Key Challenges Facing Green Hydrogen Production and Valorization Pathways in Algeria

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Abstract
Algeria's immense potential in green hydrogen provides significant competitiveness for future domestically produced hydrogen, paving the way for the country to become a regional hub and meet the growing global demand for clean energy while strengthening its position in the international energy market.

Algeria's abundant renewable energy resources (PV potential in fixed structures: 180,000 TWh/year), planned desalination projects (total production capacity of around 2.2 million m³/day), and treated wastewater exceeding 1 billion m³/year, combined with its extensive expertise in hydrogen downstream products (Power-to-X technologies), position the country to produce hydrogen at one of the world's lowest costs—potentially reaching $1.5/kg by 2050, according to experts. Additionally, Algeria's strong expertise in gas pipeline transportation, along with the Memorandum of Understanding (MoU) signed for the H_2 South Corridor project, further reinforce its status as a reliable energy provider.

This paper explores the main technical challenges facing large-scale green hydrogen industrialization, particularly those related to production costs, electrolysis technology maturity, and emerging techniques such as PEM and SOE electrolysis, which are gaining significant interest (with efficiencies reaching 80% and 90%, respectively). It also addresses transportation challenges and provides a comprehensive analysis of key factors that need to be optimized to enhance the feasibility of large-scale projects and reduce the Levelized Cost of Hydrogen (LCOH).

Furthermore, this study opens new avenues for exploring the best routes to locally valorize Algeria's green hydrogen production, considering its role as a promising Power-to-X vector (e-fuels, fuel cells, ammonia, etc.) and its potential to significantly reduce greenhouse gas (GHG) emissions through CO_2 remediation. Additionally, this paper fills a gap in recent literature by investigating the key electrolysis inputs that influence process efficiency and impact LCOH optimization.

Keywords: Green hydrogen, Electrolysis, LCOH, valorization, Power-to-X.

1. Introduction

With the increasing global population, industrialization, and urbanization, energy demand is rapidly rising [1]. Currently, about 85% of the overall energy consumption worldwide is derived from non-renewable resources, namely coal, natural gas, and oil, which contributes to environmental issues (such as global warming), economic challenges, and political crises [1]. Hydrogen, like electricity, is a secondary energy carrier, but it is also an energy vector that can be used to convert, store, and release energy. With the growing share of electricity generated from variable renewable sources such as wind and photovoltaics (PV), hydrogen is gaining interest as a long-term storage solution for surplus electricity [2]. In addition, hydrogen is serving as a decarbonization carrier, particularly in hard-to-abate sectors such as the cement and iron industries, alongside its conventional role as a raw material in large petrochemical industries—such as fertilizer and methanol production—as well as for e-fuel generation coupled with CO_2 capture. Moreover, green hydrogen production requires large amounts of renewable energy and water resources. Therefore, areas with abundant renewable energy and access to water have been identified as optimal for large-scale green hydrogen production [3].

Algeria is well-positioned to become a regional hub for hydrogen production due to its significant potential, established infrastructure, and expertise in green hydrogen. Furthermore, its ambitious desalination program and strategic geographic location are key assets that strengthen Algeria's position and enable the country to meet European demand while developing a solid industrial base related to green hydrogen. In this regard, Algeria has launched an ambitious strategy aimed at reaching an export threshold of 40 TWh of green hydrogen and its derivatives by 2040 [4].

However, large-scale green hydrogen production faces many hurdles and challenges that must be overcome to make this type of hydrogen more competitive and economically viable. From this perspective, the valorization of green hydrogen into higher value-added derivatives is emerging as a viable and economical solution, given the broad range of industrial applications for hydrogen and its derivatives.

2. Key Challenges Facing Green Hydrogen Production

Many technical issues are preventing the establishment of large-scale green hydrogen production plants. In this regard, the development of a green hydrogen value chain implies technological mastery of the entire process, from the production phase to the establishment of long-term contracts with offtakers.

2.1 Electrolyzer Development:

Electrolyzers are the main components in the hydrogen production process. Developing new low-cost materials and enhancing the efficiency of electrolyzers remain major challenges, particularly concerning the availability of materials used in their manufacturing. In this context, it becomes evident that scaling up green hydrogen production requires a clear separation between the development of electrolyzers and the construction of hydrogen production plants.

2.2 Storage:

Hydrogen has a very low volumetric energy density. For instance, at standard conditions, 1 kg of hydrogen occupies 11 m³ with a volumetric energy density of 10.9 kJ/L [5], necessitating a liquefaction step that is highly energy-intensive and requires cryogenic facilities. Several alternative techniques are emerging, such as physisorption, metallic hydrides, and complex hydrides [6]. Storage is among the primary challenges that must be addressed to expand hydrogen utilization. Compression requires thick vessels, resulting in low gravimetric energy density. Furthermore, technologies involving metallic hydrides with heavy metals show low storage capacities and require high temperatures for hydrogen desorption. Researchers are working on new storage methods that combine conventional techniques, such as cryogenic adsorption, which has achieved high storage capacities with volumetric densities reaching 46 kg/m³ [6]. Table 1 summarizes the main hydrogen storage techniques and compares the different methods.

Table 1: Comparison between hydrogen storage methods

Storage technic	Compression	Liquid hydrogen	Metal hydrides	LOHC	Ammonia
TRL	10	7-9	6-7	6-8	10
Hydrogen content wt %	1-5.7	14	7.6	6.2	17.6
LCHS ($/kg)	0.4	1	0.7	1.3	3.5
Energy consumption (kWh/kg)	6.0	13	4	33	44
Maximun Storage duration	Short term	Mid-term	Long-term	Long-term	Long-term

2.3 Transportation:

Hydrogen transported through pipelines is subject to a critical form of corrosion known as embrittlement. In this regard, the use of coating layers such as ethylene vinyl alcohol (EVOH), polyvinylidene chloride (PVDC), oriented Nylon 6, PVA, epoxies, or polyurethanes is emerging as a key solution to prevent pipeline corrosion [7], especially as increasing pipeline thickness is economically unfeasible. Additionally, advancements are moving toward the use of nanomaterials, which have shown promising results; however, their high cost hinders widespread deployment. Many studies emphasize that existing natural gas pipelines can withstand a hydrogen-methane blend with up to 20% hydrogen by volume without significant damage.

Algeria has signed a Memorandum of Understanding (MoU) for a feasibility study on the ‘SoutH2 Corridor,’ a 3,300 km dedicated hydrogen pipeline project connecting North Africa, Italy, Austria, and Germany. This corridor is expected to meet 40% of Europe’s green hydrogen demand, equivalent to 4 million tonnes per year by 2030.

2.4 High Cost of Green Hydrogen Production:

The development of a local green hydrogen learning curve aims to reduce the cost of this energy source to enhance its competitiveness in the energy market. Economic forecasts predict a sharp decrease in investment costs for electrolyzer systems dedicated to green hydrogen production, reaching a competitive level by 2040, estimated at around 500 euros/kW [8].

Table 2: Levelized Cost of Hydrogen [9].

Technology	SMR	Alkaline Electrolysis	PEM Electrolysis	SOEC Electrolysis
Hydrogen cost (€/kgH_2)	10	7-9	6-7	6-8

2.5 Safety Concerns:

Despite its advantages, hydrogen is considered a hazardous fuel due to its wide flammability range (4%–75% vol) and low ignition energy (0.017 mJ in air). It is colorless and odorless, making leak detection difficult. Hydrogen is also the smallest and lightest element, which increases the risk of leaks. Its low density at standard temperature and pressure (0.0838 kg/m^3 at 293 K, 101.3 kPa [10]) makes it highly buoyant, allowing it to disperse easily in open environments. However, in confined spaces, leakage can rapidly create an explosive atmosphere. Therefore, when considering the production, transportation, and utilization of hydrogen, safety aspects must be carefully evaluated.

2.6 Hydrogen Market:

The lack of agreements with offtakers is a major hurdle preventing large-scale investment in green hydrogen. Most countries are launching green hydrogen roadmaps with targets set for 2030–2040. The European REPowerEU plan includes a joint hydrogen purchasing mechanism aiming to import 10 million tonnes of hydrogen per year by 2030. Establishing such agreements is essential for boosting investment and scaling up green hydrogen production. Algeria, with its substantial water desalination capacity of 3.8 million m^3 per day and an ambitious plan to install 15 GW of photovoltaic renewable energy by 2035, is well-positioned to lead in low-cost green hydrogen production. Its strategic geographic location and established reputation as a reliable energy supplier further reinforce its potential to meet European demand. To sum up, the era of hydrogen is emerging, and the first movers will dominate the market.

3. Green hydrogen transformation:

Hydrogen is widely used as a raw material for direct applications or in transformation industries to obtain high added-value products, known as Power-to-X (PtoX) applications. In this regard, hydrogen is an energy carrier contributing to the decarbonization of hard-to-abate industries such as cement and steel. Furthermore, hydrogen, through fuel cells, offers a promising solution for the electrification of isolated areas where conventional electrification faces technical or economic barriers. Additionally, hydrogen is a viable candidate to alleviate the pressure on natural gas for electricity production, especially in light of the sharp increase in domestic electricity demand. Regarding H_2 transformation, many more valuable products can be synthesized, enabling a high degree of valorization and profitability.

3.1 Green Fuel:

A synthetic fuel contributing significantly to decarbonization and carbon neutrality, based on green hydrogen and CO_2 capture through the Fischer–Tropsch process. Figure 1 shows the production diagram of e-fuel via the RWGS and FTS reactions using renewable hydrogen and direct air CO_2 capture. This valorization route is gaining increasing interest for reducing the carbon footprint in the aviation sector. However, the main challenges lie in the CO_2 capture mechanism, in addition to green hydrogen production. The production cost is gradually decreasing; for instance, it has been reported that the production cost of e-fuel in the U.S. is around $181/bbl [11].

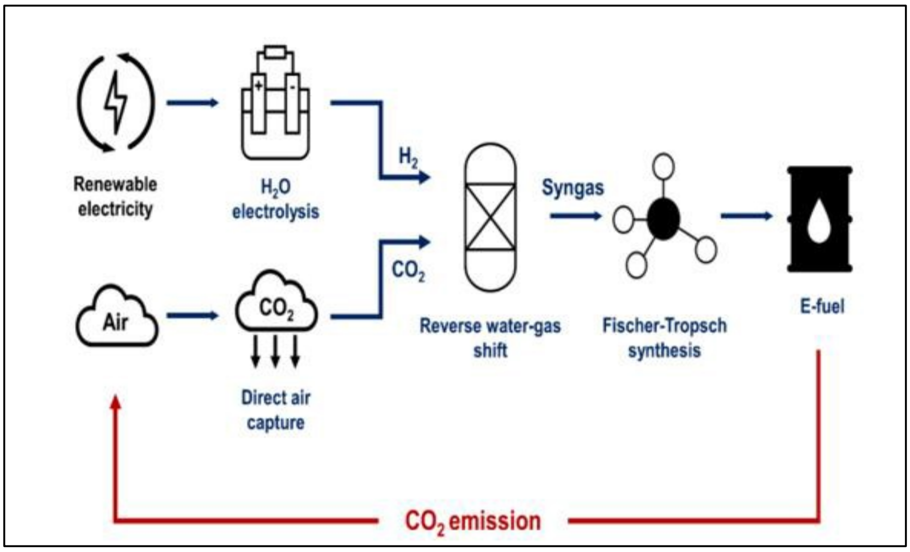

Fig.1: Schematic diagram illustrating the production of e-fuel through the RWGS and FTS reactions using renewable H2 and atmosphere CO2 [11].

3.2 Green Ammonia:

Clean ammonia is produced from low-carbon hydrogen and nitrogen extracted from the air. Its synthesis via the Haber-Bosch process is efficient and has been practiced for over a century. Clean ammonia helps abate CO_2 emissions as it contains no carbon. Beyond ammonia cracking, it can serve as a chemical building block, replacing grey ammonia in the fertilizer and chemical industries. It also shows great potential as a marine fuel, offering an alternative to marine diesel oil.

Ammonia can contribute to the energy system for electricity generation or industrial heat, especially during peak demand periods. However, its combustion requires careful control of NOx emissions. Given the strong existing infrastructure and rapid investment in production sites, ships, and storage, clean ammonia is becoming a more attractive energy carrier.

Conclusion:

The hydrogen era is approaching, and the establishment of large-scale projects requires complete mastery of the hydrogen value chain—from production to marketing. This new resource aims to diversify the energy mix and meet soaring energy demand. Despite hydrogen's significant role in decarbonization—since IRENA's 1.5°C scenario for greenhouse gas reduction estimates hydrogen could contribute up to 25%—natural gas remains the primary vector for energy transition due to its low carbon intensity, leading the IEA to classify it as clean energy in 2024.

The development of green hydrogen is facing many technical and economic challenges. However, with the rapid pace of technological advancement in the sector, these obstacles are expected to be overcome. First movers will dominate the market either through proprietary solutions or by establishing production plants with optimized systems that lower production costs and increase value creation. This is why the valorization of hydrogen into chemical derivatives is emerging as a viable strategy to maximize its value.

Algeria, as a leading country in terms of solar potential and with strong expertise in natural gas and grey hydrogen, has launched a comprehensive green hydrogen strategy. This includes a set of initiatives to accelerate its learning curve and be prepared for the opportune moment when the green hydrogen market booms, seizing the opportunity to strengthen its position in the global hydrogen energy landscape.

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