire supply chain, from raw materials to final Al products, the sustainability hotspots can be summarized as follows:

1. **Mining**: Conventionally, Al is extracted from bauxite ore. Bauxite is primarily mined in Australia, Guinea, China, Brazil, and India. The regional environmental and social impacts in these mining locations need to be assessed within their specific context.
2. **Bauxite refining:** Bauxite refining is one of the most significant sustainability hotspots in the entire supply chain, mainly due to bauxite residue (red mud) and its typical waste treatment approach. The residue is stored in large bauxite lakes, where the alkaline, iron-rich red powder is mixed with water to prevent airborne dispersion. However, this leads to soil alkalinity, water and air pollution, and long-term human health risks (Healy 2022). Although alternative treatment methods are under development, they have not yet provided a techno-economically feasible solution due to the low economic value of the extracted minerals (Ujaczki et al. 2018).
3. **Transportation:** The Bayer process (bauxite refining) is usually conducted at the mining site, after which alumina is transported over long distances to countries where high-value-added Al products are manufactured.
4. **Hall-Héroult Process:** The conventional aluminum smelting process is highly energy-intensive. Additionally, the use of carbon anodes in electrolysis leads to CO_2 and perfluorocarbon (PFC or PFAS) emissions. Several mitigation strategies are being developed, including:

- Electrolyzer optimization and alternative designs to improve energy efficiency and reduce greenhouse gas emissions.
- Integration of inert anodes and drain cathodes, which eliminate direct carbon and PFC emissions. Significant progress has been made in these areas, and wider adoption of these solutions is expected in the near future (Light Metal Age 2025).

The sustainability hotspots outlined above are critical for ensuring the sustainable implementation of the proposed concept. Since aluminum is used in a circular system within the considered conversion pathway, most of these impacts, except those from the smelting process are minimized, as aluminum can theoretically and practically be recycled indefinitely. However, the Hall-Héroult process requires special attention, as it serves as the charging phase in the energy storage cycle, whereas discharging occurs via wet combustion. The energy intensity of this process significantly influences the round-trip efficiency of the overall system. However, when benchmarked against Power-to-X conversion efficiencies, the findings indicate high potential for Al as an energy carrier, particularly due to its high volumetric energy density. If ongoing decarbonization efforts in the Hall-Héroult process achieve the desired advancements, a breakthrough adoption of aluminum-based energy storage could occur.

Another critical consideration is ensuring that the oxides produced during the combustion process are of smelter-grade purity, as impurities could hinder aluminum's circular reuse. The feasibility of this approach will depend heavily on experimental demonstrations to validate the purity and recyclability of post-combustion aluminum oxides.

5 Relevant KPIs

For the further development of the charging infrastructure and consideration of Al-based hybrid energy storage, key technical, economic, environmental, and social KPIs are identified.

From an energetic perspective, energy density and round-trip efficiency remain as crucial parameters. In particular, the high volumetric energy density of Al makes it an attractive energy carrier, allowing large amounts of energy to be stored in a stable, inert solid. Theoretical assessments suggest that the round-trip efficiency of the proposed concept has the potential to outperform or compete with other Power-to-X technologies. Additionally, the system's versatility in providing both electricity and H_2 is a notable advantage. Another key KPI is the reaction time, ensuring the system delivers energy promptly. While experimental validation is required, a maximum reaction time of minutes must be ensured for practical implementation.

From an economic perspective, critical KPIs include the levelized cost of electricity/ H_2, cost of Al, operation and maintenance costs, and recycling cost and value recovery. These factors are further influenced by parameters such as charging station energy capacity, refueling and regeneration cycle time, H_2 storage and handling capacity, and scalability.

Given the sustainability objectives of the proposed concept, evaluating environmental KPIs such as global warming potential, water consumption, acidification, and resource depletion is essential. As circularity is a major advantage of this approach, waste by-products and material circularity index are also key considerations.

Reliability and safety are fundamental, particularly in the context of charging stations. Key KPIs include system stability and performance lifetime, fire and explosion risks, resilience to grid disruptions, and compliance with public and industrial safety standards. From a social perspective, social acceptance plays major role regarding visual impact, health and safety considerations and overall sustainability. Addressing these factors will be crucial for the successful deployment and public adoption of the proposed Al-based HESS.

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