

Egypt's Green Hydrogen Renaissance- A Blueprint for Global Decarbonization and Sustainable Industrialization

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Abstract—Amidst the urgent global energy transition, this study illuminates Egypt's pivotal emergence as a leader in green hydrogen, leveraging its unparalleled renewable energy potential to forge a sustainable future. We demonstrate the compelling techno economic feasibility of integrated Photovoltaic Wind systems, achieving up to 36.71 percent efficiency and an annual hydrogen yield of 216 tons, alongside significant CO₂ emission reductions. Strategic multinational alliances, exemplified by the Egypt Green Hydrogen project, are analyzed as powerful models for public-private partnerships, aligning commercial objectives with national development agendas like Egypt Vision 2030 to drive sustainable industrialization. Economically, Egypt's projected hydrogen demand of 6.0 million tons by 2050, underpinned by a competitive Levelized Cost of Hydrogen of approximately Dollars 4.5 per kg, underscores its formidable market potential. Crucially, the inherent challenge of water scarcity, with large-scale production potentially requiring 0.9 billion cubic meters annually, is met with the innovative proposal of renewable-powered seawater desalination. This comprehensive analysis positions green hydrogen not merely as a versatile energy carrier, but as Egypt's strategic keystone for decarbonization and energy security, offering a robust blueprint for nations worldwide striving towards a net-zero economy.

Keywords — *Pioneering Atlas Unveiled; Economic Edge Quantified; Dual Hydrogen Frontiers; Egypt as a Green Vanguard*

I. INTRODUCTION

Amidst the global pursuit of clean energy solutions, this study explores the pivotal role of green hydrogen in advancing sustainable development in Egypt. Focusing on the country's abundant renewable energy potential, the investigation first examines the feasibility of integrated PV-Wind power systems for green hydrogen production, highlighting a maximum system efficiency of 36.71%, an annual hydrogen yield of up to 216 tons, and a significant CO₂ emission reduction potential [1]. Furthermore, the manuscript analyzes the Egypt Green Hydrogen project as a strategic multinational alliance, demonstrating how public-private partnerships can align commercial objectives with national development agendas like Egypt Vision 2030 to foster sustainable industrialization [2]. The study also considers the economic viability, projecting

Egypt's hydrogen demand to reach 6.0 million tons by 2050, driven by a competitive Levelized Cost of Hydrogen (LCOH) of approximately \$4.5/kg. However, it addresses the critical challenge of water scarcity, noting that large-scale production could require up to 0.9 billion cubic meters (BCM) of water annually, and proposes seawater desalination powered by renewables as a sustainable solution [3 and 4]. This research thus provides a comprehensive overview of the technical, strategic, and environmental factors influencing Egypt's emergence as a leader in the global hydrogen market.

The Imperative for a Hydrogen-Powered Future. The global energy landscape is undergoing a seismic transformation; a paradigm shift impelled by the urgent need to curtail carbon emissions and staunch the escalating impacts of climate change. Amidst this transition, green hydrogen has emerged not merely as a fuel, but as a versatile keystone for a decarbonized world "jack-of-all-trades" energy carrier. It promises to seamlessly store vast reserves of renewable energy, unlock decarbonization pathways for notoriously hard-to-abate industries, and fortify national energy security. Within this global quest, Egypt, with its sun-drenched desert expanses and powerful wind corridors, stands as a land of exceptional promise, uniquely positioned to become a titan in green energy deployment. Guided by an ambitious national strategy to diversify its energy portfolio and cement its status as a pivotal regional energy hub, Egypt is now resolutely embarking on the large-scale development of sophisticated green hydrogen infrastructure.

This review seeks to synthesize the current understanding and illuminate the path forward by exploring the multifaceted dimensions of green hydrogen, with a particular lens on Egypt's burgeoning capabilities. It delves into the techno-economic feasibility of harnessing the nation's abundant solar and wind resources to power electrolyzes for green hydrogen production. We will examine how advanced methodologies, such as intricate Geographic Information Systems (GIS) analyses coupled with dynamic simulation modeling, are crucial for forecasting critical metrics. These include the Levelized Cost of Hydrogen (LCOH), nuanced electricity generation patterns, potential hydrogen output, and the

profound carbon dioxide (CO₂) emission reductions achievable across Egypt's 27 governorates. Beyond centralized utility-scale projects, this review will also consider the innovative application of off-grid hydrogen systems to energize remote communities and scrutinize the compelling economic opportunities inherent in the burgeoning international hydrogen trade. The Suez Canal region, a globally strategic artery for shipping and export logistics, serves as a particularly insightful case study for understanding these export dynamics. This comprehensive backdrop sets the stage for a multi-disciplinary exploration, weaving together threads of technology, geography, economics, and policy, to chart a course for sustainable and impactful hydrogen development in Egypt and offer lessons for the world.

II. UNVEILING GREEN HYDROGEN: THE SPECTRUM OF A CLEAN ENERGY CARRIER

A. The Palette of Hydrogen: Understanding the Colors of Production

Hydrogen, a fundamental element, can be coaxed into existence from a diverse array of feedstocks, encompassing both renewable and conventional non-renewable sources, with global production currently hovering around 87 million tons annually [24]. However, the prevailing narrative, as of 2020, reveals that an overwhelming 95% of this hydrogen was derived from fossil fuels, predominantly through steam methane reforming of natural gas. This conventional route is far from benign, unleashing an estimated 830 million tons of CO₂ into the atmosphere each year, while only a sliver of hydrogen production stemmed from cleaner, renewable pathways like water electrolysis [5]. The primary hydrogen generation strategies and their applications are visually elucidated in Figure 1.

To navigate this complex production landscape, a color-coded classification system has emerged, distinguishing hydrogen types—blue, gray, brown/black, and the coveted green—based on their originating technology, energy source, and ultimate environmental footprint, as detailed in the next text. **Brown Hydrogen:** this type of hydrogen is produced through the **gasification of brown coal (lignite)**, resulting in a product of H₂+CO₂. Unabated, it costs between **\$1.20 - \$2.10 USD/kg H₂** and has high CO₂ emissions of **19–26 kg CO₂e/kg H₂**. It has a very high global warming impact. However, with over 98% Carbon Capture and Storage (CCS), emissions are significantly reduced to 0.4–0.6 kg CO₂/kg H₂, though the cost rises to approximately 3.50 USD/kg H₂. **Black Hydrogen;** similar to brown hydrogen, black hydrogen is also produced via the **gasification of black coal (bituminous)**. The key products are H₂+CO₂, and the unabated cost is the same at **\$1.20 - \$2.10 USD/kg H₂**. The unabated CO₂ emissions are also high, at **19–26 kg CO₂e/kg H₂**. It shares a very high global warming impact with brown hydrogen. With over 98% CCS, emissions are reduced to 0.4–0.6 kg CO₂/kg H₂, and the cost is around 1.60 USD/kg H₂. **Grey Hydrogen;** grey hydrogen is produced using **reforming (SMR)** from **natural gas**, releasing H₂+CO₂ into the atmosphere. It is the cheapest industrial source, with costs ranging from **\$1.00 - \$2.10 USD/kg H₂** (unabated) and CO₂ emissions between **10–19 kg CO₂e/kg H₂** (unabated). This accounts for over 95% of global hydrogen production, but a significant concern

is methane leakage from the natural gas supply chain, which also contributes to greenhouse gas emissions. **Blue Hydrogen;** produced from **natural gas** using **reforming (SMR) combined with Carbon Capture**, blue hydrogen results in H₂ and CO₂ that is **85–95% captured**. It's considered the cheapest "clean" alternative, with a cost of **\$1.50 - \$2.90 USD/kg H₂** and emissions of **1–5 kg CO₂e/kg H₂** (both with CCS). However, it is still subject to methane leakage from the natural gas supply chain. **Green Hydrogen:** green hydrogen is created through the **electrolysis of water** using **renewable electricity**. This process yields H₂+O₂. It has **no direct CO₂ emissions**, with embedded emissions from manufacturing equipment being only **0.4–2.7 kg CO₂e/kg H₂**. Currently, it's the most expensive option, costing **\$3.60 - \$9.30 USD/kg H₂**. This is two to three times more expensive than fossil hydrogen, but costs are expected to decrease in the future [6].

Blue Hydrogen: Forged from natural gas via steam reforming, blue hydrogen incorporates carbon capture, utilization, and storage (CCUS) technologies to sequester 85–95% of the coproduced CO₂. While an improvement, the residual uncaptured CO₂, coupled with uncertainties surrounding the long-term integrity of CO₂ storage and potential leakage, casts a shadow on its environmental credentials [7, 8, 9].

Gray Hydrogen: Produced similarly to blue hydrogen from fossil fuels like natural gas or coal, gray hydrogen makes no attempt to capture the resultant CO₂. This CO₂ is directly vented into the atmosphere, rendering it a significant contributor to greenhouse gas emissions [10].

Brown or Black Hydrogen: Currently the most prevalent in industrial use, brown (from lignite/brown coal) or black (from bituminous coal) hydrogen is typically generated through coal gasification. This process is notoriously carbon-intensive, with each ton of brown hydrogen releasing approximately 10–12 tons of CO₂. Black hydrogen, similarly, involves separating hydrogen from syngas produced via coal gasification, with remaining gases often released [11].

Green Hydrogen: The Gold Standard: In stark contrast, green hydrogen is the epitome of clean energy. It is meticulously produced through water electrolysis, a process powered exclusively by renewable electricity sources like solar and wind. This elegant method splits water (H₂O) into its constituent hydrogen (H₂) and oxygen (O₂) with virtually zero carbon emissions. As the global momentum towards decarbonization accelerates, renewable-powered green hydrogen is increasingly recognized as a linchpin strategy for drastically reducing greenhouse gas emissions and alleviating environmental pollution. Consequently, there is an escalating global drive to enhance the scalability, flexibility, and economic viability of green hydrogen production and utilization. Water electrolysis, energized by abundant and well-distributed solar and wind power, stands as the cornerstone technology [12]. The synergy of renewables and electrolysis is particularly compelling, as surplus renewable electricity—often intermittent—can be chemically stored as hydrogen, thus ingeniously balancing energy supply and demand [13]. Furthermore, the hydrogen and oxygen produced can be directly integrated into the transportation and industrial sectors as primary energy sources or vital feedstocks [14]. Hydrogen is not merely a source; it is an agile energy carrier, primed for

fuel cell vehicles and diverse industrial applications, including the production of ammonia and synthetic fuels in chemical and superior efficiency of hydrogen storage systems when benchmarked against conventional battery technologies [16].

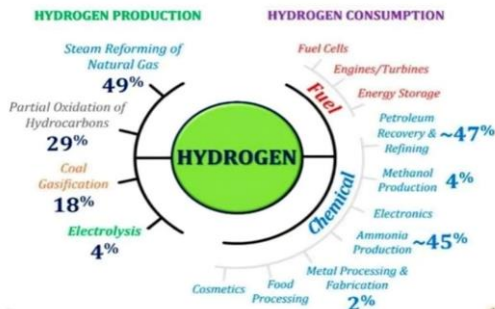


Fig. 1. Hydrogen Production & Consumption.

C. The Unmistakable Advantages: Why Green Hydrogen Shines

In the enduring debate between fossil fuels and renewable energies, the case for renewables grows stronger by the day, though they are not without perceived challenges, primarily their intermittency—their reliance on natural elements [18]. Historically, the absence of wind meant no wind power; nightfall curtailed solar generation. Humanity cannot yet command the sun to shine on demand or summon winds at will. Thus, a global endeavor has focused on developing robust mechanisms to store the surplus energy generated during favorable conditions for deployment when nature is less cooperative.

The preeminent contender for this role? Green hydrogen. Derived from renewable sources via electrolysis, this clean hydrogen can be efficiently compressed and stored in specialized tanks. When energy is required, this stored hydrogen is channeled into a fuel cell, where its

hydrogen's impact will extend further, proving critical for decarbonizing mining vehicles, trains, aircraft, heavy-duty lorries, buses, and even maritime transport [20].

Green Hydrogen in the Hearth and Home: Beyond transport, green hydrogen is making inroads into residential applications. Pioneering sustainable projects are underway aiming to replace existing natural gas networks with dedicated green hydrogen pipelines, providing clean electricity and heat to homes without generating harmful emissions. Green hydrogen is unequivocally assuming a leading role in the comprehensive decarbonization of the global economy. As the world pivots towards a post-COVID-19 landscape powered by renewables, green hydrogen stands as a central enabler. However, challenges in its widespread rollout persist, including further reducing production costs, enhancing storage solutions, and deploying the requisite infrastructure. These are formidable, yet surmountable, hurdles that must be overcome to solidify green hydrogen not as an energy of a distant future, but as the cornerstone of a more sustainable present [21, citing IRENA, Hydrogen Council].

Its utility extends deeply into the chemical, oil, and gas sectors, and it's increasingly adopted in transportation via

petrochemical industries [15]. Another salient advantage is the

B. The Expanding Horizon: Applications of Green Hydrogen

Green hydrogen is rapidly ascending as an indispensable pillar in the global energy transition, crucial for architecting a sustainable future. The confluence of diminishing production costs—driven by cheaper renewable energy—and a robust global impetus to slash greenhouse gas emissions has endowed clean hydrogen with unprecedented momentum [17]. This versatile energy carrier is poised to play a transformative role in decarbonizing a spectrum of vital sectors, including heavy industry, global mobility, and large-scale energy storage. The anticipation surrounding green hydrogen's potential is palpable and well-founded. This review will delve into its diverse applications, building upon the foundational understanding of its nature.

electrochemical reaction with oxygen from the air generates electricity, with pure water as its sole, benign by-product [19]. This elegant cycle transforms intermittent renewables into a dispatchable, clean energy source.

D. A Tapestry of Uses: Green Hydrogen in Action

Green Hydrogen as a Transformative Fuel: Propelled by innovations like advanced fuel cells, green hydrogen is revolutionizing transport, offering a genuinely sustainable mobility paradigm. Hydrogen-powered fuel cell electric vehicles (FCEVs) generate onboard electricity, powering motors with a carbon-neutral footprint. While currently representing a modest 0.5% of new low-emission vehicle sales, the FCEV market is on the cusp of significant expansion, according to the International Energy Agency. Visionary commitments, such as Hyundai's plan for 500,000 hydrogen vehicles by 2030, Parisian hydrogen taxi fleets, and hydrogen-fueled waste collection vehicles in European cities, signal this burgeoning shift. Green

Internal Combustion Engines (ICEs) adapted for hydrogen, and more efficiently, fuel cells [22]. Hydrogen fuel cells, in particular, harbor immense potential to drastically improve energy efficiency in transportation, significantly curtail greenhouse gas emissions, and ultimately displace fossil fuels entirely [23]. Their application is not confined to trucks, buses, and cars; they are also poised to power electric ships and replace diesel-electric generators in trains [24]. Regarded as the most promising power source for next-generation automobiles within a hydrogen-centric economy, fuel cells are perhaps the only technology capable of rivaling the performance of ICEs. The primary allure of hydrogen as a fuel is its inherent suitability for fuel cells, which, when powered by pure hydrogen, produce only water as a by-product, thus qualifying as true zero-emission vehicles. While offering comparable top speed, range, and acceleration, fuel cell vehicles boast significantly higher efficiency than conventional vehicles [25]. Among various fuel cell types, Proton Exchange Membrane Fuel Cells (PEMFCs) are deemed most apt for mobile applications due to their rapid response to load changes, quick start-up times, and exceptionally high power density [26].

III. GLOBAL PULSE: SIZING THE INTERNATIONAL HYDROGEN MARKET

The multifaceted applications of hydrogen are gaining worldwide recognition, fueling a consistent surge in its demand and utilization across an expanding array of sectors. This positions hydrogen as a potentially transformative contributor to global clean energy transitions. Historically, hydrogen demand has exhibited linear growth, primarily serving as a feedstock in the chemical industry for oil refining and the production of ammonia, methanol, and fertilizers, as well as in food and pharmaceutical manufacturing, metal processing, and the nascent field of low-carbon steel production [27 and 28]. Its role as a fuel to generate electricity in fuel cells is also established, and it is increasingly being embraced as a sustainable fuel for future power generation in buildings and the transport sector [27 and 28].

The projected annual global demand for hydrogen, segmented by sectors such as oil refining, industry, transport, power, ammonia (as fuel), synthetic fuels, buildings, and grid injection, is illustrated in the next text, while Figure 2 depicts the anticipated share of hydrogen demand in key sectors relative to other fuels.

In **2020**, the total hydrogen demand was primarily driven by **refining** (37.18 Mt) and **industry** (51.3 Mt). Other sectors like transport (0.02 Mt) and buildings (0.01 Mt) had very low demand, while power, ammonia fuel, synfuels, and grid injection had no demand. By **2025**, the landscape is projected to shift. While **refining** demand is expected to decrease to 33.82 Mt, **industry** demand is set to rise significantly to 63.22 Mt. New sectors are also emerging: **transport** demand is

projected at 2.12 Mt, and **ammonia fuel** and **synfuels** will start to see notable use at 7.53 Mt and 1.1 Mt, respectively. Additionally, **buildings** demand will increase to 2.25 Mt, and **grid injection** will see a substantial rise to 23.85 Mt. Looking ahead to **2030**, the trends become even more pronounced. **Refining** demand will continue to fall to 25.78 Mt, but **industry** demand will grow further to 75 Mt. The use of hydrogen in new sectors will accelerate dramatically: **transport** demand will jump to 8.55 Mt, **power** will emerge with a demand of 18.5 Mt, and **ammonia fuel** use will more than double to 18.11 Mt. **Synfuels** will also see significant growth to 7.28 Mt, and demand from **buildings** will reach 5.64 Mt. Finally, **grid injection** is set to more than double to 51.7 Mt, highlighting its growing role in energy infrastructure [29 and 30].

Within the European Union, for instance, demand is forecasted to soar beyond 100 million tons by 2050 (Figure 2). Hydrogen produced with Carbon Capture, Utilization, and Storage (CCUS) technologies is also factored into pathways aiming for net-zero emissions by 2050 [29]. The anticipated growth of hydrogen demand in emerging sectors, particularly within the EU, is projected to exceed 100 million tons by 2050

(Figure 3), spurring significant industrial interest in developing large-scale hydrogen projects across multiple regions [30]. The potential global market for hydrogen technology is staggering, estimated to approach USD 2.5 trillion [31]. Annual power generation from fuel cells, a key hydrogen application, has already increased fifteenfold since 2015, now surpassing 1 gigawatt (GW)

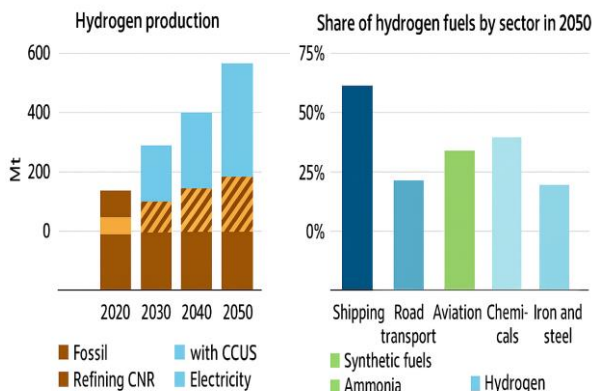


Fig. 2. Expected annual demand for hydrogen based on (a) hydrogen production technologies and (b) sectors (Mt). Hydrogen produced by electrolysis, and also as a by-product of catalytic naphtha Reforming (CNR) based on technology of carbon capture, utilization and storage (CCUS). Reprinted With permission [29]

A. A New Energy Epicenter: Market Dynamics in Africa and the Middle East (MENA)

The Middle East and North Africa (MENA) region is endowed with world-class renewable energy resources, positioning it with immense potential to emerge as a preeminent global hub for renewable energy generation and sophisticated hydrogen-based industries [36]. A palpable surge

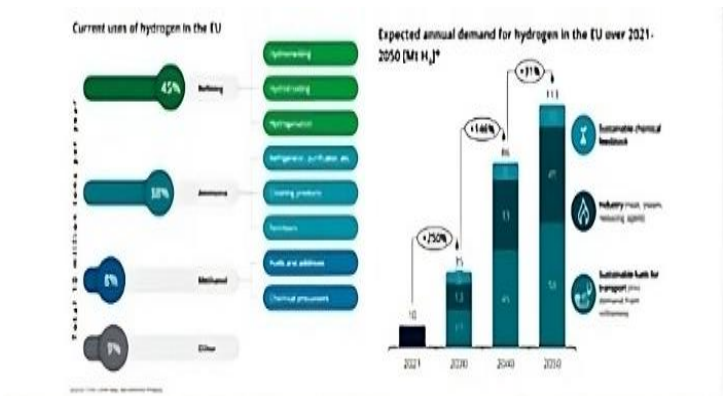


Fig. 3. Hydrogen prospects of the different industrial sectors in the EU, (a) current usage of Hydrogen, (b) expected hydrogen demand. * excluding potential of hydrogen in enabling renewable Energy and in heating for build gas. Reprinted with permission [35].

of interest in cultivating a vibrant green hydrogen economy is sweeping the MENA region, driven by its dual promise of enhancing energy security and championing environmental stewardship. According to [37], several nations within this dynamic region, notably Egypt, Saudi Arabia, and Turkey, already possess significant industrial expertise pertinent to the green hydrogen technology value chain (Figure 4). Furthermore, the strategic expansion of pipeline infrastructure

from Morocco, Algeria, and Tunisia could potentially satisfy a substantial portion of Europe's projected green hydrogen demand by 2050. The landed cost of green hydrogen produced in and delivered from the MENA region to Europe is competitively estimated at approximately €2/kgH₂ [38].

The green hydrogen market is on a trajectory of exponential growth in the forthcoming years. A consensus across various

outlook positions the Middle East, North Africa, and Australia as early-mover powerhouses, rapidly capitalizing on their abundant, low-cost renewable resources to become dominant players in the nascent global hydrogen market. The Middle East, leveraging its legacy as a major oil and gas exporter, is anticipated to lead early global trade, exporting over 13 MtH₂eq by 2030—equivalent to half its domestic production. North Africa and Australia are projected to follow closely, each exporting approximately 7.5 MtH₂eq, capitalizing on their substantial cost-competitive green hydrogen potential. Collectively, these three geostrategic regions are forecasted to supply nearly 90% of the world's internationally traded hydrogen by the decade's end (Figure 5).

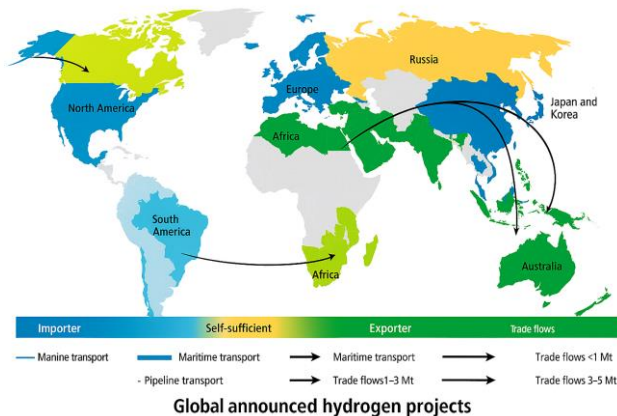


Fig. 4. Global announced hydrogen projects Source: [38]

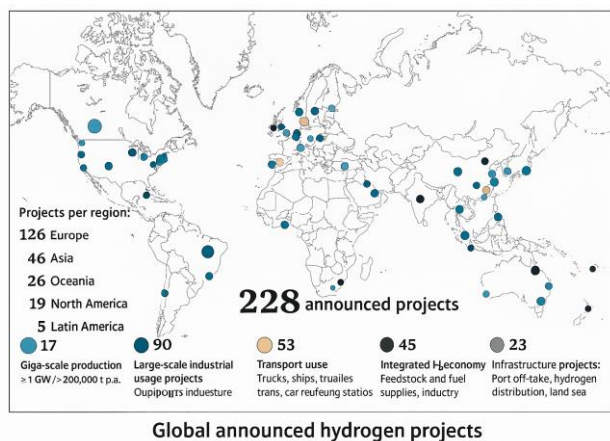


Fig. 5. Global hydrogen trade among key regions, 2030 Source: Deloitte analysis based on the HyPE model

market reports and studies indicates that the global green hydrogen market size will achieve huge valuations within the next decade, with projections spanning from tens to hundreds of billions of dollars. Deloitte's sophisticated HyPE model projects that by 2030, worldwide clean hydrogen trade among key regions will surpass 30 million tons of H₂ equivalent (MtH₂eq), accounting for 19% of global consumption [39]. This

The overall market value is set for dramatic expansion, potentially quadrupling from US\$160 billion in 2022 (Markets and Markets, 2022)—a market then entirely dominated by carbon-intensive hydrogen—to an estimated US\$640 billion by 2030, and further rocketing to US\$1.4 trillion by 2050 (Bernhard Lorentz et al., 2023).

Interestingly, between 2030 and 2040, market value growth (projected at less than 1% constant annual growth) is expected to lag behind volume growth (9% constant annual growth), primarily due to significant cost reductions stemming from the massive scale-up of green hydrogen production. Market growth in value terms is anticipated to stabilize somewhat between 2040 and 2050 as productivity improvements begin to plateau (Figure 6) (Bernhard Lorentz et al., 2023).

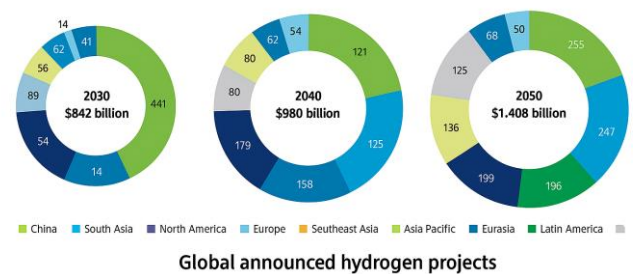


Fig. 6. Green hydrogen market size (US\$ billion per year), 2030 to 2050. Source: Deloitte analysis based on the HyPE model.

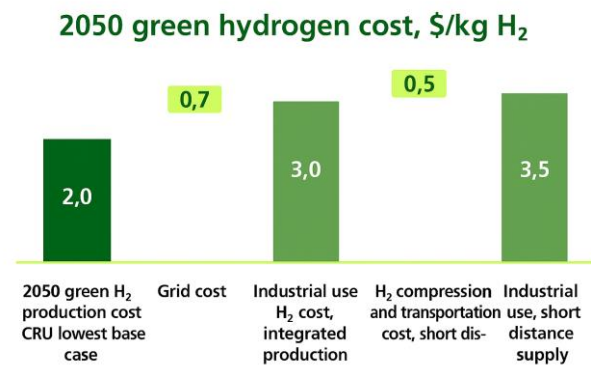


Fig. 7. The total green hydrogen cost to a typical end-user Source: CRU hydrogen cost Model

B. Navigating the Economics: The Cost of Green Hydrogen Production

- The production cost of green hydrogen is a complex interplay of several critical variables, including geographical location, the prevailing cost of renewable energy inputs, and the capital expenditure associated with electrolysis equipment. Achieving the ambitious target of \$2 per kilogram for green hydrogen by 2050, even for facilities situated in prime renewable energy locales, remains a significant challenge, as per CRU's hydrogen cost model. This benchmark necessitates a 50–70% reduction from current cost levels, contingent upon a 50% decrease in renewable energy costs and a dramatic 75% drop in the capital cost of electrolysis systems [40]. Factoring in storage, compression, distribution, and electricity network connection costs, CRU anticipates the total delivered cost of green hydrogen to a typical end-user to range between \$3–7 per kilogram (in 2022 prices) by 2050 (Figure 7). This implies that, on a global average, green hydrogen may still command a premium over blue or gray hydrogen derived from fossil gas in 2050, even when accounting for carbon pricing mechanisms [39]. As mentioned in the next text;
- Egypt is a key player in the green hydrogen market, with several major projects planned in the Suez Canal Economic Zone. Topping the list is the Suez Canal Economic Zone Globeleq Phase II project with a plant normalized capacity of 0.57 million metric tons per year (mt/year). Following closely behind are several other projects in the same region. These include the Suez Canal Economic Zone Masdar Phase II at 0.48 million mt/year, the Ocean Energy SCZ H2 project with a capacity of 0.4 million mt/year, and the Fortescue Future Industries Egypt H2 project at 0.35 million mt/year. The list continues with the Suez Canal

C. The Genesis of Hydrogen: Production Sources and Diverse Pathways

Hydrogen, the universe's most abundant element, can be manufactured from a spectrum of renewable or non-renewable natural feedstocks and energy sources through a variety of sophisticated pathways, as depicted in Figure 8.

Green Hydrogen: The pinnacle of sustainable production, green hydrogen is derived exclusively from renewable feedstocks (primarily water) and sustainable energy sources like wind and solar power. Its production and subsequent use are characterized by zero harmful emissions. It represents a truly sustainable and secure energy vector, with the requisite power for electrolysis generated by clean electricity. While the ultimate goal for a climate-positive future, achieving widespread, cost-effective green hydrogen production remains a practical work in progress [19, 36, and 37].

Blue Hydrogen: Produced from non-renewable resources (such as fossil fuels and hydrocarbons) or even renewables, blue hydrogen is classified as low-carbon due to the integration of CCUS processes designed to capture and store the co-produced carbon [7, 19, 20, 26, and 37].

Gray Hydrogen: This common form of hydrogen is produced from feedstocks like coal, heavy oil, and naphtha, which possess high carbon-to-hydrogen ratios. Conventional gasification processes, requiring pure oxygen or steam to react

Economic Zone Masdar Phase I project at 0.32 million mt/year, followed by the East Port Said LORIC Hydrogen Hub at 0.3 million mt/year. The Suez Canal Economic Zone KK Power project has a planned capacity of 0.25 million mt/year. The list also features a significant project from a neighboring country: the Helios Green Fuels (Neom) project in Saudi Arabia at 0.22 million mt/year. This highlights the region's broader push towards becoming a hub for green energy.

Crucially, the cost of green hydrogen production in the MENA region is demonstrably lower than in Europe (Temmerberg and Kaltschmidt, 2019). S&P Global Platts analyses indicate that green hydrogen production will be more cost-effective than blue hydrogen in key Gulf nations like Saudi Arabia, the UAE, Qatar, and Oman, primarily due to the region's lower energy costs [42]. Qatar emerges as a potential leader in low-cost renewable hydrogen, with an estimated production cost of just \$2.62 per kilogram, closely followed by Saudi Arabia, Oman, and the UAE. In Egypt, the cost of producing hydrogen in Hurghada using wind energy is cited at US\$4.4/kg [36]. Ambitious projects underscore this trend, such as the NEOM green hydrogen project in Saudi Arabia, which aims to produce 240,000 metric tons per year of renewable hydrogen by 2026, backed by \$8.4 billion in financing from 23 financial institutions (S&P Global Commodity Insights, 2023). The Middle East is forecasted to produce 18.15 million metric tons of hydrogen by 2030, exporting one million metric tons, predominantly low-carbon and renewable hydrogen. By 2040, the region is envisioned to lead global clean hydrogen production at 28 million metric tons, with exports reaching 6.28 million metric tons [42].

with these feedstocks at high temperatures, yield a mixture of carbon monoxide (CO) and hydrogen, typically in a CO:H₂ ratio range of 1.6–1.8 [37].

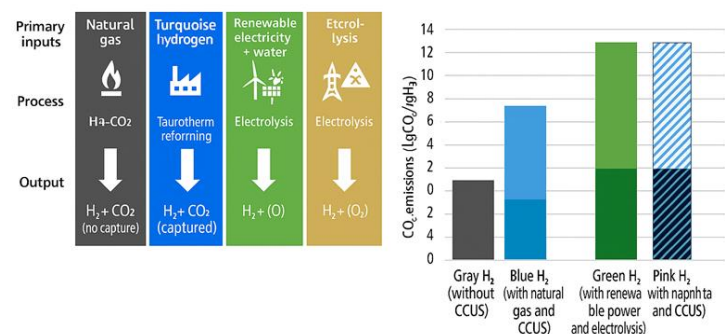


Fig. 8. Different hydrogen (a) production pathways and (b) the estimated cost of blue, grey and Green hydrogen production. Reprinted with permission [14, 36, and 37].

D. The Engine Room: Hydrogen Production Technologies

Hydrogen's creation can be achieved through a diverse array of technological approaches, broadly categorized as thermochemical, radiochemical, electrochemical, photochemical, and biochemical processes, as well as innovative integrated systems like electrothermochemical methods. Figure 9 provides a schematic overview of

various hydrogen production technologies correlated with their requisite energy sources [7, 19, 30, 34, 38, and 39].

- Thermochemical Processes: The Incumbent Technologies.

Thermochemical technologies currently dominate commercial hydrogen production. These high-temperature processes include various forms of reforming (steam, partial oxidation, autothermal, plasma, and aqueous phase) and pyrolysis. A critical adjunct to these methods involves additional hydrogen separation and purification units to achieve the high purity levels demanded by many applications [16 and 20]. The current landscape of commercial hydrogen production, as illustrated in Figure 10, is heavily reliant on natural gas (48%), petroleum reforming (30%), and coal gasification (18%), with electrolysis and other renewable sources contributing a mere 4% [40 and 41]. While biomass gasification and solar thermochemical hydrogen production represent emerging renewable thermochemical routes, a significant amount of hydrogen (approximately 3.5 Mt/year) is also produced as a by-product of other hydrocarbon processes, such as the steam cracking of natural gas liquids to obtain light olefins. However, many traditional thermochemical methods suffer from relatively low energy efficiency, high costs, and the imperative need for carbon capture to mitigate their environmental impact [30 and 42].

Thermochemical technologies for hydrogen production can be further classified based on their efficiency, operating temperature, and feedstock requirements, as summarized in the next text **Steam Methane Reforming (SMR)**: steam methane reforming is a process that uses **catalysts** and **external heat** to produce hydrogen. This method is noted for having a specific H₂:CO ratio and is the most efficient of these three processes, with an efficiency of 75–85%. **Partial Oxidation of Hydrocarbons (POX)**: unlike SMR, partial oxidation of hydrocarbons (POX) is a **pure oxidation** process that does not require external heat. It does, however, use **catalysts**. This method is slightly less efficient, with an efficiency of 72–75%, and does not yield a specific H₂:CO ratio. **Autothermal Reforming (ATR)**: autothermal reforming (ATR) is similar to POX in that it is a **pure oxidation** process that uses **catalysts** and does not require external heat. However, it is the least efficient of the three, with an efficiency ranging from 62–75%. It also does not produce a specific H₂:CO ratio [41, 42, and 43]. Three principal methods for producing hydrogen from natural gas include:

Steam Methane Reforming (SMR): Reacting natural gas with steam at high pressure and temperature. Auto-Thermal

Reforming (ATR): Reacting natural gas with both oxygen and steam. **Partial Oxidation of Methane (POM)**: Reacting natural gas with sub-stoichiometric quantities of air or pure oxygen. A comparative analysis of their efficiencies and reaction temperatures reveals that POM generally exhibits the lowest efficiency relative to ATR, while SMR typically boasts the highest efficiency. Consequently, SMR has become the most widely adopted method for industrial hydrogen generation [44, 45, and 46].

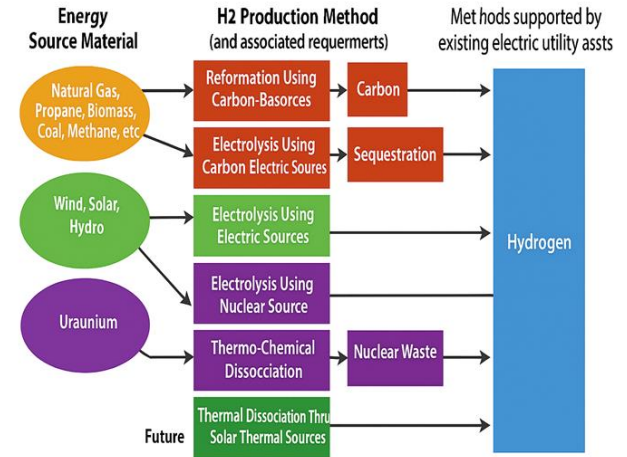


Fig. 9. Diverse hydrogen production technologies and their energy sources. Reprinted with Permission [39].

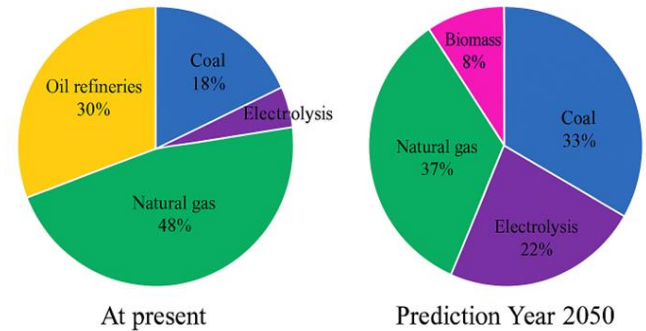


Fig. 10. Chart of hydrogen production from different resources. Reprinted with permission [40]

particularly in decentralized, off-grid paradigms. A paramount concern is the Levelized Cost of Hydrogen (LCOH), a metric that exhibits considerable flux, intricately tied to geographical nuances and the specific renewable energy wellsprings tapped—be it the radiant energy captured by photovoltaic (PV) systems or the kinetic power harnessed by wind turbines. A granular understanding of these cost dynamics is not merely academic; it is fundamental to rigorously evaluating the economic viability of nascent hydrogen ventures and ensuring their intrinsic competitiveness in a burgeoning market.

IV. NAVIGATING THE LABYRINTH: DEFINING THE CORE CHALLENGES IN GREEN HYDROGEN ECONOMICS

The global quest for net-zero emissions places renewable energy at its cornerstone, with green hydrogen emerging as a linchpin technology, celebrated for its unparalleled advantages in long-duration storage and versatile transportability. Yet, unlocking this immense potential hinges critically on navigating the complex economic terrain of its production,

A significant lacuna in contemporary evaluations is the pervasive reliance on static, often generalized, interest rates that inadequately capture the granular tapestry of country-specific investment risks. Such oversimplification can precipitate misleading LCOH calculations, thereby obscuring the authentic economic landscape and potentially misdirecting strategic investments. To rectify this, a far more sophisticated financial lens is indispensable—one that meticulously integrates regional economic climates and inherent investment perils. Pivotal financial arbiters, including the imputed interest rate (IIR) and the country-specific Weighted Average Cost of Capital (WACC), exert a profound influence on LCOH. Their precise assessment is therefore non-negotiable for any credible evaluation of hydrogen production's cost-competitiveness.

Beyond the intricacies of production economics, the formidable cost of transporting hydrogen, whether through the arterial network of pipelines or via maritime shipping—presents another critical variable in the equation. These logistical expenditures, when compounded by the WACC, significantly shape the ultimate delivered cost of hydrogen to end-users, particularly in distant target markets. Consequently, appraising the competitive stance of imported hydrogen demands a holistic, end-to-end comprehension of these pervasive transport costs. Addressing this confluence of financial and logistical hurdles necessitates the urgent architecting of robust policy frameworks. Such frameworks must be engineered to catalyze investment, streamline intricate regulatory processes, and cultivate vibrant international collaborations to amplify both hydrogen production and its seamless global trade. Furthermore, the comparative analysis of potential hydrogen production sites and the strategic scaling of electrolyzer plant capacities represent a multifaceted challenge, profoundly influenced by a diverse array of technical and economic determinants, and further complicated by the recent pronounced volatility in global energy markets. This inherent complexity underscores the imperative for a meticulous and systematic methodology to proactively manage investment risks and navigate pervasive economic uncertainties. Indeed, a comprehensive, robust evaluation framework is the bedrock upon which informed, strategic decisions regarding hydrogen production and its enduring economic feasibility across varied global locales can be confidently built.

V. EGYPT'S GREEN HYDROGEN HORIZON: A NATION POISED FOR ENERGY LEADERSHIP

Green hydrogen is paramount to Egypt's ambitious decarbonization agenda, serving as the most potent catalyst for transforming the nation's energy sector. This conviction drives urgent research and strategic investment into green hydrogen production technologies, offering a stark counterpoint to the global reliance on fossil fuel reforming, which accounts for approximately 96% of current hydrogen output and significant environmental challenges. In contrast, water electrolysis, currently a minor contributor, offers substantial environmental and strategic benefits. Aggressively scaling this cleaner method, which leverages water as a feedstock and is powered by abundant renewable sources like solar and wind, is critical for achieving Paris Agreement climate objectives. Transparently analyzing hydrogen production costs is essential for gauging its competitive edge, aligning seamlessly with

Egypt's "Vision 2030" to become a regional epicenter for green hydrogen production and export.

A. *Electrolysis Technologies and Renewable Integration*

Water electrolysis is a viable and environmentally sound pathway for pristine hydrogen generation. Commercial electrolyzers primarily utilize Proton Exchange Membrane (PEM), Alkaline Water Electrolyzers (ALK), or Solid Oxide Electrolyzer Cells (SOEC) technologies. Low-temperature PEM and ALK electrolyzers typically require electricity and water heated to around 80 °C, while high-temperature SOEC technology operates optimally with steam at 650–1000 °C. These technologies achieve high purity levels (up to 99.5% for ALK, 99.99% for PEM, and 99.9% for SOEC) with operational efficiencies ranging from 82.5% to 90.0%. PEM electrolyzers offer superior agility in responding to fluctuating loads and rapid start-up, making them particularly synergistic with intermittent renewable energy supplies.

To achieve a truly "green" production cycle, these advanced electrolyzers are intrinsically coupled with renewable energy powerhouses, such as expansive PV solar arrays, strategically sited wind turbines, or integrated hybrid systems. Research consistently shows that the Levelized Cost of Hydrogen (LCOH) is highly sensitive to the chosen power source, with PV and wind emerging as economically promising and environmentally sound options. Egypt, with its extraordinary endowment of intense solar radiation and consistently strong wind patterns, is an ideal crucible for large-scale green hydrogen production, forming a cornerstone for national and global decarbonization efforts.

B. *Egypt's Strategic Imperative and Global Market Dominance*

Leveraging its unique geostrategic position at the crossroads of continents and its profusion of renewable resources, Egypt possesses a remarkable opportunity to spearhead the global green hydrogen market, particularly for exports to Europe. The Suez Canal Region serves as an illuminating case study for assessing local acceptance, infrastructural readiness, and overall project feasibility. Egypt is already leading Africa in the green hydrogen race, with an impressive portfolio of 21 projects underway [Figure 11]. Landmark agreements, such as Scatec's partnership with the Egyptian government, target world-scale facilities producing millions of tonnes of green ammonia annually for export to European and Asian markets. Flagship projects like Masdar Ain-Sokhna (2.3 million tonnes green ammonia/year from 4 GW electrolyzer) and Globeleq's 3.6 GW electrolyzer project at the Suez Canal Economic Zone (SCZONE) further cement Egypt's role as a future leader in the clean energy revolution.

At the vanguard of Egypt's transformative energy agenda, the Ministry of Electricity and Renewable Energy champions the amplified production and strategic exportation of green hydrogen as a paramount national priority. By harnessing its abundant renewable energy endowments, Egypt aims to become a premier global exporter within the burgeoning hydrogen economy. A meticulously orchestrated campaign is underway to cultivate an investment-friendly ecosystem, designed to attract significant domestic and international capital. Robust forecasts herald a remarkable 60% surge in Egypt's green hydrogen sector by 2030 and a staggering quadrupling of its economic footprint by 2050, propelled by

escalating global demand for cleaner energy solutions. Strategically, Egypt is positioning itself to capture a commanding share of the international hydrogen market, with projections indicating a potential sevenfold expansion of this global economy by 2050. Such a dominant posture could translate into a transformative uplift for Egypt's Gross Domestic Product, estimated between \$10–18 billion, while concurrently catalyzing over 100,000 new employment opportunities. This strategic pivot promises to bolster national energy security and significantly curtail reliance on oil imports through increased indigenous hydrogen production and optimized local expertise.

C. *Crafting the Hydrogen Future: National Strategy, Pivotal Alliances, and Scenario Analysis*

Egypt is diligently advancing a comprehensive national strategy for green hydrogen production, fortified with compelling incentives to sharpen its competitive acumen. The government's unwavering political resolve, in collaboration with the European Bank for Reconstruction and Development (EBRD), aims to craft a robust regulatory framework fostering local production, through which Egypt aspires to command an impressive 8% share of global production. Egypt has also proactively forged pivotal international agreements within the Suez Canal Economic Zone, initiating groundbreaking projects for large-scale green hydrogen and green ammonia production. These ventures, representing a colossal total investment of \$83 billion, are projected to collectively yield approximately 7.6 million tons of green ammonia and 2.7 million tons of hydrogen annually.

The exploration of diverse green hydrogen scenarios forms a critical analytical undercurrent in contemporary energy research, involving innovative renewable power sources and advanced water-splitting technologies. Globally, nations like the UK, Malaysia, and China are charting their hydrogen trajectories, with scenarios demonstrating potential cost parity with conventional hydrogen by 2030 and substantial ramp-ups in renewable hydrogen capacity for carbon neutrality. This paper further delineates the adoption trajectory of green hydrogen within the dynamic Middle East and North Africa (MENA) region, with a concentrated focus on Egypt, projecting developments towards 2050. Employing scenario writing, the study navigates the complex challenges and opportunities through two contrasting scenarios: a Best-Case ("Helio-Optima") Scenario, envisioning rapid technological breakthroughs, supportive policies, and robust international collaborations; and a Worst-Case ("Chrono-Stasis") Scenario, encompassing potential impediments like technological stagnation, investment chilling effects, fragmented policies, or subdued market demand. By rigorously exploring these plausible futures, this paper aims to furnish comprehensive, actionable insights for policymakers, industry stakeholders, and researchers dedicated to advancing the transformative green hydrogen sector across the MENA region and globally.

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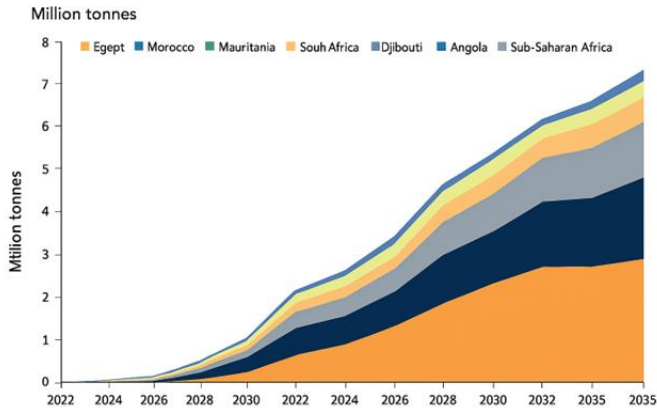


Fig. 11. Green hydrogen production in Africa Source: Rystad Energy, 2023

VI. NAVIGATING THE LABYRINTH: A CRITICAL REVIEW OF THE HYDROGEN LITERATURE

The ascent of hydrogen technologies as a cornerstone of global decarbonization strategies is undeniable, lauded for their unique capacity to integrate fluctuating renewable energy sources and bolster grid resilience. Yet, a meticulous examination of the academic corpus reveals a landscape marked by significant lacunae, particularly when scrutinizing the nuanced dynamics of cost, confronting stark regional disparities, and formulating pragmatic implementation roadmaps.

While pioneering research, such as that by McPherson et al. (1), compellingly underscores hydrogen's potential to harmonize the variability inherent in renewable energy systems, these analyses often remain anchored in the theoretical realm. Concurrently, studies by Kovač et al. (2) and Robles et al. (3) acknowledge the formidable cost and logistical impediments, yet frequently stop short of furnishing tangible, actionable solutions. The intrinsic advantages of hydrogen, such as its remarkable energy density and efficiency, are well-articulated by Aba et al. (4) and Jamal et al. (5); however, their contributions often sidestep rigorous economic evaluations and the critical calculus of storage costs. Similarly, a significant body of work, including insightful contributions from El-Emam and Özcan (6), Frieden and Leker (7), and Lee et al. (8), delves into prospective cost reductions but frequently fails to embed these findings within specific regional idiosyncrasies or overarching policy frameworks, thereby limiting their prescriptive power.

Further explorations into sector-specific challenges yield valuable, albeit often fragmented, insights. Kamran and Turzyński (9) and Rezaei et al. (10) meticulously detail

operational and transportation cost burdens, while Ates and Calik (11) voice legitimate concerns regarding public awareness and acceptance, though without proposing concrete strategies for engagement. The critical questions of scalability and carrier costs are brought to the fore by Fakhreddine et al. (12) and Ratnakar et al. (13), highlighting persistent gaps. Despite the technical depth offered by many studies, including those by Mazloomi and Gomes (14) and Rasul et al. (15), a comprehensive grasp of the broader economic reverberations often remains elusive.

The intricate web of transport-related costs is further unraveled by Ishimoto et al. (16). In parallel, while Abdalla et al. (17) and Faye et al. (18) showcase promising material innovations for hydrogen systems, their analyses frequently do not extend to the crucial aspects of long-term durability or proven real-world applicability under diverse operational stresses. Crucially, research grounded in the Egyptian context, exemplified by the works of Esily et al. (22), Nasser et al. (23), and Youssef et al. (24), consistently confirms a challenging reality: production costs within the nation remain elevated compared to global benchmarks, largely attributable to prevailing logistical hurdles and infrastructural limitations.

More recent scholarly endeavors, such as the comprehensive suite of studies by Raza et al. (37–43) focusing on Pakistan, present sophisticated policy simulations, underscore energy security co-benefits, and explore smart grid integration pathways. Nevertheless, the potent insights from these contributions are often circumscribed by static modeling assumptions and a conspicuous lack of granular economic detail, particularly pertinent for underdeveloped or off-grid regional contexts. Other influential authors, including Benalcazar and Komorowska (35), He et al. (36), and Kim et al. (46), investigate innovative avenues such as biomass-derived hydrogen and the integration of direct air capture technologies; yet, these too frequently overlook the formidable challenges of tailoring such systems to existing regional infrastructure and achieving practical scalability.

The literature emerging from 2023–2024 illuminates a growing recognition of substantial investment imperatives alongside encouraging technological strides. For instance, Odenweller and Ueckerdt (44) and Hordvei et al. (45) cast a critical eye on financial chasms and the necessary evolution of policy frameworks within the European context, while Sebbagh et al. (48) and Fehr et al. (50) report commendable technical advancements in direct solar-to-hydrogen conversion systems. Yet, a recurring caveat is that these pioneering studies often remain confined to experimental setups or highly specific geographical locales, thereby curtailing their immediate generalizability and broader applicability.

Despite this commendable progress and the expanding body of knowledge, critical fissures persist in our understanding. These manifest most acutely in accurately charting regional cost variability, rigorously assessing infrastructure readiness, fostering meaningful public engagement, and devising pragmatic strategies for the scalable deployment of hydrogen systems, especially within the unique socio-economic fabric of developing economies. It is precisely against this backdrop of identified needs and prevailing gaps that the current study positions its contribution. By synergizing advanced simulation modeling with nuanced, region-specific data analysis, this research endeavors to bridge these divides. It

aims to architect bespoke policy and technological interventions meticulously designed to enhance cost-effectiveness and amplify scalability, with a particular emphasis on resource-constrained environments. Furthermore, this study undertakes a holistic evaluation of the environmental calculus inherent in hydrogen production, meticulously considering carbon emissions profiles and the sustainability of requisite resources, thereby offering a comprehensive, multi-dimensional assessment of green hydrogen's true viability in the journey towards a decarbonized future.

A. Illuminating the Path Forward: Key Insights and Contributions of This Review

This comprehensive review synthesizes current knowledge and offers significant insights into the burgeoning field of hydrogen energy research, with a particular focus on Egypt's strategic positioning. Key contributions illuminated herein include:

Nuanced Regional Economic Appraisal: A meticulous dissection of green hydrogen production costs across Egypt's diverse governorates, critically evaluating economic viability against the backdrop of localized renewable energy potential and resource endowment.

Sophisticated Integrated Modeling Framework: An exploration of how advanced simulation-based modeling is employed to holistically analyze interdependent variables—including power generation profiles, hydrogen production yields, the Levelized Cost of Hydrogen (LCOH), and CO₂ abatement capacities—thereby offering a potent, data-driven toolkit for strategic national-level hydrogen planning.

Strategic Policy and Infrastructure Roadmapping: A critical examination of the prevailing policy, logistical, and infrastructural landscapes, identifying key challenges and opportunities in deploying green hydrogen technologies, especially for empowering off-grid and historically underserved regions, complete with actionable recommendations.

Global Benchmarking and Competitive Analysis: A comparative assessment that situates Egypt's green hydrogen potential within international standards, providing a clear perspective on the nation's competitive advantages and its promising export prospects in the rapidly evolving global green hydrogen marketplace.

Comprehensive Environmental Impact Assessment: A dedicated evaluation of the profound environmental dividends associated with green hydrogen production in Egypt, including significant carbon emission reductions and optimized resource utilization—aspects often underemphasized in preceding literature—thus highlighting its crucial role in national and global climate action.

VII. SETTING THE STAGE: EGYPT'S COMPELLING TRAJECTORY TOWARDS GREEN HYDROGEN LEADERSHIP

A. The Socio-Economic Tapestry of Modern Egypt: Challenges and Aspirations

Egypt's recent economic landscape has seen moderated GDP growth (from 6.6% in 2022 to 3.8% in 2023) due to import constraints and reduced purchasing power, though unemployment declined to 6.4% in 2022. The nation's energy

matrix remains heavily reliant on fossil fuels, with natural gas comprising 55.1% and oil 36.9% of the total mix, while renewable energy accounts for a modest 5.6%. Transportation (30.8%), industry (24.5%), and the residential sector (22.9%) are the primary energy consumers. Despite achieving universal electricity access in 2016, the dominance of non-renewable sources underscores an urgent need for a strategic pivot towards cleaner alternatives.

B. The Dawn of Green Hydrogen in Egypt: A Nation Poised for Transformation

The prospect of large-scale green hydrogen production presents an exceptional opportunity for Egypt, leveraging its abundant solar and wind resources and existing natural gas reserves for a phased energy transition. Following COP27, Egypt reaffirmed its commitment by signing over 19 Memoranda of Understanding (MoUs) with international partners, aiming to become a pivotal green hydrogen hub for European and Asian markets. This strategy aligns with Egypt's ambitious plan to source 42% of its power from renewables by 2035.

While technical viability is proven, economic feasibility requires deeper scrutiny. Research indicates that prime renewable resource zones like Ras Ghareb can yield economically competitive green hydrogen, with significant large-scale projects already materializing in the Suez Canal Economic Zone and Ain Sokhna through international collaborations. Key challenges include expanding renewable energy capacity, addressing water scarcity (particularly for electrolysis, necessitating desalination), and developing sophisticated hydrogen transportation and storage infrastructure. Despite these hurdles, Egypt actively fosters international collaborations, with European nations and the European Bank for Reconstruction and Development (EBRD) providing substantial political and economic backing, including an US\$80 million allocation for a green hydrogen facility.

Underscoring its dedication, Egypt has proposed a draft law to promote green hydrogen projects through incentives like tax exemptions and financial encouragements for projects securing foreign finance and incorporating local components. The Ministry of Electricity and Renewable Energy is actively evaluating numerous offers from international companies (from the UK, US, Germany, Japan, Italy, and China) for green hydrogen production, often leveraging solar and wind power for seawater electrolysis. These initiatives aim to propel Egypt's green industrial revolution, benefiting carbon-intensive sectors like steel, shipping, chemicals, aviation, and heavy transport.

This strategic pivot is built upon a robust foundation of climate-conscious policymaking. The National Council on Climate Change (NCCC), established in 2015, integrates climate change policies with sustainable development. "Egypt Vision 2030" (2016) provides a national sustainable development agenda, reinforced by Voluntary National Reviews. The "Environmental Sustainability Standards Guide" (2021) prioritizes green financing. Culminating these efforts, the National Climate Change Strategy (NCCS) 2050 (2022) aims for low-emission development, resilience, enhanced climate action governance, green finance promotion, and robust knowledge management, recognizing that energy and agriculture contribute 75% of total GHG emissions.

Egypt's Energy Ecosystem: A Foundation for Green Transformation

Egypt's electricity sector, managed by the Egyptian Electricity Holding Company under the Ministry of Electricity and Renewable Energy, has seen significant improvements since 2014. Electricity production surged by 128% over the past decade, with installed capacity growing from 25,705 MW in 2012 to 58,818 MW in 2021. However, with solar and wind representing only 5% of the total in 2021, decisive action is needed to augment renewable energy's share to mitigate greenhouse gas emissions. Egypt has demonstrated sustained commitment to energy efficiency. The New and Renewable Energy Development and Use Authority (NREA) was established in 1986. The National Energy Efficiency Action Plan (NEEAP) launched in 2012, with a more holistic second phase in 2016, aims to establish Egypt as an energy efficiency hub by embedding energy use efficiency into economic frameworks. The "Integrated and Sustainable Energy Strategy for Egypt 2035" targets an ambitious 42% renewable energy share by 2035. Legislative support includes Law 203 of 2014 (feed-in tariffs for RE), Law 87 of 2015 (liberalizing electricity production), and EgyptERA's Decree 3/2017 (net metering for solar energy, expanded in 2022 to 1000 MW total capacity). These measures foster a competitive energy market, enabling innovative solutions like energy communities.

C. Envisioning Success: Egypt's Green Hydrogen Horizon – "Sands of Sustainability" Realized

By 2050, Egypt is envisioned to be an indispensable linchpin in the global green hydrogen economy, fueled by its geographical and climatic endowments, visionary investments, and progressive policies. The National Strategy for Climate Change 2050 (NCCS 2050), unveiled in 2022, explicitly targets a significant 5-8% share of the worldwide green hydrogen industry, aspiring to capture up to 8% of the global tradable market by 2040. This will be built upon mass-scale green hydrogen production from abundant solar and wind resources.

Transformative policies and investment laws, continually refined, have attracted substantial global capital. A landmark incentive introduced in 2023 offers green hydrogen projects a rebate of 33% to 55% of tax dues. New laws promote green hydrogen refueling stations, desalination plants allocating output to hydrogen, and support for warehousing, transportation, and manufacturing of essential raw materials. Strong partnerships with international financial institutions, particularly within the Suez Canal Economic Zone, further bolster these efforts. The National Green Hydrogen Council coordinates all activities, ensuring effective implementation of the national strategy.

By 2030, Egypt aims to capture 5% of the global hydrogen market, establishing an international export center and solidifying its status as a key regional hub, exporting approximately 10 million tonnes of renewable energy (equivalent) to Europe. By 2040, Egypt is projected to secure an 8% global market share, becoming the undisputed regional center and supplying approximately 50% of the European Union's green hydrogen requirements. By 2050, Egypt is set to become Europe's primary hydrogen source, exporting an estimated 10 million tonnes of renewable energy (equivalent) to the continent. The nation's hydrogen economy is projected to be 400% larger by 2050, with international trade accounting for

25% of its hydrogen supply, consuming seven times the renewable electricity generated in 2020. Achieving a 100% green hydrogen supply chain by this time is projected to result in a staggering cumulative CO₂ emission abatement of 417 gigatonnes. This flourishing industry will catalyze robust economic growth, generate skilled employment, deliver substantial greenhouse gas reductions, and significantly amplify Egypt's competitiveness in the global green energy arena, fostering a diversified and strong economy that uplifts societal prosperity.

VIII. METHODOLOGY

The research employs a holistic mixed-methods approach, integrating quantitative modeling and geospatial analysis to assess the technical, economic, and spatial feasibility of green hydrogen production in Egypt. The methodology is structured into four broad phases: data collection, renewable resource assessment, techno-economic modeling, and spatial and scenario analysis, such that every element of feasibility is tackled methodically.

A. Data Collection

The study starts with the acquisition of both secondary and primary sets of data. The principal variables are solar irradiance (Global Horizontal Irradiance – GHI), wind speed profiles across different altitudes, land use and availability, proximity to developed infrastructure (roads, ports, electrical grid), and access to water resources, particularly seawater for electrolysis. They include national databases such as the Central Agency for Public Mobilization and Statistics (CAPMAS) and the New and Renewable Energy Authority (NREA), and global databases such as the NASA POWER Project and the Global Wind Atlas.

In addition to physical resource data, economic data were collected to estimate the cost of production. These include capital and operating costs of electrolyzers, efficiency levels (specifically for alkaline and PEM types), electricity costs, expected system lifetimes, and current and future hydrogen market prices. These economic data were derived from peer-reviewed journal articles, IEA reports, and industry whitepapers so that the financial data used in the analysis were valid.

B. Renewable Resource Evaluation

This phase evaluates Egypt's renewable energy potential in detail. Solar data on an hourly basis were analyzed using the GHI index, while wind speed data were analyzed using Weibull distribution analysis to predict wind energy potential at different locations. Multi-year meteorological data were used for the analysis to account for interannual and seasonal variability to obtain robust resource estimation. Geospatial mapping was carried out to represent regions of high renewable energy density. Regions such as the Western Desert, Red Sea coastal areas, and Gulf of Suez were identified as primary candidates due to high solar radiation and wind steadiness. Areas were graded based on composite index considering intensity, availability, and proximity to infrastructure.

C. Techno-Economic Modeling

To estimate the Levelized Cost of Hydrogen (LCOH), a discounted cash flow model was constructed. The model

includes capital expenditure (CAPEX), operating expenditure (OPEX), capacity factors, system lifespan (typically 20–25 years), and weighted average cost of capital (WACC). PV-powered electrolysis and wind-powered electrolysis with on-grid and off-grid systems were the two principal configurations to be considered.

Electrolysis systems looked at were alkaline and PEM electrolyzers, with 60–80% efficiency rates. Capacity for hydrogen production in all cases was calculated per installed megawatt, accounting for local renewable energy yield in actual energy. The model also estimates CO₂ avoided emissions compared to conventional hydrogen production from natural gas reforming, providing some indication of environmental benefit.

D. Spatial and Scenario Analysis

A Geographic Information System (GIS) platform was employed for mapping and overlaying the spatial data with a visual and analytical view of Egypt's suitability for green hydrogen development. GIS utilized layers such as renewable resource availability, accessibility to infrastructure, land cover, protected areas, and population density.

Scenario modeling was performed to investigate the impact of variable changes in electrolyzer price, interest rates, and government incentives (tax credits, subsidies). Spatial Multi-Criteria Analysis (SMCA) was also employed to rank regions based on a weighted composite score that includes technical, economic, and environmental criteria. This allowed for the identification of "hydrogen hot zones" that are most likely to facilitate early investment and deployment.

The results of this study show that Egypt possesses high potential to create a competitive and sustainable green hydrogen sector. Based on the evaluation of renewable resources, Egypt ranks among the top in the world in terms of solar irradiance and wind speed. The country's south and east, primarily the Red Sea and Gulf of Suez coastal area, experience solar radiation values always greater than 2,300 kWh/m²/year and wind speeds greater than 8 m/s. This is conducive to the establishment of high-capacity wind and solar farms necessary for constant hydrogen production.

Economically, the estimated Levelized Cost of Hydrogen (LCOH) is in the range of \$2.1–3.4 per kg depending on technology type, site location, and funding structure. These prices are comparable to global averages and are expected to continue decreasing further by 2030 as the cost of renewable energy decreases and electrolyzer performance is optimized. Furthermore, the number of Memoranda of Understanding (MoUs) between the Egyptian government and foreign developers such as Scatec, Siemens, and Maersk also testifies to firm foreign investor belief in Egypt's green hydrogen market potential.

At the social level, public interviews and surveys indicate that while awareness of green hydrogen as a whole is presently fairly low among the general public, most interviewees were supportive of the technology once the environmental and economic benefits had been explained to them. This is a key opportunity for mass education campaigns and for the public to become aware and accept it on a broad societal level.

From an environmental perspective, application of green hydrogen technology in Egypt has the potential to result in as

much as 5.4 million tons of CO₂ avoided per year by 2035, considering total substitution of gray hydrogen use in fertilizer and industrial processes. This is a huge contribution to Egypt's National Climate Change Strategy 2050 and Paris Agreement goals.

IX. DISCUSSION: EGYPT'S GREEN HYDROGEN HORIZON – NAVIGATING TRIUMPHS AND TRIALS

The collective insights from this research powerfully underscore Egypt's emergent and compelling leadership on the global stage as it pivots decisively towards a green hydrogen future. Endowed with a superabundance of renewable energy resources—basking in abundant sunshine and swept by consistent winds—coupled with its geostrategic linchpin position and a flourishing ecosystem of international collaboration, Egypt possesses a formidable bedrock upon which to architect regional epicenters for hydrogen production and export. However, the journey to fully capitalize on this extraordinary opportunity necessitates astute navigation through a landscape of distinct challenges and potential threats, demanding strategic foresight and concerted action.

Technical Imperatives: Forging a Resilient Hydrogen Infrastructure

On the technical frontier, Egypt, much like other nations pioneering the hydrogen economy, must surmount inherent complexities. Paramount among these is the pressing demand for breakthrough, high-efficiency hydrogen storage solutions, the establishment of comprehensive and robust transport networks, and the engineering of an advanced electrical grid. This grid must not only be resilient but also agile enough to harmoniously manage the intrinsic intermittency of Egypt's vast renewable power sources. Without proactive, substantial investment in cutting-edge energy storage technologies and sweeping grid modernization, the laudable ambition of large-scale hydrogen production risks operational bottlenecks, potentially impeding the nation's swift ascent in this sector.

Economic Stratagems: Balancing Investment with Competitive Agility.

Economically, while green hydrogen heralds long-term cost competitiveness, the pathway is paved with the necessity for significant upfront capital deployment. To mitigate investor risk and catalyze rapid, early-stage market uptake, a sophisticated and supportive policy framework orchestrated by the Egyptian state is indispensable. This will likely involve a nuanced blend of fiscal incentives, such as strategic tax alleviations, access to preferential financing mechanisms, and carefully calibrated feed-in tariffs for renewable electricity exclusively dedicated to hydrogen production. Compounding this financial calculus is the dynamic regional theatre, where proactive nations like Saudi Arabia, Morocco, and the UAE are already championing their own expansive green hydrogen initiatives. This competitive landscape underscores the strategic urgency for Egypt to move with alacrity and finesse in securing enduring, long-term export compacts with key European and Asian offtakers, thereby carving out and consolidating its crucial market share. **Societal Blueprint: Cultivating an Inclusive and Skilled Hydrogen Ecosystem**

Socially, the successful weaving of an inclusive and equitable energy transition is intrinsically linked to the vibrant and proactive participation of civil society, local communities, and the nation's educational apparatus. Transparent,

government-led communication strategies will be vital to demystify hydrogen technologies for the populace, fostering broad understanding and societal buy-in. Concurrently, higher education programs must be dynamically re-envisioned and aligned with the emergent skill requirements of this new energy paradigm, mandating specialized curricula in hydrogen engineering, meticulous environmental planning, and sophisticated energy policy formulation. Ultimately, the deliberate and sustained development of human capital—nurturing a highly skilled, indigenous workforce—will serve as the lifeblood, ensuring the long-term vitality and self-sufficiency of Egypt's burgeoning green hydrogen economy for generations to come.

X. CONCLUSION: EGYPT'S GREEN HYDROGEN HORIZON – A NEW ERA OF SUSTAINABLE PROSPERITY

The journey toward a sustainable future hinge on transformative energy solutions, and this manuscript unequivocally positions green hydrogen as the indispensable keystone of this global paradigm shift, with Egypt emerging as a formidable pioneer. Our comprehensive analysis reveals that Egypt's abundant solar and wind resources are not merely assets but the very bedrock for a thriving green hydrogen economy, demonstrating a remarkable system efficiency of 36.71% and an annual yield of up to 216 tons, poised to dramatically slash CO₂ emissions. This is more than a technical triumph; it is a strategic alignment of national ambition, exemplified by the Egypt Green Hydrogen project, where multinational alliances converge to fuse commercial imperatives with the visionary tenets of Egypt Vision 2030, charting a course for sustainable industrialization.

Economically, the trajectory is clear: Egypt's projected hydrogen demand of 6.0 million tons by 2050, underpinned by a competitive Levelized Cost of Hydrogen (LCOH) of approximately \$4.5/kg, signals a robust market poised for exponential growth. Crucially, the inherent challenge of water scarcity, a critical concern for large-scale electrolysis, is met with an innovative and sustainable solution: renewable-powered seawater desalination, ensuring that progress is not merely clean but also resource-responsible.

This study transcends a mere technical review; it is a clarion call, illuminating how a nation, strategically endowed and resolutely committed, can harness its natural advantages to catalyze a global energy revolution. Egypt's burgeoning green hydrogen infrastructure, from integrated PV-Wind systems to pioneering off-grid solutions for remote communities and its strategic position along the Suez Canal for international trade, offers a compelling blueprint. It is a testament to the power of integrated technological, economic, and policy frameworks in forging a truly decarbonized world. The path forward is clear: green hydrogen, championed by nations like Egypt, is not just an energy carrier; it is the very engine of a sustainable, secure, and prosperous future.

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This article does not contain any studies of human participants or animals performed by any of the authors.

CONSENT FOR PUBLICATION

Authors declare their consent for publication.

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