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An Overview on Green Hydrogen Production from Renewable Energies and Perspectives for Morocco

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Abstract. Environmental concerns have driven the quest for clean energy solutions, with green hydrogen emerging as promising choice. This paper underscores various production methods for green hydrogen, examining their relevance and providing an overview of the utilization of Morocco's renewable energies in its production. Key challenges will be given, including water scarcity, storage, and transportation. Overall, this paper delivers a comprehensive assessment of the role of green hydrogen in Morocco's energy transformation.

Introduction

The escalating environmental concerns associated with greenhouse gas emissions, shown by the 0.9% rise in worldwide carbon dioxide emissions to an unprecedented 36.8 billion tonnes in 2022, motivate technological progress towards diminishing our dependence on fossil fuels [1]. The increase in emissions is associated with factors such as population growth, improved living conditions, and the industrialization of developing nations. If this trend persists, it could lead to a concerning total of 69 billion tonnes of emissions according to the simulation on World Data Lab [2]. Given these circumstances, green hydrogen, renowned for its ability to efficiently store and release environmentally friendly energy, is employed in transportation, industry, and as a fundamental component in chemical reactions. Green hydrogen emerges as a pivotal approach to reducing emissions and addressing the intermittent nature of renewable energy sources.

Innovative approaches to green hydrogen production will be explored in this paper, and a perspective on Morocco will be discussed to determine the most effective methods for producing green hydrogen in the country.

Hydrogen Production

As awareness grows for the need to reduce greenhouse gases and enable new energy paradigms, hydrogen is being seen as playing a critical role [3].

Hydrogen is an abundant colourless element that is found in many forms on Earth. In its molecular form of H2 (two protons and two electrons), it is not readily found but rather needs to be extracted or "reformed" from hydrocarbon fuels, both fossil and biological, or extracted from water using a "water splitting" process. Hydrogen is a widely produced and used industrial commodity for fertilizer production, oil refining, food production, and metallurgy, used at a level of tens of millions of tons per year around the world [4] [5].

This versatility in hydrogen production methods is a significant advantage, enabling us to tailor the production process based on available resources, economic viability, and environmental concerns. Within this context, the quest for efficient and environmentally-friendly methods to produce hydrogen becomes essential, this section will explore the meaning of 'green hydrogen' and a survey of various methodologies for green hydrogen production will be undertaken, shedding light on the diverse technological approaches that contribute to its sustainable generation.

Green hydrogen. In 2021, hydrogen production reached 94 million tonnes, with only 1 million tonnes originating from environmentally friendly techniques [6]. Unfortunately, a significant portion of hydrogen (95%) is produced from non-renewable fossil fuels, particularly through steam reforming of natural gas, emitting 830 million tons/year of CO^2 [7]. The remaining portion, green hydrogen, is produced from renewable resources, including water electrolysis [8].
The costs and environmental emissions associated with hydrogen production exhibit significant variations depending on the specific production process and the type of energy source employed. As a result, hydrogen generation technologies are commonly classified into distinct categories denoted by various colors, including grey, blue, turquoise, green, purple, and yellow as shown in Table 1 [9]. Until now there has been a lack of standardized nomenclature for hydrogen colors. The numerous definitions outlined differ between literature, reports, and national plans, the most common colors reported are gray, green, and blue hydrogen.
The grey hydrogen is generated from fossil fuels like natural gas through processes like steam reforming or auto-thermal reforming, the resulting CO^2 is directly emitted into the atmosphere [10]. Brown and Black hydrogen, the most widely utilized type at present, is derived from hydrocarbon-rich feedstocks like coal or methane via the gasification process that yields syngas from the gasifier [11]. In the other hand, the blue hydrogen, similar to grey hydrogen, is produced from the steam reforming of natural gas but with CO^2 captured and stored, allowing the use of existing infrastructure while reducing greenhouse gas emissions [12]. During this process, natural gas is split into hydrogen (H2) and carbon dioxide (CO^2), the produced $CO^2$is captured (85%–95%) and stored underground using industrial carbon capture and storage techniques. In addition, is seen as a short-term transition towards achieving net-zero emissions [13]. The most suitable hydrogen for a fully sustainable energy transition is the green hydrogen, it is produced through the process of water electrolysis that utilizes renewable energy sources to split water into hydrogen and oxygen and does not generate carbon emissions. Electrolytic hydrogen can also be produced from nuclear power, and this has been referred to pink or red hydrogen, and in some literatures to yellow hydrogen, this approach could provide significant operational advantages both for existing nuclear power stations and micro nuclear reactors, which are currently under development by Rolls-Royce and other companies worldwide [14].
In the transition toward global decarbonization, this paper will center its attention on hydrogen produced from renewable energy sources, which is recognized as a viable means of reducing greenhouse gas emissions and environmental pollution.

Production methods from renewable resources. This subsection encloses different renewable hydrogen production methods, capable of addressing the urgent challenge of climate change and attain global net-zero emissions. Our central long-term approach is to focus on the advancement and refinement of renewable energy systems and its wide applications.

Table 1. Major hydrogen production methods and applications. [11]

Colors	Production Method	Hydrogen Feedstock	Cost [EUR/kg]	CO^2 Emission
Brown/Black	Gasification	Coal (Lignite)/(Bituminous)	1,34	High
Grey	Steam reforming	Natural Gas with CO^2 released into the atmosphere	2,08	Medium
Yellow	Electrolysis	Water with a mixture of renewable and fossil energies	3,5 – 6,87	Medium
Blue	Steam reforming	Natural Gas with CO^2 captured and stored or processed industrially	2,27	Low
Red/Pink/purple	Electrolysis	Water with nuclear power	4,15-7,00	Minimal
Green	Electrolysis	Water with renewable energy	5,78-23,37	Minimal
Withe	-	Hydrogen as a waste product of other chemical processes	0	None

Green hydrogen stands out as an exemplar energy carrier, recognized for its impeccable environmental credentials, it can be produced from four different renewable sources commodities: electricity, thermal energy, photonic energy, and biomass. We can use electricity and light to create hydrogen through water splitting, while thermal energy can be utilized within thermochemical cycles for hydrogen production, fuel resources, can also produce hydrogen through biomass pyrolysis and gasification, and a few other configurations found in the literature.
Moreover, the integration of renewable energy with green hydrogen technologies can offer significant advantages. Excess electrical energy can be stored chemically as hydrogen, effectively aligning energy supply and demand. Furthermore, the hydrogen and oxygen produced can directly serve as primary energy sources in both the transportation and industrial sectors. Hydrogen also finds application as a raw material in the chemical and petrochemical industries, facilitating the production of ammonia and synthetic fuels. Additionally, these systems exhibit increased efficiency as energy carriers when compared to batteries [15].
Several international projects are already underway, with a focus on green hydrogen production using renewable energy sources [16]. However, the transition to a global "hydrogen economy" " is not expected to take place in the short term, primarily due to the current cost associated with renewable green hydrogen productions. Nevertheless, it's important to highlight that the global demand for green hydrogen and its various applications is projected to experience exponential growth. Within just a decade, it is projected to become economically competitive with grey hydrogen production. To reach this cost parity, it is imperative to improve technical efficiency, reduce equipment production costs and material prices, and ultimately scale up manufacturing processes [17].

Water electrolysis. Water electrolysis, an established and well-known method, is the most effective technique for water splitting. As shown in Fig.1, it consists of a cathode and an anode immersed in an electrolyte, driven by the continuous circulation of electrons through an external circuit, if powered by a renewable source, it will generate nearly pure green hydrogen. [10].

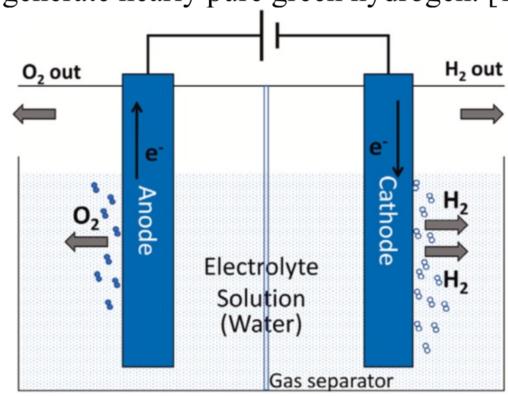

Fig. 1 Scheme of water electrolyze principle [18].

The basic reaction of water electrolysis is as follows in Eq. (1).

$$H_2O\text{+Electricity +Heat} \rightarrow H_2+\frac{1}{2}O_2 \tag{1}$$

Similar to the process of fuel cells, the reversible cell voltage U_{theo} of a water electrolyzer is thermodynamically related to the free enthalpy of reaction. Considering the Gibbs free energy of liquid water at 298,15 K, and the number of transferred electrons per mole n, as shown in Eq. (2). The theoretical thermodynamic cell voltage can be calculated at standard condition at minimum potential of 1,23V, to efficiently split water into hydrogen and oxygen.

$$U_{theo}^{0} = \frac{\Delta G^{0}}{z * F} = 1{,}23\ V \tag{2}$$

However, no gas evolution reaction occurs until 1.65–1.7 V, this is due to kinetical hindrance of both half-cell reactions, losses through ohmic resistances and irreversibilities. With the respective anodic and cathodic overpotentials η and the ohmic resistance R, the cell voltage can then be described by Eq. (3).

$$U_{cell} = U_{theo} + \eta_{cathode} + \eta_{anode} + i * R_{total} \quad (3)$$

R_{total} is the sum of ionic resistances in the electrolyte (Re) and the membrane (Rm), as well as electrical resistances from the electrodes, current collectors, and bipolar plates (Rc). Additionally, there is the resistance (Rb), due to bubble formation on the electrode surface area, where their dispersion can also affect (Re) during operation while (Rc) and (Rm) remain constant. This results in a practical cell voltages of water electrolysis in industrial cell around 1.8-2.6 V [19] [20].
The energy efficiency ηe is defined by th theoretical amount of energy needed to split water divided by the real energy input as shown in Eq. (4).

$$\eta_e = \frac{W_{theo}}{W_{real}} \quad (4)$$

There are still several challenges to overcome in order to enhance efficiency. Recently, Australian researchers [21], introduced a new concept of water electrolysis, achieving inherently bubble-free operation at the electrodes, reaching an energy efficiency of 98%.
The efficiency of the hydrogen production via the electrolysis in most cases, is only 80% when the electricity is considered. However, the heat efficiency of this electricity generation varies on the average from about 25%–40%. Despite their low efficiency, these systems are extremely vital because of the fact that they have no negative impact on the environment and use renewable energy [22].
There is four distinct electrolyzers technologies currently available on the market, each having distinct operational costs with varying levels of maturity, are detailed in Table 2, along with their characteristics, advantages, and drawbacks [23] [24] [25].
The Alkaline water electrolyzer characterized by its long-term stability and relatively low costs, in contrast, the proton exchange membrane electrolyzer (PEM), incurs high component expenses, despite being less widespread, can operate at high current densities. The efficiency of the PEM system is higher due to a faster cellular reaction and a compact structure compared to alkaline electrolysis [26].
On the other hand, Anion Exchange Membrane (AEM) electrolyzers, although less mature and still under development, is a promising technology. They combine the less aggressive environmental conditions of alkaline electrolyzers with the efficiency of proton exchange membrane (PEM) electrolyzers. However, they face challenges related to chemical stability and performance due to the low conductivity of AEMs and slow catalytic kinetics [10].
Lastly, solid oxide electrolyzer cells (SOECs) operate at high temperatures, offering enhanced efficiency and the potential for co-electrolysis of CO^2 and water to produce synthesis gas. Nevertheless, challenges such as accelerated degradation and operational complexity persist.
Thermolysis and thermochemical Processes. Thermochemical water splitting, stands as a promising approach for large-scale hydrogen production from solar thermal energy, it covers a wide range of approaches, each distinguished by the number of reactions occurring within the entire cycle. This method involves breaking down water into hydrogen and oxygen through a series of intermediate chemical reactions. Depending on the specific attributes of the thermochemical cycle, the process can utilize both thermal and electrical energy to drive the decomposition of water. The single-step thermal dissociation of water (5), it’s not effected to drive chemical reactions for hydrogen production until the temperature over 2500 °C [10].

$$H_2O \longrightarrow H_2 + \frac{1}{2}O_2 \quad (5)$$

Rather than relying on a single-step thermolysis of water at high-temperature, which demands substantial energy, the adoption of multi-step cycles, can significantly reduce the maximum temperature required for the cycle and improve the overall efficiency. This expansion of the multi-step approach enhances the potential and viability of thermochemical hydrogen production.
A two-step process involves the use of metal oxides, where it's first decomposed into the metal and oxygen in an endothermic step and then the metal is then combined with water to re-form the metal oxide and hydrogen in a second exothermic step, in one example, the zinc oxide cycle as shown in eq. (6), when heated at 2300 °K, dissociates to zinc and oxygen gases, then the zinc reacts with water to form zinc oxide and hydrogen gas.

$$2\,ZnO + heat \longrightarrow 2\,Zn + O_2 \tag{6}$$

$$2\,H_2O + 2\,Zn \longrightarrow 2\,ZnO + 2\,H_2 \tag{7}$$

Results are oxygen and hydrogen gazes from water, and zinc dioxide, this process can be repeated to produce more hydrogen from water and solar energy and can use other metal oxide in multiple steps [27].
The literature contains multiple approaches for thermochemical cycles using renewable resources, for example it can be coupled with photo-electrochemical methods from solar resource, boosting the overall solar-to-hydrogen conversion efficiency, another aspect is to transform biomass into hydrogen and hydrogen- rich gases through pyrolysis and gasification.
Photo-electrochemical/ photocatalytic decomposition of water. Water splitting through renewable sources like solar and water also involves photo-electrochemical cells, the main components of a PEC cell are presented in figure 5, Photocatalytic principle of decomposing water, consist of an anode and a cathode immersed in an electrolyte, oxygen and hydrogen are then produced. The anode is semiconducting electrode, that absorbs sunlight and generates electrons, the other electrode is typically a metal or both being photoactive [28].

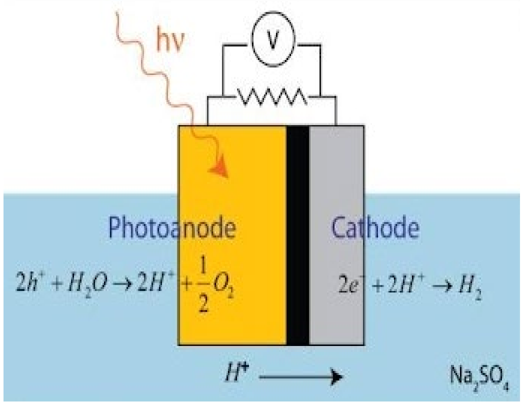

Fig. 2 Photo-electrochemical components illustration [29].

Typically, especially when working at the laboratory scale, the system includes a reference electrode for monitoring half-reactions within the cell. This electrode system is usually immersed in an aqueous electrolyte, commonly Na2SO4. The reactor is either designed to be transparent to light or incorporates an optical window to allow irradiation to reach the photoelectrode.

Biological processes. Before we proceed to the next section, it is essential to mention biological processes, given their significant contribution to the overall reduction of waste and sustainable development. Currently, research in this field is on the rise. Biological processes operate at ambient temperature and pressure, harnessing renewable energy sources, and effectively recycling waste materials [30].
The primary biological processes employed for hydrogen gas production include direct and indirect bio-photolysis, photo and dark fermentations, as well as multi-stage or sequential dark and photo-fermentation. These processes utilize water and biomass as feeds.

Direct bio-photolysis replicates the process of plant photosynthesis to generate hydrogen, and some types of algae are naturally equipped for this process. In the case of indirect bio-photolysis, enzymes like hydrogenase and nitrogenase are involved. Dark fermentation, which operates under anoxic, dark conditions, primarily employs anaerobic bacteria to convert carbohydrates into hydrogen and other byproducts. This process can use a variety of substrates, including agricultural waste and cellulose.
Another biochemical process, photo-fermentation, uses solar energy and organic acids under nitrogen-deficient conditions. The presence of nitrogenase allows certain photosynthetic bacteria to convert organic acids into hydrogen and carbon dioxide. Enhanced hydrogen yields can be achieved through hybrid systems that combine anaerobic and photosynthetic bacteria. These systems can utilize different carbohydrates, resulting in increased hydrogen production. Factors affecting hydrogen yield include temperature and pH. While multi-stage, sequential dark and photo-fermentation hydrogen production costs are not available, they are expected to be lower than individual stages, with estimated costs of 2.57 $/kg for dark fermentation and 2.83 $/kg for photo-fermentation [10].

Green hydrogen for Morocco

In recent years, the world has grappled with various crises resulting in disruptions to the global energy supply, amplifying the urgency of securing energy resources for nations. In response to these challenges, numerous countries, including Morocco, have embraced a decarbonized hydrogen roadmap as part of their commitment to achieving carbon neutrality by 2050 as mentioned in the section 3.2.
Against this backdrop, Morocco has undergone a notable transition towards sustainability and the adoption of renewable energy sources. Green hydrogen is poised to play a transformative role in this transition. The unique convergence of Morocco's renewable energy infrastructure and its untapped potential for harnessing solar and wind resources presents an unparalleled opportunity for green hydrogen production. Moreover, it offers a solution to the challenges of renewable energy intermittency and excess energy production in Morocco.
This section delves into the significance of green hydrogen production in Morocco, exploring how the nation's existing renewable energy assets, in conjunction with its geographic advantages, position it as a key player in the emerging global green hydrogen market. We will investigate the implications of harnessing Morocco's renewable resources for green hydrogen production and its potential to revolutionize energy systems and create export opportunities regionally and beyond.

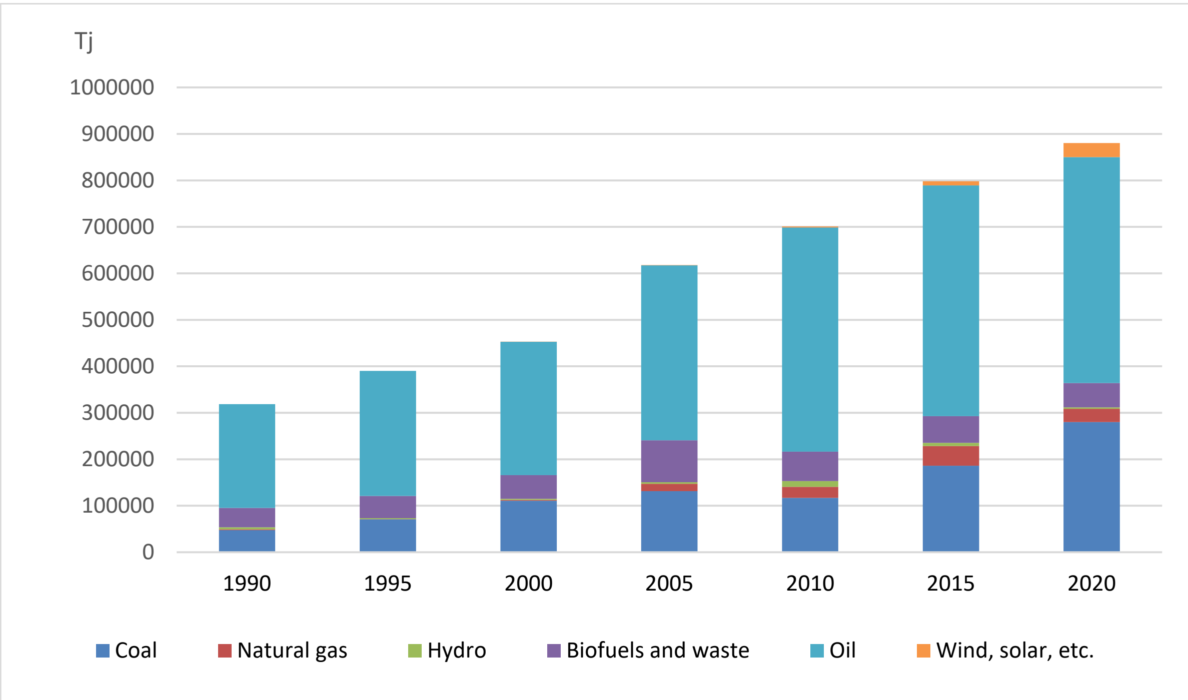

Fig. 3 Total energy supply by source, Morocco 1990-2020 (adapted from [31].

Morocco's energy landscape. Morocco's energy landscape has experienced significant transformations in recent years, with a focus on diversifying its energy mix through substantial investments in renewable sources, particularly solar and wind power. This section offers an overview of Morocco's energy situation and the initiatives that underscore its commitment to sustainable energy practices and its ongoing efforts to achieve a greener, more secure energy future.

Renewable Energy path. Morocco initiated various strategies since the 2000s to enhance energy security and reduce dependence on traditional sources. In 2007, the country launched an initiative to escalate its wind power capacity from 124 MW to 1000 MW by 2012, and in 2009, introduced a solar plan with a target of 2 GW by 2020 [32]. Additionally, in 2015, the nation joined the Paris Climate Agreement, pledging to increase the share of renewable energy in its energy mix to 42% by 2020 and 52% by 2030. Despite these efforts, by the end of 2021, the proportion of renewable energy in the electricity capacity mix failed short of the government's 42% target. In response, Morocco initiated a green hydrogen project in 2022, focusing on producing hydrogen from renewable sources for diverse applications in industries, transportation, and the energy sector [32] [33].
Morocco has indeed made impressive strides in expanding its renewable energy capacity. The nation has introduced a range of regulations and laws carefully designed to align with its ambitious energy transition goals. Morocco has also established several institutional structures to support and facilitate the transition towards cleaner, more sustainable energy sources.

Energy situation. Nonetheless, the country still maintains a dependency on fossil fuels. In 2020, according to the international energy agency (IEA), Morocco's net energy imports reached 800.1 Petajoules (Pj) with a total energy supply at 880 Pj. Oil and coal dominated the distribution, accounting for 86%, while natural gas made a contribution of approximately 3.23%, and renewable sources constituted nearly 10%, as illustrated in Figure 4.

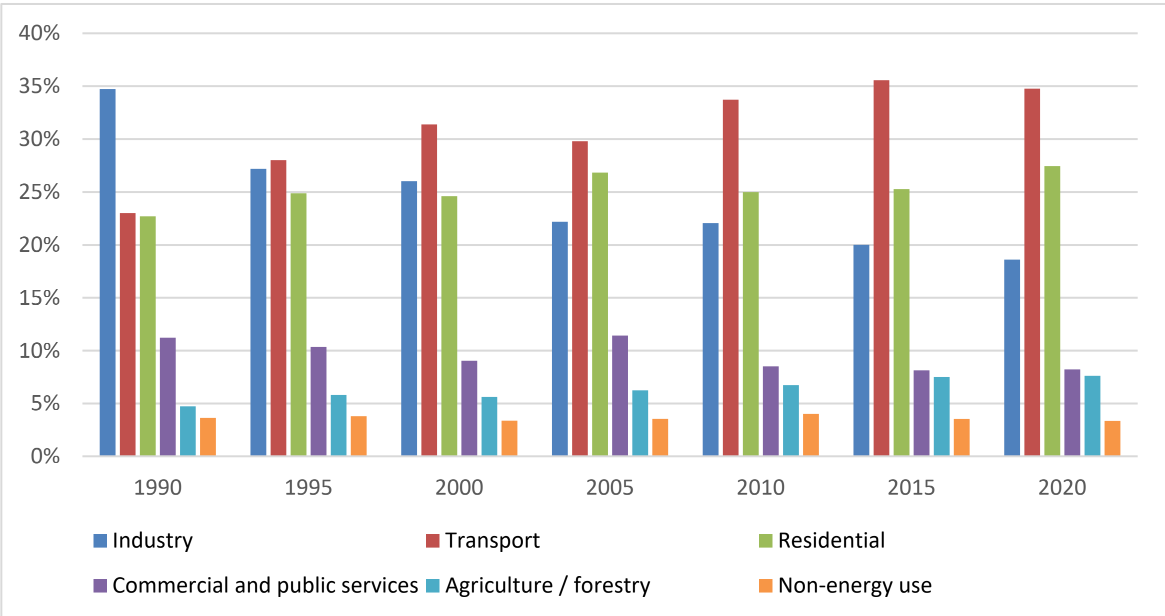

Fig. 4 Total final consumption by sector, Morocco 1990-2020 (adapted from [31].

The final energy consumption, which accounts for 74% of the total supply, amounted to 653 Pj. Notably, as indicated in Figure 5, the transportation sector led the energy consumption statistics, representing roughly 35% of the total final energy usage, followed by the residential sector and the industrial sector respectively at 27% and 19%. Given the nation's rapid population growth and ongoing development across various sectors, there is a well-founded expectation of an increase in energy consumption [31].
At the close of 2021, the share of renewable energy in the electricity capacity mix reached only 37.08%, which was below the government's aim of 42% as outlined in the Paris Agreement. Despite

the pandemic's adverse effects on the renewable energy sector, the government maintains a positive outlook and remains confident in the potential for renewable energy sources to account for 52% of the total installed capacity by 2030 [34].

Moroccan green hydrogen roadmap. In 2020, the European Commission, in conjunction with various member states, unveiled its hydrogen strategy. This initiative gained further momentum in 2022 when EU member states reached a consensus to invest over 50 billion euros by 2030 to facilitate the adoption of hydrogen technologies [35].

Beyond the borders of the EU, several countries likewise presented their hydrogen strategies and financial commitments. Notably, Morocco emerged as a pioneer among African nations, launching its green hydrogen roadmap. This strategic plan was established in 2021 under the National Hydrogen Commission, which was created in 2019. The roadmap is structured around three key pillars: the adoption of essential technologies, the development of the market and demand, and investment in the supply sector.

The primary objective is to progressively advance the development of green hydrogen, with an emphasis on maximizing its utilization for both the national economy and export opportunities. The strategy is designed to unfold over three distinct phases: short, medium, and long-term [36].

In the short term (2020-2030), the focus revolves around two core objectives: employing hydrogen as a feedstock for local green ammonia production and exporting green hydrogen to countries committed to ambitious decarbonization goals.

Looking to the middle term (2030-2040), as the cost of hydrogen production decreases, and environmental regulations become more stringent, the strategy envisions the production and export of not only green hydrogen but also green ammonia and synthetic fuels. Concurrently, hydrogen is expected to find applications as an electricity storage and a transport fuel.

In the long term (2040-2050), the strategy anticipates the global expansion of the hydrogen trade, alongside increased use in various sectors, including industry, residential heating, and transportation within the country [37].

Morocco's proximity to the European continent places it in a prominent strategic position. Several European countries, including Germany, have expressed their willingness to strengthen their energy partnership with Morocco. This is a competitive advantage, especially as Morocco already has established energy interconnection infrastructures.

Indeed, Morocco could leverage its well-connected gas and port infrastructures to create a logistics platform for exporting green hydrogen and its products to Europe, with connections to both the Atlantic and the Mediterranean. The World Energy Council, in its "Power-to-X Roadmap" study, has identified Morocco as one of the six countries with a strong potential for the production and export of green hydrogen and related derivatives [38].

Key challenges. While Morocco has embarked on an ambitious journey to develop a green hydrogen strategy, several key challenges must be addressed to ensure its successful implementation. These challenges are multifaceted and encompass technical, economic, and environmental aspects, some of these challenges occur to be crucial in the short, medium and long term.

Water scarcity. Water stands as the indispensable cornerstone of green hydrogen production, a pivotal resource whose significance bears profound implications, especially in Morocco's context. With various technologies already available for the production of green hydrogen, as explored in the preceding section, the acute water resources scarcity in Morocco poses a substantial challenge [39].

As of 2020, the average water resources available per individual in Morocco stood at a mere 645 cubic meters, significantly below the internationally recognized "water poverty line" of 1000 m^3 per capita. This chronic water scarcity situation has been exacerbated over the years. Between 1960 and 2020, the annual availability of renewable water resources per person plummeted from 2560 m^3 per

capita to approximately 620 m³ per capita, highlighting the alarming decline in available water resources [40].
Currently, Morocco is on the brink of crossing the critical threshold of absolute water scarcity, defined as a mere 500 m³ per capita per year. To address this looming crisis, the Moroccan government has taken decisive steps. A substantial budget of Moroccan dirham (MAD) 383 billion Moroccan dirham (MAD) (around $37.6 billion) has been allocated for a 30-year period from 2020 to 2050. This funding is designated to enhance the country's water distribution networks, catering to both household consumption and the vital agricultural sector [41].
Additionally, the Moroccan government has recently unveiled ambitious plans to initiate three new seawater desalination projects in El Jadida, Safi, and the Oriental region. The aim of these projects is to significantly boost the country's desalinated water production to a minimum of 1 billion cubic meters by 2030. However, it's crucial to consider the cost implications of desalinated water and its energy requirements. One viable solution to mitigate these challenges involves powering desalination plants with on-site green electricity. Any surplus green electricity generated can serve dual purposes, including the production of potable water, which can be stored in dams, contributing to a more efficient and sustainable utilization of the limited water resources available [42]. Addressing the water scarcity issue is paramount to realizing Morocco's green hydrogen aspirations.

Hydrogen storage. The storage of hydrogen presents a fundamental challenge to advance hydrogen applications in supplying stationary power, transportation, and portable power systems. Therefore, an efficient and reliable storage technologies will be required to realize a clean hydrogen economy. Many hydrogen storage methods are currently used and some other methods are under investigation [43] [44] [45]. Hydrogen can be stored as compressed gas, liquefied in cryogenic containment, cryo-compressed form, and solid storage [46].

- Compressed storage: Compressed hydrogen storage is a widely employed technique within the industrial sector, involving the compression of hydrogen to high pressures and its subsequent storage in specialized tanks, constructed from a variety of materials such as reinforced steel, composites, or advanced polymers to guarantee safe and dependable storage [43]. However, a prominent challenge inherent to this storage approach lies in the relatively low energy density of hydrogen, at 100 bar and 20 °C, the density of hydrogen gas is approximately 7.8 kg/m3, necessitating the utilization of large bulk tanks [47]. Furthermore, there exists a potential risk of gradual hydrogen leaks through sealing materials and tank walls, emphasizing the critical importance of rigorous safety measures and the regular maintenance of gaseous hydrogen storage facilities. [48].
- Liquid storage: Liquid hydrogen storage provides a more space-efficient energy storage solution with a density of approximately 70 kg/m³ at 1 bar [48]. This method has both advantages and disadvantages. Liquid hydrogen offers release rates similar to compressed hydrogen but with lower energy requirements for adiabatic expansion. It also allows for the use of smaller storage tanks due to its higher density at high pressures. However, the liquefaction process is expensive and energy-intensive, resulting in a notable loss of hydrogen's heating value. Boil-off, where hydrogen evaporates when energy is drawn from the environment, poses a challenge and requires specialized storage solutions. To mitigate evaporation losses, larger containers with improved insulation can be used, although this may reduce the gravimetric energy density [45].
- Solid storage: Solid storage using metal hydrides is a promising and innovative method for hydrogen storage, where hydrogen is absorbed and desorbed in a reversible manner within solid compounds, primarily metal hydrides [49]. The metal hydrides can offer higher hydrogen storage capacity than the compression and the liquefaction and store hydrogen at moderate temperature and pressure [50]. While metal hydrides offer a safe way of storing hydrogen without the risk of leakage, they do have some drawbacks. One notable challenge is the substantial thermal energy required to release hydrogen from the metal hydrides. Additionally, metal hydrides are relatively massive, which can impact their application in portable devices and vehicles. The kinetics of hydrogen absorption

and release in metal hydrides are also relatively slow, which can limit their practicality in certain applications [48]. Nonetheless, ongoing research seeks to address these challenges and improve the efficiency of metal hydride storage. This includes exploring new materials with enhanced energy efficiency, durability, and cost-effectiveness [51] [52]. As the development of metal hydride storage continues, it holds the potential to play a vital role in the future of hydrogen storage, particularly in applications where safety and the prevention of hydrogen leaks are paramount.

- Underground storage: Another method for large-scale hydrogen storage involves utilizing underground hydrogen storage. There are three major types of geological formations for gas storage options, including depleted gas/oil reservoirs, aquifers, and salt caverns [53]. The process involves compressing hydrogen and introducing it into these geological sites, where it becomes securely trapped under high pressure [54]. Current research, exemplified by the Melhy project [55], is actively exploring the practicality of extensive hydrogen storage within the salt cavities of Morocco's Mohammedia mine. The primary aim of the Melhy project is to store an energy equivalent of 10 gigawatts (GW), which is roughly equivalent to powering Casablanca for 6 hours.

Indeed, various methods for hydrogen storage exist in the literature, and needs to be investigated. for example: methanol and ammonia. These alternative approaches are gaining attention due to their efficiency in storing hydrogen, offering innovative solutions to the challenges of hydrogen transportation and utilization. Methanol, in particular, is known for its high hydrogen content, making it an attractive carrier. Similarly, ammonia has been explored as a viable option, enabling safe and compact storage [47]. By leveraging these alternative storage methods, Morocco can enhance the versatility and effectiveness of its hydrogen initiatives, paving the way for a more sustainable energy landscape.

Hydrogen transportation. Hydrogen transportation is a pivotal aspect of the hydrogen economy, demanding a profound understanding of its properties to mitigate the potential risks associated with explosions and leaks. Establishing reliable, safe, and efficient means of transporting hydrogen is paramount for realizing its full potential in a wide array of applications. This not only ensures the efficiency of the entire hydrogen supply chain but also contributes to its safety and sustainability.

The diversity in hydrogen's physical states, dictated by temperature and pressure variations, adds complexity to the transportation methods employed. Depending on the unique requirements of each scenario, one must consider factors like the distance of transportation, the volume of hydrogen to be moved, the availability of infrastructure such as existing liquefied natural gas or ammonia pipelines, and the specific purpose of the transported hydrogen [56].

In response to these multifaceted challenges, researchers and industries are actively exploring innovative technologies and methods to meet the transportation needs of hydrogen [46]. The objective is to develop a robust and secure hydrogen transportation system that complies with stringent safety standards and simultaneously paves the way for integrating hydrogen into diverse industrial sectors, effectively contributing to a cleaner and more sustainable energy landscape.

Opportunities and future prospects. Despite the challenges, Morocco's green hydrogen journey presents numerous opportunities and promising future prospects. The following section highlights the potential benefits and positive outcomes that can emerge from the country's commitment to green hydrogen production.

Economic Growth. The rise of Morocco's green hydrogen industry offers a revolutionary chance to promote job creation and economic prosperity. A competent labour force will be required for the building of green hydrogen production facilities and the related supply chain, creating a variety of job possibilities in a range of industries, including engineering, research and development (R&D), construction, and daily operations. This promotes professional development and competence within the local labour market in addition to meeting the urgent needs for professionals.

Furthermore, Morocco is well-positioned to establish itself as a competitive worldwide supplier in the rapidly expanding green hydrogen industry. Morocco's strategic investment in green hydrogen production will boost export earnings and strengthen its domestic economy, contributing to a more stable and diverse economic landscape as the demand for environmentally sustainable energy solutions grows globally.

Energy Security. Morocco has made a calculated strategic move by integrating the production of green hydrogen in the context of energy security. Morocco can considerably reduce its reliance on imported fossil fuels by utilising its large renewable energy potential for the production of hydrogen. In addition to promoting increased energy security, this diversification of energy sources also promotes increased independence and stability within the country's energy framework. By embracing green hydrogen, Morocco is lowering its exposure to geopolitical unpredictability and global market fluctuations while also advancing its vision of a resilient and self-sufficient energy landscape.

Environmental Benefits. Morocco's adoption of green hydrogen is a concrete demonstration of its commitment to mitigating climate change and reducing greenhouse gas emissions. By producing hydrogen using renewable energy sources, Morocco is positioned to achieve significant progress in lowering its carbon footprint. This calculated move helps create a more ecologically conscious and sustainable energy sector, supporting international initiatives to lessen the effects of climate change.

Energy Integration. In order to integrate and balance renewable energy sources into Morocco's energy grid, green hydrogen plays a crucial role. Hydrogen can be effectively stored from surplus electricity produced by solar and wind power plants, offering a consistent supply of energy that can be used when renewable energy output is low or energy demand is high. This capability contributes to a more robust and flexible energy infrastructure by reducing the risk of power outages while also improving grid stability and reliability.

Regional Collaboration. Morocco is positioned as an appealing hub for regional and international collaborations in the green hydrogen domain due to its advantageous geographic location and established energy interconnections. Partnerships with European nations and institutions can promote technology transfer, draw in capital, and open up export markets, securing Morocco's place as a major player in the quickly developing global green hydrogen market.

Innovation and Research. Investing in the production of green hydrogen stimulates innovation and research in the fields of hydrogen technologies, renewable energy, and associated industries. With the potential to become a global centre for research and development in these fields, Morocco could draw academics, scientists, and entrepreneurs from all over the world. This boosts Morocco's reputation as a hub for cutting-edge research in the field of sustainable energy while also accelerating technological advancements.

Results and Discussion

Hydrogen Production Potential and Cost Analysis. Morocco possesses a strong potential for green hydrogen production due to its rich renewable energy resources. The combination of high solar irradiation and strong wind currents, particularly in regions like Dakhla and Ouarzazate, enables continuous and cost-effective hydrogen production. Studies suggest that the Levelized Cost of Hydrogen (LCOH) in Morocco could reach as low as \$2.54/kg under optimal conditions, making it competitive in the global market [57]. However, achieving this cost efficiency requires substantial investments in infrastructure, electrolyzers, and energy grid integration.

Water electrolysis remains the most viable method for green hydrogen production in Morocco. However, other approaches such as biomass gasification also present potential alternatives. Biomass gasification, which involves converting organic material into hydrogen-rich syngas, can utilize agricultural and forestry waste, contributing to a circular economy. While electrolysis benefits from Morocco's abundant solar and wind resources, biomass gasification could complement it by providing hydrogen production from organic residues, reducing dependence on imported fossil fuels. The selection between these methods depends on cost efficiency, resource availability, and technological advancements. While concerns exist regarding water scarcity, desalination has been identified as a feasible solution, contributing less than 0.5% of the total hydrogen production cost [58]. Implementing large-scale renewable-powered electrolysis plants could ensure a stable supply while minimizing environmental impact.

Feasibility of Implementation in Morocco. To ensure Morocco's green hydrogen industry reaches its full potential, it is crucial to address several technical, economic, and infrastructural hurdles. The successful deployment of green hydrogen in Morocco depends on addressing several key challenges:

- Water Availability: Morocco faces water scarcity, which could limit hydrogen production capacity. Expanding desalination infrastructure using renewable energy can mitigate this issue.
- Infrastructure and Storage: Hydrogen storage options, including compressed gas, liquid hydrogen, and underground storage, require further investment and technological advancements to ensure efficiency and safety.
- Hydrogen Transport: Developing a robust hydrogen transportation network, such as pipelines and shipping infrastructure, is critical for export, particularly to Europe.
- Economic Viability: Scaling up hydrogen production to reduce costs is essential for competitiveness in global markets.

Economic and Policy Considerations. Morocco's commitment to green hydrogen aligns with its decarbonization goals and international energy strategies, including partnerships such as the European Green Hydrogen Alliance and agreements with Germany's H2Global initiative. These collaborations aim to facilitate knowledge exchange, funding, and technology transfer to accelerate hydrogen development in Morocco. However, policy and regulatory frameworks must support investment and innovation in hydrogen production. Government incentives, international partnerships, and advancements in electrolyzer technology will play a crucial role in ensuring economic viability. Additionally, creating a favorable market environment will attract foreign investment and facilitate technology transfer.

Conclusion

Morocco's renewable energy resources position it as a promising leader in green hydrogen production. By leveraging solar and wind energy for electrolysis, the country can develop a competitive hydrogen economy while contributing to global decarbonization efforts. However, achieving large-scale hydrogen deployment requires strategic investments in infrastructure, policy support, and international collaboration. Addressing key challenges such as water availability, storage, and transportation will be essential in establishing Morocco as a key player in the global hydrogen market. For example, Germany has successfully integrated hydrogen into its energy mix by investing in underground storage and a robust pipeline network, while Australia has developed large-scale desalination projects to support hydrogen production. Learning from these international experiences can help Morocco navigate similar obstacles and optimize its hydrogen strategy. With the right investments and strategic planning, Morocco can unlock the full potential of green hydrogen, ensuring a sustainable and economically viable energy transition.

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