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Green hydrogen integration in aluminum recycling: Techno-economic analysis towards sustainability transition in the expanding aluminum market

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ABSTRACT

The use of aluminum-based products is widespread and growing, particularly in industries such as automotive, food packaging, and construction. Obtaining aluminum is expensive and energy-intensive, making the recycling of existing products essential for economic and environmental viability. This work explores the potential of using green hydrogen as a replacement for natural gas in the smelting and refining furnaces in aluminum recycling facilities. The adoption of green hydrogen has the potential to curtail approximately 4.54 ktons/year of CO_2 emissions, rendering it a sustainable and economically advantageous solution. The work evaluates the economic viability of a case study through assessing the Net Present Value (NPV) and the Internal Rate of Return (IRR). Furthermore, it is employed single- and multi-parameter sensitivity analyses to obtain insight on the most relevant conditions to achieve economic viability. Results demonstrate that integrating on-site green hydrogen generation yields a favorable NPV of €57,370, an IRR of 9.83%, and a 19.63-year payback period. The primary factors influencing NPV are the initial electricity consumption stack and the H_2 price.

Introduction

The aluminum market has witnessed remarkable expansion, poised to reach 38 million tons by 2025, driven by robust growth rates over recent years [1]. This trend is primarily fueled by the food packaging and construction sectors [1]. Noteworthy, growth rates were observed during 2015–2020 (4.9 % annually), and a continued positive trend is predicted for 2020–2025 (4.7 %) [1]. Expansion key contributors include the food packaging (2.2 % cumulative annual growth) and the construction (4.1 % cumulative annual growth) sectors [1]. In light of these trends, the aluminum industry's energy profile emerges as a critical factor. According to the International Energy Agency (IEA), the aluminum industry is responsible for 5 % of the total energy consumption in the industrial sector, and consumes half of the energy as electricity, 40.0 % as high-temperature thermal energy, 8.0 % as medium temperature thermal energy and 2.0 % as low-temperature thermal energy [2].

The prospect of integrating hydrogen into the aluminum industry holds the potential to enhance its sustainability, in line with contemporary energy transition policies [2,3]. Such integration serves a dual purpose: enabling the adoption of renewable energy sources in the production process and supplementing natural gas for thermal energy provision [2]. These strategies are well-aligned with recent energy

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Nomenclature

Symbol	
CAPEX	Capital Expenditure (€)
i	Time-period (Years)
Ir	Inflation Rate (%)
IRR	Internal Rate of Return (%)
NPV	Net Present Value (€)
OPEX	Operational expenditure (€)
PB	Pay-Back period (Years)
PV	Present Value (€)
τ	Discount rate (%)
WACC	Weighted average cost of capital (%)

transition policies, exemplified by Spain's Integrated National Plan of Energy and Climate for 2021–2030 [3], aiming to reduce greenhouse gas emissions by 23 % compared to 1990 levels by 2030. The aluminum industry's role in achieving this goal is pivotal, necessitating a 14.3 % reduction in eq-CO_2 emissions [3]. The Spanish Hydrogen Roadmap further underscores the importance of green hydrogen, proposing a 25.0 % minimum contribution to total demand by 2030 [4]. Furthermore, greenhouse gas emissions reduction and measures such as Social Carbon Cost (SCC) are concepts that are increased in awareness, forcing project to take sustainable aspects into their considerations. By the use of green hydrogen, general reduction of gas emissions can be achieved. For example, [5] analyzed the benefits of using surplus renewable energy for hydrogen production, offering economic benefits in the short term (39.0 % savings) and long term (83.0 % savings) by reducing emissions and replacing fossil fuels.

Aluminum production involves two primary methods: extraction from Bauxite ore, rich in aluminum oxide, or recycling of metal scraps [6]. The latter method is preferred due to its significantly lower energy requirements – recycling consumes 15 times less energy compared to primary aluminum production, thus contributing to environmental preservation and circular economy principles [7,8]. Notably, a substantial portion (90.0 %) of the aluminum from building and automotive components is recycled [9,10].

Recent efforts in waste classification and improved separation processes have driven a notable increase in the recycling of aluminum-based products, particularly containers [11] (e.g. approximately 50,000 tons of aluminum based containers were recycled in 2019 in Spain).

The recycling process for aluminum products involves several stages, including metal scrap milling, separation of aluminum-rich residuals via Eddy's currents and magnetic separators, removal of coatings through abrasive processes, and smelting in a rotating or vortex furnace [8]. Subsequent refining occurs in a reverberatory furnace, allowing chemical composition modification [8].

Green hydrogen presents a promising alternative to fossil fuels as a clean energy vector [12]. Diverging from grey or blue hydrogen, green hydrogen is derived from renewable energy sources, primarily via water electrolysis [13,14]. Additionally, alternative green production methods, such as biomass gasification and bio-alcohol reforming, are under exploration [15].

The integration of electrolyzers and fuel cells augments the efficiency of hydrogen as an energy vector, yielding 47.0 % to 82.0 % higher efficiencies once compared to traditional fuel-based thermodynamic cycles [16]. With renewable energy sources, efficiencies around 30.0 % are attainable, fostering the viability of green hydrogen [17,18].

Strategies such as hydrogen blending with natural gas streams or utilizing modified apparatus for pure hydrogen combustion are noteworthy in the pursuit of enhanced energy efficiency [19]. In fact, a considerable effort by different authors has been made to evaluate the use of blended gas mixtures with origins from fuel cell's produced hydrogen. The characteristic of performing blending and transportation for systems implementation defines extra benefits of green hydrogen, once compared to other renewable sources. For example, Jia et al. [20] and Ozturk and Dincer [21] analyzed the blending of hydrogen for its implementation in different distribution networks. The need of blending fosters the implementation of green hydrogen without modification of current distribution systems. Currently, it is possible to introduce around 5.0–10.0 %vol. of hydrogen into natural gas pipelines. Cerniauskas et al. [22] evaluated this option (a blend of green hydrogen for natural gas pipeline) in a case study in Germany and also considered the full reassignment of pipelines.

Sharma et al. [23] reviewed opportunities, and applications of green hydrogen and its blends in various sectors and also an overview of the roadmap for India. The applications in different countries depended on specific demands from the different sectors that include: Chemical feedstock, Medium and Heavy Duty, Buses, Heating, Rail, Refining, Iron Steel, Passenger Vehicle, Aviation, and Power Generation (Including European Union, Japan, US, and South Korea). Similarly, Rasul et al. [24] review different applications and sector in which hydrogen can be used; as described these include: raw material for fertilizer production, petroleum refineries, methanol production, reducing agent for metal (steel, aluminum), ore processing and manufacturing of glass, HCl production, food industries, atomic hydrogen welding, coolant, hydrogen peroxide, analytical chemistry, aerospace, electronics, weather balloons, and fuel for rockets and transport industry. Therefore, the incorporation of hydrogen into industrial processes offers a range of opportunities for sector coupling [24,25].

In order to foster the integration of hydrogen within the industrial sector and achieve a higher insight into the integration of hydrogen as an energy vector, this work analyses a pioneering and environmentally conscious initiative for the aluminum sector—employing green hydrogen as a substitute for natural gas in the smelting and refining furnaces of aluminum recycling facilities. This innovative approach not only supersedes conventional carbon-intensive energy sources but also unlocks ancillary advantages such as surplus electricity storage and on-site energy autonomy. Additionally, by employing cutting-edge alkaline electrolyzer technology the study presents a proficient and sustainable approach to green hydrogen production, aligning with the forefront of renewable energy exploration. The evaluation is performed using a real-case scenario in Spain. A thorough assessment affirms the economic and ecological feasibility of this proposal, signifying a noteworthy stride towards bolstering the sustainability of the aluminum industry.

Methodology

In this section it would be covered the requirements and definitions for the analysis on implementing hydrogen as a substitute for natural gas in the smelting and refining furnaces. In section 2.1 the facility sizing is performed, in which nominal requirements, together with the operational unit specification is performed. Then, in section 2.2 the approach used for the economical evaluation, together with the sensitivity analysis are presented.

Facility specification

The technical and economic data of the main components that are part of the System proposed for the installation come from commercial offers of first level suppliers, which cannot be disclosed due to the existence of confidentiality agreements.

Requirements

The facility sizing commences by addressing the essential requirements of the Aluminum industrial plant's refining and recovery processes. Table 1 details specific energy consumptions, encompassing average and nominal flows, as specified by the case study.

Table 1
Aluminum energy requirements of the refinery and recovery processes.

Equipment	Nominal Q (Nm^3/h)	Q measured under operating conditions (Nm^3/h)
Refinery		
Rotary kiln I	210	150
Rotary Kiln II	550	150
Rotary Kiln III	550	150
Reverberatory oven 25 T	187	100
Reverberatory oven 25 T	187	100
Reverberatory oven 15 T	135	100
Ingot mold	72	72
Vessel heater	80	80
Vessel heater	80	80
Total Refinery	**2,051**	**982**
Recovery		
Steam boiler	230	140
Incinerator gas	50	37
Total Recovery	**280**	**177**
Total consumption	**2,331**	**1,159**
Natural gas PCI (kWh/Nm^3)	10.83	10.83
Total Energy (kWh)	25,244.73	12,551.97
Total Energy (MWh)	**25.24**	**12.55**

The process planning involves 16 h run / day, spanning 220 days annually, providing insight into the energy demand. The main goal involves producing renewable hydrogen, to be blended with natural gas (typically used in refining and recovery) at a 20.0 % ratio (specific factory percentage without modification in the combustion equipment [26]), improving combustion by mitigating greenhouse gas emissions. To facilitate readers to track the impact of blending hydrogen and natural gas, Table 2 provides physicochemical information for the components and the blend. The physicochemical properties were calculated by using the hydrogen package of Aspen/Hysys software. These variables provide a comprehensive overview of the thermodynamic, transport, and flow properties of the substances. The differences highlight the unique characteristics of each substance and the potential effects of mixing them. Additionally, 11 heavy hydrogen fuel cell-powered trucks would be used, incorporating an internal consumption of approximately 32 kg/day of hydrogen.

For the design, the hydrogen and renewable oxygen production plant are expected to reduce the emission of greenhouse gases. To achieve this, these options need to be evaluated:

- Reduction of the amount of natural gas consumed in the refining process and recovery of the industrial process of Aluminum.
- Reduction of the amount of diesel as a result of the use of hydrogen in the fleet of 11 Hyundai XCIENT heavy-duty vehicles.
- Reduction of the amount of electricity needed for the production of oxygen and of the fuel needed for the transport of oxygen from the production plant to the place of consumption.

As defined in Table 1 (last row), the case study requires 25.24 MWh of energy for its refinery and valorization processes. To secure this demand, green hydrogen will be produced in two ways: alkaline electrolysis and salt slag recycling. The first process considers the green hydrogen production by 2.5 MW alkaline electrolyzer. The late process is capable of generating up to 50 Nm^3/h of hydrogen at atmospheric pressure per ton of salt slag treated.

To facilitate readers' understanding of the overall process, a PFD diagram of the plant is presented in Fig. 1. This figure describes the main streams of O_2, electrolytic H_2, H_2 from slag, natural gas and the mixture of 80 % Natural Gas and 20 % H_2. The green hydrogen is used for the industrial process of aluminum and supply the energetic demand of 11 heavy duty vehicles.

Table 2
Main physicochemical properties of Hydrogen, Natural Gas (NG, mainly methane) and a blended of 80 % NG / 20 % H_2 (calculated by using the hydrogen package of Aspen/Hysys software).

Property	Unit	100 % H_2	100 % Natural Gas (CH_4)	Blended 80 % CH_4 20 % H_2	Property	Unit	100 % H_2	100 % Natural Gas (CH_4)	Blended 80 % CH_4 20 % H_2
Molecular Weight	kg/kmol	2.016	16.043	13.237	Z Factor		1.000	0.998	0.998
Molar Density	kmol/m^3	0.041	0.041	0.041	Watson K		88.116	19.516	21.951
Mass Density	kg/m^3	0.082	0.657	0.542	Cp/(Cp-R)		1.403	1.300	1.316
Volume Flow	m^3/h	24.468	24.410	24.428	Cp/Cv		1.404	1.304	1.319
Mass Enthalpy	kcal/kg	1.630	−1,116.137	−1,082.061	Ideal Gas Cp/Cv		1.403	1.301	1.317
Mass Entropy	kJ/kg•°C	0.872	−5.093	−4.597	Ideal Gas Cp	kJ/kmol•°C	28.923	35.969	34.560
Heat Capacity	kJ/kmol•°C	28.929	36.066	34.630	Mass Ideal Gas Cp	kJ/kg•°C	14.347	2.242	2.611
Mass Heat Capacity	kJ/kg•°C	14.351	2.248	2.616	Kinematic Viscosity	cSt	111.214	17.154	21.063
LHV Molar Basis (Std)	kcal/kmol	57,825.590	191,850.833	165,045.785	Liquide Mass Density (Std)	kg/m^3	28.518	117.768	107.543
HHV Molar Basis (Std)	kcal/kmol	67,627.226	211,454.105	182,688.729	Liquide Volume Flow (Std)	m^3/h	0.071	0.136	0.123
HHV Mass Basis (Std)	kcal/kg	33,547.248	13,180.656	13,800.969	Molar Volume	m^3/kmol	24.468	24.410	24.428
LHV Mass Basis (Std)	kcal/kg	28,685.036	11,958.717	12,468.157	Thermal Conductivity	W/m•K	0.172	0.034	0.049
Phase Fraction (Mass Basis)		1.000	1.000	1.000	Viscosity	cP	0.009	0.011	0.011
Gas Flow	m^3/h	24.468	24.410	24.428	Cv (Semi-Ideal)	Kg/kmol•°C	20.615	27.752	26.315
Liquide Density (average)	kmol/m^3	18.671	18.671	18.671	Mass Cv (Semi-Ideal)	kJ/kg•°C	10.226	1.730	1.988
Specific Heat	kJ/kmol•°C	28.929	36.066	34.630	Cv	kJ/kmol•°C	20.608	27.666	26.253
Gas Flow (Std)	m^3/h	23.644	23.644	23.644	Mass Cv	kJ/kg•°C	10.223	1.725	1.983
Ideal Liquide Mass Density (Std)	kg/m^3	37.639	299.541	247.161	Liquide Volume Flow – Sum (Std)	m^3/h	0.071	0.136	0.123

Std: Standard conditions (temperature 25 °C and pressure 1.013 bar).

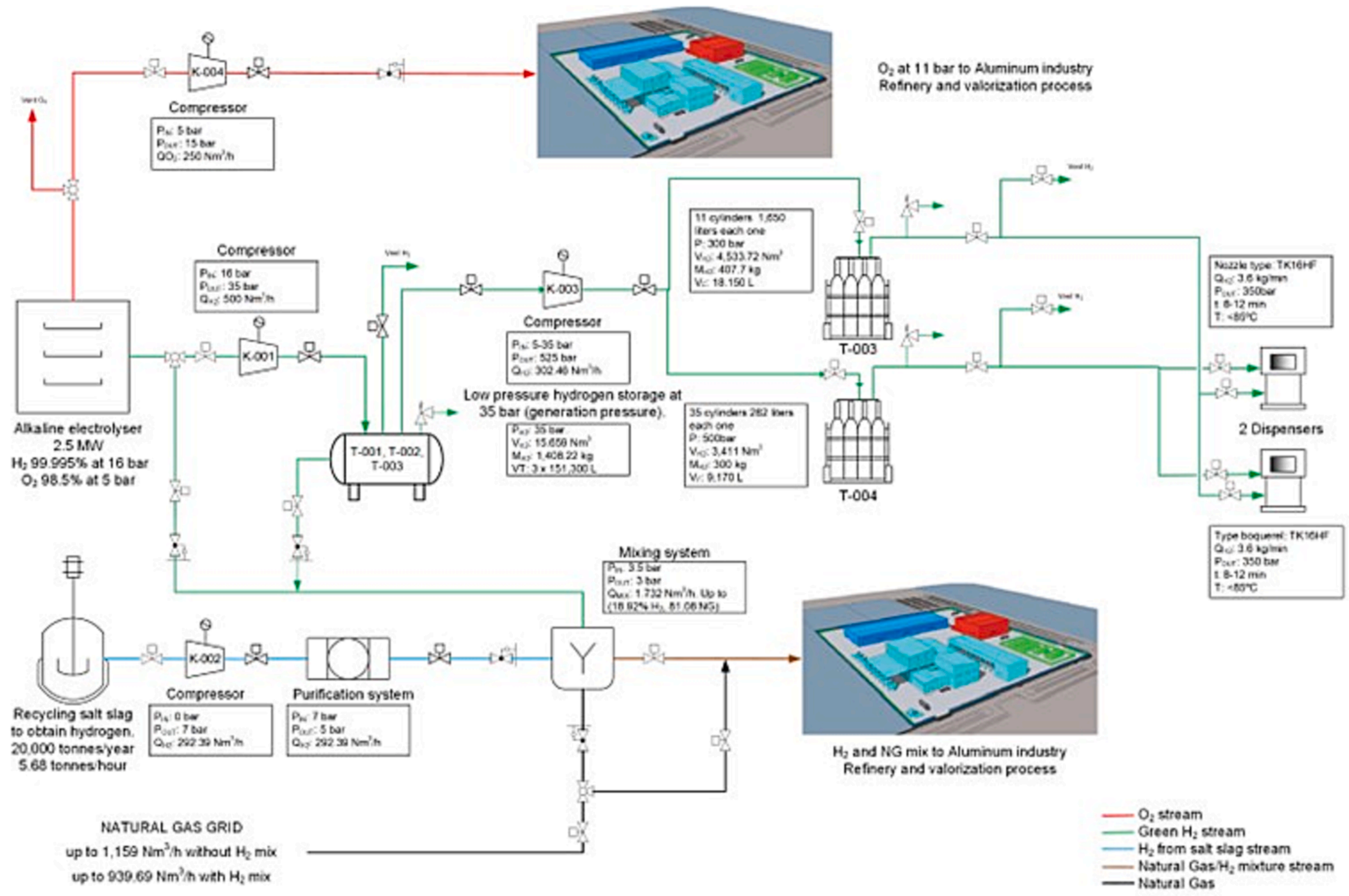

Fig. 1. Layout of the hydrogen and oxygen supply plant for the Aluminum industrial process.

Facility sizing

To meet both, the energy requirements of the Aluminum plant's processes and the fueling needs of the vehicles, alkaline electrolysis is adopted. A photovoltaic solar installation (1,926 MW capacity) and a renewable-origin PPA will supply renewable energy. Furthermore, hydrogen recovery from salt slags is planned, yielding up to 50 Nm^3/h per ton of slag, subsequently cleaned and compressed for utilization. The envisaged slag recovery scheme is projected for 20,000 tons for the operational time required in the case study (i.e. 3,520 h/year), which translates into 5.68 tons/hour or 292.39 Nm^3/h of hydrogen.

An evaluation was conducted concerning the optimal design of electrolysis capacity, coupled with the utilization of hydrogen derived from slag reclamation. Among the various feasible alternatives, presented in Table 3, the 2.5 MW alkaline electrolyzer was chosen. This decision was made based on the availability of substantial renewable energy and grid assisted power through a Power Purchase Agreement (PPA) with assured origin, enabling continuous 24/7 operation over 220 days annually. The 16 h shift for the electrolyzer involves producing 719.42 kg of hydrogen; the remaining 8 h are used to produce hydrogen for the truck fleet (359.71 kg of hydrogen).

The electrolyzer maximum capacity is 500 Nm^3/h of hydrogen at 16 bar. To ensure adequate storage, two compressors (one operational and one reserved) are positioned downstream of the electrolyzer (see Fig. 1), facilitating compression up to 35 bar. Simultaneously, the electrolyzer yields up to 250 Nm^3/h of oxygen, compressed to 11 bar, to meet the process demand (574 Nm^3/h at 11 bar). This oxygen constitutes 43.55 % of the plant's oxygen requisites.

Estimation of photovoltaic output involves solar radiation data aligned with Aluminum Process coordinates. Employing the System Advisor Model (SAM) tool developed by the National Renewable Energy

Table 3
Energy analysis of electrolysis and slag recycling.

	nominal Q (Nm^3/h)	kg/h	Energy (kWh)	% electrolysis and slags	hydrogen to mobility (kg)
Electrolysis (1 MW)	200	17.99	599.46	40.62	143.88
slag recycling	292.40	26.29	876.40	59.38	
Total Energy			1,475.86		
% energy input			**11.76**		
Electrolysis (2 MW)	400	35.97	1,198.92	57.77	287.77
slag recycling	292.40	26.29	876.40	42.23	
Total Energy			2,075.33		
% energy input			**16.53**		
Electrolysis (2.5 MW)	500	44.96	1,498.65	63.10	359.71
slag recycling	292.40	26.29	876.40	36.90	
Total Energy			2,375.06		
% energy input			**18.92**		
Electrolysis (3 MW)	600	53.96	1,798.38	67.23	431.65
slag recycling	292.40	26.29	876.40	32.77	
Total Energy			2,674.79		
% energy input			**21.31**		

Laboratory (NREL, USA), the analysis indicates a projected electrical energy production of 2,816,184 kWh/year. This equates to 1,827.74 h of full-load equivalent operation (Table 4). For the electrolysis process, a constant demand of 2.5 MW electrical energy is settled for the predefined operational time - equivalent to 13,200,000 kWh/year.

By analyzing the photovoltaic solar array atop the plant structures, it is estimated a supply of 21.33 % of the required energy, indicating that a PPA contract with guaranteed renewable origin must provide the remaining 78.67 %.

Following subsections will specify the main operational units.

Electrolysis system

The establishment of a 2.5 MW alkaline electrolysis system stands as a significant stride towards sustainable hydrogen generation. This system includes different components, each contributing to the efficient conversion of electrical energy into hydrogen and oxygen. The intricate assembly encompasses:

kV Transformer: A pivotal element facilitating voltage adaptation to match the requisite level for subsequent rectification processes

Rectifier: An integral unit orchestrating the transformation of alternating current electricity into a direct one. This vital conversion is a precursor to the downstream electrolysis stack.

Water Feeding System: A system used to deionize water, reducing its conductivity to levels below 1 μS/cm. This step ensures optimal conditions for subsequent electrolysis.

Electrolysis Stack: The main component of the system, where the orchestrated interplay of water and electricity generates hydrogen and oxygen.

Gas Separation System: An orchestrated system designed for the separation of hydrogen and oxygen. This separation transpires subsequent to their generation via the electrolyte-mediated process, further underscoring the intricate engineering at play.

Gas Purification System: A subsystem dedicated to the elimination of residual moisture and oxygen from the hydrogen stream. This purification stage culminates in the production of high-purity hydrogen.

The hydrogen consumption within the aluminum refinery and recovery process unfolds at a subdued pressure regime, approximately 3 bar. Towards this end, the last stage of the electrolysis process integrates a pressure regulator and a sophisticated mixing apparatus. This mixture seamlessly blends hydrogen from diverse sources - the electrolysis system, salt slag recycling system, and natural gas network. The balanced mixture is subsequently directed to designated consumption points, as outlined in Table 1 – Total Consumption row.

Additionally, a membrane compressor of two-stage configuration, characterized by a D-shaped architecture and water-cooling, elevates hydrogen pressure from 16 to 35 bar, a crucial prerequisite for storage. This compression system operates at a flow rate of 500 Nm^3/h, adhering to case study specifications. Noteworthy, specifications include suction and discharge pressures, inlet and outlet temperatures, and the prevailing operational duration.

Table 4
Monthly energy production.

Period	Energy (kWh)	AC output (kWh)	DC output (kWh)	equivalent hours
January	194,976	194,976	202,967	126.54
February	192,255	192,255	200,385	124.78
March	257,514	257,514	268,454	167.13
April	273,752	273,752	285,448	177.67
May	252,210	252,210	263,483	163.69
June	288,710	288,710	301,095	187.38
July	331,626	331,626	345,557	215.23
August	325,521	325,521	339,112	211.27
September	260,677	260,677	271,566	169.18
October	183,881	183,881	192,016	119.34
November	163,133	163,133	170,218	105.88
December	91,929	91,929	96,482	59.66
TOTAL	2,816,184	2,816,184	2,936,783	1,827.74

Similarly, a parallel D-shaped, water-cooled membrane oxygen compressor is used to elevate oxygen pressure from 5 to 15 bar, tailored to harmonize with industrial Aluminum processes operating at 11 bar pressure. In this context, a comprehensive strategy is harnessed for oxygen compression, allowing for seamless integration into the industrial environment.

Salt slag recycling system

As specified, the production of green hydrogen follows two distinct methodologies: alkaline electrolysis and the innovative recycling of salt slag. The latest exhibits a yielding up to 50 Nm^3/h of hydrogen, operating at atmospheric pressure, for every ton of saline slag subjected to treatment.

Based on the requirements, it is needed the treatment of 20,000 tons of salt slag within the constrained timeframe (i.e. 5.68 tons of saline slag per hour). Given the inherent potential of each ton to generate 50 Nm^3/h of hydrogen, the outcome translates into a production rate of 284.09 Nm^3/h or 25.54 kg/h of hydrogen.

The subsequent treatment and integration of the hydrogen reservoir necessitate a series of orchestrated steps. Initial compression to 7 bar precedes a comprehensive purification and cleansing process. Subsequently, the hydrogen is supplied at a pressure of approximately 3 bar, where it is mixed with hydrogen sourced from the electrolysis system and natural gas. This mixture is later on sent to the refining and recovery processes, inherent to the Aluminum industrial case study.

Integral to the process is the membrane. This compressor is characterized by a two-stage configuration, featuring a distinctive D-shaped architecture, and augmented with water-cooling mechanisms. Noteworthy, technical specifications encompass a suction pressure range of 0 to 0.10 MPa(g), a discharge pressure of 0.70 MPa(g), and a hydrogen gas flow rate of 300 Nm^3/h. Stringent temperature considerations dictate an inlet temperature below 40 °C, alongside an outlet temperature below 45 °C.

Equally paramount is the hydrogen purification system, tasked with a dual mandate of processing hydrogen from the salt slag recycling process while adhering to precise pressure loss thresholds. A minimum capacity to treat a flow rate of 300 Nm^3/h of hydrogen is specified, with a requirement that the pressure loss induced by the purification process remains below 2 bar. This definition ensures a continuous pressure profile, sustaining the requisite of 3 bar pressure for posterior integration of the system in the case study.

Low-pressure hydrogen storage system

Hydrogen storage tanks at 35 bar were selected for low pressure storage. These were defined as being single-walled horizontal tanks in carbon steel quality P355N s/EN 10028, with design pressure: 35 bar, test pressure: 52.5 bar and design temperature: −20 °C + 50 °C. The approximate capacity of each tank is 470 kg of hydrogen. Three tanks are defined for the case study to decouple the generation of hydrogen from the consumption for supply of hydrogen mobility. This setting translate into a total storage volume of approximately 1,410 kg of hydrogen at 35 bar. The pressure was set as a standard pressure within the range of industrial and on-board applications without further considerations [27].

Hydrogen refueling infrastructure

In the context of establishing a functional and efficient hydrogen refueling infrastructure, it is imperative to consider the specific requirements posed by the Hyundai XCIENTE trucks. These requirements encompass the capacity to fully load 11 trucks, each with a maximum storage capacity of 32 kg of hydrogen. A critical parameter in this scenario is the ability to refill a total of 353 kg of hydrogen within a span of 6 h, which holds pivotal significance in dimensioning the hydrogen refueling infrastructure.

Central to the design are three primary components: compression systems, storage systems, and pumps. The system comprises 407 kg of hydrogen available at 300 bar and an additional 300 kg of hydrogen at 500 bar. The configuration allows for filling via pressure difference, with an operational range of up to 190 kg. To facilitate the required daily hydrogen refill of 353 kg in the allocated 6-hour window, the storage systems must introduce 163 kg of hydrogen over this period (the difference between the daily requirement of 353 kg and the system's 190 kg capacity). Consequently, a compressor capable of compressing up to 27.2 kg/h of hydrogen is necessary. This compressor will operate for approximately 7 h to refill 190 kg during the day and for about 6 h to refill the additional 163 kg within the designated 6-hour refueling period.

Detailed specifications for the primary components of the hydrogen refueling infrastructure are as follows:

Hydrogen Compression System: The hydrogen compression system must accommodate the compression of up to 27.2 kg/h, transitioning from a pressure range of 5–35 bar to a final pressure of 525 bar. A three-stage, D-shaped, water-cooled compressor is envisaged for this purpose. Specifications include a suction pressure of 0.5–3.50 MPa (g), discharge pressure of 52.5 MPa(g), inlet temperature below 40 °C, and outlet temperature below 45 °C.

Storage Systems: The infrastructure incorporates 11 cylinders, each with a water volume of 1,650 L, operating at a pressure of 300 bar. This corresponds to a volumetric capacity of 4,533.72 Nm^3 of hydrogen, equivalent to a hydrogen mass of 407.7 kg. The tanks are constructed using Type IV technology, featuring a polyamide 6 liner and fiberglass composition, designed to withstand temperatures ranging from −20 °C to + 50 °C. Additionally, the system includes 35 cylinders, each with a water volume of 262 L, operating at a pressure of 500 bar. This translates to a volumetric capacity of 3,411 Nm^3 of hydrogen (or 300 kg H_2). These tanks utilize Type III technology, constructed from aluminum and carbon fiber liner, with a design temperature range of −20 °C to + 50 °C.

Dispensing System: Two dispensers, each equipped with a single nozzle, are integrated into the infrastructure, capable of supplying hydrogen at a rate of up to 3.6 kg per minute at 350 bar. These dispensers feature an infrared communication system and a card payment mechanism. The dispensing process incorporates the WEH TK17 35 MPa nozzle, with infrared communication facilitated through RFID technology.

Injection system of hydrogen and natural gas mixture to the refinery and recovery processes

The primary objective of the case study is to establish an efficient hydrogen and natural gas mixture injection system in its refinery and recovery processes. The aim is to achieve a meticulously balanced and uniform blend, comprising 18.92 % hydrogen and 81.08 % natural gas, the latest being sourced from the gas company's distribution network.

The hydrogen incorporation into Aluminum's refining and recovery operations is a multifaceted process. Of the entire hourly hydrogen inflow, a significant portion, precisely 63.10 %, emanates from the alkaline water electrolysis system. Complementing this, the remaining 36.90 % is derived from the salt slag recycling system.

The heart of this system resides in the mixing mechanism, which plays a pivotal role in generating a mixture of hydrogen and natural gas. The ensuing mixture is prepared to be introduced at an optimal pressure of 3 bar and calibrated to facilitate the subsequent stages of the refining and recovery processes.

Principle of operation of the hydrogen and oxygen generation system

Alkaline water electrolysis process. The alkaline water electrolysis process demands a consistent supply of 2.5 MW of electrical energy per hour. This energy can be sourced either from the photovoltaic solar plant or from the renewable-origin-guaranteed electricity grid. Concurrently, a volume of 674.46 L of water is required per hour, where 449.64 L are consumed in the electrolysis process, while 224.82 L are rejected by the water treatment system. This process yields hydrogen and oxygen. Specifically, up to 500 Nm^3/h (44.96 kg/h) of hydrogen is generated at 16 bar, alongside up to 250 Nm^3/h (359.71 kg/h) of oxygen at 5 bar. The produced hydrogen follows two distinct routes: (1) Pressure reduction to the design pressure of the gas mixing system (16 h/day) for integration into Aluminum's refining and recovery operations and (2) Compression to 35 bar for storage in low-pressure storage tanks, intended for refueling heavy vehicles via the hydrogen infrastructure (8 h/day). The by-product oxygen at 5 bar is elevated to 15 bar using a membrane compressor to satisfy the refinery and recovery plant's oxygen requirements. A subsequent pressure regulator moderates the oxygen supply, maintaining a requisite pressure of 11 bar. Oxygen is directed to the process for 16 h a day, 220 days a year. During periods of inactivity in the Aluminum plant, excess oxygen is vented to the atmosphere at 5 bar.

Hydrogen storage. The Aluminum plant deploys three hydrogen storage tanks, each with a capacity of 470 kg of hydrogen at 35 bar (totaling 1,410 kg). This storage configuration offers two pivotal benefits: decoupling hydrogen production from demand and enabling hydrogen generation during periods of nonoperation in the Aluminum refining and recovery process. The low-pressure storage tanks serve dual purposes: (1) Facilitating the hydrogen refueling infrastructure to supply heavy vehicles and (2) allowing pressure reduction to align with the mixing system, enabling controlled enhancement of the alkaline electrolysis system's hydrogen percentage in the mixture. The stored hydrogen aids in supplying the refining and recovery process during electrolyzer maintenance downtime.

Hydrogen refueling infrastructure. The hydrogen refueling infrastructure features a hydrogen compression system that elevates pressure from 10 to 35 bar in the low-pressure storage tank to 525 bar, facilitating high-pressure storage. The compression system's flow rate of 27.2 kg/h enables the fleet of heavy vehicles to be refueled. Complementing this, the infrastructure comprises a cascade storage system at 300 and 500 bar (300 kg hydrogen at 500 bar and 407.7 kg hydrogen at 300 bar) and two dispensers supplying hydrogen at 350 bar to the heavy vehicles. This comprehensive setup empowers the delivery of up to 353 kg of hydrogen to the existing fleet of heavy-duty vehicles.

Costs and sensitivity analysis

The economic analysis in based on capital costs (CAPEX), with operational costs (OPEX), contingencies, and other components derived from the estimated CAPEX. CAPEX assessment integrates supplier data with considerations from bare module and Lang factor project evaluation methodologies.

Capital costs encompass the electrolyzer-based hydrogen production system, salt slag recycling system, hydrogen and oxygen compression systems, hydrogen storage tanks, dispensers, hydrogen and natural gas mixing system, hydrogen purification system, and associated equipment, integration, and civil works. Operational costs encompass water, electricity, maintenance, staffing, and property leasing.

The evaluation involves Net Present Value (NPV; Equation (1), Internal Rate of Return (IRR), and Pay-Back Period (PB) calculations, based on project evaluation methods [28,29,30]. Main equipment costs were estimated using prominent European manufacturers' data.

Sensitivity analyses were conducted through single-parameter modifications (hydrogen prices, electricity price) using Oracle Crystal Ball simulations (with 10,000 iterations using Beta-Pert distributions for parameters like Initial Electricity Consumption Stack (kWh/Nm3), H_2 Price for Industry (€/kg), Electrolyzer Plant Size (kW), H_2 Price for Mobility (€/kg), O_2 Price (€/t), Alkaline Electrolyzer System (€), and Other Costs (€)).

$$NPV_t = \sum_{i=0}^{t} PV = \sum_{i=0}^{t} \frac{net\_income}{(1+\tau)^i} \tag{1}$$

The following considerations are taken into account in the techno-economic study:

- Yearly operation of 3,250 h per year for the Aluminum process and 1,760 h per year for the hydrogen refueling infrastructure process.
- Electrolyzer efficiencies that could range from 70.0 % up to 76.5 % (given a degradation of 4 μV per hour). This implies that more electric energy to produce the same amount of hydrogen would be required (i.e. less hydrogen is produced every year).
- An electrolysis stack replacement would be needed after 80,000 h or after 10 years of use at full load, which implies an initial value of 30.0 % the investment cost and would decrease at a rate of 1.0 % per year from the first to the last year of the study.
- A specific hydrogen system production based on recycling salt slag is considered together with the electrolyzer system.
- A mix between the hydrogen produced by the electrolyzer system and recycling salt slag will be mixed with natural gas and will be used as a fuel for the Aluminum process. Hydrogen produced by the electrolyzer will be used as fuel for the truck's captive fleet.
- Oxygen generated in the electrolyzer will be used in the Aluminum process.
- Heat generated in the electrolyzer, and the heat generated in the compressor would not be valued.
- 30.0 % of the investment on the centralized generation plant would be made with own resources; the remaining would be made by a 10-year loan (using the French payment method).
- Facility lifetime: 20 years.
- The investment cost of the production plant (industrial and mobility) is €9,270,000.
- Electricity costs: 81.98 €/MWh (36 €/MWh electricity comes from the PV and 87.5 €/MWh electricity comes from the grid).
- Staff cost: 120,000 €/year.
- Gross Water Cost: 1.75 €/m^3.
- Land leasing cost: 25,000 €/year.
- Weighted Average Cost of Capital (WACC): 9.65 %.
- Inflation rate (*Ir*): 1.5 % per year.
- Hydrogen sales cost for industrial process of 5 €/kg.
- Hydrogen sales cost for mobility of 9.5 €/kg.
- Oxygen sales cost for industrial process of 350 €/t.

The CAPEX and OPEX data of the main equipment being part of the centralized generation plant are the following:

- Alkaline electrolyzer. CAPEX: 920 €/kW of stack power. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost. Stack replacement: 80,000 h or 10 years.
- Hydrogen compression system. Flow rate 500 Nm^3/h from 14 to 16 bar up to 35 bar. CAPEX 850 €/ Nm^3/h of hydrogen flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen storage system at 35 bar. CAPEX 337 €/kg of capacity. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Recycling salt slag: CAPEX: 4,100 €/Nm^3/h of hydrogen production flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Recycling salt slag: CAPEX: 4,100 €/Nm^3/h of hydrogen production flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen compression system. Flow rate 292.39 Nm^3/h from 0 bar up to 7 bar. CAPEX 1.624 €/ Nm^3/h of hydrogen flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen purification system. Flow rate 292.39 Nm^3/h. CAPEX 1,197 €/Nm^3/h of hydrogen flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen – natural gas mixture system. CAPEX €200 k. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen compression system. Flow rate 302.46 Nm^3/h from 10 bar up to 525 bar. CAPEX 1.624 €/Nm^3/h of hydrogen flow rate. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen storage system at 35 bar. CAPEX 337 €/kg of capacity. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen storage system at 35 bar. CAPEX 1,150 €/kg of capacity. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Hydrogen dispenser. CAPEX €125 k. OPEX (considering only maintenance cost): 1.5 % of the initial investment cost.
- Cost of integration and civil works corresponding to 2,500 k€.

Results and discussion

Based on the centralized hydrogen generation plant (electrolyzer and recycling salt slag) and the previously defined hydrogen refueling station, the study brings a Net Present Value (NPV) of €57,370 an Internal Rate of 9.83 % and a payback period of 19.63 years.

Fig. 2 provides a visual representation of the Net Present Value (NPV) in relation to the Sales Price of H_2 for Industry (€/kg), a critical metric for determining the economic viability. Fig. 2 demonstrates significant variability in NPV values dependent on industry sales prices, encompassing both positive and negative values, highlighting the project's economic reactivity to these prices. A critical value is identified on the Fig. 2 where the NPV turns positive, marking the minimum sales price in the industry that renders the project economically viable. At an industry H_2 sales price of 4.5 €/kg and a H_2 mobility sector sales price of 11.5 €/kg, the first positive NPV value is observed. This specific point is of considerable relevance as it sets a benchmark for pricing strategies that will ensure the project's profitability. Furthermore, the variability in the H_2 sales prices for mobility contributes to the dispersion seen in Fig. 2. The varying sizes of the points reflect a range of prices in the mobility sector, indicating that NPV is sensitive not only to industry sales prices but also to how H_2 is valued in the mobility market. This sensitivity may be key to understanding market dynamics and to formulating strategies that maximize NPV while considering both sectors.

Another parameter that has more influence on the viability of the economic model is the price of the electric energy required to power the hydrogen production and supply plant. The energy price considered in the model is a weighted energy price of the energy coming from the photovoltaic plant and the energy coming from the grid, expressed in €/MWh. Fig. 3 shows the variation in Net Present Value (NPV) in response to differing electricity prices, which are critical for powering the hydrogen production and supply facility. The blue bars on the left side of the graph depict positive NPV values, whereas the orange bars on the right indicate negative NPVs. A dotted vertical line denotes the "Base Case", which represents the current or benchmark electricity price used

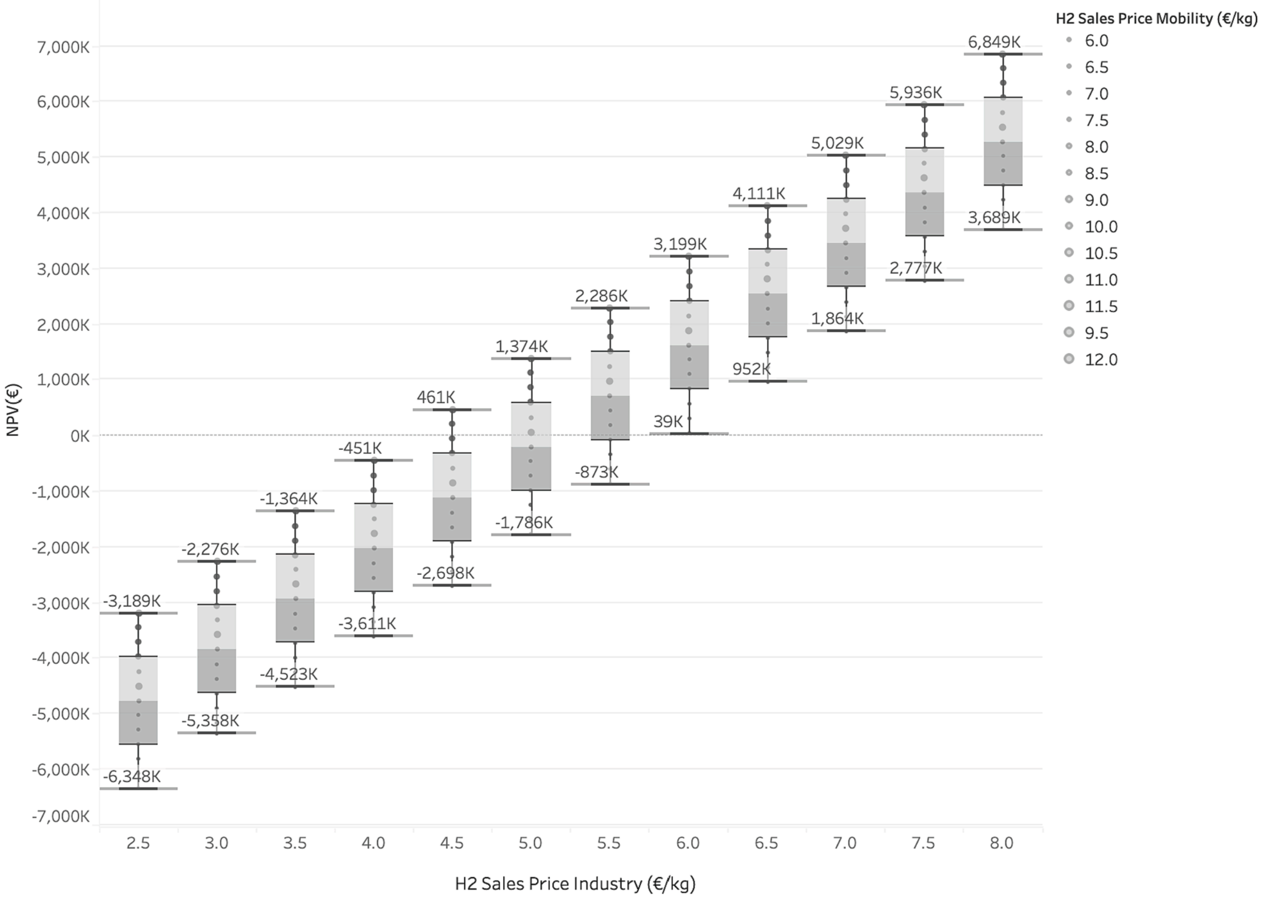

Fig. 2. Net Present Value (NPV) relative to hydrogen sales price for industry and mobility sectors.

in the economic model.

The Fig. 3 analysis suggests that for the business model to remain feasible, electricity prices must remain below 84 €/MWh. NPV turns negative, as indicated by the transition to orange bars, when electricity prices exceed this threshold, signifying that higher electricity costs render the hydrogen project unprofitable. Furthermore, the graph indicates that as the price of electricity falls below 84 €/MWh, the NPV correspondingly increases, thereby enhancing the economic viability of the business model.

This visual representation is an indispensable tool for investors and project managers, as it swiftly pinpoints the range of electricity prices within which the project is financially sustainable, providing a clear and technical perspective on the economic parameters influencing the project's success.

Starting from the base case considered (NPV of €57,370), some simulations were performed to estimate the probability of project success. The variables considered were specified from a preliminary oracle / expert analysis that allowed us to determine the variables that affected the most the NPV. Each variable, with values within a certain range, was managed using a Beta-Pert distribution.

- Initial electricity consumption stack (kWh/Nm^3): between 3.6 and 5.4, with a most likely value of 4.5 kWh/Nm^3.
- H_2 price for the industry (€/kg): between 4 and 6, with a most likely value of 5 €/kg.
- Electrolyzer plant size (kW): between 2,000 and 3,000, with a most likely value of 2,500 kW.
- H_2 price for mobility (€/kg): between 7.6 and 11.4, with a most likely value of 9.5 €/kg.
- O_2 price (€/kg): between 280 and 420, with a most likely value of 350 €/kg.
- MW alkaline electrolyzer system (€): Between 1.840 M€ and 2.760 M€, with a most likely value of 2.3 M€
- Other costs (integration and civil works): between 2.0 M€ and 3.0 M€, with a most likely value of 2.5 M€.

The Beta-Pert distribution uncertainty and allows for a more realistic sensitivity analysis, considering the minimum, most probable, and maximum estimates of these variables. The Beta-Pert is well-suited to this context, providing a balanced and detailed view of the impact of variability on the project's critical factors. The Beta-Pert distribution is a versatile tool used for modeling uncertainty in project management and risk analysis. Its equation (Equation (2) is given by:

$$f(x) = \frac{(x-a)^{c-1} \bullet (b-x)^{d-1}}{B(c,d) \bullet (b-a)^{(c+d-1)}} \tag{2}$$

In this equation: a is the minimum value, b is the maximum value, c and d are shape parameters calculated as $c = 1 + \frac{4(m-a)}{b-a}$ and $d = 1 + \frac{4(b-m)}{b-a}$, with m being the most probable value. The function $B(c,d)$ is the Beta function, serving as a normalization factor to ensure the total area under the distribution curve is 1. This distribution is useful for modeling uncertainty in estimates based on a range of values (minimum, most probable, maximum). This distribution is particularly useful for its ability to incorporate asymmetric data and provide a more nuanced estimation in scenarios with limited or subjective data. It's widely used in sensitivity analysis to understand the impact of variable uncertainty on project outcomes.

Fig. 4 shows the stochastic results (with 95.0 % confidence) that

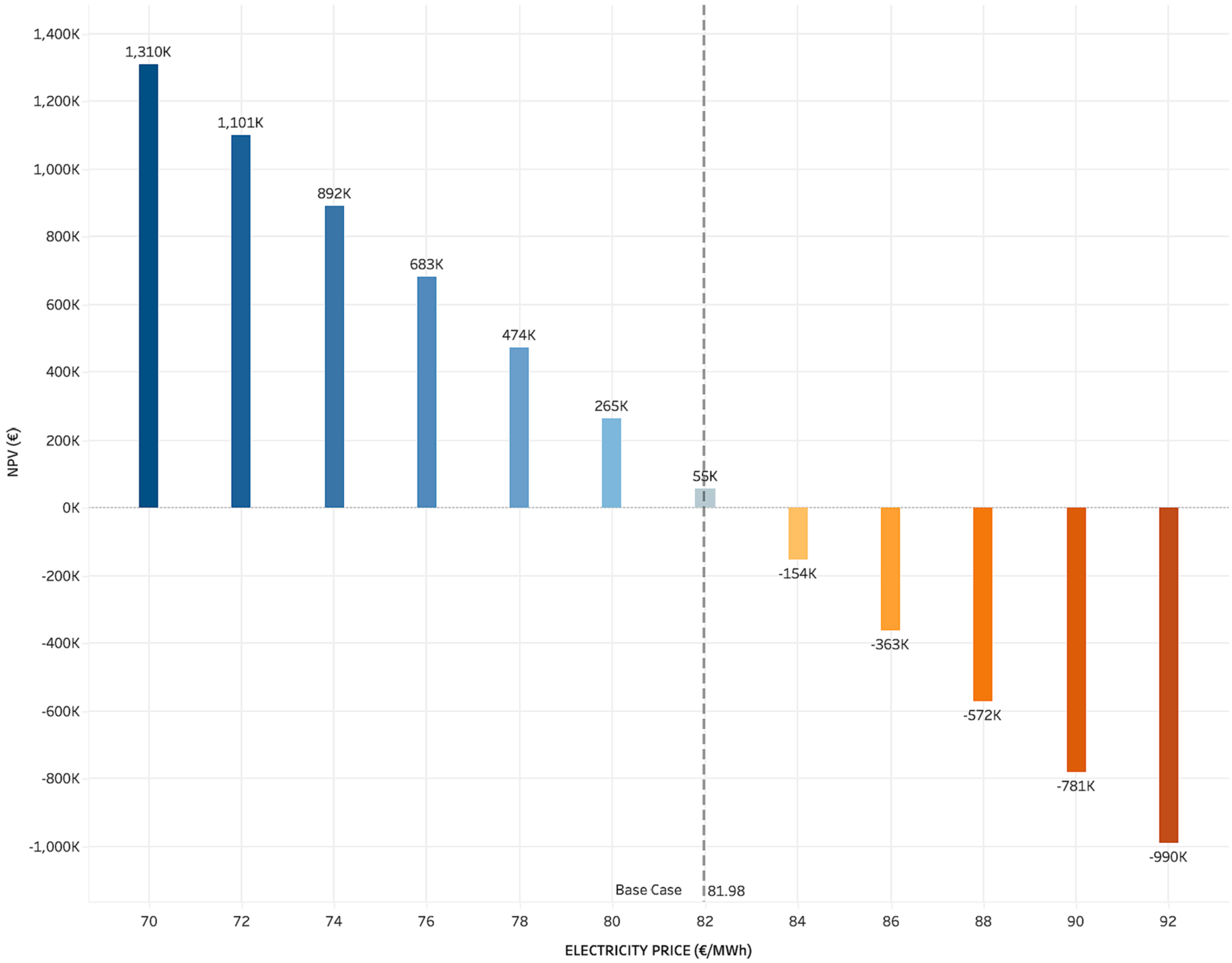

Fig. 3. Sensitivity analysis NPV vs electricity price (€/MWh).

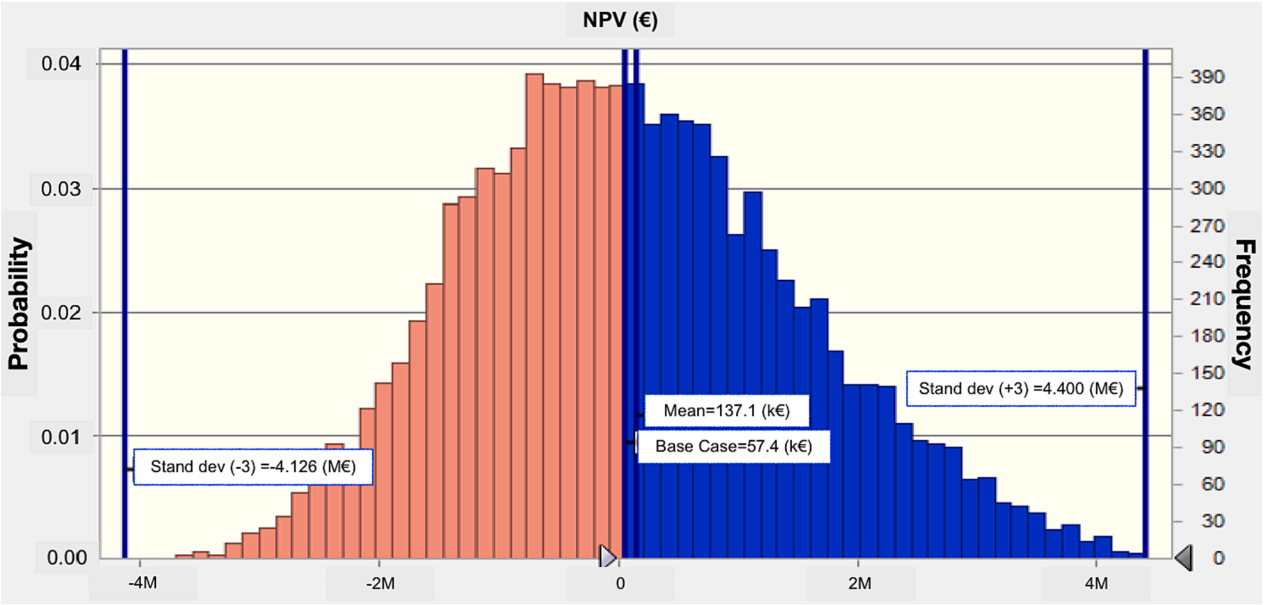

Fig. 4. Probability of projects success.

Table 5
Analysis of the sensitivity to net present value.

Assumptions	Contribution to Variance (%)	Rank Correlation
Initial Electricity consumption stack (kWh/Nm^3)	53.54	−0.72
H_2 price industry (€/kg)	23.73	0.48
H_2 price trailer (€/kg)	6.88	0.26
O_2 price (€/t)	6.86	0.26
Electrolyzer plant size (kW)	6.25	0.24
2.5 alkaline electrolyzer system (€)	1.47	−0.12

describe a 50.97 % of the NPVs greater than zero. Table 5 shows the most important variables that generate contributions to the obtained NPV distribution; as observed, the Initial Electricity consumption stack explains 53.54 % of the NPV variance and therefore has the greatest effect on the NPV (i.e., the Net Present Value is negatively correlated with the Initial Electricity consumption stack). In second place, the H_2 price industry in €/kg, explains 23.73 % of the NPV variance, positively correlated. Other variables, such as H_2 price trailer in €/kg, O_2 price in €/t, Electrolyzer plant size in kW, explain less than 7 % of the variance of the NPV. Similarly, the 2.5 alkaline electrolyzer system in € explains less than 2 % of the variance of the NPV. Previous studies carry out by the authors [31,32,33] show that the main variables affecting NPV are: Electricity Price, Electrolyzer Size and electricity consumption, and Hydrogen Price. Therefore, the results obtained in this study and the sensitivity analysis of the main variables is in agreement with previous literature.

Importantly, when estimating a reduction of the amount of natural gas consumed in the refining and recovery process, results show that 792.39 Nm^3/h or 71.25 kg/h of hydrogen will be consumed, for the operational timeframe, which implies a total amount of 2,789,212.8 Nm^3/year or 250,828 kg/year. Considering the 250.828 tons per year for the factor of 12.1 tons of carbon dioxide per ton of hydrogen, an annual reduction of 3,035 tons of carbon dioxide is obtained annually.

Further benefits also include the reduction in the amount of diesel used for the fleet of 11 Hyundai XCIENT heavy-duty vehicles. As analyzed, 353 kg of hydrogen will be consumed to power them (for the 220 days a year), or 77,660 kg of hydrogen. It can be considered that 1 kg of hydrogen is equivalent to 4.75 L of diesel, which implies an annual diesel fuel reduction of 368,885 L of diesel. The emission factor is 2,493 kg of carbon dioxide per liter of diesel, so the reduction of carbon dioxide emissions as a result of the use of hydrogen is 919,630.3 kg of carbon dioxide annually.

Other reductions that benefit the sustainability of implementing the approach proposed include the reduction of the amount of energy and diesel as a result of local oxygen production instead of external supply. The oxygen consumption required by the refinery and recovery processes is 574 Nm^3/h of oxygen for the operational periods. The hydrogen production system by alkaline electrolysis is 250 Nm^3/h, which will be used directly during the hours in which the refining and valorization processes work, which are 220 days a year for 16 h a day. The energy consumption in liquid oxygen production in conventional plants is 1,504 kWh/Nm^3 and 0.026 L of diesel per Nm^3 for its transport (average in Spain). According to the above data, for the 880,000 Nm^3 of oxygen obtained as a by-product, it implies a reduction of 1,323,520 kWh/year and 22,880 L of diesel annually. Considering the emission factors of 0.40 kg of carbon dioxide per kWh and 2,493 kg of carbon dioxide per liter of diesel, a reduction of greenhouse gas emissions of 529,408 kg of carbon dioxide from the reduction of electricity consumption and 57,039.84 kg of carbon dioxide from the transport of oxygen from the production plant to the point of consumption is obtained. Considering the two aspects, greenhouse gas emissions are reduced by 586.44 tons of carbon dioxide annually. Adding the reduction of greenhouse gases caused by the saving of natural gas (3,035 tons per year), by the saving of diesel for the mobility of a captive fleet of heavy vehicles of 11 vehicles (919.63 tons per year) and by the use of the by-product oxygen (586.44 tons per year), a total reduction in greenhouse gas emissions of 4,541.07 tons of carbon dioxide is obtained annually.

Today, the market demands that the production of aluminum and other metals be decarbonized. The use of renewable hydrogen, partially replacing natural gas, will allow the partial production of green aluminum, without greenhouse gas emissions (annual reduction is around 3,035 tons of carbon dioxide considering a 20.0 % replacement of natural gas). This aluminum will be used in processes that can afford the extra cost of low-carbon aluminum, such as the automotive industry.

To implement the proposed solution described in this study, it is also necessary to consider the availability of physical space for the installation, the availability of water for the electrolysis process and access to the electricity grid. In addition, it is necessary to consider all necessary permits to integrate this solution into an existing industry. Regulations will depend on each country or geographical area where the solution will be implemented.

Conclusions

This study evaluates the economic and environmental feasibility of integrating green hydrogen into aluminum recycling facilities in Spain, specifically as a replacement for natural gas in smelting and refining furnaces. Key findings include potential economic benefits based on market values, stochastic evaluations indicating positive NPV in 50.97 % of cases, and sustainable improvements reducing annual carbon dioxide emissions by 4,541.07 tons. The business model is economically viable with an NPV of €57,370, IRR of 9.83 %, and a payback period of 19.63 years. Sensitivity analyses highlight critical thresholds, with the initial electricity consumption stack and hydrogen price for industry as key variables. The multivariable sensitivity analysis emphasizes their substantial influence. The integration of renewable hydrogen and oxygen significantly reduces greenhouse gas emissions, showcasing the project's positive environmental impact. In summary, this study underscores the economic viability, sustainability benefits, and potential for broader applications of integrating renewable hydrogen in industrial processes and transportation systems, contingent on market and technical considerations.

CRediT authorship contribution statement

Lorenzo Reyes-Bozo: Writing – original draft, Funding acquisition, Data curation, Conceptualization. **Carlos Fúnez-Guerra:** Methodology, Data curation, Conceptualization, Writing – original draft. **José Luis Salazar:** Conceptualization, Methodology, Data curation. **Eduardo Vyhmeister:** Writing – review & editing. **Héctor Valdés-González:** Validation, Software. **María Jaén Caparrós:** Investigation, Visualization. **Carmen Clemente-Jul:** Writing – review & editing. **Francisco Carro-de Lorenzo:** Investigation, Visualization, Formal analysis. **Miguel de Simón-Martín:** Validation, Software, Formal analysis, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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References

[1] Global Market Insights, Aluminum Flat Products Market Size By Product (Flat Bars, Foil Stock, Fin Stock, Sheets, Plates, Circles), By End-Use (Building & Infrastructure {Residential, Commercial, Transport Networks, Utilities}, Automotive & Transportation, Consumer Goods, Equipment & Machinery, Electrical & Electronics, Packaging), Industry Analysis Report, Regional Outlook, Application Development Potential, Price Trend, Competitive Market Share & Forecast, 2019 – 2026, https://www.gminsights.com/industry-analysis/aluminum-flat-products-market; 2020. [accessed 23 June 2023].

[2] International Energy Agency, The Future of Hydrogen. Seizing today’s opportunities, https://www.iea.org/events/the-future-of-hydrogen-seizing-todays-opportunities; 2019. [accessed 27 June 2023].

[3] Ministry for Ecological Transition and Demographic Challenge, Government of Spain, National Integrated Energy and Climate Plan 2021-2030, https://www.miteco.gob.es/images/es/pnieccompleto_tcm30-508410.pdf, 2020. [accessed 23 August 2023].

[4] Ministry for Ecological Transition and Demographic Challenge, Government of Spain, Hydrogen Roadmap: a commitment to renewable hydrogen, https://www.miteco.gob.es/en/ministerio/planes-strategias/hydrogen/hojarutahydrogenorenovable_tcm30-525000.PDF, 2020. [accessed 27 August 2023].

[5] Rahil A, Gammon R, Brown N, Udie J, Usman MM. Potential economic benefits of carbon dioxide (CO2) reduction due to renewable energy and electrolytic hydrogen fuel deployment under current and long term forecasting of the Social Carbon Cost (SCC). Energy Rep 2019;5:602–18. https://doi.org/10.1016/j.egyr.2019.05.003.

[6] Brough D, Jouhara H. The aluminum industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. Int J Thermofluids 2020;1–2:100007. https://doi.org/10.1016/j.ijft.2019.100007.

[7] Schlesinger ME. Aluminum Recycling. 2nd ed. Boca Raton, FL: CRC Press; 2014.

[8] Capuzzi S, Timelli G. Preparation and melting of scrap in aluminum recycling: a review. Metals 2018;8(4):249. https://doi.org/10.3390/met8040249.

[9] Infinitely Recyclable. The Aluminum Association, (n.d.). https://www.aluminum.org/Recycling [accessed 26 May 2023].

[10] Rombach G. Raw material supply by aluminum recycling – efficiency evaluation and long-term availability. Acta Mater 2013;61(3):1012–20. https://doi.org/10.1016/j.actamat.2012.08.064.

[11] ARPAL Association, ARPAL promotes the recycling of aluminum packaging in Spain since 1994, (n.d.). https://aluminio.org/. [accessed 13 April 2023].

[12] Llorca Piqué J. Hydrogen and our energy future, Universitat Politècnica de Catalunya, 2010. https://upcommons.upc.edu/handle/2099.3/36579, 2010. [accessed 28 May 2023].

[13] Naimi Y, Antar A. Hydrogen generation by water electrolysis. Advances in Hydrogen Generation Technologies 2018. https://doi.org/10.5772/intechopen.76814.

[14] Mohammadi A, Mehrpooya M. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. Energy 2018;158:632–55. https://doi.org/10.1016/j.energy.2018.06.073.

[15] de Simón-Martín M, Cortés-Nava BR, Rodríguez-Parra R, Carro-de LF. The role of green hydrogen in the energy transition of the industry. DYNA 2021;96:200–6. https://doi.org/10.6036/9890.

[16] Mazza A, Bompard E, Chicco G. Applications of power to gas technologies in emerging electrical systems. Renew Sustain Energy Rev 2018;92:794–806. https://doi.org/10.1016/j.rser.2018.04.072.

[17] Khan MA, Al-Shankiti I, Ziani A, Idriss H. Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability. Sustain Energy Fuels 2021;5:1085–94. https://doi.org/10.1039/D0SE01761B.

[18] Chen C, Lu Y, Xing L. Levelling renewable power output using hydrogen-based storage systems: a techno-economic analysis. J Energy Storage 2021;37:102413. https://doi.org/10.1016/j.est.2021.102413.

[19] Goldmeer J. Power to gas: Hydrogen for power generation. Fuel Flexible Gas Turbines as Enablers for a Low or reduced Carbon Energy Ecosystem. General Electric Company; 2019.

[20] Jia Z, MacKenzie K, Dalcin J, Abismail B, Yeung A. ATCO Electrolyzer Hydrogen Production and Blending Plant Case Study. 2023. https://www.gasliquids.com/wp-content/uploads/2023_ATCO-Hydrogen-Blending-Case-Study-Paper-Draft-10-.pdf [accessed 03 Jan 2024].

[21] Ozturk M, Dincer I. System development and assessment for green hydrogen generation and blending with natural gas. Energy 2022;261(B):125233. https://doi.org/10.1016/j.energy.2022.125233.

[22] Cerniauskas S, Chavez Junco AJ, Grube T, Robinius M, Stolten D. Options of natural gas pipeline reassignment for hydrogen: cost assessment for a Germany case study. Int J Hydrogen Energ 2020;45(21):12095–107. https://doi.org/10.1016/j.ijhydene.2020.02.121.

[23] Sharma S, Kumar A, Jain P. Green Hydrogen in India- Applications, Opportunities and Challenges, 2023. 1st International Conference on Intelligent Computing and Research Trends (ICRT), Roorkee, India, 2023, pp. 1-6. 10.1109/ICRT57042.2023.10146660.

[24] Rasul MG, Hazrat MA, Sattar MA, Jahirul MI, Shearer MJ. The future of hydrogen: challenges on production, storage and applications. Energ Conver Manage 2022;272:116326. https://doi.org/10.1016/j.enconman.2022.116326.

[25] Thema M, Bauer F, Sterner M. Power-to-gas: electrolysis and methanation status review. Renew Sustain Energy Rev 2019;112:775–87. https://doi.org/10.1016/j.rser.2019.06.030.

[26] E&M Combustion. Hydrogen combustion systems for the decarbonization of the industry. https://emcombustion.es/wp-content/pdfs/en/EM&C_hydrogen_burners.pdf [accessed 03 Jan 2024].

[27] U.S. Department of Energy, High-Pressure Hydrogen Tank Testing: Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/eere/fuelcells/high-pressure-hydrogen-tank-testing [accessed 8 September 2023].

[28] Dimian AC, Bildea CS, Kiss AA. Economic Evaluation of Projects. In: Dimian AC, Bildea CS, Kiss AA, editors. Computer Aided Chemical Engineering, vol 35. Elsevier; 2014. p. 717–55.

[29] Remer DS, Nieto AP. A compendium and comparison of 25 project evaluation techniques. Part 1: Net present value and rate of return methods. Int J Prod Econ 1995;42:79–96. https://doi.org/10.1016/0925-5273(95)00104-2.

[30] Bartošová V, Majerčák P, Hrašková D. Taking risk into account in the evaluation of economic efficiency of investment projects: traditional methods. Proc Econ Financ 2015;24:68–75. https://doi.org/10.1016/S2212-5671(15)00614-0.

[31] Fúnez Guerra C, Reyes-Bozo L, Vyhmeister E, Salazar JL, Jaén Caparrós M, Clemente-Jul C. Sustainability of hydrogen refuelling stations for trains using electrolysers. Int J Hydrogen Energ 2021;46:13748–59. https://doi.org/10.1016/j.ijhydene.2020.10.044.

[32] Fúnez Guerra C, Reyes-Bozo L, Vyhmeister E, Jaén Caparrós M, Salazar JL, Godoy-Faúndez A, et al. Viability analysis of underground mining machinery using green hydrogen as a fuel. Int J Hydrogen Energ 2020;45(8):5112–21. https://doi.org/10.1016/j.ijhydene.2019.07.250.

[33] Fúnez Guerra C, Reyes-Bozo L, Vyhmeister E, Jaén Caparrós M, Salazar JL, Clemente-Jul C. Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan. Renew Energ 2020;157:404–14. https://doi.org/10.1016/j.renene.2020.05.041.