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FUTURE SCENARIOS OF GREEN HYDROGEN IN THE MENA COUNTRIES: THE CASE OF EGYPT*

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Abstract. Green hydrogen is a clean and renewable energy source that has the potential to play a major role in decarbonizing the global economy. Green hydrogen has become a promising decarbonization strategy for several industries, including transportation and manufacturing. The widespread use of green hydrogen technology still confronts several obstacles, such as high costs, a lack of infrastructure, and regulatory restrictions. The paper commences by examining the potential of green hydrogen production in MENA countries with a specific emphasis on Egypt as best practice example. It proceeds to identify the key drivers that will shape future scenarios of green hydrogen and outlines the best and worst-case scenarios for green hydrogen in MENA region by 2050. Through scenario analysis, the paper presents potential pathways for green hydrogen deployment in Egypt and the wider MENA countries, highlighting key drivers and potential barriers. According to the findings, Egypt emerges as pivotal player in driving the deployment of green hydrogen within the MENA region. The MENA region, rich in solar and wind resources and strategically located, emerges as a potent hub for green hydrogen production. Egypt, in particular, is at the forefront of this initiative, aiming to become a key exporter in the global hydrogen economy by leveraging its renewable resources, strategic projects, and conducive investment environment. The study employs a multifaceted methodology, integrating PEST analysis and identifying key drivers like renewable targets and technological advancements to assess green hydrogen's potential in the MENA region, focusing on Egypt. It constructs best- and worst-case scenarios by 2050, utilizing these drivers to evaluate the implications of various influencing factors. In the best-case scenario, by 2050, Egypt aspires to be a pivotal player in the global green hydrogen economy, aiming for up to 8% market share. Through strategic investments, policy enhancements, and global partnerships, Egypt plans to become a major exporter, particularly to the European Union, aligning with global decarbonization goals. Comprehensive strategies are expected to drive economic prosperity, potentially increasing Egypt's GDP by \$10-18 billion by 2025. Collaborations with global entities have fostered a robust infrastructure, enabling an integrated ecosystem for green hydrogen innovation and production.

Keywords: Green hydrogen; Egypt; best case scenario; worst case scenario; renewable energy; economic development; sustainability

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JEL Classifications: Q1, Q2

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1. Introduction

To address the challenges of reducing greenhouse gas emissions (GHGs) and decreasing dependence on fossil fuels in energy markets, countries worldwide are actively prioritizing the development of renewable energy sources (RESs) as a key driver for the energy transition and to reduce reliance on external supplies (Squadrito et al., 2023). The complete decarbonization of the economy is now a top priority on political agendas globally. The Paris Agreement, ratified in 2015, established the commitment of most nations to limit global warming to within 1.5 to 2 degrees Celsius above pre-industrial levels. To achieve this objective, it is crucial to significantly decrease GHG emissions in all sectors by replacing fossil fuels with carbon-free alternatives (Liponi et al., 2023). As the international community moves towards a sustainable and low-carbon energy future, hydrogen is emerging as a leading energy carrier with vast potential to decarbonize various sectors (IEA, 2021).

Although there are some clean and renewable energies that are considered more cost-effective in terms of use globally, such as solar energy and wind energy (IEA, 2021), they depend greatly on the location and weather conditions, which depend on technologies. Storage is mainly through batteries (Pleßmann et al., 2014), which suffer from several technical shortcomings, such as: a limited number of useful cycles (discharge), the use of important raw materials and/or polluting compounds, and the difficulty of recycling (expensive and/or lacking to techniques) (Dehghani-Sanij et al., 2019). For this reason, interest in hydrogen as an environmentally friendly and economically competitive solution for energy storage is growing dramatically (McKinsey & Company, 2022).

Green hydrogen, which is made using renewable energy sources to electrolyze water, has gained appeal as a sustainable solution for energy storage and use. Unlike its counterparts, green hydrogen is not limited by geographic or meteorological requirements, giving it broader applicability in different regions and conditions (Furfari & Clerici, 2021). Since its production involves using surplus electricity from renewable sources such as wind and solar energy to split water into hydrogen and oxygen, it represents a powerful strategy in reducing carbon emissions (Kovač et al., 2021). The flexibility and adaptability of green hydrogen are noteworthy as well. Green hydrogen can be easily stored and transported, and its energy can be retrieved as needed through fuel cells or combustion, ensuring a continuous and reliable power supply (Winter, 2009). Furthermore, green hydrogen integrates effectively into various sectors, including transportation, industry, and power generation, enabling a comprehensive approach to decarbonization (Kazi et al., 2021 & Mazzeo et al., 2022). In the transportation sector, for instance, green hydrogen could have a transformative impact by providing a viable and emissions-free alternative to conventional fossil fuels, particularly in heavy haulage and long-distance transport applications where battery technologies may not be suitable due to their bulk and weight.

Green hydrogen is a clean and sustainable source of energy and is of great importance. It is recognized as the cleanest fuel by the World Energy Organization and has the potential to contribute to achieving zero fuel emissions strategies, however, despite its potential, the production cost of green hydrogen remains a key challenge. Economies of scale, technological innovations, and supportive policy frameworks are pivotal to making green hydrogen more economically competitive (Falcone et al., 2021). The decline in renewable energy costs, advancements in electrolyze technologies, and increased global commitment to sustainability are promising indicators of the growing feasibility and expanding role of green hydrogen in a future global energy landscape (Noussan et al., 2020). The global demand for green hydrogen is expected to increase significantly in the coming years (Figure 1). According to a report by PwC, hydrogen demand by 2050 could vary from 150 to 500 million metric tonnes per year, depending on global climate ambitions and the development of sector-specific applications (PwC, 2023).

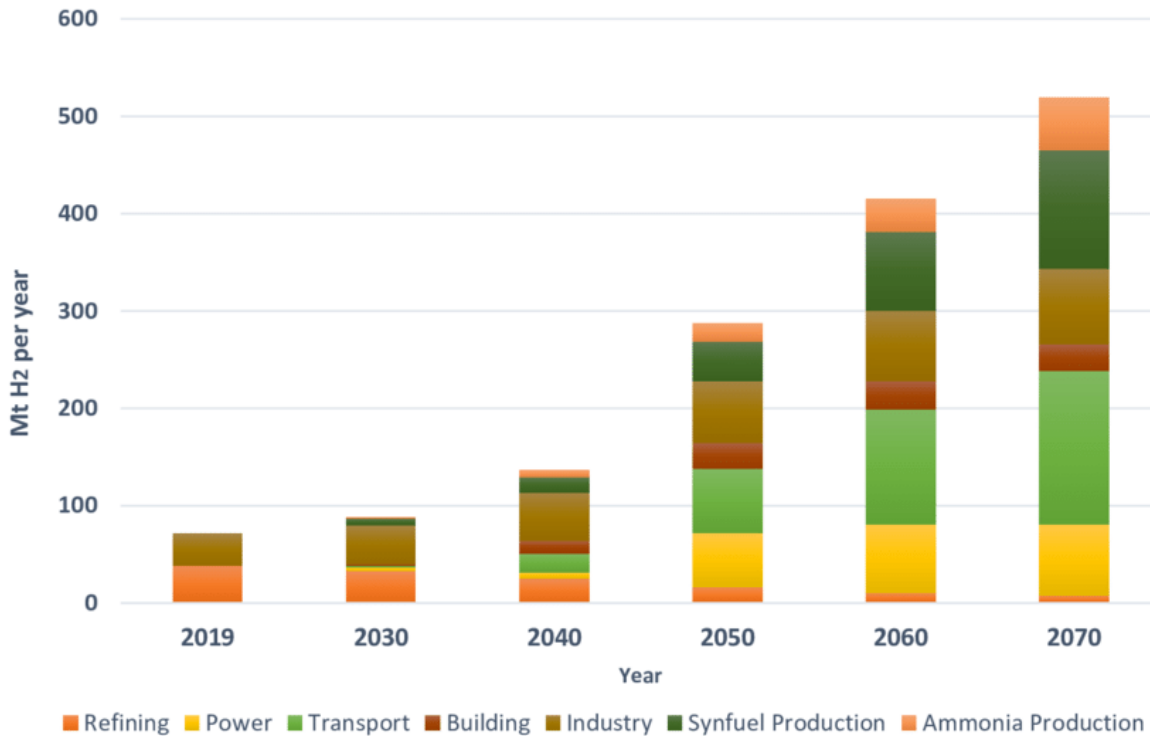


Fig. 1. Global demand for hydrogen by sector 2019-2070

Source: Okonkwo et al., 2021

The Middle East and North Africa (MENA) region possesses substantial potential for green hydrogen production and utilization (Razi & Dincer, 2022), attributed to several key factors. Primarily, the region boasts an abundance of renewable energy, particularly solar and wind resources, with significant investments already made by countries such as Egypt, Saudi Arabia and the United Arab Emirates (Chedid & Chaaban, 2003). Geographically, MENA’s strategic location facilitates the efficient export of hydrogen or hydrogen-based products to Europe and Asia, enhancing the feasibility of hydrogen transportation due to its proximity to major global markets. Additionally, the region’s existing infrastructure, stemming from the oil and gas industry, could be repurposed for hydrogen production and transportation, thus minimizing the need for new investments. In terms of industrial application, green hydrogen can be immensely beneficial to various local industries, including petrochemicals, fertilizers, and refineries, assisting in the reduction of their overall carbon footprint. Economically, the production and exportation of green hydrogen presents an opportunity for economic diversification, steering the region away from fossil fuel dependency and towards embracing future technologies (Charles et al., 2009).

In recent years, ambitious initiatives have emerged in the Middle East and North Africa (MENA), specifically in countries like Egypt, Morocco, Saudi Arabia, Oman, and the United Arab Emirates (UAE), aimed at establishing the region as a hub for carbon-friendly fuel supply to Europe and Asia-Pacific. A remarkable plan unfolds in Egypt, which ambitiously targets a green hydrogen production cost of 1.7 \$/kg by 2050, aspiring to occupy an 8% share of the global hydrogen market (Gado & Hassan, 2023). Concurrently, innovative roadmaps are being adopted in NEOM, Saudi Arabia, UAE, and Oman, manifesting a collaborative regional effort (Hafner et al., 2023).

Egypt enjoys an abundance of sunlight and wind, making it a mine of photovoltaic energy and wind energy, which are essential for producing low-cost green hydrogen (Moharram et al., 2022). Egypt is leading Africa in

green hydrogen production (Figure 2) with 21 projects underway. A significant agreement has been made between Scatec and the Egyptian government to develop a facility producing up to 3 million tonnes of green ammonia annually, primarily for export to Europe and Asia. Key projects include the Masdar Ain-Sokhna project, developed by Masdar and Hassan Allam Holding Group, aiming to produce 2.3 million tonnes of ammonia annually for the European market, utilizing a 4 GW electrolyzer plant located at the Suez Canal Economic Zone (SCZONE). Globeleq also plans to establish a 3.6-GW electrolyzer project at SCZONE to produce ammonia for export to Europe and Asia. Other notable projects include the ACME, Fortescue-Egypt, and SCZONE-ReNew Power projects, contributing significantly to the production capacity of green ammonia (Rystad Energy, 2023).

Million tonnes

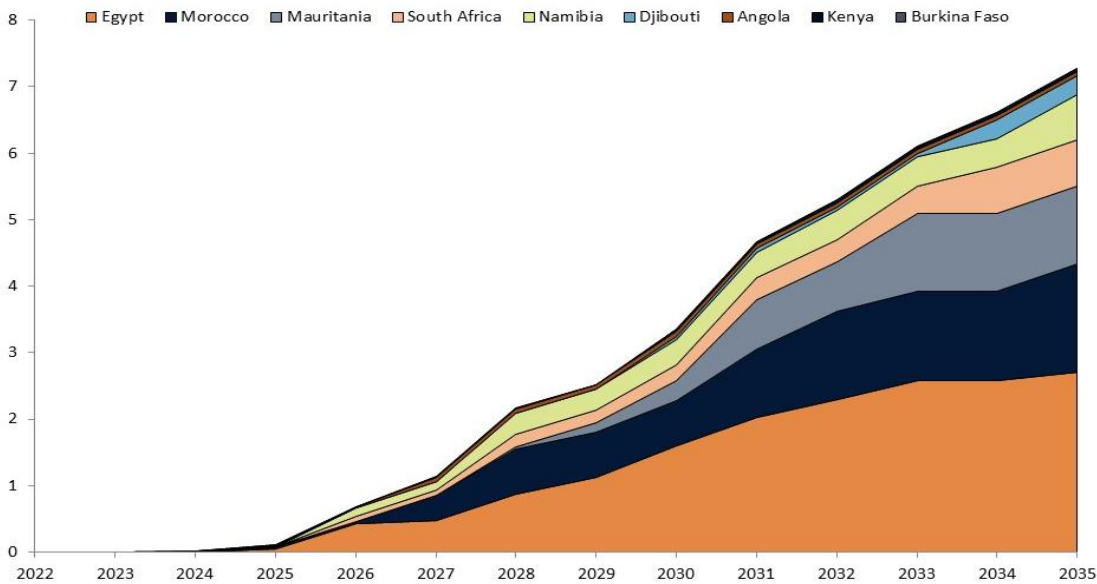


Fig. 2. Green hydrogen production in Africa
 Source: Rystad Energy, 2023

The Egyptian Ministry of Electricity and Renewable Energy is strongly focused on amplifying the production and exportation of green hydrogen, making it a pinnacle priority (Table.1). By harnessing renewable energy sources, the ministry aspires to solidify Egypt’s standing as a premier exporter in the burgeoning global hydrogen economy. A concerted effort is being made to foster an investment-friendly environment, attracting both domestic and international investments to fuel this ambition. Anticipated growth in the green hydrogen sector is impressive, with forecasts indicating a 60% surge by 2030 and a quadrupling of the economy by 2050, driven primarily by escalating global demands for cleaner energy and concerted efforts to diminish carbon emissions. Strategically, Egypt is positioning itself to seize a substantial share of the international market, predicting a sevenfold increase in the hydrogen economy by 2050. This strategic positioning could potentially elevate Egypt’s GDP by \$10–18 billion and generate over 100,000 new jobs, thereby enhancing national energy security and reducing dependency on oil imports through a combination of increased indigenous hydrogen production and the optimization of local expertise across hydrogen-related value chains (Dokso, A., 2022).

Table 1. Egypt's hydrogen projects

Time	Initiatives	Target
January 2021	Letter of intent (LoI) with Siemens of German	Egypt's green hydrogen
April 2021	Egypt and Belgium's DEME struck a deal	Egypt's green hydrogen
May 2021	Egypt received six offers from six various firms.	Egypt's green hydrogen
July 2021	Eni signed an MoU with EEHC and Egyptian Natural Gas Holding Company (EGAS)	The technical and commercial feasibility of projects for Egypt's hydrogen generation
August 2021	letter of intent was promoted to a Memorandum of Understanding (MoU) with the Egyptian Electricity Holding Company (EEHC)	“co-developing hydrogen-based industry in Egypt with export capabilities” which includes “the creation of a trial project with an electrolyzer capacity of 100–200 MW”.
October 2021	Fertiglobe, an Egyptian Emirati firm, and Scatec, a Norwegian renewable energy company, inked an agreement to be located in Ain Sokhna on the Red Sea coast.	The collaborative development of green and blue hydrogen projects
Before June 2022	The National Committee is responsible for formulating the hydrogen strategy is working with the European Bank for Reconstruction and Development (EBRD)	Unveil its \$40 billion hydrogen strategy, which includes plans for a production capacity of 1.4 GW by 2030

Source: Esily et al., 2022

Egypt is actively working towards unveiling a national strategy dedicated to green hydrogen production, incorporating numerous appealing incentives aimed at bolstering its competitive edge in this sector. The government manifests a strong political resolve to embrace a cohesive national vision for green hydrogen, collaborating with the European Bank for Reconstruction and Development to craft this strategy. A comprehensive regulatory framework focusing on the local production of green hydrogen is a crucial part of this strategy, with Egypt aspiring to account for 8% of global production. Furthermore, Egypt has been proactive in forging several pivotal agreements pertinent to hydrogen. Notable accomplishments include securing agreements within the Suez Canal Economic Zone, focusing on initiating projects that specialize in the production of hydrogen and green ammonia. These projects, valued at an impressive total investment of 83 billion dollars, are projected to collectively generate approximately 7.6 million tons of green ammonia and 2.7 million tons of hydrogen each year.

Green hydrogen scenarios are being explored in various studies. These scenarios involve the use of renewable power sources and water-splitting technologies to produce green hydrogen as a decarbonization solution (Al-Orabi et al., 2023, Correa et al., 2022 & Peterssen et al., 2022). In the UK, several scenarios have been illustrated to show potential economic trajectories in hydrogen production. One such example demonstrates that by 2030, the manufacturing of green hydrogen using offshore wind resources could rival the costs of grey and blue hydrogen, projecting a notable decrease in expenses. In alternative scenarios, focusing on the evolution of hydrogen storage and transportation technologies, for projects initiating in 2050 under these scenarios, the levelized cost of hydrogen might potentially descend to £2 per kilogram or below (Giampieri et al., 2023).

In Malaysia, the scenario has been reviewed by discussing energy demand, current population, energy policy synopsis, conventional energy sources, carbon emissions, and the direction of renewable energy in Malaysia. Besides, the conceptual framework for hydrogen as renewable energy was discussed covering the hydrogen

economy, production technology, storage, and energy production using green hydrogen (Ahmad et al., 2021; Zakaria et al., 2023). In China, the scenarios envision an increase in the annual capacity of renewable hydrogen in China, with renewable hydrogen becoming a powerful support for the country's carbon-neutral mission (Liu, 2023).

This paper aims to explore the trajectory of green hydrogen adoption within the MENA region, focusing particularly on Egypt as case study and projecting towards the year 2050. Through scenario writing, this study navigates through the multifaceted challenges and opportunities that might unfold in the journey towards establishing a robust green hydrogen economy in these nations.

Two contrasting scenarios are envisaged: a best-case scenario, where factors such as technological advancements, policy frameworks, international collaborations, and market developments align favorably to promote the widespread adoption and integration of green hydrogen within the energy systems; and a worst-case scenario, which encompasses possible setbacks such as technological stagnation, lack of investment. By exploring these divergent pathways, this paper aims to provide comprehensive insights, fostering informed decision-making and strategy formulation for policymakers, industry stakeholders, and researchers dedicated to advancing the green hydrogen sector in the MENA region.

2. Methodology

The methodology employed in the study integrates several components to comprehensively analyze the potential development and outcomes of green hydrogen in the MENA region, with a specific focus on Egypt. It begins with a PEST analysis, which assesses the political, economic, social, and technological factors influencing green hydrogen adoption on a global scale, followed by a zoomed-in analysis of the MENA region, Egypt. This analysis provides valuable insights into the current landscape, opportunities, and challenges associated with green hydrogen development in the region.

Subsequently, key drivers are identified based on their potential impact on green hydrogen deployment (Rikkonen et al., 2021). These drivers encompass various factors, including renewable energy targets, carbon reduction commitments, technological advancements, international collaborations, and public awareness. The identification of key drivers serves as a crucial step in shaping the best- and worst-case scenarios for green hydrogen in Egypt by 2050, as these drivers influence the potential outcomes. The next stage involves scenario writing (Rezk et al., 2020), wherein the identified key drivers are utilized as inputs to construct plausible future scenarios.

In addition to the mentioned methodology components, the study incorporates a literature review, previous studies, and expert input to enhance the analysis and scenario development. The literature review allows researchers to build upon existing knowledge, identify gaps, and incorporate relevant findings from previous studies. Furthermore, expert input from academia, industry, government, and relevant organizations is sought to gather diverse perspectives and informed opinions. This inclusion of expert input, along with the literature review, ensures that the analysis and scenarios are grounded in up-to-date information, existing knowledge, and expert insights. Consequently, the methodology employed in the study fosters a robust and credible assessment, providing a comprehensive understanding of the potential best- and worst-case scenarios for green hydrogen in Egypt by 2050.

3. PEST analysis

A PEST analysis is a valuable tool for evaluating the political, economic, social, and technological factors that can influence the development and acceptance of green hydrogen in MENA countries, with a specific focus on Egypt. This analysis is widely employed worldwide to identify present or potential challenges, enabling effective

planning to overcome these barriers (Sammut-Bonnici & Galea, 2015; Barbara et al., 2017; Yang, 2022). The following PEST analysis provides insights into the current trends and status of green hydrogen in Egypt:

3.1. Political Factors

New strategy for green hydrogen

Egypt unveiled its National Strategy for Climate Change 2050 in 2022 with the goals of preserving its natural resources, enhancing the standard of living for its people, and fostering sustainable economic growth. Egypt's National Climate Change Strategy aims to provide a comprehensive overview of climate change in a single document, serving as a fundamental guide to guarantee the incorporation of climate change considerations into the overall planning of all sectors within the nation. It was created at the National Council for Climate Change's suggestion. The plan is to electrolyze water with renewable energy sources to produce hydrogen, which may be utilized as a clean fuel. (Ministry of Environment, 2022).

Egypt has been developing a new strategy for producing green hydrogen to lower carbon emissions and support renewable energy sources. The strategy seeks to establish Egypt as a global leader in the low-carbon hydrogen economy and to gain a 5-8% market share in the green hydrogen industry worldwide. Targeting up to 8% of the worldwide tradable market by 2040, Egypt's ambitious objectives in the hydrogen industry will be realized with Egypt's competitive capabilities in the national strategy. The strategy was unveiled at the UNFCCC Conference of the Parties (COP27), which took place in Sharm El-Sheikh in November 2022 (Ministry of Environment, 2022).

Investment Incentives

Egypt has been working on a green hydrogen strategy to reduce carbon emissions and promote sustainable energy, Egypt aims to be one of the largest exporters of clean hydrogen in the region and secure a 5-8% share of the global commercial market for green hydrogen. The Egyptian government has approved a new bill to incentivize green hydrogen projects and companies. The law provides incentives for green hydrogen projects and companies involved in its production during the project implementation period. The incentives include a cash investment incentive equivalent to 33% to 55% of the tax paid on revenues generated by the project. Equipment and materials will be exempt from value-added tax (VAT), and taxes and contracts and land registration fees will be waived. The government aims to accelerate the deployment of green hydrogen projects in Egypt, with the country relying on its status as one of the world's leading locations for green hydrogen production (Egyptian Cabinet, 2023).

Strategic Partnerships and Agreements

The government has signed several memoranda of understanding (MoUs) and contracts to produce green hydrogen and has approved a new bill to incentivize green hydrogen projects and companies. Egypt has entered collaboration with the European Union to progress in the area of green hydrogen production. Additionally, coinciding with COP27 in 2022, Egypt initiated a range of Memoranda of Understanding with various global entities to attract overseas investments for green hydrogen production, positioning itself as a pivotal clean energy hub for Europe. During this event, Egypt endorsed seven new agreements to drive the development of industrial complexes dedicated to green hydrogen production, particularly in the Ain Sokhna industrial area. These agreements involved partnerships between several Egyptian government entities and distinguished international and regional firms focused on renewable energy production. Partners include Globeleq from the UK, Alfanar from Saudi Arabia, UAE's Alcazar Energy and K & K, MEP Energy which is a joint venture between the US and Egypt, India's ACME group, and Actis from the UK. The planned investments in these pioneering green hydrogen

projects, led by eight Arab and international consortiums, are estimated to inject approximately \$7.4 billion over the forthcoming four years (Egypt Today, 2022).

3.2. Economic Factors

Market Size and Growth

The MENA region provides world-class renewable energy resources and has huge potential to become a leading hub for renewable energy and hydrogen-based industries (Gado & Hassan, 2023). The MENA region is becoming more interested in creating a green hydrogen economy since it may help with energy security and environmental preservation. According to Müller & Eichhammer (2023), several countries in the region, including Egypt, Saudi Arabia, and Turkey, already have industrial knowledge of the components of green hydrogen technology (Figure 3). The installation of further pipelines from Morocco, Algeria, and Tunisia may be able to meet a sizeable amount of the projected 2050 demand for green hydrogen in Europe. Green hydrogen production and delivery from the MENA region to Europe are predicted to cost roughly €2/kgH₂ (Jalbout et al., 2022).

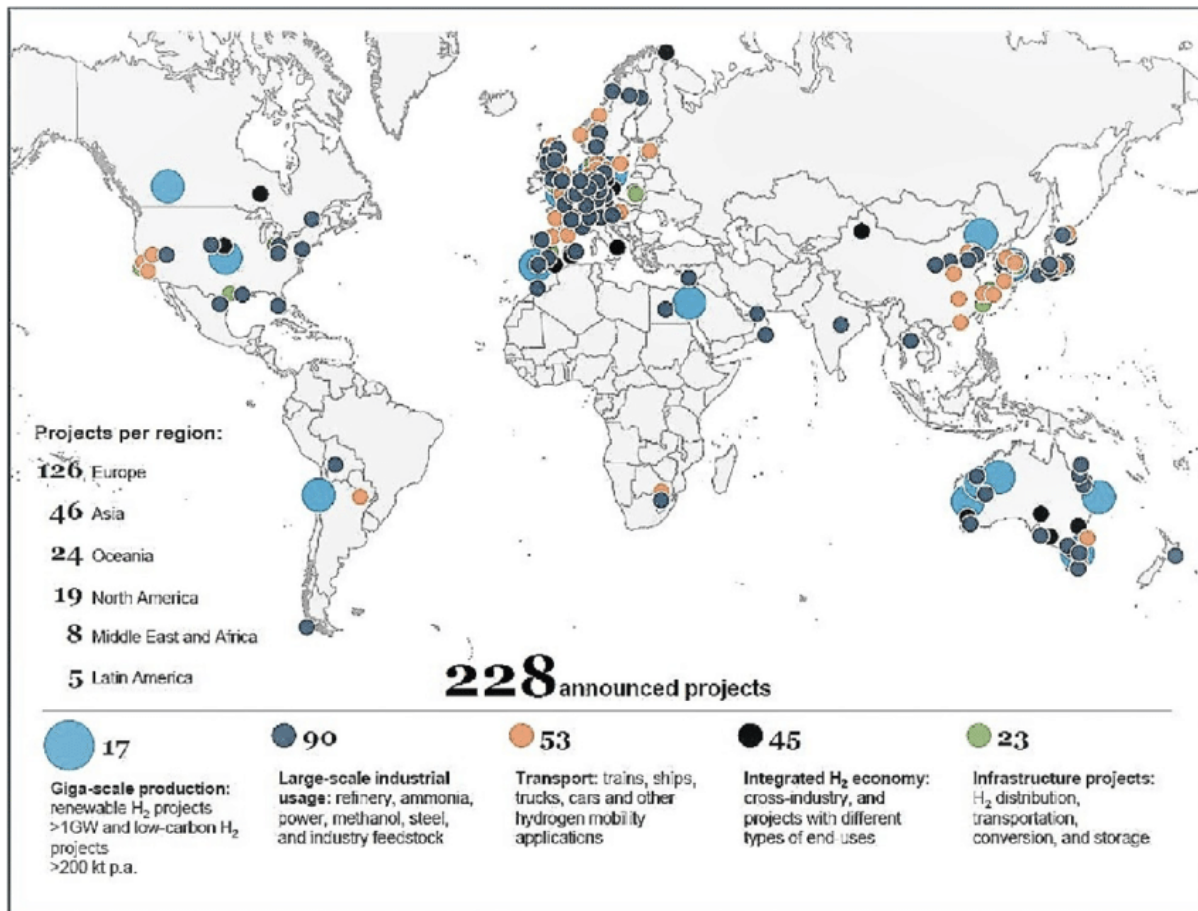


Fig. 3. Global announced hydrogen projects

Source: Okonkwo et al., 2021

The market for green hydrogen is projected to experience substantial growth in the coming years. According to various reports and market studies, the global green hydrogen market size is expected to reach significant values

in the next decade, with estimates ranging from tens of billions to hundreds of billions of dollars. By 2030, worldwide clean hydrogen trade among key areas is expected to reach above 30 MtH₂eq, representing 19% of global consumption, according to Deloitte's projection (Bernhard Lorentz et al., 2023). The Middle East, North Africa, and Australia have quickly made use of extra low-cost supply, placing them as major players in the global hydrogen market, according to Deloitte's outlook. The Middle East, historically a big exporter of oil and gas, takes the lead in early years of global commerce, exporting more than 13 MtH₂eq by 2030, which is equal to half of its domestic production. North Africa and Australia follow closely, exporting 7.5 MtH₂eq each, taking use of their substantial green hydrogen cost-competitive potential. Nearly 90% of the world's hydrogen will come from these three places by the end of the decade Figure (4).

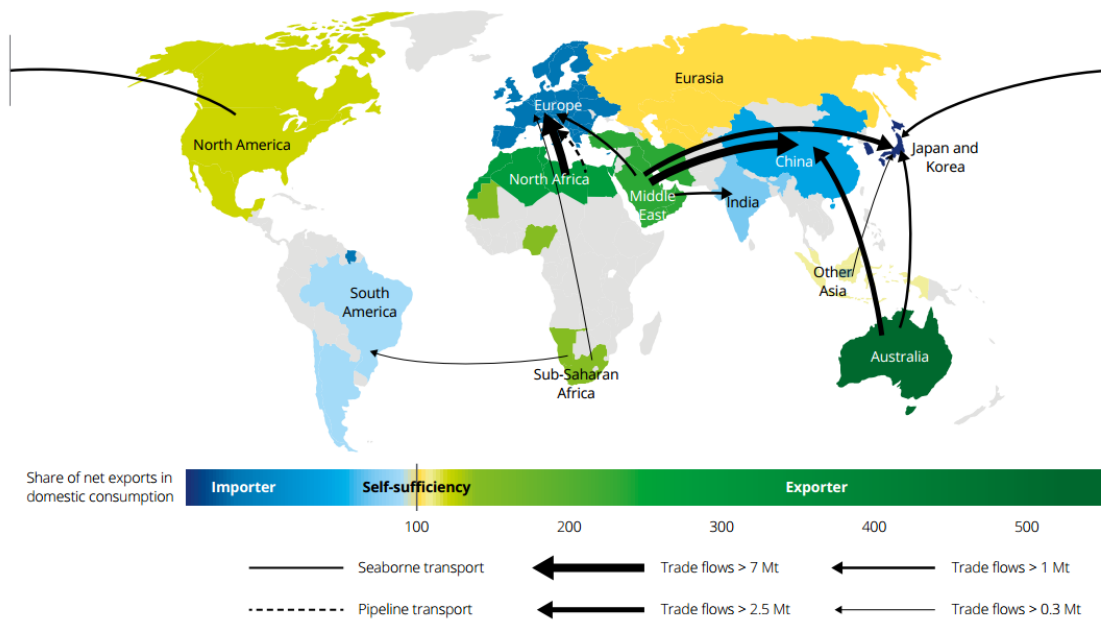


Fig. 4. Global hydrogen trade among key regions, 2030

Source: Deloitte analysis based on the HyPE model.

The market as a whole might expand significantly with clean hydrogen driving growth, from US\$160 billion in 2022 (Markets and Markets, 2022)—completely carbon-intensive hydrogen—to US\$640 billion in 2030 and US\$1.4 trillion in 2050 (Bernhard Lorentz et al., 2023). Because of cost reductions brought about by the large scale-up of green hydrogen, between 2030 and 2040, the market size will expand less in value (less than 1% constant annual growth) than in volume (9% constant annual growth). Market growth is projected to balance out between 2040 and 2050 as productivity improvements slow, figure (5) (Bernhard Lorentz et al., 2023).

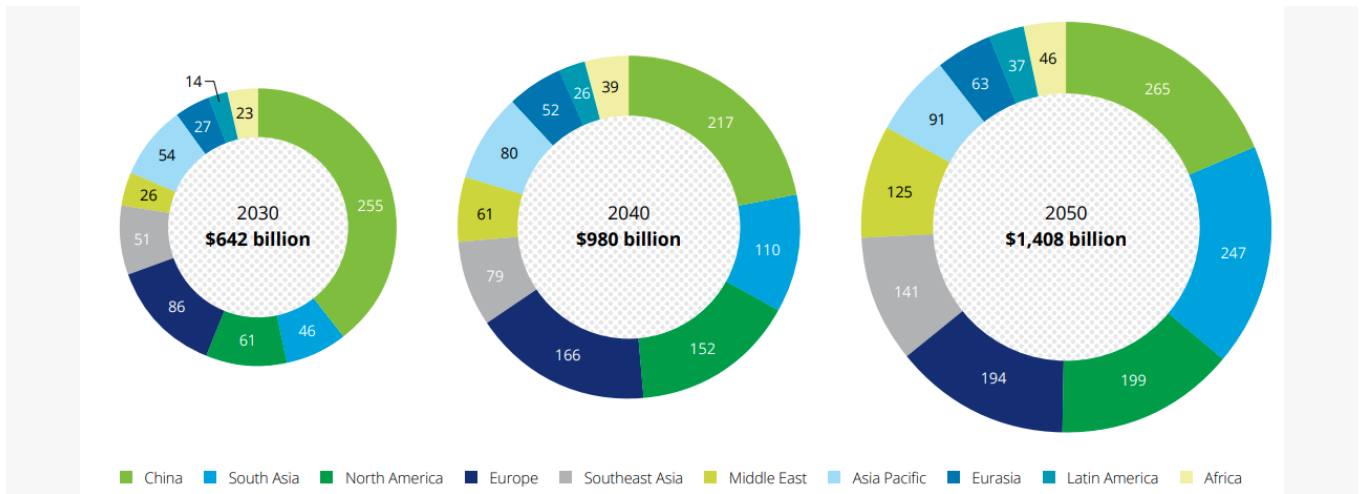


Fig. 5. Green hydrogen market size (US\$ billion per year), 2030 to 2050.

Source: Deloitte analysis based on the HyPE model.

The cost of green hydrogen production

The price of producing green hydrogen depends on a number of variables, such as location, the cost of renewable energy sources, and electrolysis equipment capital expenses. Even for green hydrogen production plants in prime locations for renewable energy, \$2 per kg is already a stretch goal for 2050, according to CRU's hydrogen cost model. Depending on the nation, this translates to a 50–70% decrease from current levels, with the cost of renewable energy having decreased by 50% and the capital cost of electrolysis systems having decreased by 75% (Butterworth et al., 2023), CRU expects the total cost of green hydrogen to a typical end user to be between \$3-7 per kilogram (at 2022 prices) in 2050, figure (6), taking into account the cost of storing, compressing and distributing the hydrogen, as well as electricity. Network connections. This means it will still be more expensive globally, on average, than blue-gray hydrogen derived from fossil gas in 2050, even when a carbon price is included (Paul Butterworth et al., 2023).

Figure (6)

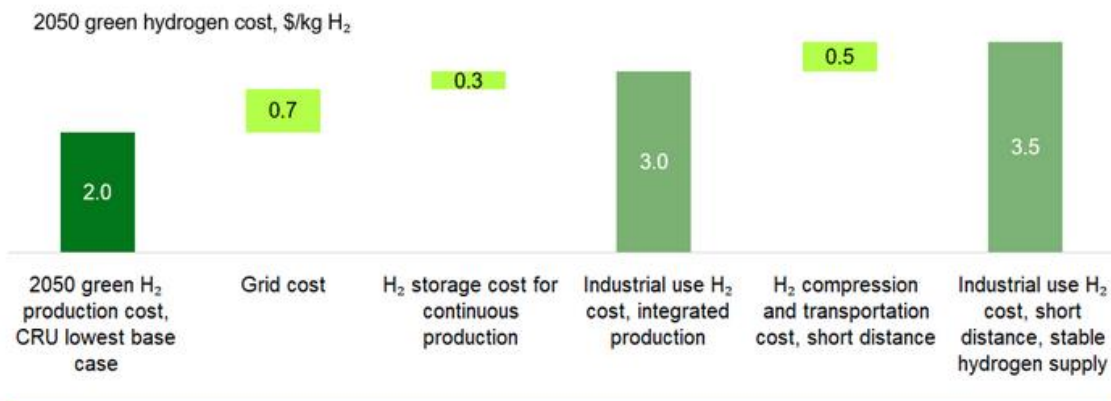


Fig. 6. The total green hydrogen cost to a typical end-user

Source: CRU hydrogen cost Model

The cost of producing green hydrogen in the MENA region is much lower than in Europe (Temmerberg and Kaltschmidt, 2019). According to S&P Global Platts, producing green hydrogen will be cheaper than producing blue hydrogen in Saudi Arabia, the UAE, Qatar and Oman, due to lower energy costs in the region (S&P Global Commodity Insights, 2023). The cheapest location for renewable hydrogen is Qatar, at a cost of just \$2.62 per kilogram, followed by Saudi Arabia, Oman and the United Arab Emirates. The cost of producing hydrogen in Hurghada, Egypt, using wind energy is US\$4.4/kg (Gado and Hassan, 2023), and the NEOM green hydrogen project in Saudi Arabia aims to produce 240,000 metric tons per year of renewable hydrogen by the end of 2020. 2026, With \$8.4 billion in financing provided by 23 banks and investment firms (S&P Global Commodity Insights, 2023). The Middle East is forecast to produce 18.15 million mt hydrogen by 2030, exporting one million mt of mostly low carbon and renewable hydrogen, by 2040, Middle East is seen leading all other regions with production projected at 28 million mt of clean hydrogen, with exports at 6.28 million mt (S&P Global Commodity Insights, 2023).

Table 2. Middle East: selected large hydrogen projects

Project	Country	Platts normalized capacity (million mt/year)
Suez Canal Economic Zone Globeleq Phase II	Egypt	0.57
Suez Canal Economic Zone Masdar Phase II	Egypt	0.48
Ocior Energy SCZone H2	Egypt	0.40
Fortescue Future Industries Egypt H2	Egypt	0.33
Suez Canal Economic Zone Masdar Phase I	Egypt	0.32
East Port Said /LOHC Hydrogen Hub	Egypt	0.30
Suez Canal Economic Zone KK Power	Egypt	0.23
Helios Green Fuels (Neom)	Saudi Arabia	0.22

Source: Hydrogen Production Assets database, S&P Global Commodity Insights

3.3. Social Factors

Green Education

Egypt's National Climate Change Strategy 2050 places a strong emphasis on the value of incorporating climate challenges into scientific research, education, technological transfer, and public awareness campaigns. Climate change, biodiversity, and environmental sustainability are just a few of the environmental themes and ideas that are highlighted in the new educational system and have been incorporated into several kindergarten and primary curriculum. Furthermore, a comprehensive plan to teach 25 million kids the value of protecting the environment was adopted by the Ministry of Education. In the Matrouh Governorate, the Ministry also started to develop the environmentally friendly smart community school's initiative. Targeting 100 schools in the governorates of Cairo, Giza, and Qalyubia, the similar project is currently underway Along with developing technical education, Egypt has established numerous technical schools, including several technological colleges and a solar energy school in Aswan (Ministry of Education, 2022).

Job Creation and Social Impact

The energy sector may undergo a significant reorganization, with the hydrogen economy playing a significant role. By 2030, clean technologies may generate up to 14 million new jobs, with an additional 16 million coming from the fossil fuel sector. Jobs related to renewable energy are typically labor-intensive compared to jobs using fossil fuels, hence energy employment increases as energy transitions. Furthermore, the clean hydrogen economy might provide a special conversion path for the numerous transferable talents from the fossil fuel business, like large project engineering, renewable energy deployment, and hydrogen transport and storage. The fact that a large portion of the positions created in the renewable energy sector require a postsecondary degree—60% of them, which is more than double the norm for the economy—is another factor contributing to productivity increase (Bernhard Lorentz et al., 2023). Egypt has succeeded in signing 9 agreements with international investors to implement projects to produce green hydrogen, with a total investment cost amounting to about 83.6 billion dollars in direct foreign investment, providing renewable energy capabilities of about 9.7 gigawatts in the pilot phase, reaching about 36.5 gigawatts in the first phase of the implemented projects, and allowing. These projects create about 44,000 direct job opportunities and 220,000 indirect job opportunities and contribute to reducing emissions by 37.6 million tons annually (SIS, 2023).

3.4. Technological Factors

The production of green hydrogen is chiefly achieved by electrolysis, a technique that involves using electricity sourced from renewables to decompose water into hydrogen and oxygen. Despite the established and validated status of this technology, several challenges persist that require resolution. For instance, there's a need to increase the efficiency of the electrolysis operations, to innovate in creating more stable and enduring electrolyzers, and to boost the energy storage density of hydrogen. Furthermore, the question of how to scale up looms large, with the expansion to wide-scale green hydrogen production demanding substantial investment in renewable energy frameworks, an endeavor that might not be immediately viable.

Technologically, critical issues remain, such as enhancing the electrolysis efficiency to make green hydrogen more cost-effective and furthering the progression of advanced electrolyzer technologies like solid oxide and proton exchange membrane (PEM) units (Hassan et al., 2023).

4. Key drivers of Scenarios

The selection of key drivers for green hydrogen involves a careful process where the various factors that significantly influence the future of green hydrogen in Egypt were examined and selected based on their potential impact on future scenarios. The selection included a comprehensive review of several elements, such as technological progress, government policies, market trends, and global economic conditions, etc., with the help of expert opinions, and analysis of current research and future reports on hydrogen, both at the global level and at MENA countries level. The next step was to identify the positive and negative trends for each driver, whether the internal drivers that can be directly influenced or the external drivers that cannot be controlled, which will help in forming the best and worst scenarios Table (3).

Table 3. list of internal and external key drives of change

Negative Direction	Internal drives	Positive Direction
Lack of coherent policies and limited government support could hamper industry growth and innovation.	Government Policies and Support	Robust policies, strategic support, and incentives could catalyze the development and adoption of green hydrogen technologies.
Limited investments could hinder technological advancements, keeping green hydrogen less competitive.	Investment in Research and Development (R&D)	Strong investments could foster innovation, lower costs, and improve the efficiency of green hydrogen technologies.
Lack of diversification strategies could make economies vulnerable and hinder green hydrogen development.	Economic Diversification Strategies	Strategies that prioritize green hydrogen could boost the industry, reducing dependency on fossil fuels.
Lack of focus on human capital development could lead to skill shortages and slow down industry progress.	Human Capital and Workforce Development	A skilled workforce could accelerate industry growth, innovation, and the implementation of green hydrogen projects.
Insufficient infrastructure could impede the efficient production and distribution of green hydrogen.	Infrastructure Development	Developing necessary infrastructure could enhance production capabilities and market accessibility.
Inconsistent or inadequate financial mechanisms could deter potential investors and developers.	Financial Mechanisms and Incentives	Financial incentives could attract investments and encourage project developments in green hydrogen.
Weak institutional support could lead to a lack of innovation and expertise in the sector.	Educational and Research Institutions	Strengthened institutions could propel research, innovation, and the availability of skilled professionals.
Lack of public awareness and acceptance could lead to resistance and slow industry growth.	Public Awareness and Acceptance	Enhanced awareness could facilitate broader acceptance and faster adoption of green hydrogen technologies.
Difficulty in integrating into existing grids and utilities could limit the practical application of green hydrogen.	Utility and Grid Integration	Successful integration strategies could maximize the utility of green hydrogen in energy systems.
Negative Direction	External drives	Positive Direction
Limited technological transfer and weak partnerships could hamper industry progress and global competitiveness.	Technological Transfer and International Partnerships	Collaborations could facilitate technological exchange, advancing the industry through shared innovation.
Weak or inconsistent sustainability trends could limit the appeal and prioritization of green hydrogen initiatives.	Environmental and Sustainability Trends	Increasing focus on sustainability could drive demand and innovation in green hydrogen technologies.
Geopolitical unrest or unfavorable policies could disrupt industry operations and global market access.	Geopolitical Factors and Global Policies	Stable geopolitical landscapes and supportive policies could facilitate industry growth and international collaborations.
Weak networks and limited collaborations could isolate markets and hinder technological advancements.	International Collaboration and Networks	Strong international networks could enhance knowledge sharing, investments, and market opportunities.
Restrictive trade barriers and limited market access could hamper export potentials and industry growth.	Market Access and Trade Agreements	Favorable agreements could foster industry expansion, opening up new markets and trade possibilities.
Inconsistent or weak global commitments could impede industry momentum and strategic focus.	Global Environmental Policies and Agreements	Strong global commitments could drive supportive policies and market demand for green hydrogen.
Limited availability could raise production costs and reduce the feasibility of green hydrogen projects.	Availability of Renewable Energy Resources	Abundant renewable resources could lower production costs and enhance the sustainability of green hydrogen.
Economic downturns could reduce investments, demand, and overall industry growth.	Global Economic Conditions	A robust global economy could facilitate investment flows and market expansion for green hydrogen.

Source: Authors

5. Future Scenarios

5.1. Best Case Scenario (“Sands of Sustainability: Harnessing Green Hydrogen in Egypt”)

Egypt leveraging decades of strategic planning and execution, have carved a significant niche in the global green hydrogen landscape by 2050. By 2050, Egypt emerged as linchpin in the global green hydrogen economy, leveraging the MENA region's intrinsic geographical and climatic advantages, coupled with strategic investments and policies implemented over the decades. Egypt became a global regional center for green hydrogen in 2030 and accounted for 8% of the global hydrogen market in 2040. Abundant solar and wind energy resources were relied upon to produce green hydrogen. Some policies and investment laws in green hydrogen have been changed to attract more investments. Egypt was able to export 50% of green hydrogen to the European Union in 2040, and by developing the green hydrogen industry in Egypt, it has supported economic growth, created job opportunities, reduced greenhouse gas emissions, and increased the country's competitiveness in the green energy sector. The Egyptian economy is witnessing an era of diversification and strength, fueled by the spread of the green hydrogen industry. Employment creation is rising, education and skill development are flourishing, and various sectors, from transportation to industry, are revitalized, creating a prosperity multiplier effect across societal strata.

Government Policies and Support

The Egyptian government has implemented a number of policies and support that will help Egypt achieve its goals, Egypt has worked to enhance its green hydrogen business, and since 2022 Egypt has signed several memorandums of understanding and contracts for the production of green hydrogen. Green hydrogen investment policies and laws have been changed to attract more investment and concessions to export green hydrogen to other regions, such as Europe and Asia, that are looking to decarbonize their economies. In 2023, an incentive for green hydrogen production ranging between 33% and 55% of tax dues was provided (Sarah Samir, 2023). Egypt has issued a number of laws aimed at promoting green hydrogen projects and related projects. Which encouraged the establishment of green hydrogen stations, as well as water desalination plants that allocate part of their production to green hydrogen.

The law also includes renewable energy facilities that allocate at least 95% of their production to green hydrogen and water desalination plants. In addition, projects dedicated to warehousing were encouraged; Transportation; And the distribution of green hydrogen also included projects to manufacture the raw materials needed for green hydrogen factories. Egypt has worked with a number of international partners, such as the European Bank for Reconstruction and Development, to support green hydrogen projects in the Suez Canal Economic Zone, and the National Green Hydrogen Council was established to coordinate and manage all aspects of green hydrogen activities in Egypt. A comprehensive national hydrogen strategy has been developed that defines the country's approach to developing and harnessing the potential of green hydrogen.

Market Access and Trade Agreements

By 2030, Egypt aimed to capture 5% of the global hydrogen market. The country established an international export center for hydrogen and its derivatives, successfully enhancing energy security and achieving sustainable development goals during this period. Additionally, Egypt became a regional hub for green hydrogen, exporting approximately 10 million tonnes of renewable energy to Europe. As the world focused on decarbonization and

improving energy security, Egypt's hydrogen demand increased significantly, reaching around 2% of global hydrogen demand. To facilitate the development of a hydrogen economy, Egypt collaborated with the European Bank for Reconstruction and Development to draft a national plan for green hydrogen, which outlined a phased approach consisting of a Pilot Phase, Scale-up Phase, and Full Implementation Phase. The Pilot Phase involved experimental projects, while the Scale-up Phase witnessed the expansion of green hydrogen initiatives. Egypt played a leading role in supplying hydrogen and its derivatives for the establishment of a low-carbon hydrogen economy.

by 2040, Egypt successfully captured 8% of the global hydrogen market. The country became the global regional center for green hydrogen, exporting approximately 50% of the European Union's green hydrogen. By this time, Egypt's hydrogen economy had entered the Full Implementation Phase, marked by the establishment of an international export center for hydrogen and derivatives, which significantly contributed to energy security and the fulfillment of sustainable development goals, the European and Asian markets will be key focus areas for establishing a strong export network. In 2050, Egypt successfully became the primary source of hydrogen for Europe, exporting around 10 million tonnes of renewable energy to the continent. The country's hydrogen economy was 400% larger by 2050 (Al-Orabi et al., 2023), with intentional trade accounting for 25% of the supply. To support this growth, Egypt's hydrogen production consumed seven times the amount of renewable electricity generated in 2020. By 2050, Egypt successfully captured up to 8% (10 million tonnes per annum) of the tradable market (Gado & Hassan, 2023). Achieving 100% green hydrogen by this time led to a cumulative CO₂ emission abatement of 417 gigatonnes of CO₂.

Reform of Education

Egypt has embarked on an ambitious path to become a global leader in green hydrogen production and technology. Over the next two decades, the nation underwent a remarkable transformation, not only in its energy landscape but also in its educational system, serving as an inspiring model for the entire MENA region. To realize its comprehensive roadmap for green hydrogen development, the government acknowledged the significance of a highly skilled workforce and initiated a series of educational reforms aimed at equipping the nation's youth to embrace the challenges and opportunities presented by the green hydrogen sector. This included the integration of green hydrogen education into the national curriculum from primary to tertiary levels, ensuring that students were exposed to concepts related to renewable energy, electrolysis, and hydrogen production from an early age. Egypt also established specialized institutes and research centers across the country, focusing on hydrogen technology and renewable energy. These institutions offered state-of-the-art programs and attracted leading experts and researchers from across the globe. Furthermore, to incentivize students to pursue degrees in fields related to hydrogen technology, the government introduced substantial scholarships and research grants, guaranteeing a continuous influx of talent into the sector.

Hydrogen Skills

With the high demand for skilled professionals in global and local labor markets, especially for technical positions such as engineers and technicians specializing in areas such as chemical processes, industrial engineering, health and safety, and high-voltage electricity in the hydrogen sector, Egypt has responded by expanding its educational and training programs. This expansion includes the introduction of specialized programs in hydrogen and fuel cell technologies at the master's and doctoral levels. Tailored training courses have been developed to meet the diverse needs of the hydrogen industry. Furthermore, vocational education now includes specializations designed to meet the immediate need for specialized skills and prepare the workforce for the expected expansion of the hydrogen sector. Egypt has also benefited from the widespread availability of hydrogen training globally and has established many partnerships with international universities focused on green hydrogen.

Human Capital and Workforce Development

The hydrogen economy could create up to 14 million jobs by 2030 and shift another 16 million jobs from the fossil fuel industry (Bernhard Lorentz et al., 2023), Egypt was able to obtain 8% of the global hydrogen market share. This has led to an increase in Egypt's GDP by between 10 and 18 billion dollars by 2025, in addition to providing more than 100,000 job opportunities (Fatma Ahmed, 2023). Egypt was able to develop a highly skilled and efficient workforce that meets the requirements of the green hydrogen industry. To position Egypt as a leader in the global green hydrogen market, vocational training programs and educational initiatives focusing on green hydrogen technologies were established in cooperation with educational institutions, vocational training centers and industrial associations to develop specialized courses and certificates, this has led to the availability of a skilled workforce with experience in areas such as electrolysis, hydrogen storage, and hydrogen infrastructure. International cooperation and knowledge transfer were enhanced through partnerships with leading countries in the green hydrogen sector and by facilitating exchange programs, research cooperation and technical assistance to benefit from the expertise and experience of existing players, which led to accelerating the learning curve and providing Egyptian professionals with global best practices. Support for entrepreneurship and the development of emerging green hydrogen companies was encouraged, and the establishment of incubators, accelerators and financing mechanisms that provide financial support, guidance and direction to aspiring entrepreneurs in the green hydrogen sector was encouraged.

Infrastructure Development

Egypt has created a green hydrogen infrastructure by implementing a comprehensive strategy that included a thorough evaluation of the country's existing infrastructure to identify deficiencies and establish the conditions for integrating green hydrogen technology. Hydrogen production facilities, such as electrolyzers that employ renewable energy sources like solar and wind energy, have been created. Technologies and infrastructure for the storage of compressed hydrogen as well as strategies for compounds like ammonia have been developed. Pipelines have been developed and constructed to enable safe and dependable transit of hydrogen, and a strong and effective hydrogen distribution network connecting production sites to end customers has been established. A network of hydrogen refueling stations has been established to assist the adoption of hydrogen-powered transportation as the culture of dependence on hydrogen has grown. To allow the international trade of green hydrogen, infrastructure and logistical skills have also been built. To serve the global supply chain and ensure seamless integration and compliance with trade regulations, export terminals and import facilities have been created.

5.2. Worst Case Scenario (“Sands of Stagnation: Barriers Bloating Egypt’s Green Hydrogen Vision”)

The worst-case scenario, which is a warning scenario, aims to draw a hypothetical image of what Egypt will look like if it does not exploit the current and future opportunities in green hydrogen or is exposed to some external drives that cannot be controlled.

Organizational failure

There is a delay in developing a thorough regulatory framework that focuses on local production of green hydrogen, a critical component of the national strategy, in view of expanding international prospects. This can result in unclear policies and inconsistent laws, which could hinder both domestic and foreign investment in this industry. In addition to the lack of donations that create tax incentive packages and stimulate investment, this may also result in a lack of incentives and support for the creation of green hydrogen projects, which could impede the industry's growth.

Lack of international cooperation

Egypt's ability to acquire cutting-edge technology, industrial best practices, and expertise in the field of green hydrogen has been constrained by a lack of international cooperation and a reliance on only a few nations. Egypt's attempt to establish itself as a significant regional producer of the substances has been hampered by the difficulty it now has in exporting green hydrogen to other nations. Egypt's competitiveness in the worldwide market for green hydrogen has decreased as a result of the absence of international cooperation, which has also prevented access to the most recent technology, industry best practices, and knowledge in the field.

Economic and financial challenges

In the worst scenario, Egypt would experience financial and economic issues that would impede the growth of the green hydrogen industry. The expansion of green hydrogen programs may be hampered by a lack of finance. Industry funding may be insufficient if investors fail to recognize the financial sustainability of participating in this sector. It is now more expensive to produce green hydrogen than other forms of energy, making it more expensive for investors to invest in this sector. Egypt might become too reliant on conventional energy sources, which would hurt the green hydrogen industry's ability to expand and compete. This might lead to a lack of investment in the green hydrogen market, which would prevent initiatives utilizing green hydrogen from receiving funding and assistance. Lack of funding and assistance may impede the industry's expansion, making it challenging for Egypt to win a sizable portion of the world hydrogen market. The development of the green hydrogen industry may also be hampered by inadequate infrastructure, such as a lack of access to cost-effective and dependable renewable energy sources, inadequate storage and transportation infrastructure, and a shortage of competent labor.

Technological Recession

Although Egypt developed centers and institutions for specialized study at first, their closure was caused by insufficient administration and limited funding. These universities became less competitive, and the nation's capacity to draw in foreign scholars and experts declined. The Egyptian green hydrogen industry could potentially suffer from a lack of innovation. This might happen as a result of insufficient funding for research, development, and innovation, which would cause a decline in technological advancement. Egypt might adopt new technology later than other countries, which would hurt its ability to compete in the global green hydrogen market. Because of this, Egypt may struggle to win a sizable portion of the global hydrogen industry due to a lack of innovation and competitiveness.

Reforms to green hydrogen education falter

Reforming the educational system faced resistance and bureaucratic roadblocks, even in spite of the government's early goals. With little practical implementation, the proposed educational reforms aimed at preparing the next generation of students for the green hydrogen industry have mainly stayed in theory. There hasn't been a thorough framework or depth to the incorporation of green hydrogen education in the national curriculum. Students are not gaining the necessary knowledge and abilities in these areas since subjects related to electrolysis, renewable energy, and hydrogen production have not been sufficiently developed.

Human Capital Deficits

Egypt might face a skilled labor shortage in the green hydrogen sector, which could impede the sector's expansion. This could result in a lack of expertise and experience, which could make it challenging for Egypt to create and put in place a thorough regulatory framework and draw in international investment. The green

hydrogen business may experience a shortage of qualified professionals and specialists due to a lack of emphasis on education and training, which would impede productivity, innovation, and industry expansion. Additionally, Egypt may see a brain drain as people pursue possibilities in more suitable global markets due to a lack of prospects and industry support. This could result in a lack of qualified and experienced professionals, which could hinder Egypt's ability to grow and modernize.

Infrastructural deficiencies

Egypt's assessment of existing infrastructure to identify deficiencies was insufficient. As a result, the country's efforts to integrate green hydrogen technology have been hampered by a lack of understanding of the necessary upgrades and modifications required. Planned hydrogen production facilities using renewable energy sources such as solar and wind have faced chronic problems such as lack of investment and setbacks. Technological. These facilities have struggled to operate reliably, limiting green hydrogen production. The development and construction of hydrogen pipelines has faced delays and cost overruns. As a result, the promised safe and reliable transport of hydrogen remains a distant goal. The hydrogen distribution network linking production sites to end customers was inefficient and fragmented. Egypt's plans for international trade in green hydrogen have faced logistical challenges and regulatory obstacles. Export terminals and import facilities have suffered delays, hampering the country's ability to effectively participate in the global green hydrogen market.

6. Policy Recommendations

By implementing these policy recommendations, Egypt can move away from pessimistic scenarios and create an enabling environment for the growth of the green hydrogen industry, ensuring long-term success and sustainability.

- Support a strong regulatory framework with a strong focus on domestic green hydrogen production through the National Green Hydrogen Strategy. This framework would facilitate an enabling environment for domestic and foreign investments in this sector and regulate investments.
- Strengthening international cooperation and partnerships with a variety of countries developed in green hydrogen technologies to access the latest technologies, best practices and experience in the field of green hydrogen.
- Prioritize investments in developing green hydrogen infrastructure, including access to cost-effective renewable energy sources, establishing reliable infrastructure for hydrogen storage and transportation, and developing a skilled workforce. Ensuring the necessary infrastructure is in place to support the thriving green hydrogen industry.
- Support and financially support specialized educational institutions to maintain their competitiveness, attract foreign scientists and experts, and allocate resources to research, development and innovation to drive technological progress and enhance competitiveness in the global green hydrogen market.
- Ensure the full integration of green hydrogen education into the national curriculum, with a focus on providing practical knowledge and skills related to electrolysis, renewable energy and hydrogen production to students.
- Invest in educational and training programs to address the potential shortage of skilled workers in the green hydrogen sector. Creating opportunities for local talent to gain expertise and experience, thus reducing dependence on foreign experts and professionals.
- Ensure that planned hydrogen production facilities using renewable energy sources receive adequate funding and adhere to stringent technical standards.

- Accelerate the expansion of hydrogen pipelines and distribution networks to create a safe and reliable hydrogen transportation system.

Conclusion

the future scenarios for Egypt's green hydrogen industry present a stark contrast between the best-case and worst-case outcomes. The best-case scenario, as envisioned in "Sands of Sustainability: Harnessing Green Hydrogen in Egypt," depicts Egypt as a global leader in green hydrogen production and technology by 2050. Through strategic planning, government policies, international cooperation, and educational reforms, Egypt successfully harnessed its natural resources and transformed into a key player in the global green hydrogen market. This scenario paints a picture of economic prosperity, job creation, technological innovation, and a diversified energy landscape, all driven by the growth of the green hydrogen sector. While the worst-case scenario, "Sands of Stagnation: Barriers Bloating Egypt's Green Hydrogen Vision," serves as a cautionary tale. It illustrates the potential pitfalls and challenges that Egypt could face if it fails to seize opportunities or encounters unanticipated external obstacles. Organizational failures, a lack of international cooperation, economic and financial challenges, technological stagnation, and educational inertia all contribute to a scenario where Egypt's green hydrogen ambitions are stifled. This could result in missed economic growth, job opportunities, and the failure to establish a prominent presence in the global green hydrogen market.

The contrast between these two scenarios underscores the importance of proactive and thoughtful policies, investments, and strategies to ensure that Egypt's green hydrogen vision becomes a reality. While the best-case scenario represents an inspiring vision of Egypt's potential, the worst-case scenario serves as a reminder of the risks and challenges that must be addressed to avoid stagnation and missed opportunities. Egypt's path in the coming decades will depend on its ability to overcome these challenges and leverage its strengths to become a global leader in green hydrogen production and technology.

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